APST

Asia-Pacific Journal of Science and Technology

https//:www.tci-thaijo.org/index.php/APST/index

Published by Research and Innovation Department,
Khon Kaen University, Thailand

Morphophysiological response of iceberg lettuce (*Lactuca sativa* L.) to rice hull biochar

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Received 15 April 2025
Revised 7 August 2025
Accepted 2 October 2025

Abstract

Global food insecurity necessitates innovative, localized solutions to improve agricultural resilience, particularly in sloped or marginal lands where conventional farming is limited. This study evaluated the morphophysiological response of iceberg lettuce to varying concentrations of rice hull biochar in a raised-bed system under highland agro-ecological conditions in the Philippines. A randomized complete block design with three replications was implemented, testing five treatments: conventional practice, raised-bed with growing media (RBGM), and RBGM amended with 5%, 10%, and 15% rice hull biochar. Morphological parameters, chlorophyll content, and yield components were measured across two cropping cycles. Statistical analysis revealed that biochar-amended systems significantly improved head size, plant vigor, chlorophyll content, and dry matter yield compared to the control. The 5% and 15% biochar treatments consistently outperformed the conventional and unamended systems, with the latter yielding the largest head sizes in the second cropping cycle, suggesting both immediate and residual effects. The findings underscore the potential of rice hull biochar as a cost-effective, sustainable amendment that enhances soil properties and crop productivity in household-scale gardening systems. This study contributes to the growing body of evidence supporting biochar's role in regenerative agriculture, especially for resource-constrained settings, and offers practical recommendations for strengthening food self-sufficiency through home-based production.

Keywords: Iceberg lettuce, Morphophysiological response, Rice hull biochar, Raised bed gardening, Sustainable home gardening, Soil amendment

1. Introduction

Despite significant advancements in agricultural technology and food distribution, global food insecurity persists as a critical challenge in the modern era [1]. This problem is rooted in systemic vulnerabilities—including economic disparities, limited access to arable land and water, and population pressures—and is further intensified by disruptions in interconnected supply chains caused by conflicts, extreme weather, or price shocks [2]. In regions such as Southeast Asia, Latin America, and Sub-Saharan Africa, where many communities depend on subsistence farming, geographic constraints like sloping and mountainous terrain hinder sustainable production. For instance, in the Philippines, as in Nepal, Rwanda, and Peru, steep landscapes exacerbate soil erosion, restrict irrigation, and limit access to infrastructure and support services [3,4].

In response to growing food insecurity, home gardening has re-emerged as a strategic and decentralized food production approach. From urban allotments in Europe to backyard gardens in Africa and Southeast Asia, households are turning to mixed cropping systems to supplement their food supply and reduce reliance on unstable markets [5]. These systems typically integrate vegetables, fruits, herbs, and sometimes small livestock, offering a low-cost, accessible, and ecologically sustainable food source.

However, widespread adoption of home gardens in marginal environments requires adaptive solutions. One such approach is the use of raised-bed gardens, particularly in sloped or degraded areas. Raised beds improve soil drainage, facilitate crop management, and extend the growing season—key advantages in challenging agro-ecological zones. More importantly, they allow for the customization of the growing medium, enabling experimentation with locally available inputs to enhance soil fertility and plant growth.

Biochar, a carbon-rich byproduct of pyrolyzed organic matter (e.g., crop residues, rice hulls, and wood), has gained increasing attention as a sustainable soil amendment. Its porous structure improves soil aeration and water retention while enhancing nutrient availability [6]. As soil degradation continues to threaten global food security, particularly due to declining organic carbon levels [7], biochar represents a promising intervention—especially in areas where synthetic inputs are either too expensive or environmentally unsustainable.

Among potential feedstocks, rice hulls stand out as particularly relevant for this study. They are one of the most abundant agricultural residues in rice-producing countries, yet are often underutilized or disposed of through open burning, contributing to environmental pollution. Converting this readily available biomass into biochar not only provides a sustainable waste management option but also creates value from what is otherwise an environmental burden. Moreover, rice hull biochar is distinguished by its high silica content, which contributes to improved soil structure, reduced bulk density, and enhanced nutrient-use efficiency. Its inherent porosity further promotes water retention and cation exchange capacity, making it especially suitable for improving the productivity of degraded or marginal soils. These properties make rice hull biochar an attractive candidate for smallholder farming systems, where resource constraints limit access to costly synthetic inputs.

Nevertheless, the practical application of rice hull biochar in real-world smallholder or household settings remains underexplored. Because biochar's physical and chemical characteristics vary significantly depending on feedstock type and pyrolysis conditions [8], localized studies are essential to determine its actual performance and feasibility under specific agroecological and socioeconomic contexts.

Iceberg lettuce (*Lactuca sativa* L. var. *capitata*), a popular crisphead variety cultivated worldwide, is favored for its crunchy texture and mild flavor [8]. It is commonly consumed raw in salads and sandwiches and is widely valued for its commercial potential. Nutritionally, iceberg lettuce is a source of dietary fiber, folate, and vitamin C, and is low in calories, fat, and sodium [9]. It is also prized for its short growing cycle and adaptability, making it suitable for small-scale and household-level cultivation [10]. In Southeast Asian highlands, studies have demonstrated that lettuce productivity and phytochemical content can be influenced by irrigation levels and cultivation techniques [11]. As consumer preferences shift toward fresh, health-promoting foods, optimizing iceberg lettuce cultivation in alternative systems, especially in non-traditional and marginal areas, becomes increasingly important.

This study was conducted under the agro-ecological conditions of a highland province in the Philippines to evaluate the morphophysiological response and yield performance of iceberg lettuce grown in raised-bed gardens amended with varying levels of rice hull biochar. The research aims to contribute to the global discourse on food security and sustainable home gardening, particularly in sloped terrains where conventional farming practices are not feasible. By examining how rice hull biochar influences the growth of iceberg lettuce, this study seeks to offer evidence-based insights into improving household food production and enhancing the resilience of localized food systems.

2. Materials and methods

The study utilized various materials and instruments, including lettuce seeds, a digital weighing scale, and standardized data recording sheets for accurate documentation. For the growing medium, a mixture of garden soil and organic amendments—namely coco peat, chicken manure, and rice hull biochar—was prepared. The rice hull biochar was obtained from a specialized facility to ensure uniformity in pyrolysis parameters and the resulting biochar quality. In addition, a Soil Plant Analysis Development (SPAD) 502 Chlorophyll Meter was employed to non-destructively assess chlorophyll content in lettuce leaves, serving as an indicator of plant health and photosynthetic performance. Morphological measurements such as plant length were recorded using a vernier caliper to ensure precision in data collection.

The experimental site, located at coordinates 8°36.59′ N latitude and 124°52.87′ E longitude, sits at an elevation of approximately 580 m above sea level (masl). Geologically, the area is primarily composed of volcanic flows overlaid by pyroclastic materials, with scattered basaltic andesite boulders and cobbles commonly found throughout the site. Alluvial deposits are confined to areas near watercourses, indicating localized sediment deposition influenced by hydrological activity.

The dominant soil type in the region is classified as Jasaan Clay. Soils in the lower elevation zones tend to be acidic, with pH values ranging from 3.9 to 5.2. In contrast, soils in the highland areas exhibit similar pH levels but are considered moderately fertile, which makes them suitable for certain crop production systems.

2.1 Experimental Design and Treatments

Implemented for two cropping seasons, the study employed a Randomized Complete Block Design (RCBD) with three replications to assess the effects of various agricultural production systems on iceberg lettuce. A total of 15 experimental plots were established, each measuring 1.2 m × 2.5 m (3.0 m²). The plots were spaced 1.0 m apart, with a 1.5 m distance between replications to reduce edge effects and facilitate operational tasks, including fertilizer application, data collection, harvesting, and labeling. This arrangement ensured uniform growing conditions and allowed for reliable comparisons of treatment effects across all experimental units.

The experimental treatments included five agricultural production systems: (T1) Conventional Farmer's Practice, (T2) Raised Beds with Growing Media, and (T3–T5) Raised Beds with Growing Media amended with 5%, 10%, and 15% rice hull biochar, respectively. The iceberg variety of lettuce was selected as the test crop for this study. The concentrations of biochar was based on the optimum level as presented by the results Majidi [12] where 5% RHB was found to improve the yield of leafy vegetables. This served as the reference for the additional 5 levels in the higher concentrations.

2.2 Biochar Production

In this study, rice hull biochar (BC) was sourced from a specialized charcoal production facility utilizing the pyrolysis process. The rice husks underwent pyrolysis at temperatures ranging from 350°C to 500°C for approximately 5 to 7 hours, with an anticipated recovery rate of 50% from the initial feedstock. The production process employed traditional open-type carbonization methods, where combustion was initiated using wood, dried leaves, and used paper or newspapers.

Pyrolysis was carried out in a clean, dry, and level area, preferably shaded by trees, during the early morning or late afternoon hours to ensure both safety and optimal conditions. An open-type carbonizer was positioned over the fire, and fresh rice hulls were layered on top. Each charring batch consisted of 2 to 3 sacks of rice husks. After 20 to 30 minutes, or when the top layer of rice hulls began to burn, the entire mound was continuously mixed from the bottom to the top to promote uniform carbonization. Once the rice hulls had turned uniformly black, water was applied to extinguish the fire and prevent over-burning, thus avoiding conversion into ash. The freshly carbonized rice hulls (CRH) were then allowed to cool completely before being used as a soil amendment.

2.3 Cultural Management

Cultural management practices were meticulously implemented to promote optimal growth and performance of the lettuce crop across varying production systems. The process began with mechanical field clearing using a rotavator, followed by manual leveling of the plots and incorporation of the growing media mixtures. These mixtures, which included varying proportions of chicken dung, coco peat, garden soil, and carbonized rice hull (CRH), were tailored to the specific biochar treatment levels.

Seedlings were initially sown in seedling trays and nurtured in a nursery until they reached 14 days of age, at which point they were transplanted into the prepared plots. The transplanting process was carried out with a spacing of 30 cm both between rows and within rows, ensuring uniform plant distribution across all treatment replicates.

To support healthy growth, consistent water management was maintained throughout the growing period, with plants being watered twice daily during dry spells. Fertilizer application was limited to the plots following the farmer's conventional practice, using 250 g of complete fertilizer per bed. Weed control was managed manually, with regular uprooting of unwanted plants to minimize competition.

During harvest, plants were manually uprooted, sorted into marketable and non-marketable categories, and weighed to assess yield and treatment performance. These thorough cultural management practices ensured the reliability of the data and the efficacy of the production systems being evaluated.

2.4 Data Collection and Analysis

To assess the growth and productivity of lettuce under varying treatments, several parameters were recorded, including crown size (polar and equatorial length), plant vigor, relative chlorophyll content, dry matter yield, yield per plant (both marketable and non-marketable), and return per peso investment. These indicators provided a comprehensive evaluation of the morphological, physiological, and yield responses of the crop to the different agricultural production systems and biochar amendment levels.

In determining the significance of treatment effects, the collected data were analyzed using analysis of variance (ANOVA) in SPSS software. In cases where the assumptions of normality and homogeneity of variance were not met, square root transformation was applied to certain datasets. Treatment means were compared using the Tukey test at a 5% significance level, facilitating the identification of statistically significant differences among the treatments.

3. Results and discussion

3.1 Soil and Biochar Chemical Properties

Table 1 presents the chemical properties of soils subjected to different treatments, including the application of rice hull biochar at varying concentrations (5%, 10%, and 15%). The addition of biochar resulted in notable improvements in key soil chemical properties, particularly in terms of available phosphorus, exchangeable potassium, and soil pH.

Table 1 Chemical properties of the soil.

Treatments	Soil Chemical Properties				
	Organic matter (%)	Total Nitrogen (%)	Available Phosphorus, ppm	Exchangeable Potassium, ppm	pH
GS	4.1	0.205	25	636	5.01
RB + GM (1:1:.25 GS+CCP+CD)	4.3	0.215	171	620	6.76
RBGM + 5% Biochar	4.3	0.215	144	3225	6.68
RBGM + 10% Biochar	4.2	0.210	147	3000	6.37
RBGM + 15% Biochar	4.2	0.210	148	3100	6.59

Compared to the control treatment (GS), which recorded only 25 ppm of available phosphorus and a relatively low pH of 5.01, all biochar-amended treatments exhibited significantly higher phosphorus levels (ranging from 144 to 148 ppm) and increased pH values (from 6.37 to 6.68). The increase in soil pH indicates the liming effect of biochar, which is beneficial in ameliorating soil acidity. Exchangeable potassium levels also improved markedly, reaching values above 3000 ppm across all biochar treatments, with the highest level (3225 ppm) observed in the 5% biochar treatment. These enhancements are crucial for improving soil fertility and nutrient availability, especially in acidic or degraded soils. The consistent values of organic matter (4.2–4.3%) and total nitrogen (0.210–0.215%) across treatments suggest that the biochar did not significantly alter the total C or N content in the short term. However, the substantial improvements in phosphorus and potassium availability, as well as the neutralization of soil pH, indicate enhanced nutrient retention and cation exchange capacity brought about by the biochar's physicochemical properties.

To supplement the characterization of the biochar, reference was made to closely similar studies conducted in the Philippines by Villegas-Pangga [13] and Mon et al. [14], which utilized comparable pyrolysis conditions and feedstock type. According to these studies, rice hull biochar typically possesses a surface area of 78.208 $m^2\ g^{-1}$ and a well-developed pore structure, with high porosity and the presence of both fine and coarse cellulosic structures. These features contribute to a high BET surface area, which is indicative of enhanced adsorption capacity. The reported pH value of the biochar is 7.3, slightly lower than that of rice straw-derived biochar, suggesting a near-neutral to mildly alkaline nature. Electrical conductivity (EC) was recorded at 856.3 $\mu S\ cm^{-1}$, indicating the presence of soluble salts and mineral ions. The biochar was found to contain relatively low organic carbon (5.4%) but was enriched with essential plant nutrients, including potassium (K), calcium (Ca), magnesium (Mg), silicon (Si), chlorine (Cl), and aluminum (Al), with a notably high silica content. The carbon-to-nitrogen (C:N) ratio was measured at $0.9 \pm 0.02 : 5.4 \pm 0.09$, indicating low carbon stability but potential for immediate nutrient interaction upon soil application. These physicochemical properties provide a contextual understanding of the material's behavior in soil and may explain the differential effects observed at varying biochar concentrations in this study.

3.2 Agro-climatic Characteristics

Agroclimatic conditions during the experimental period (March–April) show trends in weekly maximum and minimum temperatures and rainfall distribution. The temperature profile indicates relatively stable maximum temperatures ranging from approximately 26°C to 30°C and minimum temperatures between 19°C and 21°C across the duration of the experiment. These thermal conditions fall within the optimal temperature range for iceberg lettuce growth, which is typically 15–20°C for vegetative development and up to 26°C for head formation. The stable temperatures during the study period likely minimized thermal stress and provided conducive conditions for evaluating the effects of rice hull biochar on the morphophysiological traits of lettuce.

Rainfall patterns, on the other hand, were intermittent and low. Significant rainfall was recorded only in Week 4 of March (≈8 mm), Week 1 of April (≈2 mm), and Week 4 of April (≈14 mm), while Weeks 2–3 of April received no rainfall at all. This implies that much of the crop's water requirement during the study period may have been met through irrigation or was subjected to moisture stress in specific weeks. The erratic rainfall emphasizes the importance of soil amendments like biochar, which are known to improve soil water retention and reduce water loss through percolation and evaporation.

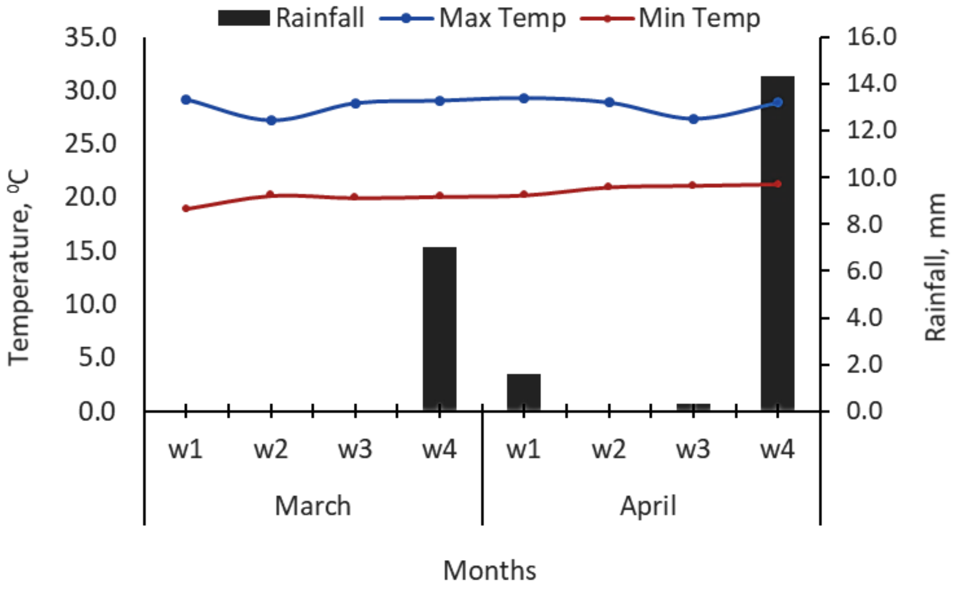

Figure 1 Agrometeorological data during the conduct of the study.

Given the rice hull biochar's high porosity and capacity for enhancing soil moisture retention—as noted in earlier discussions—its application likely mitigated the negative effects of temporary dry spells, particularly during rainless weeks. The improved soil water-holding capacity would have ensured more consistent moisture availability for the lettuce, potentially improving physiological responses such as turgor maintenance, stomatal conductance, and overall vegetative growth. Thus, the prevailing agroclimatic conditions during the study, marked by optimal temperatures and inconsistent rainfall, underscore the relevance of the biochar treatment. The results from the morphophysiological parameters observed in the study can be more confidently attributed to the biochar's effects, as the environmental conditions remained relatively stable in temperature but variable in water availability.

3.3 Head Size

The results presented in Table 2 demonstrate the significant influence of rice hull biochar on the head size of iceberg lettuce under different cropping cycles and orientations in a highland agro-ecological setting. The inclusion of biochar in the growing media substantially improved lettuce head size across all treatments compared to control groups using garden soil alone or a non-biochar amended raised-bed growing media (RB + GM). These findings support earlier studies that highlight biochar's role in enhancing soil structure, increasing water retention, and improving nutrient availability—all of which are critical for leafy vegetable growth [15].

Table 2 Effect of rice hull biochar on the head size of lettuce.

Treatments	Head Size (cm)			
	Polar		Equatorial	
	FC	SC	FC	SC
GS	12.26b	11.51c	21.27b	21.65b
RB + GM (1:1:.25 GS+CCP+CD)	20.50a	14.90b	38.73a	32.26a
RBGM + 5% Biochar	22.52a	15.21ab	39.40a	32.84a
RBGM + 10% Biochar	22.32a	14.78b	31.53a	31.45a
RBGM + 15% Biochar	21.10a	15.76a	39.40a	32.70a
F-test	**	**	*	**

Means in a column with common letter are not significantly different at 5% level of significance, Tukey
*Significant at a level of 5% probability ($p < .05$); ** Significant at a level of 1% probability ($p < .01$)
GS - Garden Soil; GM - Growing Media; CCP – Coco Peat; CD – Chicken Dung

During the first cropping (FC), the smallest lettuce heads were observed in the GS treatment, with a mean polar size of only 12.26 cm. This underscores the limitations of unamended soil in supporting optimal plant growth under marginal conditions, particularly in sloped or degraded areas where soil fertility and moisture retention are typically poor. In contrast, the highest head size (22.52 cm) was observed in the RBGM treatment with 5% biochar, followed closely by 10% and 15% biochar treatments. These improvements can be attributed to the enhanced porosity and cation exchange capacity of biochar, which facilitate better nutrient uptake and root development [16]. A similar pattern was observed in the second cropping (SC), although the mean head sizes were slightly lower across treatments, indicating potential nutrient depletion. Nonetheless, the RBGM with 15% biochar still produced the largest heads (15.76 cm), suggesting a residual or cumulative effect of biochar in maintaining soil productivity across cropping cycles.

Further, the GS control again yielded the smallest head equatorial sizes in both FC (21.27 cm) and SC (21.65 cm). Meanwhile, the RBGM treatments—especially those amended with 5% and 15% biochar—showed dramatic increases in head size, reaching 39.40 cm in both the FC and SC. These results illustrate how biochar, in synergy with organic amendments like coco peat and chicken dung, can create a highly productive microenvironment for lettuce cultivation. The porous nature of biochar allows for better moisture regulation, which is particularly beneficial in conditions where evaporation and nutrient leaching could otherwise be problematic [17]. Interestingly, the 10% biochar treatment produced slightly lower values compared to the 5% and 15% levels, suggesting that while moderate levels of biochar are beneficial, excessive application may lead to nutrient imbalances or changes in soil pH that could inhibit optimal growth [16].

3.4 Phenotypic Traits and Vigor Index

Figure 2 illustrates the effects of rice hull biochar (RHB) application on the phenotypic traits of iceberg lettuce across five different production systems (T_1 to T_5), observed over two cropping seasons. (A) displays the physical appearance of the lettuce harvested under each treatment. The visual contrast is immediately evident plants under treatments T_4 and T_5 appear larger, with more developed leaves and more extensive root systems compared to T_1, which displays visibly smaller, less vigorous plants. This visual observation is supported by quantitative data in Panels B and C, which present boxplots of vigor indices for FC and SC, respectively.

In the first cropping season (B), T_1 shows the lowest vigor index values at 28.81. This is statistically distinct from treatments T_2 to T_5, all of which are labeled "a" based on Tukey's test, indicating significantly higher vigor indices in the range 40.83 to 44.40. These results suggest that even minimal inclusion of RHB in the production system leads to a substantial improvement in plant vigor. The non-significant differences among T_2 to T_5 imply that increasing the amount or complexity of the RHB treatments beyond a certain threshold does not yield additional benefits during the first cropping cycle. These outcomes are consistent with studies that highlight how biochar enhances soil properties such as nutrient retention, and water-holding capacity, all of which contribute to improved plant health and growth [18].

In the second cropping season (Panel C), similar trends persist. Treatment T_1 again shows the lowest vigor index at 20.16, significantly different from T_2 to T_5, which have vigor indices ranging from approximately 28.63 to 30.76. The sustained advantage of the biochar-amended treatments across seasons underscores the long-term efficacy of RHB. This residual effect likely results from the biochar's stability in soil, which allows it to continue influencing physical and chemical properties over time, thereby supporting continued plant vigor even without additional applications. Such findings align with a study [19] which reported the long-lasting impact of biochar on soil improvement and crop performance.

The uniformity in performance among T_2 to T_5 in both cropping cycles has important practical implications. It suggests that lower doses or simpler application methods of RHB may be sufficient to attain optimal plant vigor, thereby minimizing input costs while maximizing output. This is particularly significant for smallholder farmers and sustainable agriculture programs where resource efficiency is a priority. Given the abundance of rice hulls as an agricultural byproduct in many rice-producing regions, including Southeast Asia, converting them into biochar and incorporating them into soil management strategies provides a circular, low-cost solution to enhancing horticultural productivity.

Moreover, the consistent positive impact of RHB across cropping seasons suggests potential benefits for climate resilience. Biochar's ability to enhance soil water retention and buffer against environmental stressors such as drought or nutrient leaching makes it a valuable amendment in the context of climate variability [18]. These properties are particularly beneficial for leafy vegetables like iceberg lettuce, which are sensitive to soil moisture fluctuations and nutrient availability. The observed increase in vigor under RHB treatments is therefore not only indicative of improved soil fertility but also of enhanced system stability and resilience.

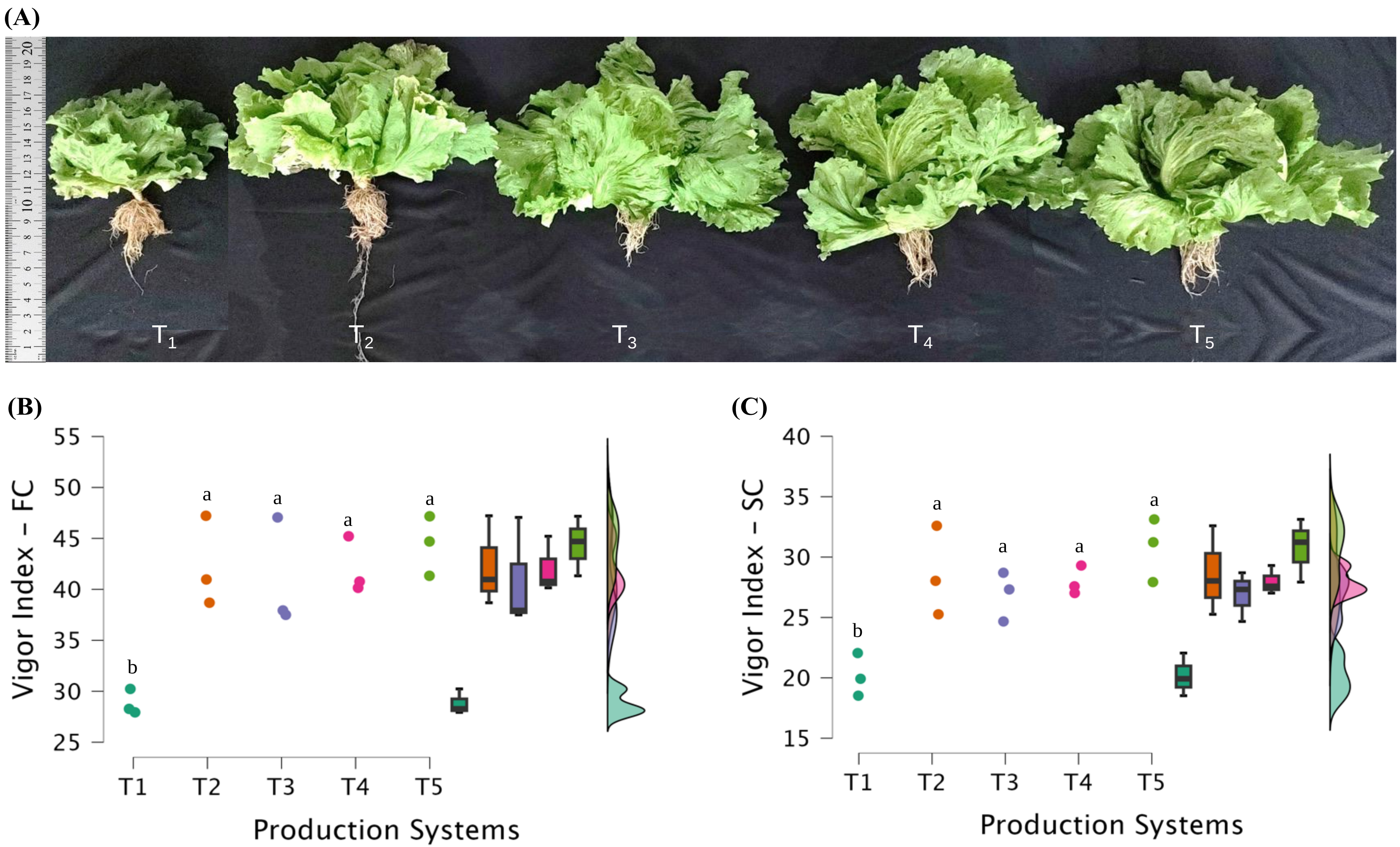

Figure 2 The effect of rice hull biochar on the phenotypic traits of iceberg lettuce (A). Values are the mean vigor of each plant. The RHB treatment was shown on the horizontal axis where a significant (*p<0.05)* difference was observed for both cropping seasons (B) and (C). Letters on each plot indicated differences between production systems in Tukey test.

3.5 Physiological Characteristics

Considering the relative chlorophyll content during the first cropping, the control group (GS) exhibited the highest value (33.46a), which was statistically significantly higher than all other treatments. The RB + GM mixture alone (28.86b) and its biochar-amended versions (RBGM + 5% Biochar: 28.26b; RBGM + 10% Biochar: 28.47b; RBGM + 15% Biochar: 27.11b) showed statistically similar, but lower, chlorophyll content compared to the control. This suggests that the initial substrate mixture, while potentially providing other benefits discussed later in dry matter yield, might have initially led to slightly reduced chlorophyll production compared to plain garden soil. This could be attributed to factors such as nutrient availability in the amended substrates that might have temporarily affected nutrient uptake necessary for chlorophyll synthesis [20].

Table 3 Physiological characteristics of lettuce in response to biochar.

Treatments	Relative Chlorophyll Content		Dry Matter Yield (g)	
	FC	SC	FC	SC
GS	33.46a	22.05	16.23d	17.38c
RB + GM (1:1:.25 GS+CCP+CD)	28.86b	21.65	24.02c	48.37a
RBGM + 5% Biochar	28.26b	22.70	30.82b	41.67b
RBGM + 10% Biochar	28.47b	21.08	21.77c	37.72b
RBGM + 15% Biochar	27.11b	21.22	34.18a	47.55a
F-test	**	ns	**	**

Means in a column with common letter are not significantly different at 5% level of significance, Tukey
ns – nonsignificant (*p*>0.05) ; ** Significant at a level of 1% probability (*p* < .01)
GS - Garden Soil; GM - Growing Media; CCP – Coco Peat; CD – Chicken Dung

However, the trend shifted in the second cropping (SC) for relative chlorophyll content. The F-test indicated no significant differences (ns) among the treatments. This implies that the effects observed in the first cropping diminished over time. The relative chlorophyll content across all treatments in the second cropping was generally lower than in the first cropping. This could be due to various factors, including nutrient depletion in the soil over successive cropping cycles if not adequately replenished, changes in soil physical and chemical properties, or even seasonal variations affecting plant physiology [21]. The fact that the biochar amendments did not significantly impact chlorophyll content in either cropping season, and the initial reduction in FC was not sustained in SC, suggests that biochar's influence on chlorophyll production in lettuce under these specific conditions might be minimal or indirect.

Examining the dry matter yield, a more pronounced and positive impact of the biochar amendments becomes evident, particularly in the second cropping. In the first cropping, the RB + GM mixture alone (24.02 g) significantly increased the dry matter yield compared to the control (16.23 g). This highlights the potential benefits of the organic-rich substrate mixture in promoting plant growth. The addition of 5% biochar (30.82 g) further significantly enhanced the dry matter yield compared to the RB + GM alone, indicating a positive effect of biochar at this concentration in the first cropping cycle. However, increasing the biochar concentration to 10% (21.77 g) resulted in a yield comparable to the RB + GM alone, suggesting a potentially non-linear or even inhibitory effect at higher concentrations during the first cropping. Interestingly, the highest biochar application rate of 15% (34.18 g) led to the highest dry matter yield in the first cropping, significantly outperforming all other treatments. This suggests a complex interaction between biochar concentration and its effects on lettuce growth in the initial cropping cycle.

The benefits of biochar became even more apparent in the second cropping for dry matter yield. The RB + GM mixture (48.37 g) already showed a substantial increase in yield compared to its performance in the first cropping, potentially indicating improved soil conditions or nutrient availability over time. The addition of biochar further augmented this effect. While 5% biochar (41.67 g) resulted in a significant increase compared to the control (17.38 g), the highest dry matter yield in the second cropping was achieved with the 15% biochar amendment (47.55 g), which was statistically similar to the RB + GM alone. The 10% biochar application (37.72 g) also showed a significant improvement over the control. The consistent positive trend of biochar, especially at higher concentrations, in enhancing dry matter yield in the second cropping strongly suggests that biochar's beneficial effects on soil properties, such as improved water retention, and nutrient availability (through increased cation exchange capacity), accumulate over time, leading to better plant growth and biomass production in subsequent cropping cycles [21].

The significant F-test results for dry matter yield in both cropping seasons underscore that the different treatments had a statistically significant impact on lettuce biomass production. The varying responses to biochar concentration across the two cropping cycles highlight the importance of considering the long-term effects of soil amendments. While the initial impact on chlorophyll content was minimal or even slightly negative with the RB + GM mixture, the substantial and often increasing positive effects of biochar on dry matter yield, particularly in the second cropping, indicate its potential as a valuable soil amendment for sustainable agriculture. The optimal biochar application rate might vary depending on the specific crop, soil type, and cropping system, as evidenced by the different yield responses to varying biochar concentrations in this study. Further research could explore the underlying mechanisms responsible for these observations, such as nutrient dynamics, and plant physiological responses over extended periods.

3.6 Yield and Economic Parameters

Table 4 reports marketable yield per plant (g), non-marketable yield per plant (g), and the return on expenses (in Philippine Pesos - Php) for each treatment in both cropping seasons. In the first cropping, the marketable yield per plant demonstrated a significant positive response to the amended substrates. The control group exhibited the lowest marketable yield (86.67 g), significantly lower than all other treatments. The RB + GM mixture alone showed a substantial increase in marketable yield (297.83 g), highlighting the benefits of the organic-rich growing medium. The incorporation of biochar further enhanced the marketable yield, with the highest yield observed at the 15% biochar amendment (425.00 g), which was statistically superior to all other treatments.

Table 4 Yield and economic performance of iceberg lettuce under varying levels of biochar amendments.

Treatments	Marketable Yield per Plant (g)		Non-Marketable Yield per Plant (g)		Return on Expenses (per Php)	
	FC	SC	FC	SC	FC	SC
GS	86.67d	113.73d	126.00c	83.87c	2.35d	0.8c
RB + GM (1:1:.25 GS+CCP+CD)	297.83c	299.33c	253.33a	343.33a	34.77c	28.35b
RBGM + 5% Biochar	346.67b	526.67b	265.00a	290.00ab	40.38b	27.78b
RBGM + 10% Biochar	335.00b	623.33a	223.33b	273.33b	38.75b	26.56b
RBGM + 15% Biochar	425.00a	633.33a	261.67a	256.67b	49.12a	31.57a
F-test	**	**	**	**	**	**

Means in a column with common letter are not significantly different at 5% level of significance, Tukey
** Significant at a level of 1% probability ($p < .01$)
GS - Garden Soil; GM - Growing Media; CCP – Coco Peat; CD – Chicken Dung

The 5% (346.67 g) and 10% (335.00 g) biochar amendments also resulted in significantly higher marketable yields compared to the RB + GM alone and the control, suggesting a dose-dependent positive effect of biochar on marketable yield in the first cropping cycle. This could be attributed to biochar's ability to improve soil physical properties like aeration and water retention, as well as enhance nutrient availability, leading to better plant growth and development of marketable heads [22].

The trend of enhanced marketable yield with amended substrates continued into the second cropping, with even more pronounced effects. The control group's marketable yield increased slightly (113.73 g) but remained significantly lower than all other treatments. The RB + GM mixture maintained a high yield (299.33 g). However, the biochar amendments showed remarkable increases in marketable yield in the second cropping. The 5% biochar amendment resulted in a yield of 526.67g, the 10% amendment yielded 623.33g, and the 15% amendment also produced the highest yield at 633.33 g (statistically similar to the 10% biochar). This substantial increase in marketable yield in the second cropping with biochar application suggests that the long-term benefits of biochar on soil health and fertility become more prominent over time. Biochar's persistent influence on nutrient cycling, water holding capacity likely contributes to sustained and improved plant productivity in subsequent cropping cycles [23].

Regarding the non-marketable yield per plant, the first cropping showed the highest non-marketable yield in the control group (126.00 g), significantly higher than all other treatments. The RB + GM mixture (253.33 g) also showed a relatively high non-marketable yield. The addition of biochar tended to reduce the non-marketable yield, with the lowest non-marketable yield observed at the 10% biochar amendment (223.33 g), although the differences among the biochar-amended treatments were not always statistically significant. This suggests that the improved growing conditions provided by the organic mixture and biochar might lead to a higher proportion of the plant biomass being allocated to marketable yield rather than non-marketable parts.

In the second cropping, the non-marketable yield generally decreased across all treatments compared to the first cropping. The control group showed a reduction to 83.87 g. The RB + GM mixture also saw a decrease to 343.33 g. The biochar-amended treatments exhibited lower non-marketable yields, with the 15% biochar amendment having the lowest (256.67 g). While the statistical differences were present, the overall trend suggests that the benefits of the amended substrates, particularly with biochar, contribute to a more efficient production of marketable yield over non-marketable biomass in the long term.

The return on expenses (per Php) provides a crucial economic perspective on the different treatments. In the first cropping, the control group had a very low return (2.35), reflecting its poor yield performance. The RB + GM mixture significantly improved the return (34.77). The biochar amendments further increased the return on expenses, with the 15% biochar amendment yielding the highest return (49.12), significantly better than all other treatments. The 5% (40.38) and 10% (38.75) biochar amendments also showed substantial economic benefits compared to the control and the RB + GM alone.

The economic benefits of biochar became even more pronounced in the second cropping. While the return on expenses for the control group remained low (0.8), all other treatments showed improved returns. The RB + GM mixture yielded a return of 28.35. The biochar-amended treatments demonstrated the highest economic returns, with the 15% biochar amendment leading (31.57), statistically similar to the 5% (27.78) and 10% (26.56) amendments. The consistently higher return on expenses with biochar application across both cropping cycles underscores its economic viability as a soil amendment for iceberg lettuce production. The enhanced yields, particularly the marketable portion, directly translate to increased revenue, outweighing the cost of biochar application in the long run.

The overall cost structure of the study further supports the economic feasibility of the biochar treatments. The primary expenses in Philippine pesos (Php) included: nails (Php 300), iceberg lettuce seeds (Php 250), bamboo poles for constructing raised beds (Php 2,880), and land preparation labor (Php 4,000 for 2 persons over 5 days). Additional costs included sowing labor (Php 300), cocopeat (Php 300.60), chicken dung (Php 590.40), and carbonized rice hull biochar (Php 162). These expenses reflect typical inputs for smallholder vegetable production under organic or semi-organic systems.

Among these, the biochar cost remained modest in relation to its contribution to yield and economic return. For example, even at the highest application rate (15%), the additional cost of biochar (Php 162) was easily offset by the significantly higher returns. Therefore, from a cost-benefit standpoint, biochar not only enhances the agronomic performance of iceberg lettuce but also provides a sustainable and scalable input with demonstrable profitability for small- to medium-scale growers.

The significant F-test results across all measured parameters (marketable yield, non-marketable yield, and return on expenses) in both cropping seasons confirm that the different treatments had a statistically significant impact on the yield and economic performance of iceberg lettuce. The consistent positive effects of biochar, especially at higher application rates, on marketable yield and return on expenses, particularly in the second cropping, strongly advocate for its use as a sustainable agricultural practice. Biochar's ability to improve soil health cumulatively over time leads to enhanced productivity and economic benefits, making it a promising tool for long-term soil fertility management and crop production [24]. Further economic analyses considering the cost of biochar production and application would provide a more complete picture of its economic feasibility at a larger scale.

4. Conclusions

This study demonstrated the significant potential of rice hull biochar as a sustainable soil amendment in raised-bed lettuce cultivation systems, particularly in highland agro-ecological environments typified by acidic, marginal soils and sloped terrains.

The integration of biochar into the growing media substantially improved morphophysiological parameters, such as head size and chlorophyll content, as well as yield performance and economic returns. Treatments with biochar-amended raised beds consistently outperformed both conventional farmer’s practices and unamended systems, with 5% to 15% biochar inclusion producing the most notable improvements. These findings reaffirm biochar’s capacity to enhance soil physical structure, water retention, and nutrient availability—critical attributes for optimizing vegetable production in resource-constrained, environmentally fragile settings.

Moreover, the results suggest that the residual effects of biochar may confer sustained agronomic benefits across successive cropping cycles, potentially reducing the need for external inputs and supporting long-term soil fertility. This is particularly relevant for household-level or community-driven food production systems, where access to synthetic fertilizers and institutional support is often limited. The economic analysis further supports the practicality of this approach, indicating favorable return-on-investment metrics for biochar-enhanced systems.

In the broader context of food security and climate-resilient agriculture, this research contributes valuable empirical evidence on the viability of integrating localized organic inputs within home garden systems. The implications are far-reaching: biochar-based interventions could strengthen household food self-sufficiency, mitigate environmental degradation, and support adaptive capacity in the face of ecological and economic stressors. Future research should build on these findings by exploring multi-season dynamics, the role of biochar-microbe interactions, and scalability across diverse agro-climatic zones. As global food systems continue to face mounting pressures, such context-specific, low-cost, and ecologically sound innovations offer a pathway toward more equitable and resilient food futures.

5. Ethical Approval

This study was approved by the appropriate research ethics committee. It did not involve human or animal subjects, and all procedures complied with ethical standards for environmental and agricultural research.

6. Acknowledgements

The author gratefully acknowledges all individuals and institutions who contributed to the successful completion of this study. Special acknowledgment is offered to the Australian Centre for International Agricultural Research for the funding of this study. Further, the author wishes to express his gratitude to the University of Science and Technology of Southern Philippines, his research adviser, Dr. Nelda R. Gonzaga, panel members, Ms. Judy Mae Pabellon, and the members of the project in their valuable support in the completion of this endeavor.

7. Author Contributions

Nagal, CJ.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, and Writing – review & editing.

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