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RESEARCH ARTICLE
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Rice Husk Biochar Outperforms Compost and Biol for Chive Growth and Yield in Pot Trials (*Allium schoenoprasum*)

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ABSTRACT

Agricultural residues can be transformed into biochar that enhances crop growth and reduces dependence on chemical fertilizers. In this study, the effect of rice husk biochar, biol from guinea pig manure, and commercial compost on the germination, growth and yield of chives (*Allium schoenoprasum*) was evaluated in 100-day pot experiments conducted under a randomized complete block design (RCBD) with 10 treatments and four blocks. Local soil was amended with biochar, compost, or biol at proportions of 2, 4, or 6%. The evaluated variables included germination percentage and growth-related parameters such as plant height, length, number of leaves, number of tillers, root surface area, and fresh weight. Results showed that rice husk biochar, particularly at 6%, increased fresh weight by 190%, plant height by 34%, and root surface area by 75% compared to the control, demonstrating its superior effect over compost, biol, and the non-fertilized soil. Compost also contributed positively, mainly improving germination and shoot growth, while biol showed limited benefits under the tested conditions. Overall, rice husk biochar demonstrated the greatest potential as a sustainable soil amendment to valorize agricultural residues, enhance fertility, and support circular economy strategies for chive production.

Keywords: *Allium spp*., Organic amendments, Soil health, Circular economy, Sustainable agriculture.

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INTRODUCTION

The increasing generation of diverse residues from agricultural and agroindustrial activities represents a significant environmental challenge, making it necessary to implement strategies that promote their reuse and valorization within the framework of the circular economy (Singh et al., 2022). Among these residues, biomass feedstocks such as crop residues, woody materials, green waste, animal manure, and agricultural by-products, including rice husks, can be used for the production of higher-value-added materials (Li et al., 2023). Rice is the staple food for more than 50% of the world's population, particularly in Asia, and in countries such as Japan it is also used for flour, animal feed, and biofuel production (Myszkowska et al., 2022). Furthermore, its increasing demand has intensified the use of nitrogen fertilizers, whose excessive application results in low nutrient use efficiency and high nitrogen losses, leading to negative impacts on air and water quality, soil biodiversity, and human health (Singh et al., 2022). Pyrolysis is one of the most widely used thermochemical processes for biomass valorization. It takes place in the absence of oxygen at high temperatures (300–700°C) and produces biochar, a carbon-rich and porous material that improves soil quality, increases crop productivity, supports sustainable waste recycling, helps sequester carbon, and immobilizes heavy metals in soil (Han et al., 2022).

Chives (*Allium schoenoprasum* L.) are leafy vegetables cultivated across a wide geographic range from Asia to Europe and North America. They are recognized for their high gastronomic and nutritional value (Nirmala & Sood, 2025). Their production depends on soil fertility, which in conventional systems relies on synthetic fertilizers whose

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intensive use has caused environmental problems such as groundwater contamination, soil degradation, and greenhouse gas emissions, highlighting the need for more sustainable fertilization alternatives (Tagkas et al., 2024). In this way, various organic fertilizers such as compost, biol, and biochar has gained increasing attention for their ability to improve soil quality and strengthen the resilience of agroecosystems. Compost contributes nutrients and improves soil structure, while biol stimulates soil microbial and enhances foliar absorption (Ghorbani et al., 2023). In contrast, biochar emerges as a sustainable alternative due to its unique properties, including high porosity, strong water and nutrient retention capacity, and carbon sequestration potential (Joseph et al., 2021). Biochar has been shown to transform soil properties and enhance plant growth. Derived from manure, agricultural residues, wood, or sludge through pyrolysis or gasification, it enhances soil quality by increasing pH (up to 8.92), cation exchange capacity, water retention, and nutrient availability, while immobilizing contaminants such as cadmium (up to 88.22% with 6–10% w/w applications) (Reyes et al., 2021). Its application consistently improves plant performance, increasing growth, biomass, and yield up to 40 % in maize and achieving optimal results in soybean with 98.4 g per pot. Biochar also stimulates soil biological activity, with a 60 % rise in mycorrhizal infection, enhanced nitrogen mineralization, and changes in microbial and nematode community structures. These effects depend on the feedstock, production method, and application rate (D'Hose et al., 2020).

In this context, several studies have highlighted the potential of biochar in different agricultural systems. For example, biochar produced from cassava stems has been reported to significantly enhance soil fertility and maize yield compared to compost alone, while its combined use with compost achieved the highest productivity. Furthermore, biochar has been shown to maintain soil macronutrient availability for up to five consecutive cultivation cycles (2.8 years), enhancing nutrient retention and increasing cation exchange capacity. Even a single application has demonstrated the capacity to sustain these benefits, underscoring its potential as a sustainable agricultural practice (Wijitkosum et al., 2025). In addition, integrating biochar with nitrogen fertilizers has been shown to increase stem, leaf, and root biomass in alfalfa, reduce soil bulk density, improve root traits, and raise the content of osmoregulatory substances, offering an effective way to mitigate the environmental impacts of inorganic fertilizers (Chai et al., 2025). Biochar has also emerged as a promising strategy for the remediation of cadmium-contaminated soils, since it shows high adsorption capacity under saline conditions and in acidic to neutral pH ranges, making it a sustainable option for immobilizing this metal (Huang & Imran, 2025). Nonetheless, its effectiveness depends on soil type and application rate, highlighting the need to consider soil characteristics and pH to optimize performance. In slightly alkaline yellow and yellow-brown soils, application rates between 2.5% and 5.0% improved organic carbon and reduced nitrate concentrations, whereas in neutral calcareous soils the effects on nutrient dynamics were less favorable (He et al., 2025). Even so, in all three soil types, increasing biochar doses significantly reduced the phyto-availability of heavy metals, confirming its potential as a sustainable soil management strategy. Thus, biochar is a promising organic fertilization strategy, enhancing soil fertility, crop growth, and environmental sustainability. Moreover, crops of the genus *Allium cepa* show notable improvements in growth and yield when amended with organic materials derived from manure, compost, and agro-industrial residues. Studies report yields exceeding 30t/ha, larger and heavier bulbs (up to 101g), and greater plant height, clearly outperforming chemical or untreated controls (Orden et al., 2021). Moreover, these practices embody circular economy principles by converting waste into resources through composting, vermicomposting, and anaerobic digestion. Such approaches not only reduce dependence on mineral fertilizers but also enhance soil fertility and stimulate microbial activity (Luo et al., 2025). However, the use of biochar in vegetables, especially chives (*Allium schoenoprasum*), has been little studied, making it necessary to assess its agronomic potential.

The most research on Allium crops has focused on bulb-forming species such as onion (A. cepa) and garlic (A. sativum), while little attention has been given to leafy species like chives (A. schoenoprasum), which have finer roots, shorter growth cycles, and distinct nutrient requirements. Consequently, the specific response of chives to biochar and other organic amendments remains poorly understood. Based on previous studies reporting optimal biochar application rates between 2% and 6% for vegetable crops (D'Hose et al., 2020; Luo et al., 2025), this range was selected to ensure effective nutrient enhancement without negatively affecting soil structure or plant physiology. Moreover, biochar doses within this range have been associated with optimal plant growth and microbial activation without inducing excessive alkalinity or nutrient immobilization, particularly in horticultural systems (Silvestre et al., 2025).

In this context, the aim of this study was to evaluate the effect of rice husk biochar, in comparison with commercial compost and biol derived from guinea pig manure, on the germination, growth, and yield of chives cultivated in pots under controlled conditions. A non-fertilized control treatment was also included in order to determine the relative effectiveness of each organic amendment on key variables such as germination percentage, plant height, number of leaves, number of tillers, fresh weight, plant length, and root surface area. This comparative assessment provides valuable insights into the potential of biochar as a sustainable soil amendment for improving crop productivity, supporting circular economy strategies through the valorization of agricultural residues, and reducing dependence on synthetic fertilizers.

MATERIALS & METHODS

Location

The experiment was conducted in a covered area using plastic pots at the Recinto Nuevo Porvenir property, located in Chillanes, Bolívar province, Ecuador (Fig. 1).

Fig. 1: Location of the experimental site in Recinto Porvenir, Chillanes, Bolivar province, Ecuador. Basemap source: Google Earth Pro.

The site is situated at 330.95 m a.s.l., with coordinates 9,755,579.92 N and 706,262.40 E (WGS84). During the experimental period, the average ambient temperature was 24.1°C, relative humidity 88.9%, atmospheric pressure 975.5hPa, and cumulative precipitation 0.022mm. The experiment was carried out under natural photoperiod conditions, typical of the local environment in Chillanes, where mean daily temperatures range between 22 and 25°C.

During the experiment, the substrate used in the pots was local soil, collected on site and prepared as a composite sample by homogenizing 20 subsamples taken at 20cm depth with a shovel. The soil chemical characterization was then performed at the National Institute of Agricultural Research (INIAP) (Table 1). Nitrogen (N), phosphorus (P), and boron (B) were determined by colorimetry; potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn) by atomic absorption; sulfur (S) by turbidimetry; pH by potentiometry; and organic matter by the Walkley–Black method with colorimetric detection. Moreover, the soil used in the experiment was classified as clay loam, based on its visual characteristics and field texture.

Preparation and Characterization of Organic Amendments (Rice Husk Biochar, Biol, and Compost)

Rice husks were collected from local mills in Riobamba, Ecuador, taking 0.5kg daily from different sites over one month to obtain a representative sample. The material showed a moisture content of 5.02wt%. After washing to remove impurities, it was ground into a fine powder and directly used for pyrolysis, following previous studies (Barzallo et al., 2025a). Pyrolysis was carried out in a GSH-5.0 reactor (Weihai Global Chemical Machinery, Weihai, China) at 500°C with a heating rate of 10°C min^{-1}, in triplicate. The biochar obtained was milled and sieved to ensure a uniform particle size for subsequent experiments. Furthermore, the rice husk biochar was subjected to physicochemical characterization prior to application, as described in the following section.

Other organic amendments were included for comparison, namely biol from guinea pig manure and compost. The biol was prepared based on previous studies conducted by our group with minor modifications, where pig and cow manure were used as the main raw materials, combined with agroindustrial residues and plant by-product (Barzallo et al., 2025b; Carpio et al., 2025). Briefly, guinea pig manure with other materials was fermented in a PVC biodigester (60 L capacity) at room temperature for 90 days with weekly stirring. After fermentation, the solid and liquid fractions were separated, and only the liquid portion was retained and stored at <12°C until use. Its chemical composition is summarized in Table 2.

In addition, the compost corresponded to a commercial product and was used as a reference amendment to contrast its properties with those of the rice husk biochar and biol. Its characterization is shown in Table 3.

Pot Experimental Design

The experiment was conducted using a randomized complete block design (RCBD) with 10 treatments and 4 blocks, resulting in a total of 40 experimental units. Each experimental unit consisted of one pot containing chives (*Allium schoenoprasum*) plants, to which the corresponding treatment was applied. Within each pot, five individual plants were evaluated as subsamples, and their measurements were averaged to obtain the representative value of the experimental unit. This approach reduced intrinsic variability among plants and increased the accuracy of treatment effect estimation. The statistical model considered blocks as random effects and treatments as fixed effects.

Table 1: Chemical properties of the soil

pH	OM **%**	N (mg L^{-1})	K (mg L^{-1})	Ca (mg L^{-1})	Mg (mg L^{-1})	P (mg L^{-1})	Zn (mg L^{-1})	Fe (mg L^{-1})	Mn (mg L^{-1})	S (mg L^{-1})
5.20	6.40	38.0	80.0	619.0	107.0	4.0	1.4	151.0	11.0	1.4

Table 2: Characterization of the chemical properties of the biol from guinea pig

pH	N %	P (mg L^{-1})	K (mg L^{-1})	Ca (mg L^{-1})	Mg (mg L^{-1})	Zn (mg L^{-1})	Fe (mg L^{-1})	EC (mScm^{-1})	TDS (g L^{-1})	R Ω (cm)	S %
5.5	0.7	52	4158	1883	686	6.0	80.0	36.3	22.3	32.9	27.7

EC= electrical conductivity; TDS= total dissolved solids; R= resistivity; S=salinity

Table 3: Characterization of compost

pH	K (cmol kg^{-1})	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})	OM %	N %	P (mg kg^{-1})	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})
6.0	20.60	49.91	17.28	22.1	1.3	2632.0	203.3	28.0	26.7	153.3

In addition, the plants were grown individually in conical plastic pots with an upper diameter of 11.5cm, a lower diameter of 6.0cm, and a height of 15.5cm, corresponding to an approximate volume of 1.0L. This pot size was suitable for chives (*Allium schoenoprasum*), as the species develops a shallow and fibrous root system that does not require large substrate volumes under greenhouse conditions. Each pot was filled with the corresponding amount of soil, as shown in Table 4. Fifteen seeds of *Allium schoenoprasum* (chives) were sown per pot. This variety has a harvest period ranging from 70 to 100 days after sowing. Fifteen days after sowing, excess seedlings were removed once the second true leaves had emerged, leaving only one plant per pot to ensure optimal development. Irrigation was carried out manually every three days, adjusted to meet the specific requirements of each treatment. Weed control was performed by hand weeding every 15 days after crop emergence. Substrates (250 g) consisted of local soil amended with biochar or compost at 2% (w/w, 5g), 4% (10g), or 6% (15g), and with biol at 2% (w/v, 5mL), 4% (10mL), or 6% (15mL). The biol was mixed into the substrate together with the other amendments, and all mixtures were homogenized to ensure a uniform distribution of the components before being placed in the pots. Each amendment was applied once at the beginning of the experiment (baseline application), and no additional fertilization was performed during the study.

Table 4: Randomized complete block design (RCBD) for chives (*Allium schoenoprasum*)

Treatment	Proportions
T0	250g Local soil (Control)
T1	245g Local soil + 2% Biochar
T2	235g Local soil + 4% Biochar
T3	220g Local soil + 6% Biochar
T4	245g Local soil + 2% Compost
T5	235g Local soil + 4% Compost
T6	220g Local soil + 6% Compost
T7	245g Local soil + 2% Biol
T8	235g Local soil + 4% Biol
T9	220g Local soil + 6% Biol

Evaluated Variables

Plant growth variables were measured at 30, 75, and 100 days after sowing of chives. In this way, the following parameters were evaluated: plant height (cm), measured from the soil surface to the tip of the longest leaf; plant length (cm), measured from the stem–root junction to the tip of the longest leaf, using a standard ruler. Root dimension (cm^2) was also calculated, and the number of leaves and number of tillers per plant were recorded. Germination tests were conducted using 15 chive *(Allium schoenoprasum)* seeds per pot and was considered successful when the radicle visibly emerged from the seed coat. Germination percentage (%) was assessed at 15 days after sowing using 15 seeds of chives per pot in each treatment. The statistical formula used was:

$$G(\%) = [(NSG) / (NSS)] \, x \, 100$$

Where: NSG: Number of seeds germinated, NSS: Number of seeds sown.

Finally, at harvest (100 days), the fresh weight (g) of the plants was measured.

Statistical Analysis

The significance of differences among treatments was assessed using analysis of variance (ANOVA), followed by mean comparisons with Tukey's test ($P<0.05$), performed with Minitab 18 statistical software.

RESULTS AND DISCUSSION

Characterization of Biochar Rice Husk

The chemical composition of rice husk biochar (Table 5) shows that it is a promising material for enhancing soil fertility. Its near-neutral pH (7.1) helps to balance acidic soils, while the high contents of K_2O (8.8%), CaO (5.2%), and MgO (2.6%) provide essential nutrients and contribute to improved soil structure. In addition, P_2O_5 (4.0%) and SO_4^{2-} (6.6%) supply phosphorus and sulfur, and zinc (0.4%) serves as a key micronutrient in deficient soils. Moreover, the carbon and nitrogen contents enhance nutrient retention and cation exchange capacity, reinforcing the fertilizing effect of biochar. Overall, rice husk biochar acts as a soil conditioner by supplying nutrients, improving structural stability, and supporting sustainable agriculture through the gradual release of nutrients.

Table 5: Chemical composition of rice husk biochar

pH	C (%)	N (%)	Zn (%)	CaO (%)	P_2O_5 (%)	SO_4 (%)	K_2O (%)	MgO (%)
7.1	17.2	1.4	5.2	4.0	6.6	8.8	2.6	0.6

The FTIR spectrum of raw rice husk showed characteristic bands associated with functional groups typical of the material (Fig. 2). The broad absorption band at 3300cm^{-1} corresponds to O–H stretching vibrations from hydroxyl groups in cellulose, hemicellulose, and lignin, while the band at 2920cm^{-1} is attributed to aliphatic C–H stretching. Additional peaks in the 1730–1600cm^{-1} region are related to carbonyl and aromatic groups, whereas absorptions between 1200–1000cm^{-1} are characteristic of C–O–C and Si–O–Si bonds, which are associated with the silica-rich mineral fraction of rice husk (Hossain et al., 2020).

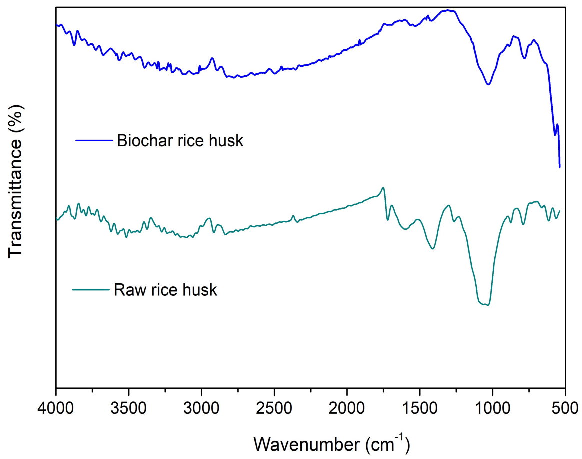

Fig. 2: FTIR spectra of raw rice husk and rice husk biochar.

In contrast, the FTIR spectrum of rice husk biochar shows a marked reduction in oxygenated functional groups, reflecting dehydration and thermal degradation of biomass during pyrolysis (Morales et al., 2021). The decrease in O–H vibrations and the disappearance or attenuation of carbonyl bands indicate the removal of volatile compounds and the progressive aromatization of the carbon matrix. However, the bands near 1100cm^{-1} and in the 800–700cm^{-1} region remain well defined, confirming the preservation of silica structures in the biochar, consistent with the high silica content of rice husk (Aziz et al., 2023). Additionally, the absorption band around 1420cm^{-1} suggests the formation of carbonate groups, possibly associated with reactions between the carbonaceous surface and inorganic species during carbonization. These chemical modifications confer properties that may enhance soil fertility, as soluble silica has been reported to promote plant resistance to biotic and abiotic stress, while carbonates contribute to acidity neutralization and improve nutrient availability (Fu et al., 2022).

Plant Grown Analysis

The ANOVA results (Table 6) indicated that all evaluated growth parameters of chives were significantly affected by the applied treatments ($P < 0.001$), whereas the block factor showed no significant effect in any case ($P > 0.05$). Germination (%) exhibited the strongest response ($F = 127.44$; df = 9, 27), confirming that the type of organic amendment markedly influenced seed emergence. Similarly, plant height at 30 days ($F = 28.33$), plant length ($F = 26.10$), and the number of leaves per plant ($F = 18.10$) were significantly affected by the treatments, reflecting consistent improvements in vegetative development under the most effective amendments. The high coefficients of determination obtained ($R^2 \geq 0.86$) indicate that most of the variation in these variables was explained by the treatments rather than by block variation, highlighting the strong influence of biochar, compost, and biol on the early growth and establishment of chives.

Table 6: Analysis of variance (ANOVA) for germination and growth parameters of chives *(Allium schoenoprasum)* under different organic amendment treatments

Variable	F value	df (Treatment, Error)	P value
Germination (%)	127.44	9, 27	<0.001
Plant height (cm, 30 days)	28.33	9, 27	<0.001
Plant length (cm)	26.10	9, 27	<0.001
Leaves per plant (n°)	18.10	9, 27	<0.001

Table 7 summarizes the germination, growth, and harvest parameters of chives under different treatments, showing clear and consistent improvements in response to the organic amendments. Germination percentage varied notably, with the highest value in T8 (78.67%), significantly superior to the control (35.00%), while intermediate values were observed in T3 and T5, indicating that the type of amendment strongly influenced seedling emergence. Similar to previous studies, these results suggest that germination is not solely dependent on the organic amendment used, but also on external factors such as seed vigor, temperature, moisture, and light conditions (Kordi et al., 2024). Likewise, the biochar (T3) and compost (T5) treatments resulted in greater plant height and leaf production, highlighting their positive impact on chive growth compared to the control. These results align with previous studies reporting that biochar application improves soil physicochemical properties and enhances plant development (Hossain et al., 2020).

Fig. 3 shows the plant height of chives after 100 days. The highest values were recorded for T3 (38.29cm), followed by T5 (37.77cm) and T6 (35.43cm), all significantly higher than the control (T0, 28.53cm). In contrast, treatments T7–T9 exhibited values similar to the control. These results indicate that biochar (T3) and compost (T5) had a more positive effect on plant growth compared to biol-based treatments and the unfertilized control. Similar plant height values were reported by Wang et al. (2021), who highlighted the importance of fertilization strategies in improving growth, nutrient uptake, and yield stability in chives, emphasizing the role of biochar in promoting sustainable productivity. A study reported in literature Algharib et al., (2021), showed that the combined application of compost tea (up to 200mL L^{-1}) and humic acid significantly improved the growth and yield of chive (Allium schoenoprasum L.), increasing plant height, biomass, and essential oil content compared with untreated plants. In the present study, a similar increase in plant height was achieved using rice husk biochar, despite applying considerably lower doses (2–6%) than those used for compost tea. This finding highlights the high efficiency of biochar as a soil amendment capable of enhancing plant performance by improving water retention, nutrient availability, and soil structure, while simultaneously contributing to residue valorization within the framework of the circular economy.

According to Gavhane et al., (2024), the number of tillers is a key indicator of plant performance, as it increases with age and strongly correlates with yield. Thus, tiller count serves as a practical parameter to assess growth and predict productive potential. Fig. 4 shows the number of tillers per plant in chives. The highest values were obtained with T6 (2.05), followed by T3 (1.85) and T5 (1.82),

Table 7: Results of germination, growth, and harvest parameters of chives (*Allium schoenoprasum*) under different treatments

Parameters	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	S
G (%)	35.00^{g}	45.00^{de}	51.00^{d}	57.33^{c}	36.67^{fg}	69.67^{b}	39.00^{efg}	41.67^{ef}	78.67^{a}	48.33^{d}	**
PT (cm)*	5.30^{f}	6.02^{ef}	8.00^{bcd}	9.40^{a}	7.99^{bcd}	9.01^{ab}	8.50^{abc}	7.45^{cd}	7.22^{d}	6.85^{de}	**
PL (cm)	30.83^{e}	33.46^{cde}	34.45^{bcde}	40.04^{a}	37.09^{abc}	39.75^{ab}	36.93^{abcd}	30.85^{e}	31.50^{de}	31.50^{de}	**
LPP (n°)	3.60^{e}	4.30^{cde}	5.90^{b}	7.35^{a}	5.45^{bcd}	6.05^{ab}	5.60^{bc}	4.20^{de}	3.90^{e}	4.75^{bcde}	**

G=germination at 15 days; PT= plant height, PL= plant length, LPP= Leaves per plant, *= measurements taken at 30 days; S= significance; **=the treatments are statistically different (P<0.001).

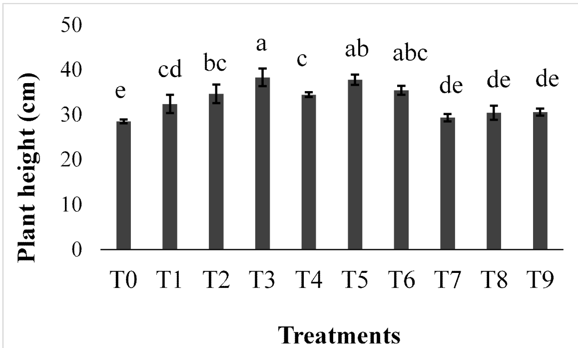

Fig. 3: Plant height at 100 days. Error bars represent the standard deviation (n=4). Different lowercase letters indicate statistically significant differences between treatments (Tukey's test, P<0.05).

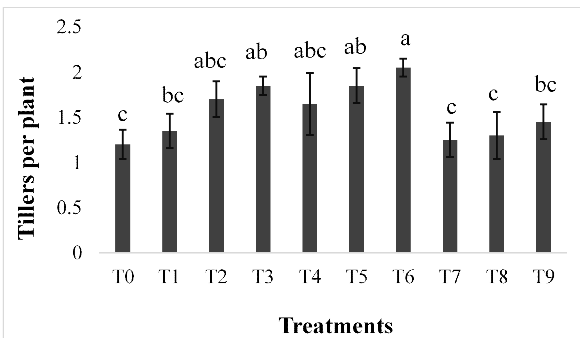

Fig. 4: Tillers per plant. Error bars represent the standard deviation (n=4). Different lowercase letters indicate statistically significant differences between treatments (Tukey's test, P<0.05).

compared to the non-fertilized control (T0, 1.25). These results indicate that biochar at 6% (T3) improved soil conditions that favored tillering, promoting better vegetative growth and higher yield potential. Furthermore, the availability of soil moisture plays a crucial role in crop development. In this way, several studies have reported Singh et al. (2022) that the incorporation of rice husk biochar (RHB) enhances the soil's water-holding capacity due to its high micro- and mesoporosity, which improves capillary action and facilitates water movement within the soil matrix. This porous structure increases the surface area and promotes more efficient water retention, particularly in coarse-textured and low-fertility soils. As a result, the application of RHB has been shown to enhance soil moisture retention, root water uptake, and plant biomass production across various soil types, with the greatest benefits observed in sandy or degraded soils.

Fig. 5 shows the fresh weight (g) of chives under different treatments. The highest values were obtained with T3 (15.25g), T5 (15.00g), and T6 (14.50 g), which were significantly greater than the non-fertilized control (5.25g). These results indicate that biochar and compost were more effective than biol in improving chive biomass production. Similar findings were reported by Oliveira et al., (2024), who observed lower plant height, fresh weight, and dry weight when only compost was applied, whereas the addition of castor cake and hoof-and-horn meal significantly increased biomass due to higher nutrient availability. They also highlighted that higher doses of organic fertilization enhanced crop yield, emphasizing the importance of biomass accumulation as a key parameter to evaluate soil amendments and sustainable fertilization strategies. Therefore, the present results demonstrate that biochar has greater potential to increase the fresh weight of chives compared to compost and biol. Moreover, the incorporation of rice husk biochar improves soil fertility by increasing cation exchange capacity (CEC), reducing nutrient leaching, and optimizing physical properties such as porosity and bulk density. Applications between 1% and 3% in sandy loam soils can raise CEC by up to 30%, while higher doses enhance total porosity and water-holding capacity. These effects promote nutrient retention, root development, and biomass production across different agricultural systems, highlighting the potential of RHB to improve soil structure, nutrient availability, and moisture retention, particularly in low-fertility or degraded soils (Singh et al., 2022).

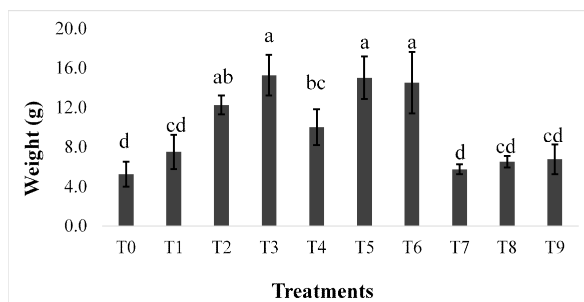

Fig. 5: Weight (g) of chives. Error bars represent the standard deviation (n=4). Different lowercase letters indicate statistically significant differences between treatments (Tukey's test, P<0.05).

Fig. 6 shows the root surface area of chives under different treatments. The highest value was recorded for T3, exceeding 320cm² and significantly surpassing all other treatments. In contrast, biol-based treatments (T7–T9) and the non-fertilized control (T0) exhibited the lowest root surface areas (<220cm²), with no significant differences among them. These findings highlight the superior effect of biochar, particularly at higher concentrations (6%), in promoting root expansion. This effect is likely related to improvements in soil porosity, aeration, and nutrient retention, which create more favorable conditions for root growth.

Fig. 7 showed the morphological differences in harvested chives under different treatments. Plants grown with biochar exhibited greater height than those under the non-fertilized control, while root surface area was also enhanced compared to the control root system. These observations suggested that biochar promoted both shoot and root development. In contrast, control plants displayed limited growth, with less vigorous shoots and sparser root systems. Biochar applied at 6% promoted more extensive root development, greater biomass, and superior vegetative growth than compost, biol, and the control. This finding is consistent with the study of Akumuntu et al. (2024), who evaluated rice husk biochar in lettuce (*Lactuca sativa)* and found that increasing biochar concentrations (0–1.5%) significantly enhanced root weight and leaf number, likely due to greater nutrient availability. Moreover, biochar improves the biological and physicochemical properties of the soil, creating favorable conditions for plant growth. Its application is also considered safe, as toxicity tests with earthworms in lettuce showed no significant ecotoxicity, reinforcing its potential as a sustainable and efficient amendment to optimize chive production.

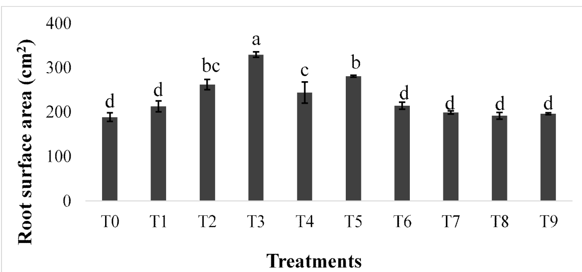

Fig. 6: Root surface area (cm^2) of chives. Error bars represent the standard deviation (n=4). Different lowercase letters indicate statistically significant differences between treatments (Tukey's test, P<0.05).

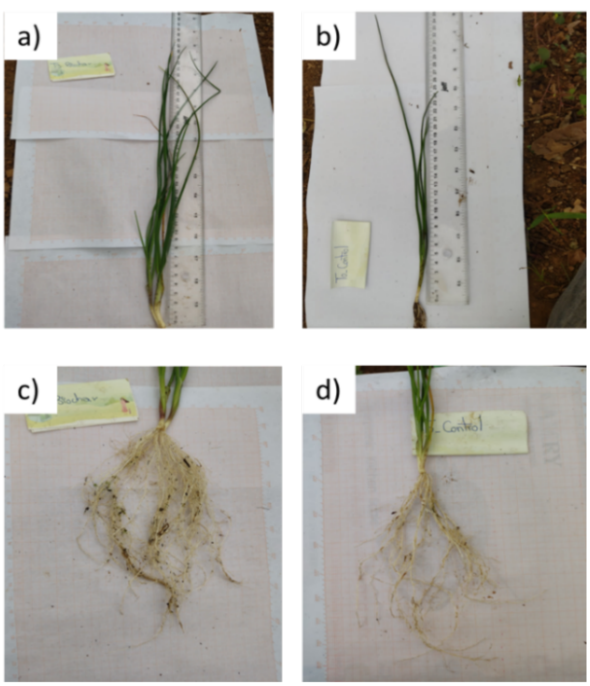

Fig. 7: Harvested chives: (a) plant height under biochar treatment; (b) plant height under control treatment; (c) root surface area under biochar treatment; (d) root system of the non-fertilized control.

Fig. 8 shows the principal component analysis (PCA) of the treatments, performed on centered and scaled data to standardize the contribution of each variable. The first two principal components accounted for 98.8% of the total variance (PC1 = 94.2% and PC2 = 4.6%), effectively summarizing the variability among the growth parameters. The biplot shows a clear separation between treatments: the control is located in the negative region of PC1, corresponding to low values for all measured variables after harvest, while biochar, compost, and biol appear in the positive region, associated with enhanced plant height (cm), weight (g), length (cm), leaf number, and root surface area (cm^2). Compost was primarily linked to higher germination, biochar to vigorous vegetative growth and foliage, and biol occupied an intermediate position, reflecting moderate effects on plant performance. Overall, both compost and biochar markedly improved chives growth compared to unfertilized soil. Eigenvalues and variable loadings are provided in the Supplementary Material.

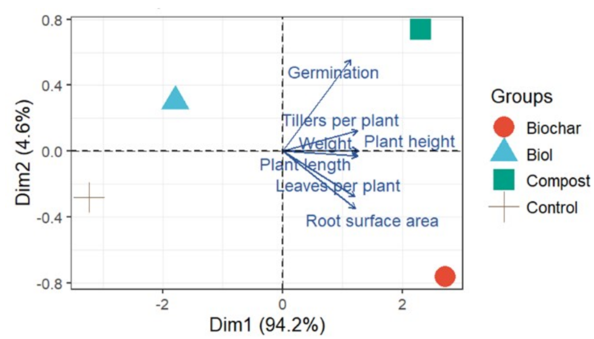

Fig. 8: Principal component analysis (PCA) of agronomic variables under Biochar, Biol, Compost, and Soil treatments.

Conclusion

This study demonstrated that rice husk biochar significantly improved plant growth, and yield of chives (*Allium schoenoprasum*) compared to compost, biol, and the unfertilized control. Biochar at 6% promoted greater plant height, number of leaves, root system development, and fresh weight, confirming its superior fertilizing effect and capacity to improve soil quality and supporting sustainable chives cultivation. Compost also contributed positively, mainly enhancing germination and growth, whereas biol showed limited benefits under the tested conditions. Moreover, the use of rice husk biochar provides a sustainable strategy to valorize agricultural residues, reduce dependence on chemical fertilizers, and promote circular economy practices in crop production.

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Ethics Statement: This study did not require ethical approval, as it did not involve human participants, sensitive personal data, or animal subjects

Author's Contribution: Diego Barzallo and Paul Palmay designed the research and conducted the data analysis, César Gavin, Edwuin Carrasquero, Diego Barzallo and Fatima Yugsan performed the field trials. Diego Barzallo reviewed and interpreted the results. All authors contributed to manuscript preparation and final review, approved the final manuscript for submission.

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