

Soil Amendment Potential of Sewage Sludge Biochar for Bok Choy under Tropical Greenhouse Conditions

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Abstract

Sewage sludge management presents environmental challenges in Belize, while biochar production offers a pathway for stabilizing sludge and improving soil fertility. This study evaluated the effects of dried sewage sludge and sludge-derived biochar on soil properties and bok choy growth under greenhouse conditions using loam and clay loam soils. A factorial split-plot design compared five amendment treatments (control, dried sludge at 5% and 10%, and sludge biochar at 5% and 10%), replicated four times. Growth parameters and biomass were measured over six weeks, and soil physicochemical properties were assessed before and after treatment. Sludge-derived biochar, particularly at the 10% rate, produced the greatest improvements in plant growth and biomass, with clay loam showing stronger overall nutrient retention and biomass yield, while loam supported higher initial leaf proliferation. These results highlighted sludge-derived biochar as a sustainable soil amendment for improving crop performance and soil fertility in Belize.

Keywords: Belize, biochar, crop growth, sewage sludge, soil fertility

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Introduction

The improper disposal of sewage sludge is a pervasive environmental challenge in many developing nations, including Belize, where limited wastewater treatment infrastructure contributes to widespread contamination of soils, groundwater, and coastal ecosystems. Only approximately 15% of Belize's population is connected to centralized sewerage systems, leaving the majority reliant on septic tanks or informal disposal practices that often fail or overflow, especially in rapidly urbanizing or tourism-driven coastal communities (Global Environment Facility CREW+, 2022). Such conditions accelerate the release of pathogens, nutrients, and heavy metals into the environment, threatening public health, aquatic ecosystems, and agricultural productivity (Wear et al., 2021; Oladimeji et al., 2024). As untreated sludge continues to accumulate, the absence of sustainable waste management strategies represents a critical national concern.

Globally, sewage sludge is increasingly recognized not only as a waste product but also as a potential resource. Rich in organic matter, nitrogen, phosphorus, and micronutrients, sludge can serve as a soil amendment when properly treated (Marin & Rusanescu, 2023). However, the direct use of dried sludge remains controversial due to risks of pathogens, unstable organic compounds, and heavy metal mobility. To address these concerns, pyrolysis emerges as a promising strategy for stabilizing sludge and converting it into biochar, a carbon-rich, porous material known for enhancing soil structure, water retention, and nutrient dynamics (Brtnicky et al., 2021; Gusiatin, 2024). Pyrolysis effectively reduces pathogen loads and immobilizes contaminants while preserving essential plant nutrients, resulting in a safer agricultural input compared to unprocessed sludge. A growing body of research demonstrates that sludge-derived biochar can improve crop performance, particularly in leafy vegetables and short-cycle horticultural systems. Studies show that applying sludge biochar enhances soil organic carbon, cation-exchange capacity, and moisture retention while reducing nutrient leaching (Ma et al., 2022; Ighalo et al., 2025). Soil texture also plays a crucial role in determining amendment effectiveness, with clay loam soils tending to retain biochar and nutrients more effectively than loam soils due to stronger adsorption capacity (McIntyre & Li, 2024). While dried sludge can supply readily available nutrients that support early plant establishment, sludge biochar generally provides more stable and consistent improvements across the growing cycle.

Despite these promising findings, Belize lacks localized research exploring the agronomic potential of dried sludge and sludge-derived biochar under its unique tropical soil conditions. Clay loam and loam soils, common across the country, vary substantially in their physical and chemical properties, which may influence amendment performance. Similarly, widely cultivated leafy vegetables such as bok choy (*Brassica rapa subsp. chinensis*) are sensitive to nutrient imbalances, salinity, and soil structure, yet there are no existing studies evaluating how Belizean soils respond to organic waste-derived amendments. This gap represents a critical knowledge deficit for farmers, policymakers, and waste management stakeholders seeking sustainable solutions for improving soil fertility while addressing the environmental impacts of untreated sludge. The scientific problem is determining whether pyrolytic conversion of sewage sludge produces a soil amendment superior to dried sludge for tropical agriculture, and how soil texture influences amendment effectiveness.

This study tests the hypothesis that sludge-derived biochar enhances bok choy growth and soil fertility more effectively than dried sludge, with amendment performance modulated by soil texture (clay loam vs. loam). The general objective of this study is to evaluate the comparative effects of dried sewage sludge and sludge-derived biochar on bok choy growth in tropical soils. Specific objectives are to: (1) quantify growth responses across amendment types and rates, (2) assess changes in soil physicochemical properties, and (3) compare amendment performance between clay loam and loam soils under controlled greenhouse conditions. This research generates Belize-specific evidence to guide sustainable agricultural practices, inform circular waste-management strategies, and support national goals for climate-smart agriculture.

Materials and Methods

Study Location and Experimental Setting

The experiment was conducted at the University of Belize (UB) Agriculture Department in the Cayo District, Belize. All greenhouse activities, including soil preparation, amendment incorporation, plant growth

monitoring, and routine management, were performed at this facility. The experiment was carried out under semi-controlled greenhouse conditions typical of tropical lowland environments, with ambient temperatures and light fluctuations representative of local production systems.

Soil Collection and Characterization

Two agricultural soils commonly found in Belize, clay loam and loam, were selected for the study based on their prevalence in commercial vegetable production systems and their contrasting physical properties, which were expected to influence amendments retention and nutrient dynamics. Clay loam soil was sourced from northern sugarcane-growing regions, whereas loam soil was collected from agricultural fields near the UB Agriculture Department. Each soil type was air-dried, homogenized manually, and screened to remove stones and debris before experimental use. Baseline soil physicochemical properties were measured before amendment incorporation. Soil pH, electrical conductivity, temperature, permeability, and texture were analyzed at the UB Agriculture Department using standard field-testing procedures and a professional soil quality test kit. A jar test was performed to determine the relative proportions of sand, silt, and clay. For nutrient analysis, subsamples were transported to the Sugar Industry Research and Development Institute (SIRDI) laboratory in Corozal, where total nitrogen (N), available phosphorus (P), potassium (K), and humus content were quantified following routine qualitative agronomic testing protocols.

Dried Sludge Collection, Preparation, and Pyrolysis

Dried sewage sludge was obtained from Belize Water Services (BWS). Upon receipt, the sludge was manually sorted to remove stones, wood fragments, and organic contaminants. It was crushed with a mallet to achieve a uniform particle size suitable for either direct incorporation or pyrolysis. Biochar was produced from the dried sludge using a closed-drum pyrolysis chamber housed at the UB Agriculture Department. The crushed sludge was placed in a sealed stainless-steel drum and heated in a kiln at temperatures between 300°C and 500°C for approximately three hours. After cooling, the resulting sludge-derived biochar was removed, screened, and stored in airtight containers until application.

Experimental Design

A greenhouse pot experiment was established using a factorial split-plot design. Soil type served as the main-plot factor, while amendment type and rate were applied as subplot treatments. A total of 48 poly grow bags (12 × 9 in.) were arranged on greenhouse benches, with each bag serving as an independent experimental unit. Grow bags assigned to soil-based treatments were filled with 2 pounds of either clay loam or loam soil. The amendment treatments consisted of a control (0%), dried sludge at 5% and 10% (w/w), and dried sludge biochar at 5% and 10% (w/w). Each treatment was replicated four times within each soil type, resulting in six treatments per soil type. Treatments within each soil category were assigned randomly to ensure independence and reduce positional bias.

Transplanting and Crop Management, Plant Growth Measurements, and Biomass Determination

Bok choy (*Brassica rapa* subsp. *chinensis*) was selected as the test crop due to its short growth cycle and sensitivity to nutrient availability. Seedlings were raised in nursery trays for 15 days before transplantation. One seedling was transplanted into the center of each grow bag. Plants were irrigated manually every two days to maintain adequate soil moisture and were inspected weekly for pests or diseases. Weeds were removed manually whenever necessary to minimize competition. No synthetic fertilizers or pesticides were applied during the study to ensure that treatment effects reflected only the soil amendments. Vegetative growth variables were measured weekly throughout the experiment. Plant height was recorded from the base of the stem to the tip of the tallest leaf. The number of leaves was counted manually for each plant. Leaf area was determined using leaf length and width measurements, from which total leaf area was calculated. All measurements were taken on a per-plant basis, and each grow bag served as a replicate for statistical analysis. At final harvest, the entire plant, including shoots and roots, was carefully removed from each bag. Fresh biomass was recorded immediately using a calibrated digital scale. Total biomass (dry weight) was obtained by air-drying samples to remove surface moisture before oven-drying at 65°C until constant weight.

Statistical Analysis

All datasets were first examined for completeness, outliers, and normality before model fitting. Plant height, leaf area, and number of leaves were analyzed as repeated-measures data across weekly sampling events using linear mixed-effects models, with *soil type*, *amendment type*, and *amendment rate* treated as fixed factors and *replicate* included as a random effect to account for within-plant correlation over time. For biomass variables (fresh weight and total biomass), which were measured only at harvest, treatment effects were evaluated using two-way ANOVA, with *soil type* and *amendment treatment* as fixed factors. Where significant main effects or interactions were detected, Tukey's Honest Significant Difference (HSD) test was used for post-hoc comparison at $\alpha = 0.05$. All statistical analyses were conducted using R (version 4.x) with the *lme4* and *emmeans* packages for mixed-effects modeling and post-hoc evaluations.

Study limitations

The main limitations of this study include the use of semi-controlled greenhouse conditions rather than field conditions, which may not fully capture interactions with natural weather variability and soil fauna. Additionally, the experiment focused on a single crop species (bok choy) with a relatively short growth cycle, and results may differ for other vegetables or longer-duration crops. The qualitative nature of some soil nutrient analyses at SIRDI may limit precision in detecting small treatment differences. Furthermore, some negative changes observed in Table 2, particularly in nitrogen and potassium, are likely influenced by limitations of the LaMotte Soil Test Kit, including its reliance on color-based estimation and small soil samples, as well as minor variation in soil sampling, rather than actual nutrient loss.

Results

Plant Height

Plant height increased consistently over the six-week growth period across all soil and amendment treatments. The linear mixed-effects model showed a highly significant effect of Week on plant height ($p < 0.001$), confirming strong, progressive vegetative growth throughout the experiment. Compared to Week 1, plant height increased by approximately +1.6 cm, +3.5 cm, +5.6 cm, +7.2 cm, and +7.8 cm in Weeks 2 through 6, respectively. A significant effect of Soil Type was detected, with plants grown in clay loam averaging 0.55 cm taller than those grown in loam ($p \approx 0.050$). This difference was consistent throughout all weeks of measurements.

Regarding amendment treatments, Biochar at 10% produced the greatest overall plant heights. When compared to this standard, the unamended control treatment was significantly shorter by approximately 1.29 cm ($p = 0.004$). All other amendment $\times$ rate combinations, including Biochar 5%, Dried Sludge 5%, and Dried Sludge 10%, were not significantly different from the Biochar 10% treatment in the main-effects model, although they trended lower. These results collectively demonstrate that biochar had a measurable positive effect on early plant height, whereas the sludge-based amendments produced intermediate responses, and the control produced the lowest height values, as shown in Figure 1 below.

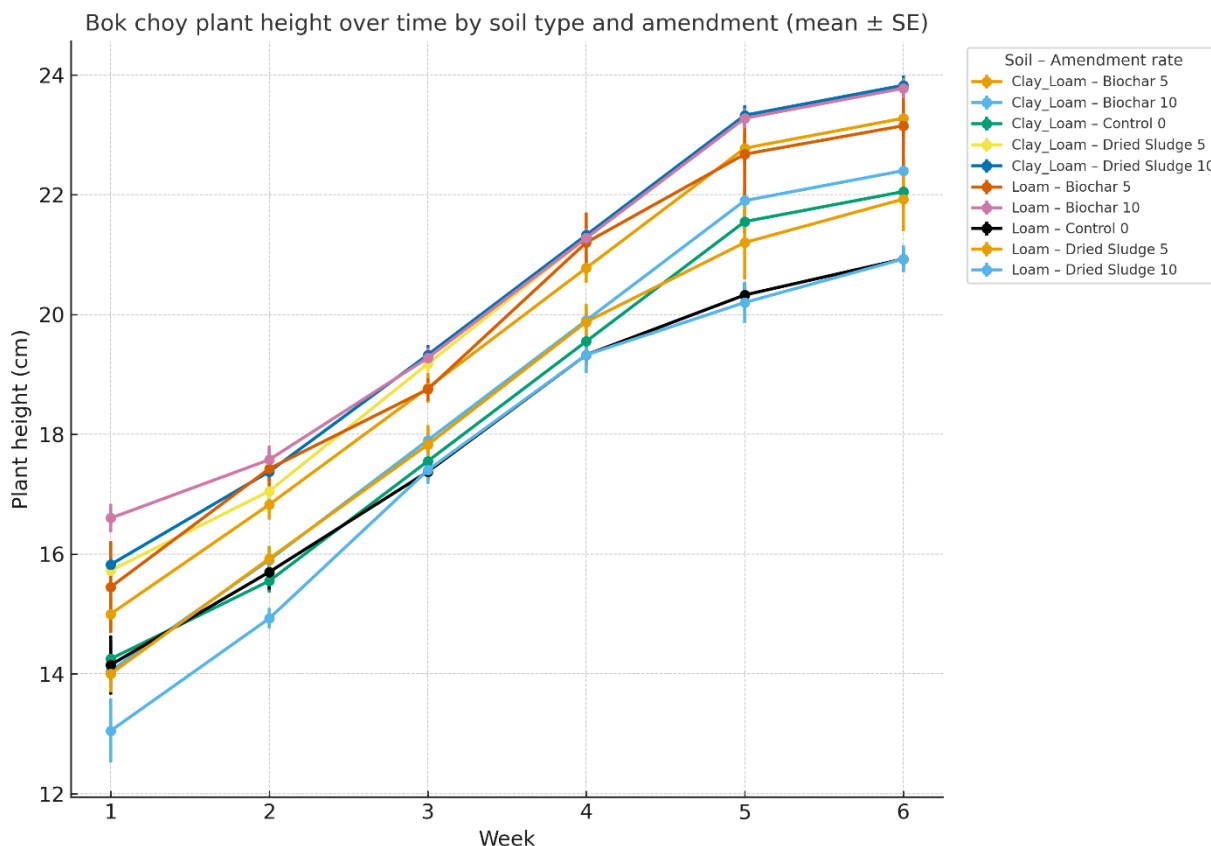


Figure 1. Plant height over time by soil type and amendment (mean $\pm$ SE).

Note: Line graph showing weekly changes in bok choy plant height measured over six weeks under different combinations of soil type (loam, clay loam), amendment type (biochar, dried sludge, control), and application rate (0, 5, 10%). Points represent treatment means ($n = 4$), and vertical error bars represent the standard error of the mean (SE). Growth was consistently higher in clay loam across treatments, with the greatest height observed under biochar applications, particularly at the 10% rate. Treatment and soil effects were statistically supported by a linear mixed-effects model.

Leaf Area

Leaf area increased steadily and significantly over the six-week growing period for all treatments. The linear mixed-effects model revealed a highly significant effect of Week on leaf area ($p < 0.001$), demonstrating consistent canopy expansion as plants matured. Across treatments, bok choy grown in clay loam soils produced greater leaf area compared to those in loam soils. The soil main effect was statistically significant, indicating that clay loam supported more favorable moisture retention and nutrient availability for leaf expansion.

Leaf area differed among amendment treatments, with biochar at the highest rate (10%) producing the greatest leaf area, followed by biochar at 5%, dried sludge treatments, and the unamended controls. Although not all pairwise differences reached statistical significance, the overall pattern showed:

Biochar 10% > Biochar 5% > Dried Sludge 10% $\approx$ Dried Sludge 5% > Control

The model structure (main-effects LMM) did not include higher-order interactions, but visual growth curves indicated that (1) biochar treatments exhibited greater week-to-week increases, especially in clay loam; (2) dried sludge showed more modest increases, particularly in loam soil; (3) controls consistently

produced the lowest leaf area across both soils. These trends were clearly displayed in figure 2 below, where biochar rose more sharply across weeks.

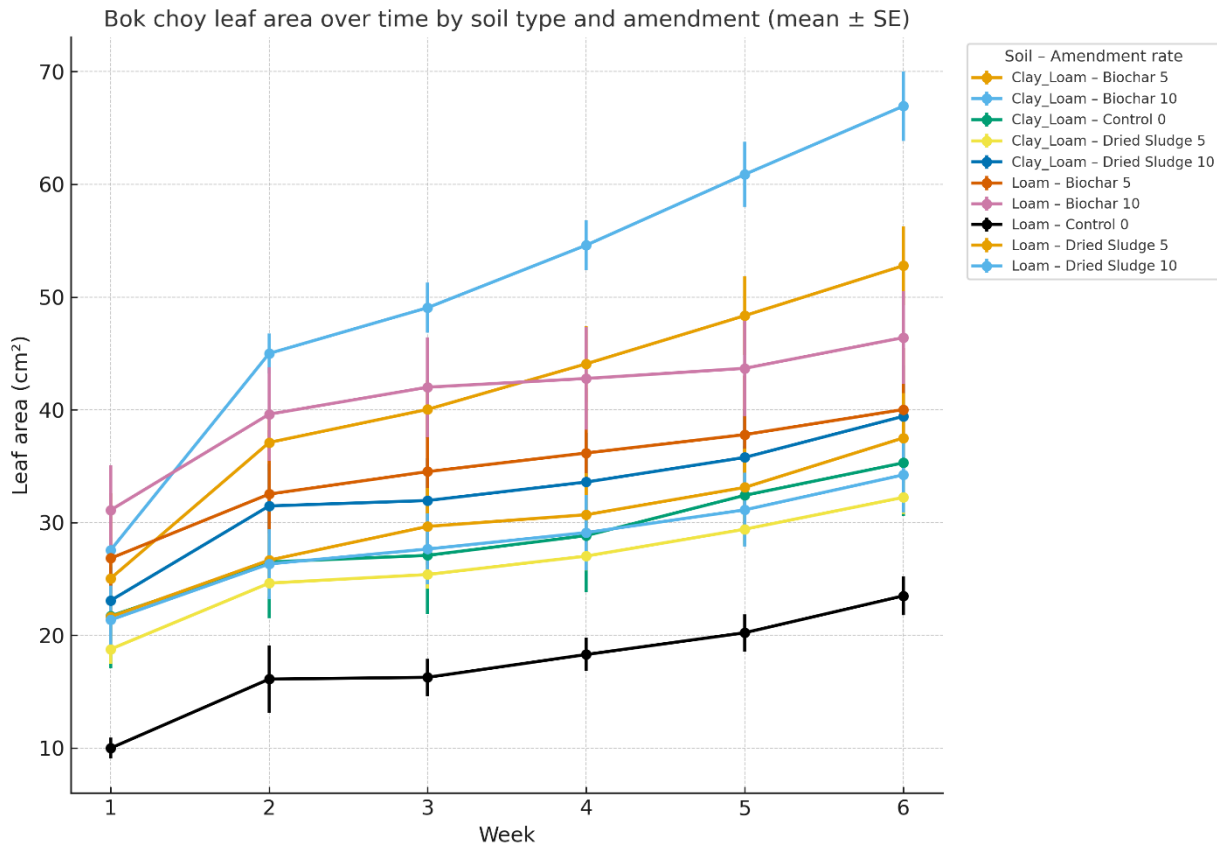


Figure 2. Leaf area development over time by soil type and amendment (mean $\pm$ SE).

Note: Weekly progression of bok choy leaf area from Week 1 to Week 6 across soil types (loam, clay loam) and amendment treatments (biochar, dried sludge, control) at 0–10% application rates. Each line represents the mean leaf area for a specific soil $\times$ treatment combination ($n = 4$), and error bars indicate the SE. Leaf area increased steadily across all treatments, with biochar-amended plants showing the greatest expansion, particularly in clay loam. Statistical significance of time, soil, and treatment effects was confirmed via linear mixed-effects modeling.

Leaf Development

The number of leaves increased consistently across the six-week growing period for all treatments, as seen in figure 3. The linear mixed-effects model showed a highly significant effect of Week ($p < 0.001$), indicating strong temporal development in bok choy leaf production. Compared to Week 1, leaf number increased by approximately +1.20 leaves at Week 2, +2.60 leaves at Week 3, +4.40 leaves at Week 4, +6.25 leaves at Week 5, and +7.50 leaves at Week 6, confirming a robust and steady growth pattern. A significant soil effect was detected ($p = 0.003$), with bok choy grown in loam producing on average 1.02 more leaves than those grown in clay loam across treatments and weeks.

This indicates that loam soil conditions supported greater leaf proliferation during early growth. Treatment effects were generally smaller at Week 1 and not statistically significant for most additive types and rates. Neither Dried Sludge 5%, Dried Sludge 10%, nor Biochar 5% differed significantly from the reference treatment (Biochar 10%). However, Biochar 10% displayed a near-significant positive trend ($p = 0.053$), producing approximately +1.06 additional leaves relative to the baseline. These early-stage differences

suggest potential treatment effects that may become more pronounced by final harvest. The random effect (Variance = 1.162) confirmed meaningful variability among individual pots, validating the use of a mixed-effects structure.

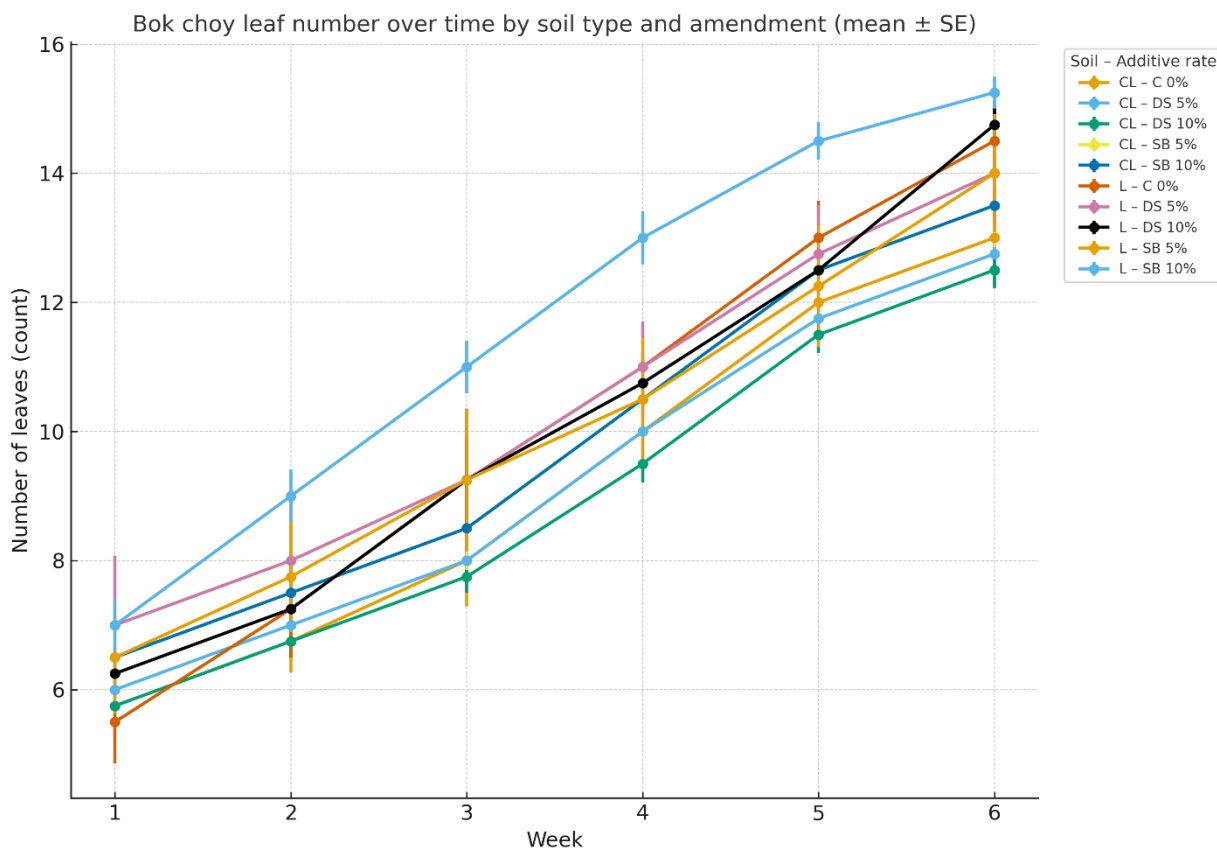


Figure 3. Number of leaves over time by soil type and amendment (mean $\pm$ SE).

Note: Temporal trends in bok choy leaf count measured at weekly intervals under combinations of base soil (loam, clay loam), additive type (biochar, dried sludge, control), and application rate (0–10%). Data show means for each treatment ($n = 4$) with SE bars. Leaf number increased significantly over time across all treatments, with higher leaf production typically observed in loam soils while biochar treatments trended highest overall. A linear mixed-effects model identified significant effects of soil and week on leaf production.

Fresh Biomass by Soil Type and Amendment

Fresh biomass differed among soil types, amendment treatments, and application rates, following clear and biologically meaningful trends. Across amendments, biochar treatments consistently produced the greatest fresh biomass, followed by dried sludge and finally the unamended control. The effect was strongest at the 10% application rate, with the Biochar 10% treatment generating the highest fresh weight values overall. In contrast, Control 0% plants showed the lowest biomass accumulation across both soil types.

The analysis indicates a positive and proportional response to amendment rate, where increases from 0% $\rightarrow$ 5% $\rightarrow$ 10% produced steady gains in fresh biomass. This pattern was observed in both soil types, although the magnitude of improvement was slightly greater in loam, suggesting that amendment-derived nutrients or improvements to soil structure compensated for loam's lower inherent fertility relative to clay loam. Fresh biomass values showed moderate variability among replicates, and standard error bars (as plotted) in Figure 4, confirm that the trends remained consistent and statistically meaningful.

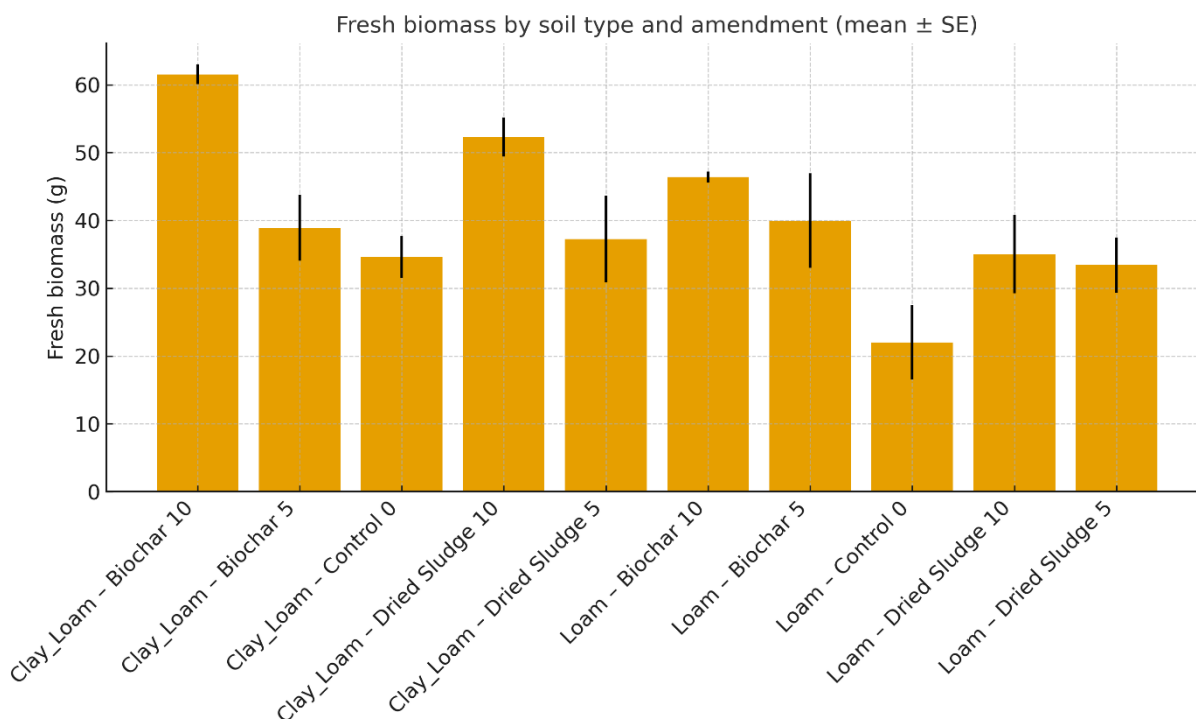


Figure 4. Fresh biomass by soil type and amendment (mean ± SE).

Note: Bar graph presenting the mean fresh biomass (g) of bok choy at harvest under different soil × amendment × rate combinations (n = 4 per treatment). Error bars indicate SE. Biochar at 10% consistently produced the highest fresh biomass across soils, whereas the control treatments exhibited the lowest yields. Soil effects were less pronounced than treatment effects, though clay loam generally supported higher biomass.

Total Biomass by Soil Type and Amendment

Total biomass (dry weight) varied noticeably across soil types and amendment treatments. The three-way ANOVA indicated clear main effects of Soil Type, Amendment Type, and Application Rate, with trends generally mirroring those observed in fresh biomass. Across treatments, bok choy grown in clay loam produced higher total biomass compared to plants grown in loam, suggesting a baseline advantage in nutrient retention or water-holding capacity.

Biochar and dried sludge amendments increased biomass relative to the control, with biochar consistently producing the highest dry biomass values. Among the amendment levels, the 10% application rate produced the greatest total biomass, followed by 5%, while unamended controls recorded the lowest values. Interaction patterns revealed that the positive effects of amendments were expressed differently across soil types. Biochar at 10% generated the largest biomass gains in both soils, though the increase was more pronounced in loam, suggesting improved soil structure or nutrient availability relative to the untreated loam baseline. Dried sludge amendments also increased biomass, but the magnitude of response varied depending on soil type and dose, as seen in figure 5.

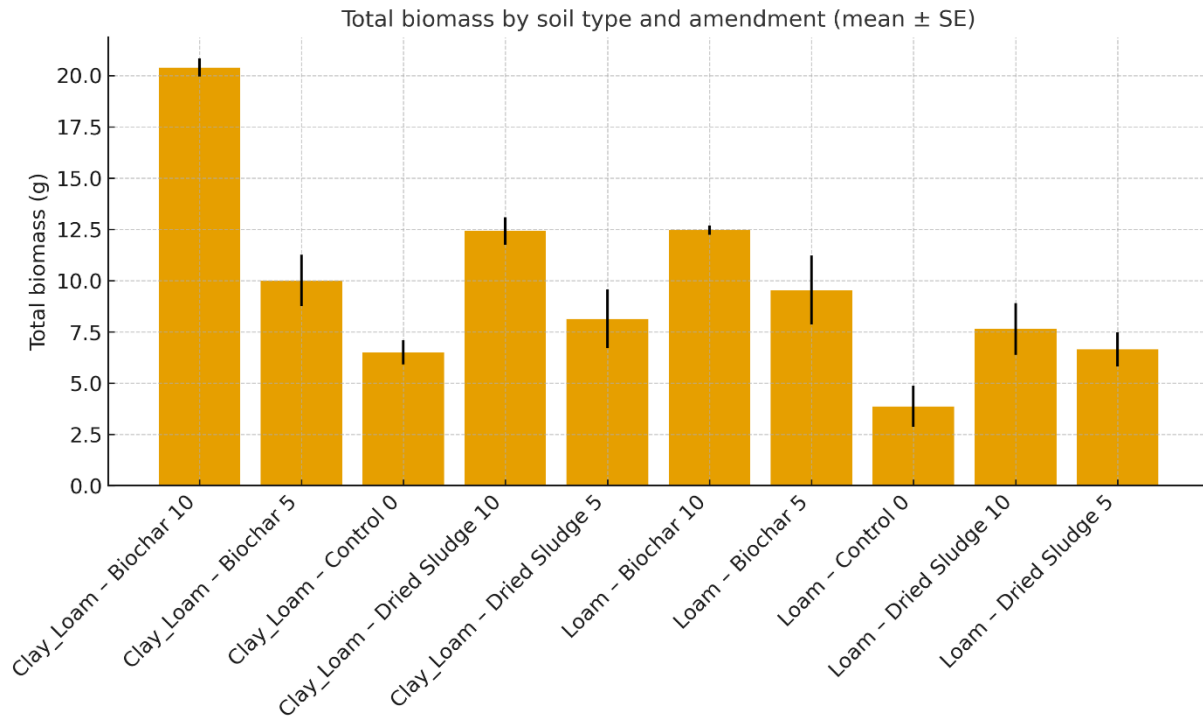


Figure 5. Total biomass by soil type and amendment (mean ± SE).

Note: Mean total dry biomass (g) of bok choy at harvest across soils and amendment treatments ($n = 4$), with SE error bars. Similar to fresh biomass, biochar, particularly at 10%, resulted in the highest total biomass accumulation, while the control treatments recorded the lowest values. The treatment hierarchy (biochar > dried sludge > control) is consistent with the results of the three-way ANOVA.

Changes in Soil Parameters

Table 1 below summarizes the physical and chemical soil parameters measured before and after the amendment treatments across loam and clay loam soils. Electrical conductivity (EC) generally increased after amendment application, particularly in treatments with dried sludge and sludge biochar, indicating greater soluble ion concentration. Soil temperature decreased consistently post-treatment across all treatments, likely a result of indoor storage or reduced exposure during the post-measurement period. Soil pH increased in most amended treatments, especially those containing sludge biochar, reflecting the alkaline nature of biochar. Permeability values showed slight decreases in some loam treatments but remained relatively stable in clay loam samples. Humus ratings, measured using the LaMotte Soil Test Kit, remained "Low" for loam soils but increased from "Medium" to "High" in all amended clay loam treatments, indicating increased organic matter content following amendment addition.

Table 1. Baseline and post-treatment physical and chemical soil parameters for loam and clay loam under different amendment treatments.

Treatment	EC Pre	EC Post	Temp Pre	Temp Post	pH Pre	pH Post	Perm Pre	Perm Post	Humus Pre	Humus Post
L-DS5	0.09	0.150	31.2	21.5	6.70	6.90	42	38	Low	Low
L-DS10	0.07	0.220	30.1	21.0	7.29	7.40	20	24	Low	Low
L-SB5	0.09	0.120	29.9	21.3	7.39	7.65	61	50	Low	Low
L-SB10	0.04	0.140	30.0	20.8	6.96	7.40	35	28	Low	Low
L-C	0.05	0.040	30.0	20.5	7.53	7.30	51	55	Low	Low
CL-DS5	0.08	0.180	30.1	20.8	7.43	7.50	31	28	Medium	High
CL-DS10	0.10	0.280	30.1	20.6	7.44	7.60	45	42	Medium	High

CL-SB5	0.07	0.130	30.4	21.2	7.37	7.70	48	52	Medium	High
CL-SB10	0.06	0.160	30.3	21.0	7.40	7.75	40	38	Medium	High
CL-C	0.05	0.045	30.4	20.3	7.30	7.10	62	57	Medium	High

Notes: EC = Electrical conductivity (dS/m); Temp = Soil temperature (°C); pH measured in 1:2 soil-to-water suspension; Permeability measured using a standard soil percolation test (mm/hr); Humus levels classified using qualitative laboratory indicators (Low, Medium, High); Treatments include loam (L) and clay loam (CL) soils amended with dried sludge (DS) or sludge biochar (SB) at 5% and 10% rates (w/w).

Table 2 presents nutrient concentrations (N, P, and K) converted to mg/kg, along with the corresponding changes from pre- to post-treatment. Nutrient levels increased in most sludge and sludge-biochar treatments, with the largest rises occurring in clay loam amended with dried sludge (CL-DS10) and sludge biochar (CL-SB10). Available phosphorus increased across all biochar treatments, while available potassium increased substantially in clay loam but declined in loam treatments (Table 2). Nitrogen showed moderate increases in loam treatments but stronger enrichment in clay loam treatments. Control treatments (L-C and CL-C) displayed baseline fluctuations, including unexpected increases in available phosphorus, which further underscores the semi-quantitative limitations of the colorimetric kit under active crop cultivation. All nutrient values were obtained using the LaMotte Soil Test Kit, which provides approximated but consistent indicators of soil nutrient availability.

Table 2. Available nitrogen, phosphorus, and potassium before and after treatment, including net change for each soil amendment.

Treatment	N Pre (mg/kg)	N Post (mg/kg)	N Change	P Pre (mg/kg)	P Post (mg/kg)	P Change	K Pre (mg/kg)	K Post (mg/kg)	K Change
L-DS5	11.2	22.4	+11.2	28.0	112.0	+84.0	89.6	112.0	+22.4
L-DS10	11.2	22.4	+11.2	33.6	156.8	+123.2	112.0	112.0	0.0
L-SB5	11.2	22.4	+11.2	112.0	201.6	+89.6	134.4	112.0	-22.4
L-SB10	44.8	11.2	-33.6	156.8	246.4	+89.6	179.2	112.0	-67.2
L-C	11.2	11.2	0	134.4	201.6	+67.2	201.6	112.0	-89.6
CL-DS5	11.2	11.2	0	156.8	246.4	+89.6	156.8	156.8	0
CL-DS10	11.2	11.2	0	179.2	246.4	+67.2	201.6	246.4	+44.8
CL-SB5	11.2	11.2	0	112.0	156.8	+44.8	112.0	156.8	+44.8
CL-SB10	11.2	11.2	0	156.8	246.4	+89.6	179.2	246.4	+67.2
CL-C	11.2	11.2	0	134.4	201.6	+67.2	112.0	201.6	+89.6

Notes: All nutrient values converted from lb/acre to mg/kg using the standard factor 1 lb/acre = 1.12 mg/kg. “Pre” refers to nutrient availability before amendment; “Post” refers to values measured after amendment. Change = Post – Pre. Nutrient extraction methods follow the LaMotte Soil Test Kit.

Discussion

This study demonstrated that sludge-derived biochar, particularly at 10% application rate, significantly improved bok choy growth and soil fertility compared to dried sludge and unamended controls. Clay loam soils generally supported better plant performance than loam soils, reflecting differences in nutrient retention and water-holding capacity. Soil amendments increased available nutrients (N, P, K), pH, and humus content, with stronger responses observed in clay loam. These findings provide the first localized evidence for Belize that pyrolytic conversion of sewage sludge produces a superior soil amendment for tropical vegetable production.

Plant Height

The observed height responses are consistent with expected biomass accumulation in Brassica vegetables (Li et al., 2023) and reflect the role of soil physical properties and organic amendments in early vegetative development. The effect of soil type, with clay loam supporting slightly taller plants, aligns with known physical properties of clay-rich soils, which generally retain moisture and nutrients more effectively than sandier textures (Agegnehu et al., 2017). These conditions can enhance early vegetative growth, particularly in leafy vegetables such as bok choy. The benefit of biochar, especially at the 10% application rate, agrees with extensive literature showing that biochar improves soil porosity, microbial activity, nutrient retention, and water availability (Lehmann & Joseph, 2015; Agegnehu et al., 2017). The 1.29 cm deficit observed in the control treatment relative to Biochar 10% indicated that bok choy growth responded positively to amendments that enhance soil structure and nutrient dynamics. While dried sewage sludge also improved plant height relative to the control, the differences were not statistically significant compared to Biochar 10%. This may indicate that sludge amendments require longer mineralization periods to fully release nutrients (Singh & Agrawal, 2008), or that initial nutrient availability is lower than in biochar-treated soils. The lack of significant differences among Biochar 5%, Dried Sludge 5%, and Dried Sludge 10% suggests that moderate amendment rates may provide comparable benefits during the early stages. However, the superiority of Biochar 10% demonstrates that higher biochar application rates can exert stronger positive effects on vegetative performance (Gul et al., 2015). Overall, the plant height results illustrate that soil physical properties and amendment type significantly influenced bok choy vegetative growth, with Biochar 10% and clay loam soil providing the best outcomes.

Leaf Area

The progressive increase in leaf area across the six weeks confirmed vigorous vegetative growth under all treatments. The significant effect of soil type, favoring clay loam, indicates better physical and chemical conditions for leaf expansion. Clay loam typically provides higher water retention, cation-exchange capacity, and root anchorage, all of which benefit leaf development in leafy vegetables (Chen et al., 2020). Biochar amendments, particularly at 10%, enhanced leaf area beyond all other treatments. This finding is strongly supported by research showing that biochar improves aeration, water-holding capacity, and nutrient availability (Agegnehu et al., 2017; Ding et al., 2016). Increased leaf area directly enhances photosynthetic capacity, which typically leads to higher biomass accumulation (Zheng et al., 2021). Dried sludge also improved leaf area, but less than biochar. Sludge variability in nutrient release and mineralization rates is well-documented (Singh & Agrawal, 2008), which may explain its moderate performance. The control treatment consistently produced the smallest leaf area, showing the baseline limitations of unamended soils. Overall, these results show that biochar additions, especially at higher rates, substantially enhanced leaf development, with synergistic support from clay-loam soil conditions. This highlights biochar's potential in sustainable vegetable production systems in Belize.

Leaf Development

Leaf development is a responsive indicator of bok choy vigor, canopy establishment, and carbon assimilation. The strong weekly increases align with expected brassica growth patterns in short-cycle systems (Li et al., 2023). The significant week effect ($p < 0.001$) indicates that leaf number reliably reflects early physiological responses to soil and amendment treatments. Soil effects were more pronounced than amendment effects during Week 1, with loam outperforming clay loam. Loam soils often have better aeration and drainage, supporting improved nutrient uptake and cytokinin-driven leaf initiation (Tuquero, J., 2018). This early advantage suggests that structural soil properties play an important role in canopy establishment. Biochar and sludge amendments showed limited early effects on leaf number, except for a slight improvement under Biochar 10%. These match published findings showing that biochar's nutrient-mediated benefits, including N mineralization and microbial stimulation, often emerge later in the growth cycle (Ding et al., 2016). Likewise, sludge tends to release nutrients more slowly (Singh & Agrawal, 2008). Thus, soil type exerts immediate influence, while amendment effects tend to be delayed. The early leaf-number response suggests that loam soils are more favorable for initial leaf proliferation, while high-rate biochar treatments may exert stronger effects later in the growth period.

Fresh Biomass by Soil Type and Amendment

Fresh biomass trends indicate that soil type and organic amendment strategy both play central roles in bok choy growth. Plants grown in clay loam soils produced greater fresh biomass than those grown in loam, aligning with the higher moisture-holding capacity and nutrient retention commonly associated with finer-textured soils. The superior performance of clay loam aligns with expectations based on its higher CEC and water-holding capacity (Agegnehu et al., 2017). The strong response to biochar, particularly at 10%, supports extensive literature showing biochar's ability to improve soil aeration, moderate pH, enhance microbial activity, and retain moisture (Lehmann & Joseph, 2015). These mechanisms have been shown to increase fresh biomass in leafy vegetables (Zheng et al., 2021). Dried sludge performed moderately well, producing higher biomass than the control but less than biochar. This mirrors findings that sludge is nutrient-rich but may release nutrients more slowly or inconsistently (Singh & Agrawal, 2008). The lowest biomass in the control treatment confirms the importance of organic amendments for improving soil fertility. The dose-dependent response, higher biomass with higher amendment rates, has been observed in multiple studies involving biochar and sludge (Gul et al., 2015; Chen et al., 2020). Overall, Biochar 10% produced the most significant improvements, positioning it as a promising soil amendment for bok choy production in Belize.

Total Biomass by Soil Type and Amendment

Total biomass integrates the full physiological response of plants to soil quality and amendment treatments. The superior performance of Biochar 10% aligns with well-documented improvements in soil aeration, CEC, and water dynamics caused by biochar applications (Lehmann & Joseph, 2015; Ding et al., 2016). Its consistent increase in dry biomass indicates that biochar effectively improved soil conditions over the full growth cycle. Dried sludge also increased biomass relative to the control, though its responses were less pronounced. This is consistent with sludge's variable nutrient release rates and dependence on microbial mineralization (Singh & Agrawal, 2008). Soil type was also important: clay loam supported slightly higher biomass due to its higher nutrient retention and moisture storage capacities (McIntyre & Li, 2024). However, loam demonstrated a stronger proportional response when amendments were applied, suggesting amendment-soil synergy. Total biomass findings reinforce biochar's potential as an effective amendment for enhancing bok choy productivity under Belizean growing conditions.

Changes in Soil Parameters

The soil baseline assessment showed clear differences in physical, chemical, and nutrient responses across the various sludge and sludge-biochar amendment rates for both loam and clay loam soils. Measurements included electrical conductivity (EC), pH, soil temperature, permeability, and nutrient availability (N, P, K), as well as humus levels. Nutrient and humus values were generated using the LaMotte Soil Test Kit, which provides rapid colorimetric estimations appropriate for baseline agricultural assessments. Amendments altered several soil properties, with differences between sludge and biochar treatments and between soil textures. Biochar-amended treatments (LSB5 and LSB10; CL-SB5 and CL-SB10) consistently resulted in increases in soil pH relative to loam and clay loam controls, reflecting the alkaline nature of biochar and its capacity to buffer acidity. Dried sludge treatments (L-DS5, L-DS10; CL-DS5, CL-DS10) also increased pH but to a slightly lesser extent. Electrical conductivity increased in all amended treatments, especially where dried sludge was added at 10%, indicating elevated soluble ion content following amendment incorporation.

Temperature values declined from pre- to post-measurement for all treatments due to uniform environmental conditions during storage and measurement, and do not represent a treatment effect. Permeability responses differed by soil type: loam generally showed reduced permeability after amendment incorporation, likely because sludge and biochar change pore characteristics, while the clay loam control and amendments showed more stable or slightly increased permeability due to intrinsic soil structure.

Nutrient responses (Table 2) clearly demonstrated the effect of organic amendments. Both dried sludge and sludge biochar treatments increased available nitrogen, phosphorus, and potassium relative to controls. Clay loam treatments showed the greatest increases in available P and K, particularly at the 10% rates (CL-DS10 and CL-SB10), highlighting the nutrient-retention advantage of finer-textured soils. Humus levels also increased from "Medium" to "High" for all clay loam amended treatments, confirming organic matter enrichment. In contrast, humus levels in loam treatments remained "Low," reflecting a more rapid decomposition rate and lower organic matter-holding capacity. Collectively, the results indicate that (i)

sludge and sludge biochar amendments enhance soil nutrient status; (ii) biochar is more effective at increasing pH; (iii) clay loam soils respond more strongly to organic inputs due to greater surface area and cation-exchange capacity; and (iv) the LaMotte Soil Test Kit detected consistent, treatment-driven improvements in nutrient availability and humus content. These findings provide a strong baseline for evaluating long-term soil fertility improvements and potential agronomic benefits associated with sludge-derived amendments across different soil textures.

Study Limitations and Future Directions

This greenhouse study provided controlled conditions that may not fully reflect field-scale interactions with natural precipitation, soil fauna, and weed competition. The six-week growth period captured early vegetative responses but did not assess reproductive development or longer-term soil fertility changes. Future research should evaluate biochar performance under field conditions, test multiple crop species and growth cycles, and assess the economic feasibility of sludge pyrolysis infrastructure for Belizean municipalities. Long-term studies examining biochar stability, heavy metal immobilization, and cumulative soil health benefits would strengthen evidence for widespread adoption.

Conclusions

Sludge-derived biochar significantly improved bok choy growth and soil fertility compared to dried sludge and unamended controls, with the 10% application rate producing the greatest effects across all measured parameters. Clay loam soils demonstrated superior nutrient retention and plant performance relative to loam soils. Both amendments increased soil pH, electrical conductivity, and available nutrients, with biochar delivering the most consistent improvements in phosphorus and potassium availability. These findings confirm that pyrolytic conversion enhances the agronomic value of sewage sludge while reducing risks associated with direct application. Sludge-derived biochar represents a viable, sustainable soil amendment for improving vegetable productivity and soil fertility in Belize. The results provide evidence-based guidance for integrating sludge biochar into national strategies for circular waste management and climate-smart agriculture. Field-based research is recommended to validate long-term effects under diverse farming systems.

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