

Synergistic Effects of Coconut Husk Biochar and Palm Fiber on Soil Nitrogen and Phosphorus Dynamics and *Pak Choi* (*Brassica rapa, subsp. chinensis*) Nutrient Uptake

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التأثيرات التآزرية لبيو تشار قشر جوز الهند وألياف النخيل على ديناميكيات النيتروجين والفوسفور في التربة وامتصاصهما بواسطة نبات الباك تشوي (*Brassica rapa subsp. chinensis*)

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Abstract

Sandy loam soil is considered to have a low capacity for water retention, making it highly susceptible to nutrient losses—particularly nitrogen and phosphorus—through leaching. This significantly reduces crop productivity under water-stressed conditions. The availability of nitrogen (N) and phosphorus (P) in such soils is influenced by several factors, including microbial activity and the decomposition of organic matter, which further complicates soil fertility management under limited irrigation systems.

A randomized field study was conducted using four soil treatments under low irrigation (water stress) conditions, with three replications, over a period of 35 weeks. The treatments included: untreated soil (T0) as a control, soil amended with coconut husk biochar (T1), soil amended with palm fibers (T2), and a 50:50 mixture of T1 and T2 at 5% each (T3). Throughout the study, nitrogen and phosphorus levels were measured weekly in both soil and plant tissues to evaluate soil fertility and crop productivity responses.

The results showed that treatment T3 achieved the highest concentrations of nitrogen and phosphorus in the soil, reaching 16 mg/kg for nitrogen and 22.6 mg/kg for phosphorus after the first week, compared to the control treatment (T0). It also produced the highest crop yield at harvest (110 kg), in addition to the highest nutrient content in plant tissues (4.6% nitrogen and 0.65% phosphorus). In contrast, treatment T2 (palm fibers only, as described) showed the weakest performance across all measured indicators, likely due to limited nitrogen mobility within the decomposing organic material.

Overall, the findings indicate that combining coconut husk and palm fibers is an effective strategy for improving nutrient retention in sandy loam soils, thereby enhancing agricultural productivity under conditions of limited irrigation and water stress.

Keywords: : Biochar, palm fiber, nitrogen, phosphorus, sandy loam, Pak Choi, deficit irrigation, soil amendment.

المخلص

تُعد التربة الرملية الرملية من التربة ذات القدرة المنخفضة على الاحتفاظ بالماء، مما يجعلها أكثر عرضة لفقدان العناصر الغذائية الأساسية مثل النيتروجين والفوسفور عن طريق الترشيح المائي، الأمر الذي ينعكس سلباً على إنتاجية المحاصيل الزراعية خاصة تحت ظروف الإجهاد المائي. كما أن توفر هذه العناصر في التربة يتأثر بعوامل متعددة، أبرزها النشاط الميكروبي وتحلل المادة العضوية، مما يزيد من صعوبة الحفاظ على خصوبة التربة في أنظمة الري المحدود. وقد أجريت دراسة حقلية عشوائية باستخدام أربع معاملات تربة مختلفة تحت ظروف ري منخفض (إجهاد مائي)، وبثلاث مكررات، واستمرت لمدة 35 أسبوعاً. شملت المعاملات: تربة غير معدلة (T0) كمجموعة ضابطة، وتربة مضاف إليها قشور جوز الهند (T1)، وتربة مضاف إليها ألياف النخيل (T2)، إضافة إلى معاملة خليط متساوٍ من T1 و T2 بنسبة 5%

لكل منهما (T3) وتم خلال فترة الدراسة قياس تراكيز النيتروجين والفسفور أسبوعياً في كل من التربة وأوراق النبات لتقييم تأثير المعاملات على خصوبة التربة وإنتاجية المحاصيل. وأظهرت النتائج أن المعاملة T3 حققت أعلى مستويات للنيتروجين والفسفور في التربة، حيث بلغت بعد الأسبوع الأول 16 ملغ/كغ للنيتروجين و22.6 ملغ/كغ للفسفور مقارنة بالعينة الضابطة T0، كما سجلت أعلى إنتاجية نباتية عند الحصاد بلغت 110 كغ، إضافة إلى أعلى محتوى غذائي في أنسجة النبات (4.6% نيتروجين و0.65% فسفور). في المقابل، أظهرت المعاملة T2 (ألياف النخيل فقط حسب الوصف) أضعف النتائج في جميع المؤشرات المقاسة، ويرجع ذلك إلى محدودية حركة النيتروجين داخل المادة العضوية المتحللة. وتشير هذه النتائج إلى أن دمج قشور جوز الهند مع ألياف النخيل يُعد استراتيجية فعالة لتحسين احتفاظ التربة الطميية الرملية بالعناصر الغذائية، وبالتالي رفع كفاءة الإنتاج الزراعي في ظروف الري المحدود والإجهاد المائي.

الكلمات المفتاحية: فحم الباي وتشار، ألياف النخيل، التربة الطميية الرملية، مُحسنات التربة، النيتروجين، الفسفور.

1. Introduction

Sandy loams exhibit low water retention capacity and faster drainage that restricts their agricultural potential greatly. These are high permeability soils which predispose them to extreme nutrient leaching under water-limited conditions and they thus have poor fertilizer use efficiency (Rengasamy, 2010). This challenge is even more prominent in arid and semi-arid areas as water scarcity has already limited the capacity for crop production (Lal, 2015).

Nitrogen (N) and phosphorus (P) are primary macronutrients controlling plant growth and productivity. Nitrogen has function in the biosynthesis of proteins, chlorophyll and nucleic acids while phosphorus is also needed for energy transfer, root development and cellular processes (Kirkby, 2012). But these two nutrients are prone to leaching in sandy soils. The after-warning factor of nitrate from drift is pragmatic because it actualizer above below the accomplishment breadth (Cabi et al., 2014), however phosphorus may be impenetrable due to bonding, abandonment or abridgement in size (El Sebai et al., 2016). This leads to persistent nutrient deficiency, requiring regular and expensive fertilizer applications that also cause significant environmental harm (D. et al., 2002).

Biochar, obtained by pyrolysis of organic biomass at low oxygen levels, has been highlighted as a useful amendment to soil structure, high surface area and water retention ability (Lehmann and Joseph, 2024) Coconut husk biochar has revealed positive properties for retention of nutrients and soil hydraulic characteristics in tropical sandy soils more specifically. (Zubairu et al., 2023) Coarse palm fiber, a byproduct from date palm residuals have also been shown to potentially increase soil organic carbon (SOC) accumulation in the long term and better aggregate water retention while enhanced nutrient release is expected post decomposition (Bronick and Lal, 2005) Averaged individually, the benefits of these amendments, however, and their combined effects acting synergistically on N and P dynamics are still poorly understood (Agegnehu and Bird, 2017)

Pak Choi (*Brassica rapa* subsp. Therefore, rapid growing and high in N and P demand characteristic of leafy vegetable make it an ideal candidate for the study of short-term soil amendment effects under controlled conditions (NIKLAS, 1996). This study was conducted to investigate the interactive effects of coconut husk biochar and palm fiber amendment on soil nitrogen and phosphorus dynamics, and their uptake by Pak Choi in pot cultivation under deficit irrigation.

2. Materials and Methods

2.1 Soil Sampling and Characterization

The soil utilized in this study was sandy loam which is defined low water-retaining capacity and higher-permeable material. The texture comprised of 75%, 20% and 5% sand, silt and clay respectively as determined by particle size analysis (sieve + hydrometer). Gravimetric field capacity (FC), wilting point (WP) and saturation hydraulic parameters were measured according to standards established by Bouma (2016). Hydraulic characterization was assisted by a column vadose chamber. Soil pH and electrical conductivity (EC) were determined with

a HANNA HI 9829 multiparameter meter on soil-water extracts, with neutral to moderately alkaline pH of 6.60 and moderate EC of 232 $\mu\text{S}/\text{cm}$ respectively. The constant head method was used to measure saturated hydraulic conductivity (K), which was 0.0033 cm s^{-1} and demonstrated high soil permeability.

2.2 Coconut Husk Biochar Preparation

Biochar was produced from coconut husks which is an agricultural waste product widely available in the South of Vietnam. In particular, husks were washed and rinsed multiple times with deionized water to remove surface contaminants and air-dried at room temperature for 48 h to lower moisture content. Subsequently, an oxygen-limited slow pyrolysis was performed at 500°C for 2 hours with use of a laboratory-scale retort under (Lehmann and Joseph, 2024). After pyrolysis, the biochar was air-cooled to room temperature ($23 \pm 1^\circ\text{C}$), ground and passed through a sieve with a particle size of <2 mm so that it could be homogeneously mixed with soil. The prepared biochar was kept in hermetically sealed bags in dry condition until application.

2.3 Palm Fiber Preparation

The date palms residues, particularly palm fronds were gathered as agricultural by-products or wastes during years 2024 to 2026. The collected material was washed with tap water to remove adhering dust and impurities, then air-dried at room temperature in a laminar flow hood for 48 h to reduce moisture content. Then the dried palm fronds were prepared into 1–3 cm pieces to become homogeneous with the soil matrix. The conditioned palm fibre was stored in a room with low humidity at room temperature before use. The range of the size and preparation method were chosen to enable mixed treatment-five fractionation within all samples in the same manner.

2.4 Experimental Design

An experiment was performed in a pot trial to study the effect of biochar and palm fibers application on water retention capacity of soil and growth performance of *Pak Choi* (*Brassica rapa subsp. chinensis*) under water-stress conditions. It was arranged in completely randomized design (CRD), where 4 treatments were installed:

T₀ (Control): Unamended soil.

T₁ (Biochar): Soil amended with 5% (w/w) coconut husk biochar.

T₂ (Cocos Fiber): Soil amended with 5% (w/w) palm fiber.

T₃ (Co-amendment): Soil amended with 5% (w/w) biochar and 5% (w/w) palm fiber.

All the amendments were finely mixed with soil to let every single particle blend into soil correctly. Each treatment was replicated three times (total 12 experimental units). In this study, homogeneous volumes of prepared soil mix were placed in standard plastic pots. Seeds of *Pak Choi* were sown in all pots and seedlings were thinned to one plant per pot after germination for uniform plant density.

2.5 Irrigation and Growth Conditions

All treatments were performed under controlled environmental conditions. The pots were kept at ambient temperature of 25–30°C under natural sunlight appropriate for *Pak Choi* cultivation. A deficit irrigation regime was performed for simulating limited soil moisture, by the manual application of a fixed volume (200 mL) of water per pot every 48 h during the experimental period. The salinity of irrigation water was low at approximately 1.0 dS m^{-1} as EC (Table 1). All treatments received uniform irrigation to eliminate moisture heterogeneity from soil amendment sources. Great care was taken to prevent over watering and allow for even water application among all experimental units.

2.6 Measurements and Analysis

2.6.1 Plant Growth Parameters

Pak Choi Growth Every week during the experimental period, plant growth was observed to determine the effect of soil amendments on *Pak Choi* growth under water-limited conditions. The measurement was done are plant height (cm) and number of leaves per plant weekly only when seedlings had developed 2-3 true leaves. Finally, we assessed fresh biomass (g) and dry biomass (g) 35 days after sowing at harvest. Plant samples were oven dried at 70°C to obtain dry biomass at harvest. The measurement schedule enabled the assessment of both temporal growth dynamics and final yield response to the soil amendments.

2.7 Statistical Analysis

SPSS software (version 26.0, IBM Corp., USA) was used to subject all data to one-way analysis of variance (ANOVA). Both one-way analysis of variance (ANOVA) with post-hoc Tukey's Honest Significant Difference (HSD) test at the level of $p \leq 0.05$ were used to compare treatment means. Results are presented as mean standard error (SE) of three replicates. The figures and graphs were generated utilizing Microsoft Excel 2019.

3. Result and discussion

3.1 Dynamics of Soil Available Nitrogen (N)

In six-week experiments, soil available N concentrations differed among treatments throughout the duration of the experiment ($p \leq 0.05$). Across every week, the combination treatment T₃ (biochar + palm fiber) had consistently higher N concentrations than any of the treatments tested and obtained a peak N concentration of 16 mg/kg in Week 1 only compared to an unamended control T₀ that reached only 6 mg/kg (Table2; Fig. 1). The marked superiority of T₃ is explained by synergistic mechanisms between the two amendments: biochar plays a role in reducing leaching losses of ammonium ions (NH₄⁺) through adsorption to its negatively charged surface, while palm fiber contributes organic nitrogen to the soil via mineralization (El-Naggar et al., 2019; Maçik et al., 2020).

Although T₁, treatment among all treatments studied, fed pure biochar (with 0% and no N added; data not shown) performed significantly better than the control in terms of maintaining a higher level of bioavailable N continuing from Weeks 1 to 2 wherein the level at this point was statistically identical with values obtained at these times for treatments T₂ and T₃, by Week 6 it had decreased from levels of 10 mg/kg total water-soluble nitrogen present in soil following submerged incubation during Wks. This pattern is consistent with the short-term nitrogen retention ability of biochar, especially for more fertilizer-rich deficit irrigation, where low leaching conditions of sandy loam soils largely ameliorated a well-known drawback of decoction due to its weak N-holding capacity (Che et al. 2022). Conversely, T₂ (palm fiber alone) exhibited a relatively small and erratic increase in N over T₀ (N = 2–8 mg/kg), indicating that mineralized N contained in palm fiber was prone to rapid leaching losses without the buffering effect of biochar (Ganji and Andert 2023). Soil N in all treatments showed a similar declining trend during the experiment from Week 2 onwards, which could be explained by plant uptake of N and continuing lack of external inputs. The much higher N retention in T₃ during the experimental period suggests an interactive effect between biochar and palm fiber, which is consistent with (Schirmel et al., 2016)

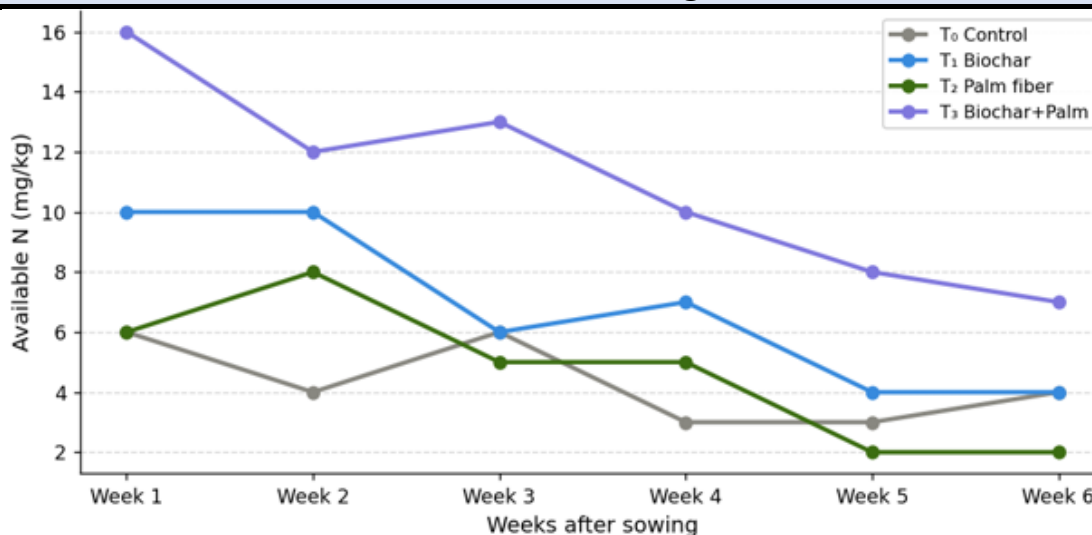


Fig. 1: Weekly soil available nitrogen (N mg/kg) under the four amendment treatments over six weeks.

Table 2: Weekly soil available nitrogen (N, mg/kg) under different soil amendment treatments.

Week	T ₀ Control	T ₁ Biochar	T ₂ Palm fiber	T ₃ Biochar+Palm
1	6	10	6	16
2	4	10	8	12
3	6	6	5	13
4	3	7	5	10
5	3	4	2	8
6	4	4	2	7

Values are means of three replicates. Significant differences among treatments at $p \leq 0.05$ (Tukey's HSD).

3.2 Dynamics of Phosphorus (P) Available in Soils

Soil available P showed a trend somewhat similar to that of nitrogen, with T₃ registration the higher values in all sampling weeks (Table 3; Fig. 2). The concentration of Available P in T₃ peaked at 22.6 mg/kg during Week 1, an increase of 151% compared to the T₀ value (9 mg/kg). This large increase in P availability under the combined treatment likely reflects several interacting mechanisms. Biochar has been found to increase soil pH slightly and create phosphate complexes, which bind to biochar surface structures that resist the fixation by soil minerals (Cheng et al. 2020; Qin et al. 2023), while palm fiber provides P albeit through organic decomposition.

For T₁ (biochar alone), P concentration was significantly more elevated as compared with control over the course of the experiment, ranging from 6 to 14 mg/kg. This supports earlier studies describing biochar's ability to reduce phosphorus sorption into soil minerals, thus increasing the availability of this nutrient for plant uptake (El-Naggar et al. 2019). In Weeks 1–2, palm fiber treatment T₂ exhibited marginally higher P values than T₀ (12 mg/kg vs. 6 mg/kg) and then, over time, reduced to similar levels thereby indicating that using 10% w:w of commercial palm fiber alone did not appear to help the sandy matrix efficiently hold

released P from ongoing fiber decomposition without biochar also being added. The drop in P observed in all treatments from Week 3 onwards reflects progressive plant uptake as well as the intrinsic nature of sandy loam soils to leach OCP. The long-term P availability during the T₃ period compared to other treatments further demonstrates that utilizing a blend of biochar and organic fiber amendments is an effective approach to enhance P retention efficiency under moisture deficit conditions (Hou et al. 2020).

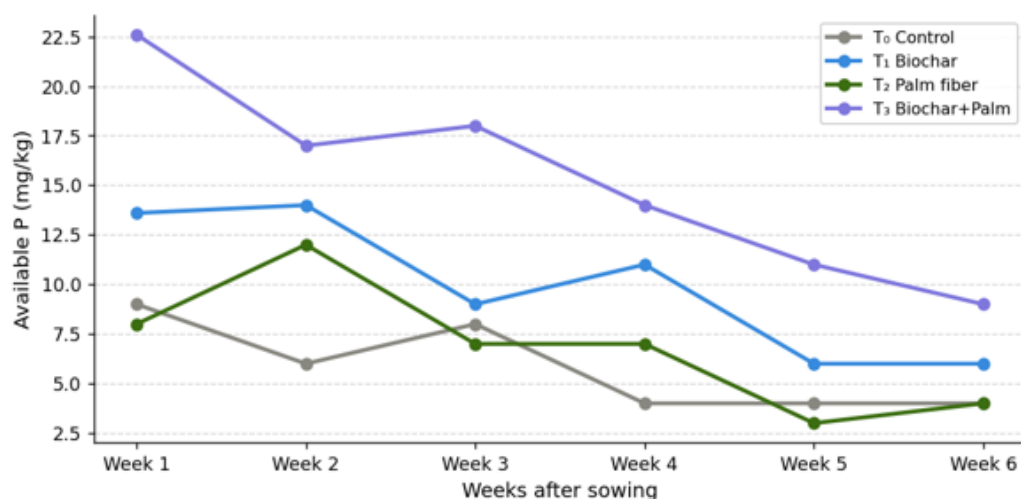


Fig. 2: Weekly soil available phosphorus (P mg/kg) under the four amendment treatments over six weeks.

Table 3: Weekly soil available phosphorus (P, mg/kg) under different soil amendment treatments.

Week	T ₀ Control	T ₁ Biochar	T ₂ Palm fiber	T ₃ Biochar + Palm
1	9	13.6	8	22.6
2	6	14	12	17
3	8	9	7	18
4	4	11	7	14
5	4	6	3	11
6	4	6	4	9

Values are means of three replicates. Significant differences among treatments at $p \leq 0.05$ (Tukey's HSD).

3.3 Plant Growth Performance

3.3.1 Plant height and leaves number

Throughout the 6-week experiment Plant height and leaf number consistently rose off of the starting value across all treatments (week 1 v. week 6). At harvest, treatment T₃ emerged as consistently taller than the remaining treatments, producing plants 15 cm in height compared with 11 cm in T₀, 14 cm in T₁ and a mere 6 cm in T₂ (Table 4; Fig. 3). The better growth of T₃ is directly related to the soil nutrient availability and moisture retention supplied by the

combination of biochar with palm fiber added to it, with T₃ showing higher soil N and P concentrations during most assessment periods. Interestingly, in every single sampling T₂ (solely palm fiber) produced the smallest plants and had least number of leaves compared with all other treatments. The lack of an immediate increase in available N during the first 35 days after treatment could be explained by immobilization that often occurs upon decomposition of high C:N ratio organic amendments (van der Merwe et al. 2020).

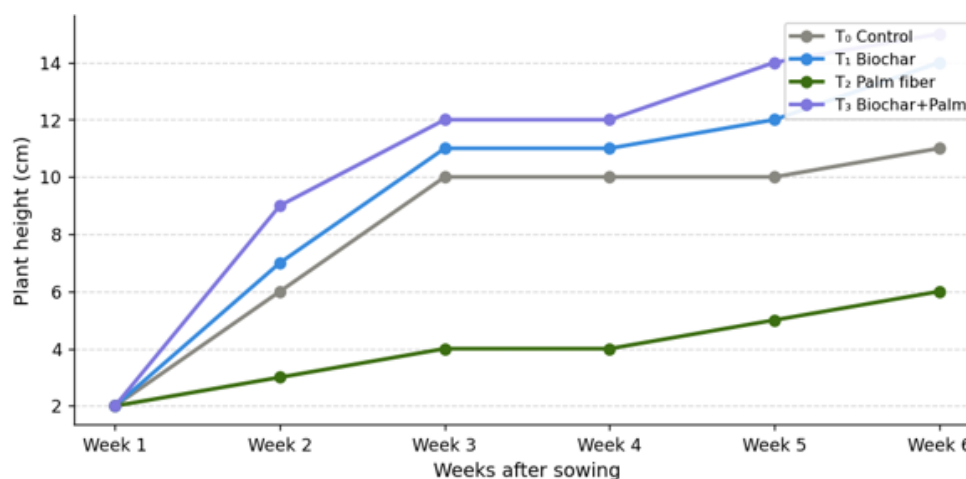


Fig. 3: Weekly plant height (cm) of Pak Choi under the four amendment treatments over six weeks.

Table 4: Weekly plant height (cm) and number of leaves of *Pak Choi* under different soil amendment treatments.

Week	T ₀	T ₁	T ₂	T ₃
1	2	2	2	2
2	6	7	3	9
3	10	11	4	12
4	10	11	4	12
5	10	12	5	14
6	11	14	6	15

Values are plant height (cm), means of three replicates.

3.3.2 Biomass production

Some treatment differences were significant both in fresh and dry biomass at harvest (Day 35) Fig. 4. The fresh biomass (g) and dry biomass (g) of T₃ was higher than that of the other groups, with 110 g and 11.5 g, respectively, followed by T₁: 85 g fresh; 8 g dry; T₀: 55 g fresh; 6 g dry; T₂: 40 g fresh; 4.4 g dry. Fresh biomass of T₃ was 100% more than the control, illustrating the important agronomic advantage of a combined amendment in under water-limited conditions in accordance with (Yao and Jiang 2021). The lower biomass in T₂ relative to the unamended control supports our hypothesis that undecomposed palm fiber may immobilize nitrogen temporarily, particularly during the early growth stages of fast-growing brassica crops.

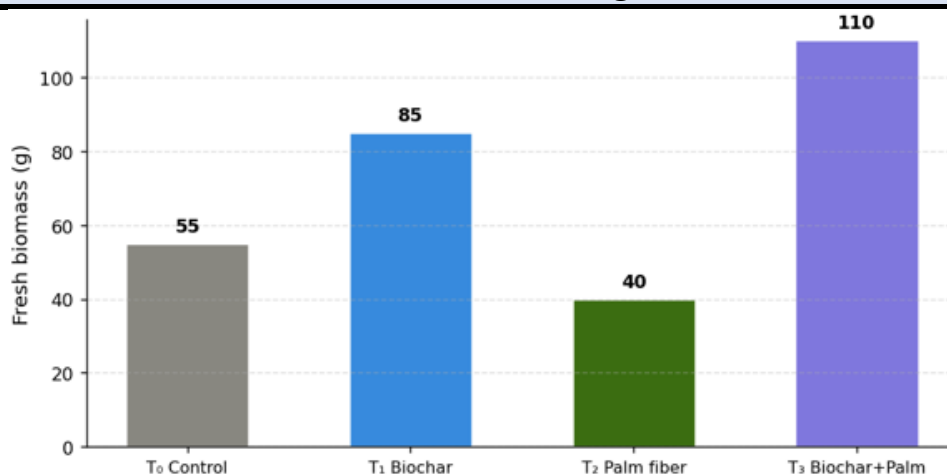


Fig. 4: Fresh biomass (g) of Pak Choi at harvest under the four amendment treatments.

3.4 Nutrient content of pak choi tissue at time of harvest

At harvest, plant tissue analysis demonstrated significant differences in N and P concentrations among treatments (Table 5; Fig. 5 and Fig. 6). T₃ had a greater tissue N content (4.6%) than controls (3.2%), and T₁ (4.0%) by 44% and 15%, respectively. In a similar manner, tissue P content was also maximal in T₃ (0.65%), followed by T₁ (0.55%), T₀ (0.45%) and minimal in T₂ (0.40%). These results affirm that the combined amendment increased both soil N and P availability and their actual uptake and assimilation by the Pak Choi plant, leading to an improved nutritional quality of harvested crop.

The consistently lower concentrations of tissue N and P in T₂ than the control further support the conclusion that palm fiber applied alone as an amendment under conditions of short-term water stress can negatively impact nutrient availability through nitrogen immobilization from decomposition. In T₃, the synergistic combination of biochar and palm fiber seems to prevent this effect by the ability of biochar to provide a stable reservoir of pre-adsorbed nutrients that can offset any short-term N tie-up associated with fiber decomposition (Agegnehu, Srivastava, and Bird 2017)

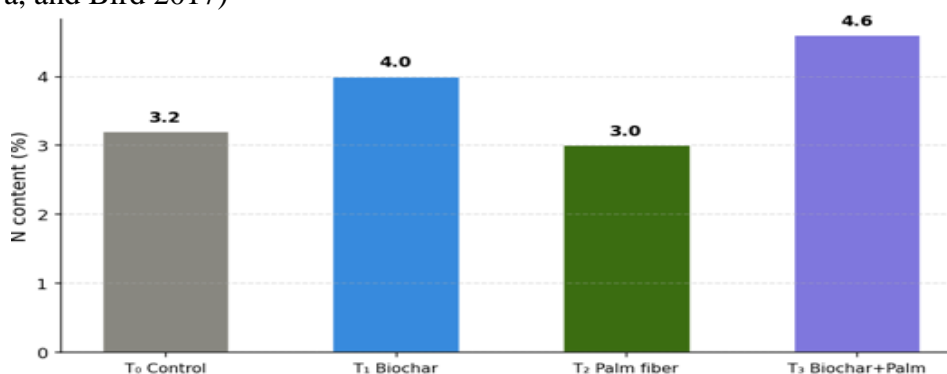


Fig. 5: Nitrogen content (%) in Pak Choi tissue at harvest under the four amendment treatments.

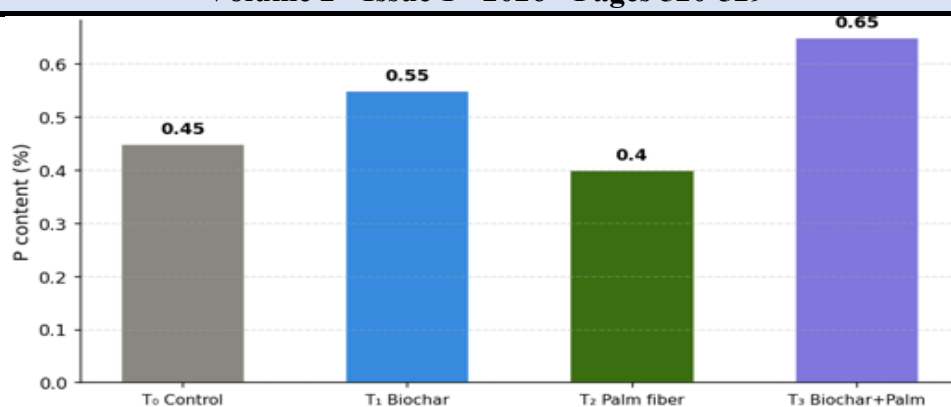


Fig. 6: Phosphorus content (%) in Pak Choi tissue at harvest under the four amendment treatments.

Table 5: Nutrient content in *Pak Choi* tissue at harvest (dry weight basis).

Treatment	N (%)	P (%)	K (%)
T ₀ Control	3.2	0.45	3.0
T ₁ Biochar	4.0	0.55	3.8
T ₂ Palm fiber	3.0	0.40	2.8
T ₃ Biochar+Palm	4.6	0.65	4.5

Values are means of three replicates. Significant differences among treatments at $p \leq 0.05$ (Tukey's HSD).

Conclusion

Result of this study showed that with the combination treatment of coconut husk biochar and palm fiber (T₃); soil nitrogen and phosphorus availability increased significantly, inside *Pak Choi* in deficit irrigation on sandy loam soil contributed to higher biomass production and nutrient uptake. The combined treatment significantly outperformed every other treatment in all measured parameters during the whole 35-day experiment, achieving fresh biomass of 110 g, tissue N and P concentrations (4.6% and 0.65%, respectively) that were each a 100%, 44%, and a 44% improvement over the unamended control. The improvements were statistically meaningful when compared with control even by adding of Biochar alone (T₁), indicating the individual benefit to use Biochar as an amend in water-stress condition in light-textured soil. Palm fiber used as a sole amendment (T₂) consistently lagged behind even the unamended control treatment, demonstrating the potential for short-term nitrogen immobilization in high C:N ratio materials when applied without an accompanying stabilizing amendment like biochar. The beneficial interaction between biochar and palm fiber demonstrates a sustainable management strategy for soil currently limited by sandy soils, water availability and reliance on synthetic fertilizers, particularly in arid and semi-arid environments. Both materials are locally available agricultural by-products, making its co-application economically feasible and environmentally appropriate. To further confirm and generalise the results from this study, future research needs to examine optimal application rates, long-term field scale responses as well as performance of these mixed amendments across crop species/soil types.

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