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# Effects of Biochar-Amended Media on Leaf Lettuce (*Lactuca sativa* L.) Growth in Raised-Bed Sloped Terrain System

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## Abstract

The COVID-19 pandemic exposed critical vulnerabilities in global food systems, notably disrupting supply chains and limiting food access in developing countries. In response, home gardening emerged as a practical strategy to bolster household food security. However, hilly and sloped terrains—common across many Southeast Asian—present significant cultivation challenges. This study investigates the efficacy of biochar-amended growing media in enhancing the productivity of leaf lettuce (*Lactuca sativa* L.) cultivated in raised-bed gardens situated on sloped land in a highland province of the Philippines. A 2×6 factorial experiment was conducted using a Randomized Complete Block Design (RCBD), evaluating two lettuce varieties ('Green Span' and 'Lollo Rosa') across six growing media treatments, including incremental levels (5%, 10%, 15%) of carbonized rice hull (CRH) biochar amendment. Growth parameters assessed included plant height, leaf count, fresh weight, and yield/m$^2$. Results showed that biochar-enhanced media significantly improved lettuce growth and yield relative to conventional methods, with the 10% CRH treatment yielding the highest productivity. Specifically, this treatment resulted a 584.7% increase in marketable yield per plant and a 584.1% increase in extrapolated yield/100 m$^2$ compared to the control group (garden soil only). Between the two varieties, 'Green Span' consistently outperformed 'Lollo Rosa' in terms of plant vigor, crown development, and total yield, producing more than three times higher marketable biomass. These results offer actionable insights for smallholder farmers and policymakers pursuing climate-resilient and nutrition-sensitive agricultural interventions in topographically constrained areas. By optimizing crop performance through resource-efficient amendments, the study charts a viable path for sustainable food production in sloped, underutilized landscapes.

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## Introduction

The COVID-19 pandemic exposed the vulnerabilities in global food systems, disrupting supply chains, limiting labor mobility, and exacerbating food insecurity—particularly in developing and food-importing countries. Lockdowns and mobility restrictions significantly affected the availability and accessibility of food, especially in labor-intensive sectors such as fruits, vegetables, dairy products, and meat processing (Kim et al., 2020). Given the deep interconnectivity of supply chain, even minor disruptions triggered cascading effects that led to yield losses and supply shortages across many regions of the world (Ihle et al., 2020).

In Southeast Asian countries like the Philippines, strict community quarantines were implemented based on regional risk levels. These measures resulted in a major contraction in the labor market, with 7.3 million individuals unemployed at the onset of the crisis (Li et al., 2021). By early 2021, the Philippine Statistics Authority (PSA) reported an unemployment rate of 8.8%, equivalent to 4.2 million jobless individuals. These trends mirrored economic downturns observed across other low- and middle-income countries facing similar pandemic-induced disruptions.

Despite economic challenges, the demand for sufficient and accessible food has remained constant. Global food demand is projected to increase by 50% to 110% by 2050 due to population growth and shifting consumption patterns (Falcon et al., 2022). However, pandemic-related transport restrictions and local lockdowns created bottlenecks in agricultural supply chains worldwide, hindering the distribution of inputs and outputs and highlighting the urgent need for resilient, localized food systems.

In response, home gardening gained renewed attention as a grassroots solution to food insecurity during the pandemic. This practice, observed across urban and rural settings globally, enabled families to grow short-term crops for subsistence. Home gardens typically feature mixed cropping systems, integrating vegetables, fruits, herbs, spices, and small livestock to supplement household nutrition and income. In both developed and developing nations, they emerged as low-cost, accessible, and sustainable food production models.

However, geography and landform present challenges to widespread home gardening. Sloping and mountainous terrains—common in many countries including those in Southeast Asia, Africa, and Latin America—limit the cultivability of land for household food production. In the Philippines, a significant portion of the land area is hilly or mountainous (Estacio et al., 2022), and farming in such areas poses challenges such as soil erosion, drought stress, and limited infrastructure and support services (Talachutla, 2024). Similar constraints have been reported in other regions with complex topographies, underscoring the importance of adapting food production methods to marginal landscapes.

One promising approach is the establishment of raised-bed gardens, particularly in sloped backyards. These beds improve drainage, extend the growing season, and enhance manageability—advantages especially relevant in marginal environments. Crucially, they allow for the manipulation of the growing medium, which plays a pivotal role in crop performance. However, the quality of growing media varies across countries due to differences in raw materials and processing techniques, leading to inconsistent outcomes in plant cultivation. This necessitates the exploration of locally available, sustainable amendments to optimize plant growth.

Biochar, a carbon-rich product of pyrolyzed biomass (e.g., wood, crop residues, straw), has emerged as a promising soil amendment. Its application can enhance soil fertility, moisture retention, and microbial activity, thereby improving crop yields (Khan et al., 2024). Addressing soil degradation—partly attributed to the loss of organic carbon (Kapoor et al., 2022)—biochar holds particular promise in regions where synthetic inputs are costly or inaccessible. Despite its benefits, real-world applications of biochar remain underexplored, particularly in smallholder and home garden contexts. Variability in biochar quality depending on feedstock and pyrolysis conditions (Pratiwi & Nurrahma, 2024) further necessitates site-specific evaluation to determine feasibility.

While the benefits of biochar as a soil amendment are well-documented in field-scale applications, its effects may differ substantially in containerized or home garden systems, particularly when employed in confined raised beds. In open-field conditions, biochar interacts with expansive root zones and broader nutrient cycling processes. In contrast, container environments concentrate nutrient availability, leaching dynamics, and microbial interactions. This can lead to variability in crop response depending on the volume and structure of the growing media, moisture and nutrient retention, and potential buildup of salinity or pH alterations (Bonanomi et al., 2017; Premalatha et al., 2022). Therefore, empirical validation of biochar performance in raised-bed settings—especially those situated on sloped terrain with elevated erosion risks and limited topsoil depth—is essential for context-specific recommendations.

Lettuce (*Lactuca sativa* L.), a globally popular salad crop, is valued for its nutritional profile—rich in fiber, iron, folate, and vitamin C, while low in calories, fat, and sodium (Kim et al., 2016). It also contains a range of bioactive compounds with recognized health-promoting effects. As consumer demand continues to grow, particularly among health-conscious populations, lettuce cultivation offers an ideal candidate for household-level production. Globally, leaf lettuce is prized for its short growth cycle, high productivity, and adaptability to diverse cultivation systems.

Beyond soil amendments, varietal selection plays a critical role in optimizing crop productivity and resource-use efficiency. Lettuce varieties differ significantly in morphological traits, growth rates, nutrient uptake efficiency, and environmental adaptability—factors that directly influence performance under amended and marginal growing conditions. Evaluating varietal responses in biochar-integrated raised-bed systems is crucial for identifying cultivar-specific interactions with growing media and microclimatic factors. Accordingly, the inclusion of two commonly cultivated varieties, 'Green Span' and 'Lollo Rosa', enables the study to generate varietal performance benchmarks essential for tailoring home gardening recommendations in sloped and highland terrains.

In Southeast Asia, high-altitude areas demonstrated that while full irrigation (100% of evaporated water) produces the highest marketable yield and water use efficiency, reduced irrigation enhances mineral content, total phenolics, and antioxidant activity in lettuce leaves (Sahin et al., 2016). Similar to other countries with limited flat arable land, maximizing lettuce productivity in non-traditional and marginal areas is increasingly imperative. In the post-pandemic era, optimizing the productivity of such crops in alternative cultivation systems—such as raised-bed gardens—can contribute significantly to food security and nutritional well-being.

Lettuce is particularly well suited for raised-bed gardening on marginal or sloped land due to its shallow, fibrous root system, low canopy biomass, and short cropping duration. These morphological and physiological traits reduce nutrient competition, enable high-density planting and minimize susceptibility to wind or slope-induced lodging. Additionally, lettuce's high market value and consistent demand make it a preferred option for smallholder and household-level cultivation (Kim et al., 2016). Despite growing interest in home gardening and biochar use, empirical studies evaluating the interaction of biochar with specific crop varieties in sloped, highland agroecosystems using confined growing systems remain limited. This study addresses that gap by examining both varietal response and soil amendment effects under site-specific constraints—offering practical insights into sustainable, slope-adaptive food production practices.

Conducted under the agroecological conditions of a highland province in the Philippines, this study evaluates the growth and yield performance of leaf lettuce in raised-bed gardens amended with varying levels of biochar. Specifically, it investigates the effects of carbonized rice hull (CRH) biochar-amended growing media on the growth and yield of 2 leaf lettuce varieties cultivated on sloped terrains. The research contributes to the global discourse on sustainable home gardening by exploring how biochar-amended growing media can enhance crop productivity in marginal landscapes—offering a viable path toward localized food resilience in the face of global uncertainties.

## Materials and methods

### 1. Pyrolysis

Carbonized rice hull (CRH) utilized in this study was produced through an open-type carbonization process—a low-cost method commonly employed in smallholder and household-level farming systems. Pyrolysis was conducted at estimated temperatures ranging from 350–500°C, with a duration of approximately 5 to 7 h. Although this open-type system inherently limits precise control over pyrolysis parameters, several measures were implemented to approximate consistency and minimize variability.

Prior to pyrolysis, the rice husk feedstock was air-dried for 5–7 days to reduce moisture content, estimated at 10–15%. Lower moisture levels are critical, as elevated moisture can delay carbonization and result in incomplete charring. Combustion was initiated using dry wood and paper, and the process was visually monitored throughout. Uniform charring was achieved by periodically mixing the husk layers during carbonization and terminating the process upon observation of consistent black coloration.

Although oxygen control was not mechanized, efforts were made to limit oxygen exposure by regulating fire intensity and manually adjusting layering to prevent flaming combustion. The resulting CRH was immediately quenched with water to prevent over-burning and ash formation, then air-cooled and stored in sealed containers.

While not laboratory-standardized, this method reflects practical biochar production conditions in low-resource environments. Future research is encouraged to compare this approach with closed-system pyrolysis wherein parameters such as surface area, fixed carbon content, pH, and cation exchange capacity can be precisely quantified and correlated with agronomic performance.

## 2. Experimental site

The experiment was conducted at coordinates 8°36.59′ N latitude and 124°52.87′ E longitude in a highland municipality in the Philippines, at an elevation of approximately 580 meters above sea level (masl). The site is characterized by sloping terrain and a dominant soil type classified as Jasaan clay. Soils in this area are moderately fertile but strongly acidic, with pH values ranging from 3.9 to 5.2—typical of highland regions experiencing prolonged leaching and organic matter depletion. Geologically, the area is underlain by volcanic materials and scattered basaltic andesite rocks, while alluvial deposits are confined to watercourse proximities.

These site characteristics—particularly slope and soil acidity—underscore the relevance of biochar as a soil amendment. Biochar has been shown to improve soil structure, enhance cation exchange capacity, and buffer acidic conditions due to its alkaline properties. In highland environments prone to erosion and nutrient runoff, its porous structure also promotes water retention and soil aggregation, thereby reducing topsoil loss. Consequently, the site's agroecological constraints directly align with the functional benefits of biochar, supporting the rationale for evaluating its application in raised-bed gardening systems on sloped terrain.

## 3. Experimental design and treatments

The study employed a 2×6 factorial experiments arranged in a randomized complete block design (RCBD) with three replications. Factor A consisted of two lettuce varieties: 'Green Span' and 'Lollo Rosa'. Factor B included six production systems: (T1) conventional farmer's practice (garden soil), (T2) conventional practice in raised beds, (T3) raised beds with growing media, and (T4–T6) raised beds with growing media amended with 5%, 10%, and 15% CRH, respectively.

A total of 36 plots were established, each measuring 1.2 m × 2.5 m (3.0 m²). Plot spacing was maintained at 1.0 m between plots and 1.5 m between blocks to minimize edge effects and ensure accessibility (Fig. 1). Blocking was implemented based on slope gradient and aspect to control for microenvironmental variability, particularly differences in solar radiation, water runoff, and drainage potential—factors known to vary in sloped terrain and influence plant growth. Within each block, treatment plots were randomly assigned to account for residual variability.

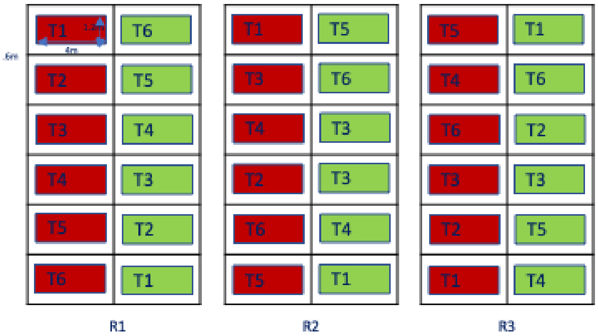

**Fig. 1** Experimental layout illustrating the treatment combinations of 2 lettuce varieties (Factor A) and six agricultural production systems (Factor B), arranged across 3 replications (R1, R2, R3) in RCBD. Green boxes represent A1 – 'Green Span', red boxes represent A2 – 'Lollo Rosa'. Each box is labeled with a treatment number (T1–T6), corresponding to a specific agricultural production system

The blocks were laid out along contour lines to ensure relatively uniform slope angles within each replicate. Prior to layout, site mapping was conducted to identify zones with comparable soil texture, exposure, and elevation. This spatial blocking strategy minimized experimental errors attributable to environmental heterogeneity and ensured comparability across treatments. By grouping similar micro-sites, the RCBD structure enabled more accurate isolation of treatment effects despite the constraints posed by the sloped terrain.

## 4. Cultural management practices

Cultural management practices were carefully implemented to ensure optimal growth and performance of the lettuce crop across the various production systems. Land preparation and plot establishment began with mechanical field clearing using a rotavator, followed by manual leveling and incorporation of the growing media mixtures. These mixtures consisted of varying proportions of chicken dung, coco peat, garden soil, and CRH, corresponding to the designated biochar treatment levels.

Seedlings were initially sown in seedling trays and maintained in a nursery until 14 days old, after which they were transplanted into the prepared plots. Transplanting was conducted with a spacing of 30 cm both between and within rows, ensuring uniform plant distribution across all treatment replicates.

Throughout the growing period, consistent water management was maintained by irrigating twice daily during dry conditions to support healthy crop development. Fertilizer application was restricted to plots following the farmer's conventional practice, using 250 g of complete fertilizer per bed. Weed control was performed manually by regularly uprooting unwanted plants to reduce competition.

Data collection commenced at 14 days after transplanting (DAT) and continued at weekly intervals until harvest. Harvesting occurred at 35 DAT when the lettuce reached physiological maturity. Plants were manually uprooted, sorted into marketable and non-marketable categories, and weighed to assess yield and treatment performance. These comprehensive cultural practices ensured the reliability of data collection and the effectiveness of the production systems under evaluation.

### 5. Data collection and analysis

Data collection encompassed morpho-physiological parameters such as crown size (polar and equatorial diameters), plant height, relative chlorophyll content, plant vigor, marketable and non-marketable yield per plant, and extrapolated yield/100 $m^2$. Chlorophyll content was measured using a SPAD-502 plus chlorophyll meter (Konica Minolta, Japan), calibrated according to the manufacturer's protocol prior to each measurement session. Readings were taken from the middle portion of the third fully expanded leaf from the apex of 5 randomly selected plants/plot, and the average SPAD value was recorded.

Plant vigor was assessed using a standardized visual scoring method adapted from vegetable crop phenotyping protocols (Suzuki, 2003), employing a 1–5 rating scale:

1 = Very poor (stunted growth, pale leaves, signs of stress)

2 = Poor (suboptimal growth with moderate yellowing or uneven canopy)

3 = Average (acceptable growth, moderate greenness and canopy coverage)

4 = Good (vigorous growth, uniform canopy, minor signs of stress)

5 = Very good (excellent growth, deep green leaves, robust and uniform canopy)

For consistency in analysis and plotting, the raw scores were multiplied by 10, thereby converting the scale to a 10–50 range. This adjustment ensured clearer visualization of treatment differences in the statistical analysis and graphical presentation while retaining the original scoring basis.

Prior to conducting analysis of variance (ANOVA), diagnostic testing was performed to validate statistical assumptions. Normality of residuals was assessed using the Shapiro–Wilk test, while homogeneity of variances was evaluated using Levene's test, both at $\alpha = 0.05$. Where violations were detected, appropriate transformations (e.g., square root) were applied to meet ANOVA requirements. Following assumption validation, a two-way ANOVA was conducted using JASP (Jeffrey's Amazing Statistics Program) version 0.19.3.

In addition to p-values, effect sizes (partial eta squared, $\eta^2$) were calculated to assess the practical significance of treatment effects. This metric provides insight into the proportion of variance explained by each factor (variety, growing media treatment) and their interaction, beyond statistical significance alone.

For all parameters, the statistical unit was the plot, with measurements derived from a representative sample of 5 plants/plot. Yield-related traits (e.g., marketable yield/plant, yield/100 $m^2$) were averaged at the plot level prior to analysis to ensure consistency and account for within-plot variability. Morphological and physiological variables, such as SPAD readings and vigor scores, were likewise aggregated per plot from 5 randomly selected plants.

## Results and discussion

### 1. Crown size

A highly significant increase in polar crown size and plant height was observed in lettuce grown in biochar-amended media, particularly at 5% and 10% CRH application rates. At 35 days after transplanting (DAT), the tallest plants were recorded under the 5% CRH treatment (24.29 cm), while the widest equatorial crown was observed under the 10% CRH treatment (34.92 cm).

These growth enhancements are attributed to the favorable modifications in the physical properties of the growing medium. Specifically, the incorporation of carbonized rice hull (CRH) biochar is known to increase soil porosity, reduce bulk density, and improve both water-holding capacity (WHC) and cation exchange capacity (CEC) (Kapoor et al., 2022). Enhanced WHC allows water to remain in the root zone for extended periods, supporting sustained hydration and mitigating drought stress. Similarly, elevated CEC improves the soil's ability to retain essential nutrients such as potassium, calcium, and magnesium, making them more readily available to developing root systems.

**Table 1** Effect of carbonized rice hull (CRH) on the crown size (cm) of 2 lettuce varieties across different production systems

| Treatments | Crown Size (cm) | |
|---|---|---|
| | **Polar** | **Equatorial** |
| Variety Comparison | | |
| 'Green Span' | $22.25^{a}$ | $33.01^{a}$ |
| 'Lollo Rosa' | $15.87^{b}$ | $22.63^{b}$ |
| p-value | < .001** | < .001** |
| Production System Comparison | | |
| T1 - GS | $10.54^{c}$ | $17.01^{b}$ |
| T2 - RB + GS | $10.41^{c}$ | $18.83^{b}$ |
| T3 - RB + GM (1:1:.25 GS+CCP+CD) | $23.18^{bc}$ | $34.37^{a}$ |
| T4 - RBGM + 5% CRH | $24.29^{a}$ | $28.32^{a}$ |
| T5 - RBGM + 10% CRH | $23.69^{bc}$ | $34.92^{a}$ |
| T6 - RBGM + 15% CRH | $22.25^{b}$ | $33.48^{a}$ |
| p-value | < .001** | < .001** |

**Remark:** Means in a column followed by the same letter are not significantly different at 5% level of significance (Tukey's HSD).
** Significance: $p < .01$ indicates statistical significance at the 1% level

**Abbreviations**: GS = Garden Soil; RB = Raised bed; GM = Growing Media; CRH = Carbonized Rice Hull; CCP = Coco Peat; CD = Chicken Dung

Mechanistically, biochar also plays a critical role in enhancing root development. Its porous microstructure provides favorable microhabitats for root proliferation and microbial colonization, stimulating rhizosphere activity and nutrient mineralization. This improved rooting environment facilitates greater nutrient uptake—particularly nitrogen and phosphorus—which are essential for shoot elongation, leaf expansion, and biomass accumulation. Tian et al. (2011) and Bonanomi et al. (2017) similarly reported that biochar-enriched media promoted robust root systems, resulting in increased vegetative growth in leafy vegetables.

In the present study, increased lateral and vertical growth responses observed in both lettuce varieties suggest that moderate biochar amendments (5–10%) optimized rhizosphere conditions without inducing nutrient imbalances. The application of 5% carbonized rice hull biochar as a soil ameliorant (T4) resulted in the tallest lettuce plants at 35 DAT, with an average plant height of 24.29 cm (Fig. 2). This indicates that integrating biochar at this specific rate into the growing media can significantly enhance vegetative growth compared to conventional production systems.

The observed increase in plant height under biochar-enriched conditions may be attributed to improved soil physical and chemical properties, including enhanced porosity, moisture retention, and nutrient availability—particularly nitrogen and potassium, which are vital for shoot elongation. However, growth performance declined slightly at the 15% CRH level, suggesting a potential upper threshold beyond which excess biochar may alter pH or cause nutrient immobilization. This aligns with previous findings indicating that biochar application rates must be calibrated to specific crop and soil conditions to

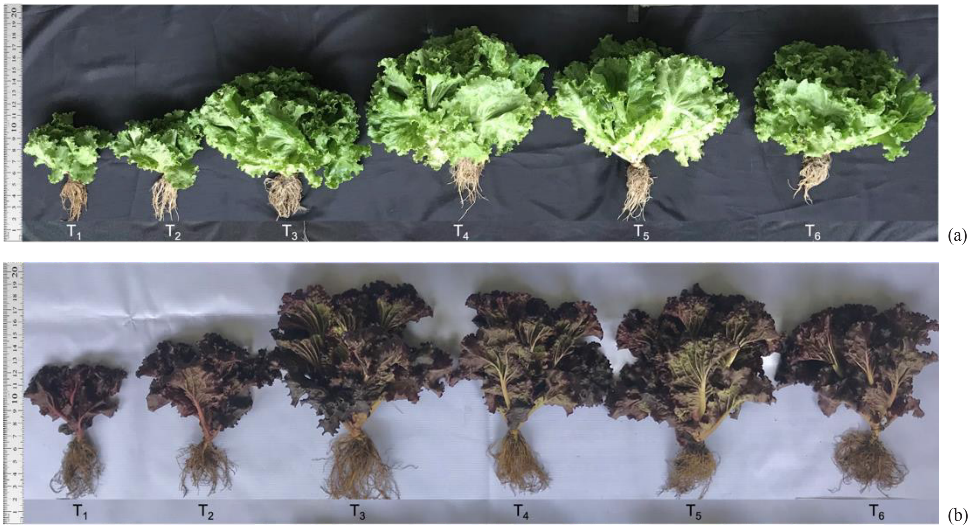

**Fig. 2** Visual comparison of crown size in 2 lettuce varieties grown under different production treatments. Panels (a) and (b) depict 'Green Span' and 'Lollo Rosa', respectively, showing observable differences in lateral growth (plant diameter) across treatments T1 to T6

avoid diminishing returns (Premalatha et al., 2022).

Overall, the improved crown size and plant height reflect a favorable aboveground response to the enhanced physicochemical environment provided by appropriately dosed biochar amendments. Excessive biochar can disrupt nutrient availability by binding essential elements such as nitrogen and phosphorus, leading to suboptimal plant development. In some cases, elevated application rates have also been associated with increased soil alkalinity, which may inhibit nutrient uptake. These results highlight the importance of identifying an optimal application range that maximizes agronomic benefits while minimizing potential trade-offs.

Comparable findings were reported by Jabborova et al. (2021), who observed that higher application rates of biochar significantly increased lettuce plant height. In contrast, Bhattarai et al. (2015) found no significant influence of biochar on vertical growth, suggesting that its effects may be highly context-dependent—shaped by variables such as feedstock type, pyrolysis temperature, application rate, and soil characteristics. This variability underscores the importance of site-specific calibration of biochar amendments to optimize agronomic outcomes.

In the present study, the shortest plants were recorded under the conventional farmer's practice applied to raised beds, averaging only 10 cm in height as shown in Fig. 2 above. Despite its long-standing use, conventional management practices may not always provide optimal conditions for plant growth, particularly when organic amendments are absent or soil quality is poor. Nutrient leaching, compaction, or limited microbial activity in these systems may have constrained shoot development.

Interestingly, statistical analysis revealed no significant interaction between lettuce variety and production system with respect to plant height. This suggests that the varietal response in terms of vertical growth was relatively stable across production systems and biochar levels. Such a finding implies that biochar's influence on plant height is more likely driven by environmental and soil-mediated factors than by genotype-specific interactions.

In terms of equatorial growth (plant diameter), biochar application had a pronounced effect. Among the varieties tested, 'Green Span' exhibited the highest mean plant diameter (33.01 cm), indicating a greater capacity for lateral leaf expansion and canopy spread. This varietal difference likely reflects inherent morphological traits, such as leaf arrangement, internode length, and photosynthetic capacity.

Agronomic treatments also significantly influenced plant diameter. The 10% CRH treatment (T5) produced the widest plants, with a mean diameter of 34.92 cm—more than double that of the control (garden soil only, T1), which averaged 17.01 cm. This substantial increase highlights biochar's potential to enhance shoot development and lateral growth, likely through improved root proliferation and nutrient uptake efficiency.

Variation in plant diameter across treatments may also be influenced by microclimatic factors such as soil temperature, which regulates root activity and above-ground biomass production. Hacke et al. (2016) emphasized that leaf expansion and canopy architecture are complex traits shaped by both genetic and environmental stimuli. Supporting this, Xiong et al. (2020) reported that biochar applications moderated soil temperature fluctuations—reducing thermal extremes by lowering soil temperature under high-heat conditions and increasing it under cooler environments.

## 2. Relative chlorophyll content and plant vigor

Relative chlorophyll content, as measured by SPAD readings, revealed a noteworthy trend: the conventional garden soil (GS) treatment recorded the highest SPAD value (31.03), while biochar-amended treatments—despite producing greater biomass—exhibited slightly lower SPAD readings, ranging from 26.02 to 28.96 units. This observation highlights a critical nuance in interpreting SPAD values: elevated chlorophyll content does not always necessarily correlate with improved yield performance, particularly in nutrient-imbalanced systems.

**Table 2** Relative chlorophyll content (SPAD units) and plant vigor (scale 1-50)

| Treatments | Relative chlorophyll content (SPAD unit) | Plant vigor index |
|---|---|---|
| Variety comparison | | |
| 'Green Span' | $27.12^{b}$ | $37.25^{a}$ |
| 'Lollo Rosa' | $30.89^{a}$ | $30.19^{b}$ |
| p-value | < .001** | < .001** |
| Production system comparison | | |
| T1 - GS | $31.03^{a}$ | $24.87^{b}$ |
| T2 - RB + GS | $28.96^{ab}$ | $23.71^{b}$ |
| T3 - RB + GM (1:1:.25 GS+CCP+CD) | $28.66^{ab}$ | $40.30^{a}$ |
| T4 - RBGM + 5% CRH | $28.63^{ab}$ | $37.61^{a}$ |
| T5 - RBGM + 10% CRH | $28.57^{ab}$ | $37.13^{a}$ |
| T6 - RBGM + 15% CRH | $26.02^{b}$ | $38.70^{a}$ |
| p-value | 0.04* | < .001** |

**Remark:** Means in a column followed by the same superscript letter are not significantly different at the 5% level (Tukey's HSD).
** Significance: $p < .01$ indicates a statistical significance at the 1% level.
* Significant at the 5% of probability level ($p < .05$)

**Abbreviations:** GS = Garden Soil; RB = Raised bed; GM = Growing Media; CRH = Carbonized Rice Hull; CCP = Coco Peat; CD = Chicken Dung

In this case, the higher SPAD value in the conventional system may reflect excessive nitrogen availability or reduced vegetative sink strength, without corresponding gains in growth or productivity. Similar decoupling between SPAD readings and biomass accumulation has been documented under conditions of abiotic stress, nutrient antagonism, or restricted root development (Faralli & Lawson, 2019).

However, a declining trend in relative chlorophyll content was observed with increasing proportions of rice hull biochar in the growing media. This inverse relationship may be attributed to biochar-induced modifications in soil-plant nutrient dynamics. Specifically, biochar can influence cation exchange capacity and soil pH, potentially leading to the immobilization of essential nutrients, particularly nitrogen, which plays a central role in chlorophyll biosynthesis. Such nutrient limitations may impair photosynthetic efficiency, delay vegetative development or reduce biomass accumulation.

These findings highlight a critical consideration: although biochar is widely recognized for its benefits in carbon sequestration and soil structural enhancement, its application must be carefully calibrated to avoid adverse trade-offs in plant nutrient availability, especially in nitrogen-sensitive crops such as lettuce, where excessive biochar may disrupt nutrient balance and compromise physiological performance.

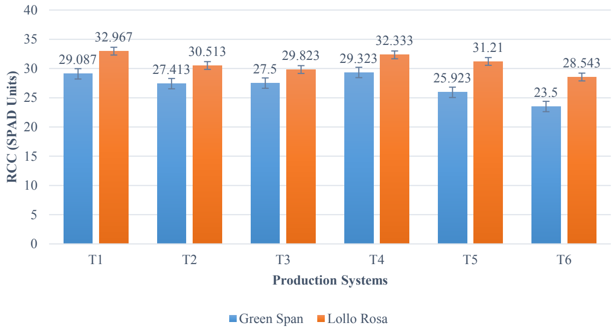

**Fig. 3** Interactive effects of lettuce variety and production system on relative chlorophyll content (RCC), measured in in SPAD units) between varieties and production systems

Consistent with the findings of Van Beek et al. (2024), who identified chlorophyll content as a proxy for photosynthetic efficiency and overall plant health, the statistical analysis revealed significant differences not only across treatments but also due to the interaction between lettuce variety and production system. This interaction effect indicates that chlorophyll accumulation is not solely determined by genotypic potential but is substantially mediated by environmental and agronomic factors (Fig. 3). The implication is that certain lettuce cultivars may exhibit enhanced physiological performance only when grown under specific cultivation regimes. Such genotype × environment (G×E) interactions are critical in precision agriculture, underscoring the importance of aligning varietal selection with site-specific management strategies to optimize photosynthetic output and resource-use efficiency.

From a broader agronomic perspective, these results highlight the limitations of one-size-fits-all recommendations. Instead, they point to the need for location- and cultivar-specific management protocols that consider both genetic potential and environmental context. This approach aligns with the principles of sustainable intensification, which aim to enhance yield and quality while minimizing external inputs and environmental impact.

Furthermore, the study elucidates how plant vigor—an integrative measure of plant health, morphological development, and physiological status—is significantly influenced by both varietal genetics and production systems. The ‘Green Span’ variety demonstrated superior vigor (37.25), markedly outperforming ‘Lollo Rosa’ (30.19). Likewise, the Raised Bed with Growing Media system (T2) supported the most vigorous growth (40.30), suggesting that modifications in the rhizosphere environment through soil amendments play a critical role in enhancing vegetative performance. A key factor contributing to this increased vigor is plant height, which likely reflects cumulative biomass gain and robust structural development.

These results are corroborated by Bonanomi et al. (2017), who reported that cereal-derived biochar can act as a phytostimulant, enhancing growth responses in lettuce. Similarly, Tian et al. (2011) found that biochar derived from urban green waste, when mixed with peat at a 1:1 ratio, significantly improved the growth of *Calathea rotundifolia* cv. Fasciata compared to peat alone. Collectively, these studies emphasize the nuanced role of biochar as both a soil conditioner and a potential biostimulant, contingent on feedstock origin, pyrolysis conditions, and application rate.

Conversely, the slightly lower SPAD values observed in the 5% and 10% CRH treatments were accompanied by significantly higher plant vigor and yield. This suggests that biochar-amended systems may promote more balanced nutrient uptake, facilitating efficient

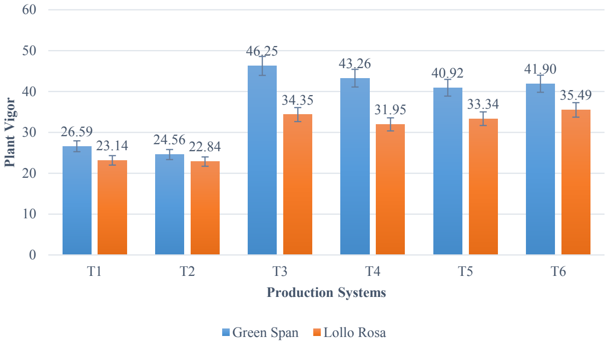

**Fig. 4** Interactive effects of lettuce variety and production system on plant vigor

nitrogen utilization rather than mere accumulation in leaf tissues. Furthermore, plant vigor—a composite indicator of growth and physiological health—was markedly enhanced in the Raised Bed with Growing Media (RB+GM) and biochar-amended treatments, with scores exceeding 37 on a standardized 1–50 scale (Fig. 4).

This improvement in vigor can be mechanistically linked to favorable changes in the root zone environment, particularly enhanced aeration, moisture retention, and microbial activity associated with biochar. The porous structure of carbonized rice hull increases oxygen diffusion around roots, reducing the risk of hypoxic stress, especially in confined raised-bed systems. Additionally, biochar supports beneficial microbial communities, including nitrogen-fixing and phosphorus-solubilizing bacteria, which enhance nutrient availability and promote root and shoot development (Ayangbenro et al., 2022). The synergy between physical soil enhancement and biological stimulation likely contributed to the more vigorous and resilient growth observed in the amended treatments.

Physiological responses of lettuce, including chlorophyll content and plant vigor, are also strongly influenced by microclimatic factors, which are further modulated by the composition of the growing medium and production system. In this study, lettuce grown in biochar-amended raised beds exhibited improved plant vigor and equatorial growth, particularly under the 10% CRH treatment. This improvement can be partly attributed to the microclimatic buffering capacity of biochar. Biochar-amended soils tend to moderate temperature fluctuations in the rhizosphere by increasing thermal insulation and regulating heat transfer. Xiong et al. (2020) reported that biochar reduces soil temperature extremes—cooling the soil under high ambient temperatures and warming it during cooler conditions. Such stabilization is beneficial for lettuce, a cool-season crop sensitive to heat stress, which often results in reduced chlorophyll content and increased bolting.

## 3. Yield parameters

Table 3 presents the yield response of 2 leaf lettuce varieties— ‘Green Span’ and ‘Lollo Rosa’—cultivated under 6 different production systems. The analysis includes marketable and non-marketable yield/plant, as well as extrapolated yield/100 m$^2$. The results highlight the substantial influence of both varietal traits and production practices on lettuce productivity. All 3 yield parameters exhibited highly significant differences among treatments, with p-values less than 0.001, indicating robust statistical variation across production systems and cultivars.

**Table 3** Yield response of leaf lettuce varieties under 6 production systems, including marketable and non-marketable yield/plant (g) and extrapolated yield /100 m$^2$

| **Treatments** | **Yield / Plant (g)** | | **Yield/ 100 m² (kg)** |
|---|---|---|---|
| | Marketable Yield | Non-Marketable Yield | |
| Variety Composition | | | |
| ‘Green Span’ | $222.36^{a}$ | $32.73^{a}$ | $235.14^{a}$ |
| ‘Lollo Rosa’ | $58.84^{b}$ | $5.36^{b}$ | $62.08^{b}$ |
| p-value | < .001** | < .001** | < .001** |
| Production System Comparison | | | |
| T1 - GS | $26.44^{e}$ | $2.56^{c}$ | $27.89^{e}$ |
| T2 - RB + GS | $28.40^{e}$ | $2.06^{c}$ | $29.96^{e}$ |
| T3 - RB + GM (1:1:.25 GS+CCP+CD) | $217.69^{a}$ | $30.37^{b}$ | $231.33^{a}$ |
| T4 - RBGM + 5% CRH | $188.33^{c}$ | $3.98^{c}$ | $198.69^{c}$ |
| T5 - RBGM + 10% CRH | $180.97^{d}$ | $38.27^{a}$ | $190.92^{d}$ |
| T6 - RBGM + 15% CRH | $201.78^{b}$ | $37.03^{a}$ | $212.87^{b}$ |
| p-value | < .001** | < .001** | < .001** |

**Remark:** Means in a column followed by the same superscript are not significantly different at the 5% level (Tukey’s HSD).
** Significance: $p < .01$ indicates statistical significance at the 1% level.

**Abbreviations**: GS = Garden Soil; RB = Raised bed; GM = Growing Media; CRH = Carbonized Rice Hull; CCP = Coco Peat; CD = Chicken Dung

Yield data revealed that the highest productivity was achieved in the Raised Bed with Growing Media (RB+GM) treatment, composed of a 1:1:0.25 mix of garden soil, coco peat, and composted chicken dung. This system produced the highest marketable yield/plant (217.69 g) and one of the top extrapolated yields/100 m² (231.33 kg), outperforming even the biochar-amended treatments. These results suggest that the synergistic effects of readily available organic nutrients from chicken dung, combined with the excellent water-holding and aeration properties of coco peat, offer immediate benefits to fast-growing crops such as lettuce.

These materials likely supplied essential nutrients—particularly nitrogen, potassium, phosphorus—in forms readily absorbed during the short 35-day cropping cycle.

Among the biochar-amended treatments, the 5% and 10% CRH applications significantly improved yield compared to the control (garden soil only). The 10% CRH treatment yielded 180.97 g/plant and 190.92 kg/100 m$^2$, representing over a 584% increase from the conventional control (garden soil only). However, increasing the CRH concentration to 15% did not result in further improvement, with yields declining slightly to 201.78 g/plant. This trend supports the existence of an optimal biochar threshold, beyond which excessive application may disrupt nutrient balance or alter soil pH—potentially reducing nutrient availability or inducing salinity stress (Premalatha et al., 2022; Cakmakci et al., 2022).

Biochar's agronomic benefits often depend on its interaction with other media components and its capacity for gradual nutrient release. In contrast, composted manure and coco peat are more immediately mineralizable, which may explain why the RB+GM treatment without biochar outperformed CRH-amended plots in this short-term study. While biochar enhances long-term soil quality and nutrient retention, its effects may be better realized in multi-cycle systems or when paired with amendments that offer rapid nutrient availability. These findings underscore the importance of tailoring amendment strategies to crop type, growth duration, and local soil conditions.

This conclusion is supported by Ayangbenro et al. (2022), who emphasized the role of organically enriched media in enhancing nutrient bioavailability and stimulating microbial interactions that promote plant growth. The integration of coco peat, known for its superior water-holding capacity, with chicken dung, a rich source of macro- and micronutrients, likely contributed to a consistent nutrient supply and improved overall plant health, resulting in superior yield outcomes.

In stark contrast, the conventional production systems—Garden Soil (GS) and Raised Bed + Garden Soil (RB+GS)—produced the lowest yields in both marketable and extrapolated terms. These treatments yielded only 26.44 g and 28.40 g/plant, and 27.89 kg and 29.96 kg/100 m$^2$, respectively. Such low productivity underscores the limitations of unamended soils, particularly in intensive vegetable cultivation. These soils are typically characterized by poor structure, low organic matter content, and diminished microbial diversity, resulting in suboptimal nutrient cycling and restricted root development (Friedel & Ardakani, 2020). The data clearly indicate that physical elevation alone (i.e., raised beds) is insufficient to boost yields without the incorporation of nutrient-rich amendments.

The effect of carbonized rice hull (CRH), used as a biochar amendment in varying proportions, presented a nuanced trend. The 5% CRH treatment produced a marketable yield of 188.33 g and an extrapolated yield of 198.69 kg/100 m$^2$, demonstrating favorable outcomes. However, the 10% CRH treatment showed a slightly lower marketable yield (180.97 g) and a higher non-marketable yield (38.27 g), suggesting a possible threshold beyond which additional biochar may negatively impact yield quality. Interestingly, increasing the CRH concentration to 15% improved the marketable yield to 201.78 g, though this was again accompanied by a high non-marketable yield (37.03 g), likely due to morphological deformities or uneven growth.

These results suggest a non-linear response to biochar incorporation, where modest additions enhance yield by improving media porosity and water-holding capacity, but excessive levels may cause nutrient imbalances, altered pH, or salt accumulation—conditions detrimental to plant growth (Premalatha et al., 2022). This pattern reinforces the concept of an optimal biochar application threshold, beyond which agronomic benefits plateau or decline. Cakmakci et al. (2022) emphasized the site- and crop-specific nature of biochar use, which must consider the native soil characteristics, crop nutrient demands, and pre-existing fertility status.

Moreover, the interaction between variety and production system proved to be a key determinant in yield performance. The 'Green Span' variety, when cultivated under the enriched RB+GM system, demonstrated its full genetic yield potential. This outcome reinforces the notion that varietal performance is closely linked to environmental and management factors, and that high-performing genotypes require optimized agro-ecological conditions to express their advantages. In contrast, the biochar-amended systems, though moderately effective, did not outperform the RB+GM system without biochar. This suggests that traditional organic amendments like chicken dung and coco peat may offer more immediate and bioavailable nutrients, leading to faster plant responses under short cropping cycles like lettuce.

Further statistical analysis revealed varying levels of interaction between genotype (lettuce variety) and environment (production system). A significant Genotype × Environment (G×E) interaction was observed for plant vigor and chlorophyll content, indicating that varietal responses to production systems were not uniform. Specifically, 'Green Span' exhibited stronger vigor and chlorophyll accumulation in amended raised-bed systems, while 'Lollo Rosa' showed lower responsiveness across treatments. This suggests that certain genotypes are better suited to biochar-enhanced or organically enriched environments, aligning with principles of precision agriculture and tailored varietal selection.

In contrast, no significant G×E interaction was observed for plant height or yield-related traits (marketable and total yield), indicating that both varieties responded similarly in terms of vertical growth and biomass accumulation across the various treatments. The absence of interaction in these variables suggests that the yield improvements were primarily driven by production system effects—namely, growing media quality and amendment level—rather than genotype. These distinctions are important for agronomic decision-making. Where G×E interactions are non-significant, broader recommendations can be made across varieties; however, significant interactions warrant variety-specific strategies. For instance, although both varieties benefitted from biochar incorporation, the superior physiological performance of 'Green Span' in certain treatments suggests its potential as a preferred cultivar in resource-limited or sloped environments with soil amendments.

## Conclusion

The findings of this study demonstrate that incorporating biochar into the growing media of raised-bed gardens significantly enhances the productivity of leaf lettuce (*Lactuca sativa* L.) in hilly land settings. Specifically, the addition of rice hull-derived biochar at moderate rates (10–15%) improved plant vigor, increased biomass accumulation, and resulted in higher marketable yields compared to conventional practices and unamended media. These benefits are attributed to biochar's capacity to improve soil structure, retain moisture, and enhance nutrient availability—key factors for successful cultivation in sloped and marginal terrains where traditional farming methods often fall short.

Moreover, the synergistic use of locally available organic materials, such as chicken dung, coco peat, and biochar provides a sustainable and cost-effective solution for smallholder households seeking to establish productive home gardens. By optimizing the quality of the growing medium, this approach empowers communities—particularly in geographically challenging areas—to strengthen their food self-sufficiency and nutritional resilience.

In the broader context of post-COVID recovery, this research underscores the vital role of localized and adaptive food production systems in enhancing food security. As disruptions in global supply chains persist and climate variability intensifies, home gardening practices supported by biochar-amended media offer a viable pathway toward more resilient, decentralized, and inclusive food systems. Promoting these practices through policy support, extension services, and community-based training can amplify their adoption and long-term impact, contributing meaningfully to food sovereignty in the Global South and beyond.

This study contributes to the wider dialogue on climate-resilient agriculture and urban food systems by demonstrating how low-cost, locally produced amendments such as carbonized rice hull (CRH) biochar can empower marginalized communities to improve food sovereignty. However, future research should explore nutrient use efficiency, microbial interactions, and the long-term soil carbon dynamics associated with biochar application in tropical horticulture. A multi-seasonal or multi-crop analysis will be essential to validate the robustness and scalability of these findings for broader adoption.

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