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Assessing compost-biochar synergy for boosting carbon sequestration and local katokkon chili agronomic performance for promoting low-emission, climate-adapted farming systems

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ABSTRACT

The Katokkon chili, an important Toraja cash crop, is increasingly threatened by climate change, necessitating climate-resilient soil management strategies. This study assessed the synergy of biochar and compost in enhancing soil carbon sequestration and improving katokkon chili performance within low-emission farming systems. A farmer-led field experiment was conducted in Ullin Rembon Village in 2024 involving 12 farmers cultivating 150 m² plots. A split-plot design was applied, with two genotypes – L1 (Limbong) and L2 (Leatung), as main plots and six compost–biochar ratios (R0–R5) as subplots, replicated four times. The L1R4 treatment (20% compost + 80% biochar) resulted in the highest improvement in plant performance, producing 2.511 g plant^{-1}, a 54.60% increase over L1R0. Soil carbon stock increased across treatments compared to the initial value of 33.82 ton ha^{-1}. The highest carbon stock was recorded under R5 (100% biochar) at 51.93 ton ha^{-1}, followed closely by R4 (20% compost + 80% biochar) at 51.06 ton ha^{-1}, reflecting substantial carbon accumulation consistent with the graph. These results, supported by an R^2 of 0.791 explaining 79.1% of yield variability, confirm that compost–biochar synergy effectively enhances soil carbon storage, improves plant growth, and strengthens the climate resilience of katokkon chili production systems.

Keywords: climate resilient, mitigation and adaptation, cash crop, carbon stock, carbon capture

INTRODUCTION

Climate change poses serious challenges to agricultural sustainability, food security, and rural livelihoods worldwide (Grigorieva et al., 2023). Increasing GHG emissions, erratic rainfall, drought, and rising temperatures are altering tropical farming systems such as those in Indonesia, where soil fertility, crop productivity, and ecosystem resilience are directly affected (Rahman et al., 2025). Conventional practices – intensive tillage, excessive fertilizers, and poor organic matter management – further contribute to CO_2, CH_4, and N_2O emissions (Syachbudy et al., 2025). Soil degradation, marked by declining organic matter and nutrient imbalance, limits the soil's capacity to act as a carbon sink (Hultgren et al., 2025), making soil carbon restoration a key strategy for climate-smart agriculture (Olusoji David, 2022).

Organic amendments, especially compost and biochar, have gained attention for improving soil health. Compost provides nutrients and enhances microbial activity but decomposes rapidly in tropical climates. Biochar, a stable carbon-rich product of pyrolysis, increases long-term carbon storage, nutrient retention, and water-holding capacity (Shoudho et al., 2024). Their combined use creates strong synergistic effects – boosting yields, total nitrogen, and soil organic matter (Qian et al., 2023) – as compost supplies labile nutrients while biochar stabilizes them and enhances microbial habitats (Xiang et al., 2022).

The benefits are highly relevant for katokkon chili cultivation in Tana Toraja, South Sulawesi, where soil degradation, fertilizer dependence, and climate variability threaten productivity. Integrating compost and biochar offers a locally appropriate, climate-smart pathway to restore soil resilience and sustain this culturally and economically important crop (Simarmata et al., 2024; Ali et al., 2025).Moreover, the compost-biochar combination can reduce nitrous oxide emissions, increase soil carbon stock, and support the development of low-emission, climate-resilient farming systems in line with Indonesia's commitment to sustainable agricultural transformation. In this study, we assess the synergistic effects of compost–biochar co-application on soil health restoration, carbon sequestration, and the agronomic performance and yield of local katokkon chili. Specifically, the research aims to (a) evaluate changes in soil physical and chemical properties, (b) quantify improvements in soil organic carbon and carbon stock, and (c) determine the resulting effects on katokkon chili growth and yield. The outcomes are expected to provide empirical evidence for developing a low-emission, climate-adapted farming framework tailored to smallholder conditions in upland ecosystems of Toraja, contributing to broader national goals of sustainable agricultural transformation.

MATERIALS AND METHODS

Location and agroecological characteristic

The farmer-led field research was located in Ullin Village, Rembon Subdistrict, Tana Toraja Regency, South Sulawesi, at approximately 3°03′ S and 119°45′ E, with an elevation ranging from 900 to 1,000 m above sea level The area has a humid tropical highland climate with temperatures of 20–26°C and 2,500–3,000 mm annual rainfall. Soils are mainly Inceptisols and Andisols with clay to silty clay texture, good drainage, and moderate to high water-holding capacity. Chemically, the soils are acidic (pH 5.2–6.0) with moderate organic carbon and low to moderate N, P, and K due to strong Al–Fe fixation.

Establish farmer led-field trials

The research was conducted in Ullin, Tana Toraja, Indonesia, from July to September 2024, involving all farmers in the village, with 12 farmers participating in a farmer-led field trial. Each farmer cultivated approximately 150 m² of katokkon chili using biochar-compost inputs. A split-plot design with four replicates was applied. The main plot consisted of two chili genotypes (L1: Limbong Sangpolo; L2: Leatung), while the subplot consisted of six compost-biochar combinations: R0 (100% compost, 15 t/ha), R1 (80% compost + 20% biochar), R2 (60% compost + 40% biochar), R3 (40% compost + 60% biochar), R4 (20% compost + 80% biochar), and R5 (100% biochar, 15 t/ha). Observed parameters included plant height, stem diameter, number of productive branches, total yield, and fruit count per kilogram. Data were analyzed using ANOVA followed by Tukey HSD at a 5% significance level to assess treatment effects. Laboratory analyses were conducted to measure soil organic carbon, bulk density, and soil carbon stock.

Crop establishment and maintenance

a) Preparation of organic fertilizer and amendments:

- Compost and biochar preparation

Compost was produced from buffalo and pig manure, Tithonia and Gliricidia leaves, banana stems, rice straw, soursop leaves, EM4, palm sugar, and water. Straw and Tithonia were chopped, mixed with manure, and moistened with MOL until the mixture clumped. The pile was covered and turned weekly. After four weeks of decomposition, the compost was ready. Biochar was produced used a simple zinc-sheet chimney with air holes was used. Dry twigs or coconut husks were burned to start the fire, then rice husks were added gradually for slow carbonization at 350–500 °C for 2–3 hours. Partially charred material was mixed regularly to ensure uniform pyrolysis. Once fully carbonized, the fire was quenched with water, and the biochar was cooled, dried, and stored.

- Liquid organic fertilizer (LOF)

LOF was made from golden apple snails, Tithonia, bamboo shoots, banana corms, shrimp paste, coconut water, rice-washing water, palm sugar, EM4, and water. All solid ingredients were ground, placed in a sack, and fermented in 20 L of water for one week.

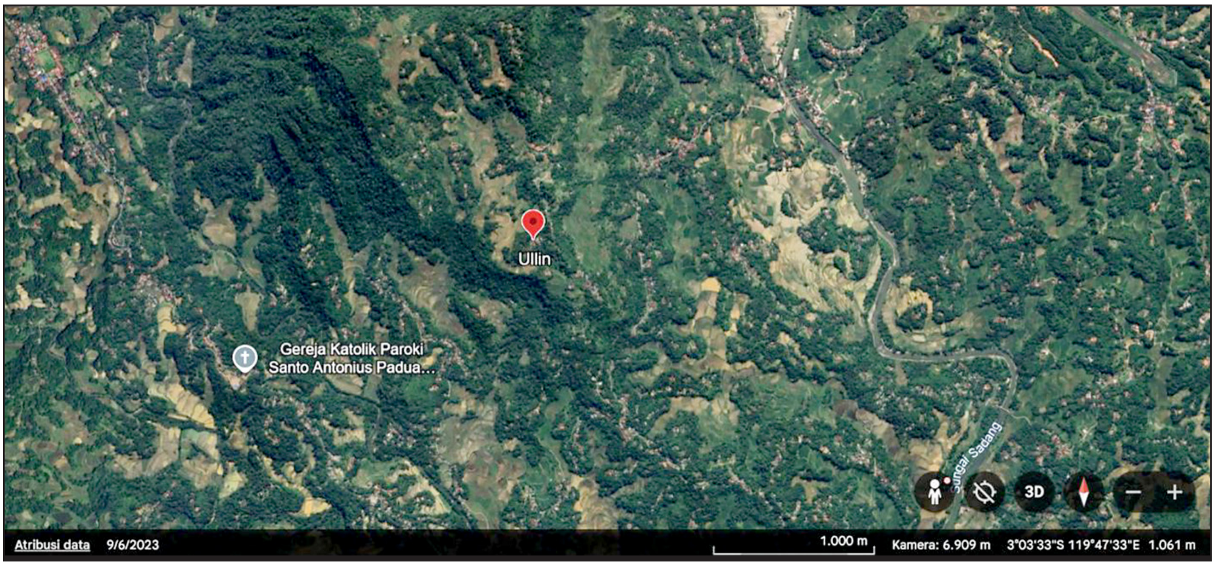


Figure 1. The location of field Trial Ullin Village, Rembon Subdistrict, Tana Toraja Regency, South Sulawesi, at approximately 3°03′ S and 119°45′ E

b) Land preparation and biochar-compost application

Experimental plots (1 × 1.5 m) were established using semi-mechanical tillage. Organic treatments were mixed evenly into each plot, which was then covered with silver mulch. Each mixture of biochar and compost was evenly mixed with soil in each experimental plot. Subsequently, all plots were covered with silver mulch. The planting of the two katokkon genotypes was carried out on the following day.

c) Planting and fertilization

Seedlings with 4–5 fully developed leaves and showing healthy growth were transplanted into the experimental plots at a spacing of 60 cm × 40 cm. The liquid organic fertilizer was applied weekly with a dilution ratio of 1:5. Maintenance included regular watering, hilling up, manual weeding, and environmentally friendly pest-disease control. These practices ensured proper soil moisture, aeration, and reduced competition for plant growth.

Measured responds

a) Plant measured response

Agronomic traits observed included the number of productive branches, stem diameter, and plant height. Plant height was measured with a ruler, stem diameter with a vernier caliper (Paturkar et al., 2022), and productive branches were counted manually. Production parameters consisted of total fruit weight, measured using a digital scale, and the number of fruits per kilogram. Agronomic measurements began at four weeks after planting and were repeated every seven days.Environmental data were also recorded, including soil water content using a handheld tensiometer (Oiganji et al., 2025) and soil permeability using a ring sampler, with laboratory analyses conducted thereafter. Additional soil bio-physico-chemical properties were assessed after harvest.

b) Soil analysis

Soil samples were collected from each experimental plot after harvest to determine their physical and chemical properties. The physical property measured was bulk density (g/cm^3), determined using the ring sampler method (Blake & Hartge, 2022). The chemical property analyzed was soil organic carbon (C-organic, %), which was determined using the Walkley and Black method (Nelson & Sommers, 2021). The analyses were performed to assess the effects of biochar and compost application on soil characteristics.

- Soil carbon stock calculation

Soil carbon stock represents the amount of organic carbon stored in the soil within a given depth and area (FAO,2020; IPCC,2019). It is calculated using the following formula:

$$SCS = BD \times SOC \times D \times 10$$

where: SCS – soil carbon stock (Mg C·ha^{-1}),
BD – bulk density of the soil (Mg·m^{-3}),
SOC – soil organic carbon content (%),
D – depth of the soil layer (m).

Statistical analysis

Statistical analysis were performed to evaluate treatment effects and interrelationships among variables. Data were subjected to analysis of variance (ANOVA) to determine significant differences among treatments at a 5% probability level. The significant differences were observed, means were separated using Duncan's multiple range test (DMRT) (Gómez & Gómez, 1984). Pearson correlation analysis was then used to quantify the strength and direction of linear relationships among key agronomic traits and soil health parameters. Subsequently, principal component analysis (PCA) was employed to identify dominant variables and to visualise multivariate patterns. Path analysis was conducted to partition the direct and indirect effects of agronomic traits and soil indicators on chili yield, offering deeper insight into causal relationships between yield of katokkon chili can improvement factors (Long et al., 2024).

RESULTS

Assessing of compost-biochar on soil quality and carbon restoration as climate change mitigation

a) Soil organic carbon

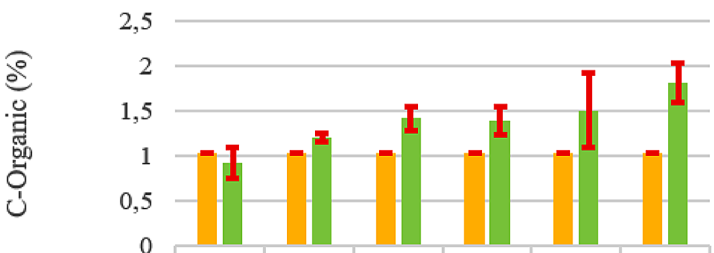
Organic carbon is a key indicator of soil quality because higher levels reflect better soil structure, microbial activity, and nutrient availability (Sari et al., 2023). Soil organic matter enhances aggregation, water retention, and biological functioning, thereby supporting sustainable productivity. In this study, the application of compost and biochar in different proportions increased soil organic carbon compared with initial conditions (Figure 2). The highest value (1.82%) occurred under the 100% biochar treatment (R5), which, although still categorized as low, indicates clear improvement in soil carbon enrichment. When linked with plant performance, the L1R4 treatment (80% biochar + 20% compost) produced the most balanced outcome by improving soil carbon while supporting optimal yield. These results align with earlier findings showing that combined biochar–compost applications enhance soil organic carbon and crop productivity through synergistic effects on microbial activity, nutrient retention, and soil stability (Zhang et al., 2022).

b) Bulk density

Bulk density is a measure of soil density that describes the mass of soil per unit volume, including pore space. The higher the bulk density, the denser and harder the soil structure (Waruwu & Bu'ulolo, 2024). Various studies explain the impact of parallel application of compost and biochar on improving the physical and chemical properties of soil. Soil density *(bulk density)* analysis was conducted using a *ring sampler* to collect intact soil samples to determine their weight and volume capacity, which were then further tested using laboratory procedures. The results of this analysis indicate that the simultaneous application of compost and biochar can reduce soil density to 0.94 g/cm³. This value represents the organic soil category in the range of 0.1–0.9 g/cm³ (Harahap et al., 2021) , indicating that the application of compost and biochar can enrich the organic content of the soil, widen the soil pores and soften the soil properties, making it optimal for katokkon chillies as a growing medium (Figure 3).

c) Soil carbon stock

Carbon stock is the amount of carbon stored in vegetation and soil, and is essential for climate



	R0	R1	R2	R3	R4	R5
Initial value	1,04	1,04	1,04	1,04	1,04	1,04
Final value	0,93	1,21	1,42	1,40	1,51	1,82

Figure 2. Effect of compost and biochar combinations on soil organic carbon (% C-organic)

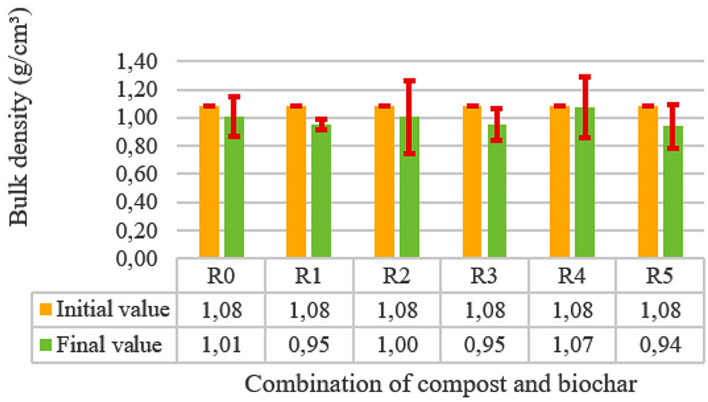


Figure 3. Effect of compost and biochar combinations on bulk density (g cm^3)

change mitigation because stored carbon does not contribute to atmospheric GHGs (Naftalia & Amalia, 2025). Its calculation commonly involves soil depth, bulk density, and organic carbon content (Edwin, 2016). In this study, compost–biochar applications caused clear differences in soil carbon stock. Although all treatments started at 33.82 ton/ha, final values diverged. The highest carbon stock occurred in R5 (51.93 ton/ha), closely followed by R4 (51.06 ton/ha), showing that higher biochar proportions strongly increase carbon accumulation. Moderate improvements appeared in R2 (42.89 ton/ha) and R3 (39.20 ton/ha), while R1 showed only a slight increase (34.56 ton/ha). Conversely, R0 decreased to 27.99 ton/ha, indicating carbon loss without organic inputs. Overall, these results confirm that compost-biochar combinations effectively enhance soil carbon sequestration (Figure 4).

Effect of compost-biochar on the growth and yield production of katokkon chilli

a) Growth performance

- Plant height

The effect of compost and biochar treatments on the average plant height up to 70 days after planting in each treatment, the ANOVA value obtained was 10.45. This value is greater than the f-table value of 2.78 (10.45 > 2.78), indicating a very strong relationship between the composition of the compost and biochar treatments (subplots) and each chilli genotype (main plots). Further analysis using the Tuckey approach (honest significant difference) at a 5% error rate showed that the combination of the Limbong Sampolo variety with 60% biochar and 40% compost composition was the best combination, with an average of 18.87 cm. The L1R2 combination significantly increased plant height by 3.49% compared to the control treatment (Figure 5).

- Stem diameter

The effect of compost and biochar treatments on the average stem diameter up to 70 days after planting in each treatment, the resulting ANOVA value was 33.27. This value is greater than the f-table value of 2.78 (33.27 > 2.78), indicating a very strong relationship between the composition of compost and biochar treatments (subplots) and each chilli genotype (main plots). The combination of the Limbong Sampolo variety with 80% biochar and 20% compost composition was the best combination, with an average of 4.49 cm.

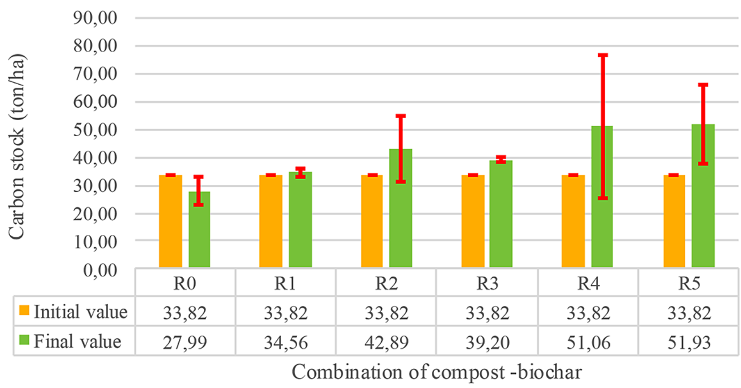


Figure 4. Effect of compost and biochar combinations on soil carbon stock (ton ha^{-1})

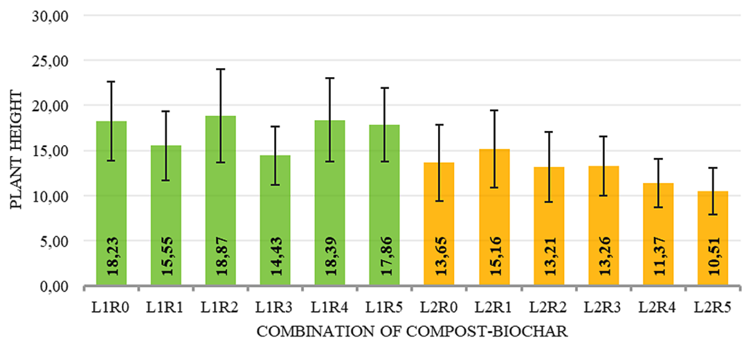


Figure 5. Effect of compost and biochar combinations on plant height (cm)

The L1R4 combination significantly increased stem diameter by 13.46% compared to the control treatment (Figure 6).

- Productive branches

The effect of compost and biochar treatments on the average number of productive branches up to 70 days after planting in each treatment, the resulting ANOVA value was 9.57. This value is greater than the f-table value of 2.78 (9.57 > 2.78), indicating a fairly strong relationship between the composition of compost and biochar treatments (subplots) and each chilli genotype (main plots). The combination of the Limbong Sampolo variety with 60% biochar and 40% compost composition was the best combination, with an average of 26.88 or 27 productive branches. The L1R2 combination significantly increased the number of productive branches by 85.88% compared to the control treatment (Figure 7).

b) Yield component

- Number of fruits

The effect of compost and biochar treatments on the number of fruits per kilogram in each treatment, the ANOVA value obtained was 7.31. This value is greater than the f-table value of 2.78 (7.31 > 2.78), indicating a fairly strong relationship between the composition of compost and biochar treatments (subplot) and each chilli genotype (main plot). The combination of the Limbong Sampolo variety with 80% biochar and 20% compost composition was the best combination for the number of chillies produced, with an average of 51.33 fruits per kilogram (Table 1).

The L1R2 combination significantly increased the number of fruits per kilogram by 115.38% compared to the control treatment. Various treatments of the research parameters explain that the effect of compost can increase the growth of katokkon chilli plants (Figure 8). This may be due to improvements in the physical conditions of the soil for plant growth along with increased availability of N, P and K in the early growth phase. These various elements help produce sturdy and tall chilli plants with many productive branches until the generative phase, such as supporting the number of fruits and total production (Ardhitama et al., 2025; Haque et al., 2025; Widowati et al., 2022). Additionally, the application of biochar as a soil structure improver does not have a direct impact on test parameters, but biochar can increase soil pH, soil organic matter availability, and soften soil properties as a plant growth medium (Tao, 2024; Yosephine et al., 2021).

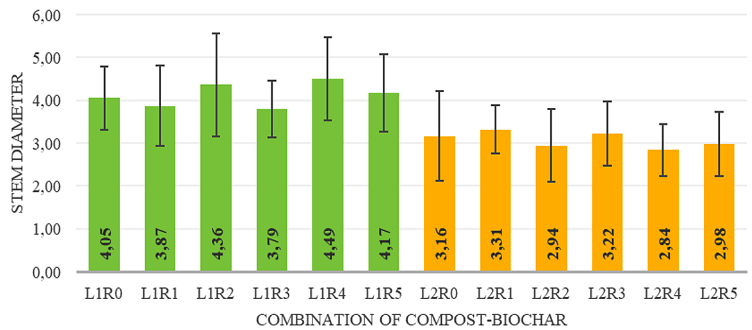


Figure 6. Effect of compost and biochar combinations on stem diameter (cm)

Table 1. Analysis of variance (ANOVA) and Tukey HSD test for the interaction between chilli genotype (L) and compost–biochar combination (R) on number of fruits of Katokkon chilli

ANOVA		
L×R	F	F5%
	7,31	2,78
Tuckey HSD		
Sd	Tuckey HSD 5%	Tuckey HSD
2,47	5,10	12,60

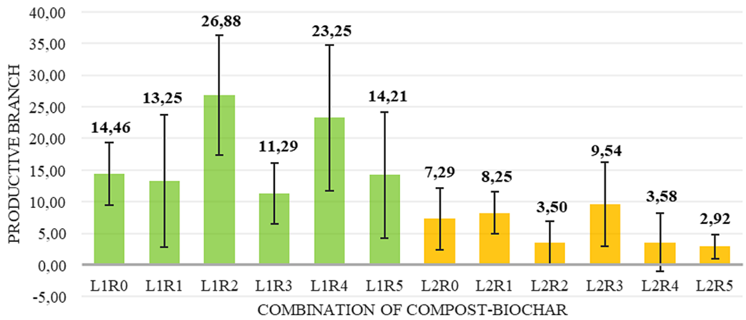


Figure 7. Effect of compost and biochar combinations on number of fruits (unit kg^{-1})

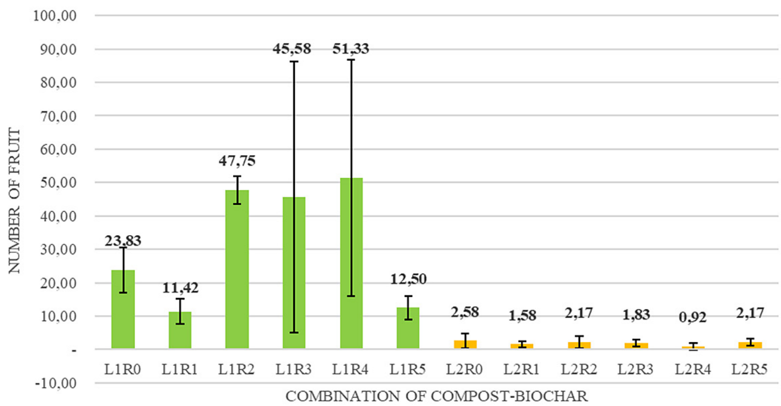


Figure 8. Effect of compost and biochar combinations on number of fruits (unit kg^{-1})

- Katokkon yield

Compost and biochar treatments significantly affected the production of katokkon chilli, with a clear interaction between compost-biochar composition and genotype. The Limbong Sampolo genotype (L1) combined with 80% biochar and 20% compost (L1R4) produced the highest yield at 2,511.20 g per plot, indicating that a high biochar proportion complemented by compost improves soil conditions and fruit production (Table 2). In contrast, the Leatung genotype (L2) yielded much lower results, with its highest yield only 176.70 g (L2R0), reflecting strong genotype-specific responses. These results emphasize the need to select both suitable genotypes and optimal compost-biochar ratios to achieve sustainable and efficient katokkon chilli production (Figure 9).

Pearson correlation analysis

The Pearson correlation analysis revealed significant relationships between soil properties and plant growth parameters. Bulk density showed a negative correlation with plant height (r = –0.23) and other growth attributes, indicating that higher soil compaction limited plant development. In contrast, soil organic carbon (%C-organic) exhibited a positive association with production, number of fruits, and plant height, suggesting that increased organic matter improved soil structure,

Table 2. Analysis of variance (ANOVA) and Tukey HSD test for the interaction between chilli genotype (L) and compost-biochar combination (R) on katokkon chilli yield

ANOVA		
L×R	F	F5%
	4,49	2,78
Tuckey HSD		
Sd	Tuckey HSD 5%	Tuckey HSD
20,18	5,1	102,92

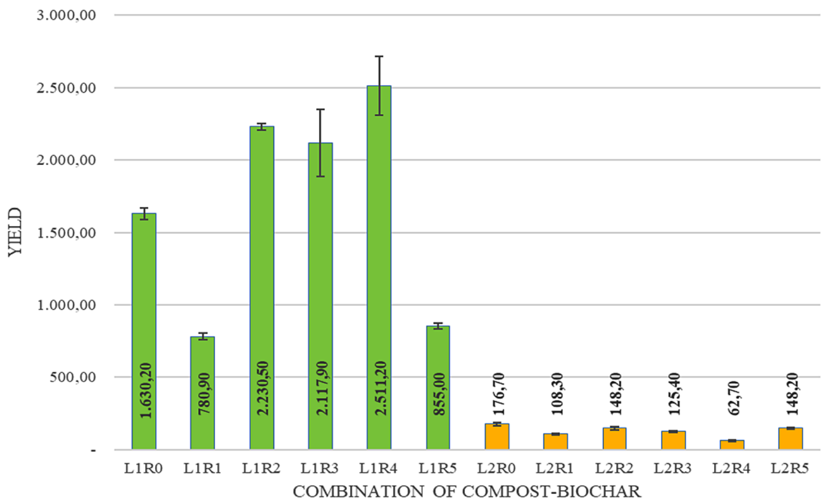


Figure 9. Effect of compost and biochar combinations on yield production (gram)

aeration, and nutrient availability. Strong positive correlations were also observed among yield components, particularly between number of fruits and total production, highlighting that fruit number was the major determinant of yield. Overall, the results suggest that improvements in soil organic carbon through biochar and compost application effectively reduce soil bulk density and enhance crop performance (Figure 10).

Principle component analysis

The PCA biplot illustrates the relationships between agronomic traits and soil properties

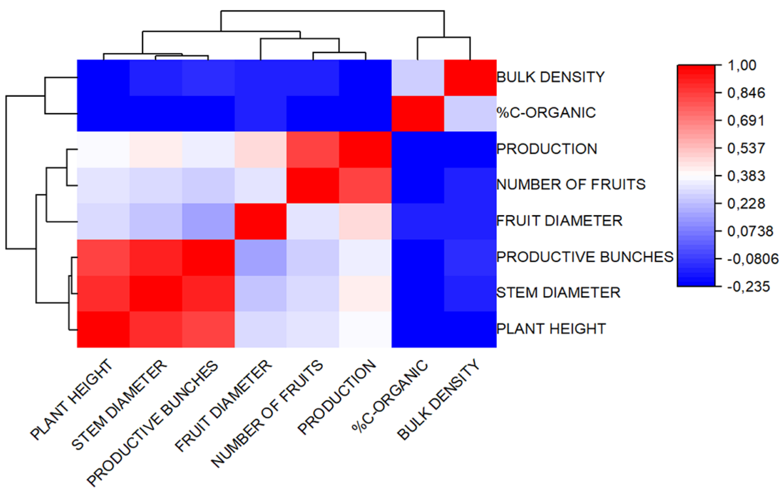


Figure10. Pearson correlation heatmap showing the relationships between agronomic traits and soil properties under different compost-biochar treatments

under different compost-biochar treatments. The first two principal components (PC1 and PC2) explain the majority of data variability, showing distinct groupings among the observed parameters. Agronomic traits such as plant height, stem diameter, and the number of productive branches are positively associated and positioned in the same quadrant, indicating that they contribute similarly to plant growth performance. In contrast, soil bulk density and %C-organic are positioned oppositely, suggesting an inverse relationship with most plant growth and yield parameters. This pattern supports the correlation analysis results, indicating that lower bulk density and higher organic carbon content enhance crop growth and productivity through improved soil structure and nutrient availability (Figure 11).

Path analysis

The correlation analysis revealed varying relationships between production and both soil parameters and plant growth traits. The most influential factor contributing to higher production was the number of fruits, showing the strongest positive correlation (r = 0.827), followed by fruit diameter (r = 0.465), stem diameter (r = 0.416), and plant height (r = 0.373). These findings indicate that morphological components of the plant play a major role in determining yield performance. In contrast, soil physical and chemical properties such as bulk density (r = –0.216) and soil carbon stock (r = –0.263) exhibited weak negative correlations with production, suggesting that higher values of these parameters do not necessarily lead to increased yields. The total determination value of 0.791 indicates that approximately 79.1% of the variation in production can be explained by the combination of analyzed variables. Overall, the results emphasize that plant vegetative and generative growth traits have a more direct influence on productivity compared to soil characteristics, although soil conditions remain essential in providing an optimal growth environment (Figure 12).

CONCLUSIONS

The combined application of compost and biochar significantly improved soil conditions, plant growth, and the yield performance of katokkon chili. The 60% compost + 40% biochar treatment (L1R2) increased plant height by 3.49% (18.87 cm) and enhanced the number of productive branches by 85.88% compared with the control. The 20% compost + 80% biochar ratio (L1R4) improved stem diameter by 13.46% (4.49 cm) and produced the highest fruit number, reaching 51.33 fruits per kilogram, or 115.38% higher than the control. Soil organic carbon increased to 1.82% under the 100% biochar treatment (R5), while soil bulk density decreased to 0.94 g cm^{-3}, indicating better porosity and aeration. Soil carbon stock values showed the highest accumulation in R5 (51.93 ton ha^{-1}), followed by R4 (51.06 ton ha^{-1}), with moderate increases in

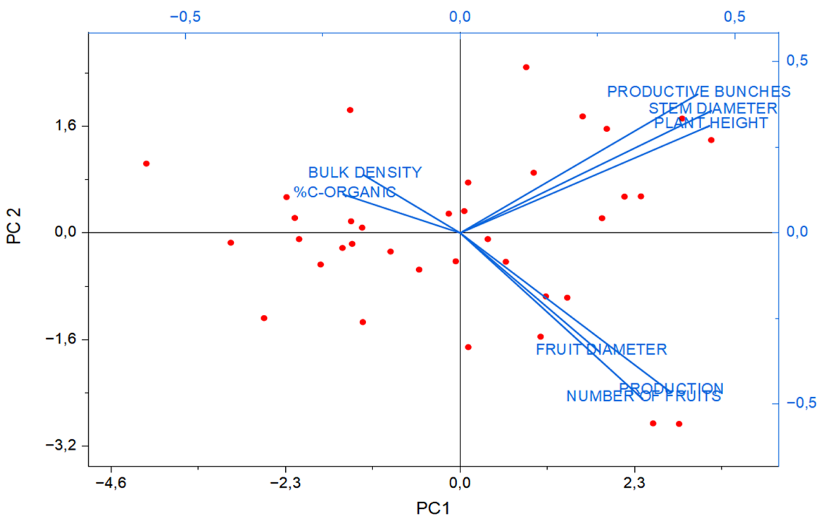


Figure 11. Principal component analysis biplot showing the relationship between agronomic traits and soil properties as influenced by compost–biochar treatments.

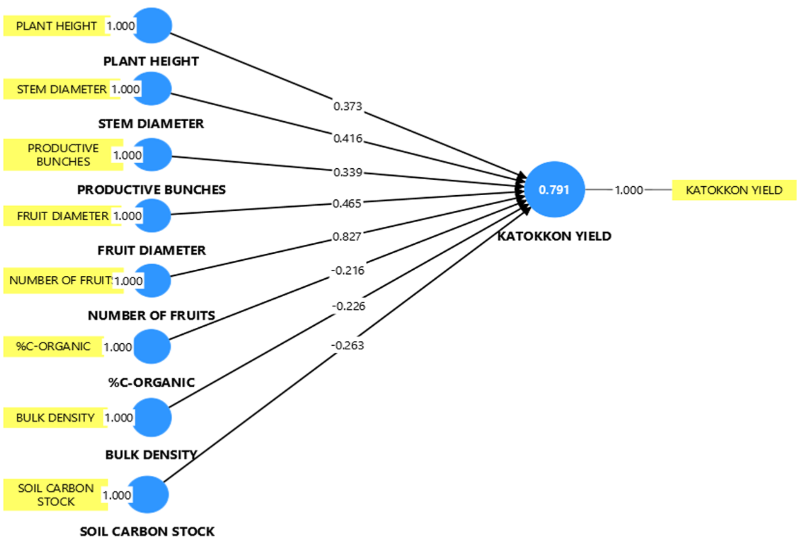


Figure 12. Correlation network between soil and plant growth parameters with katokkon yield

R2 (42.89 ton ha^{-1}) and R3 (39.20 ton ha^{-1}). In contrast, R0 declined to 27.99 ton ha^{-1}. Correlation analysis confirmed that fruit number was the strongest yield determinant (r = 0.827), followed by fruit diameter (r = 0.465) and stem diameter (r = 0.416). Overall, compost–biochar integration boosts soil health and productivity, supporting climate-resilient chilli farming.

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