

Enhancing soil health and nutrient availability for Carrizo citrange (X *Citroncirus* sp.) through bokashi and biochar amendments: An exploration into indoor sustainable soil ecosystem management

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ABSTRACT

This study investigated the efficacy of organic soil amendments: bokashi (Bok), biochar (BC), and their combination (Bok_BC) in promoting soil health, nutrient availability, and growth of Carrizo citrange (X *Citroncirus* sp. Rutaceae, Parentage *Citrus sinensis* x *Poncirus trifoliata*) under indoor greenhouse settings. Results indicate significant alterations in soil parameters like total carbon (C), total nitrogen (N), and C:N ratio due to Bok, BC, and Bok_BC treatments. BC treatments boosted total C, while Bok increased total N, compared to controls. A noteworthy 25 % average decrease in C:N ratio was observed with Bok and Bok_BC, nearing the optimal 24:1 C:N for microbial growth. This highlights the potential of waste by-products in balancing nutrient release to benefit soil health and plant development. Analysis of nitrite (NO₂-), nitrate (NO₃-), and ammonium (NH₄-N) levels revealed a dynamic relationship between soil treatments and time. Bok and Bok_BC amendments combined with both fertilizer doses [700 and 1400 Electrical Conductivity, EC] showed an initial NH₄-N spike (averaging 1513 and 1288 µg N/g dry, respectively), outperforming control soils (average 503 µg N/g dry). Other key elements like phosphorus, potassium, calcium, and chlorine also experienced initial surges in Bok and Bok_BC soils before declining, suggesting a gradual nutrient release. The concentration of potentially toxic elements remained mostly stable or inconclusive, warranting further exploration. Bok, BC, and Bok_BC treatments considerably influenced germination rate and plant growth. The germination rate averaged 24.2 %, 23 %, and 22.5 % for Bok, BC, and Bok_BC, compared to the 15.9 % control. Plant height increased with Bok, BC, and Bok_BC to 18.4 cm, 18.7 cm, and 16.4 cm, respectively, from the 14.8 cm control. The results remained consistent across fertilizer doses, emphasizing the soil amendments' role in bolstering soil and plant health. In summary, the research underscores the potential of carbon-based amendments like bokashi and biochar in enhancing soil health, reducing reliance on synthetic fertilizers, and fostering sustainable soil ecosystems. The insights are pivotal for advancing sustainable agriculture in indoor greenhouse settings for nursery plant production.

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1. Introduction

Synthetic fertilizers have played a critical role in global food production, allowing the world's population to boom. However, the intensification of agriculture due to over-reliance on synthetic fertilizers has come at a cost to the environment, climate, and health of humans, animals, and soils alike. The global production of fertilizers is responsible for around 1.4 % of annual CO₂ emissions, and fertilizer use is a major contributor to non-CO₂ greenhouse gas emissions (Viglione, 2022; Benghzi et al., 2023). Carbon-based nutrients can provide a nature-based alternative to conventional fertilizers for vegetable and tree crop production (Rashid et al., 2021; Mrunalini et al., 2022). Increases in crop yield from the application of plant-available nitrogen (N) from agricultural and processed food waste have been documented (Du et al., 2018; Chia et al., 2020; Farzadfar et al., 2021; O'Connor et al., 2021 and 2022; Rombel et al., 2022). However, N in organic amendments is bound to organic matter, and it needs to be broken down by soil microorganisms into inorganic forms (ammonium-N and nitrate-N) that plants can absorb (i.e., mineralization). Consequently, the availability of total N from organic amendments to plant roots is generally slower compared to inorganic fertilizers (Yang et al., 2015; Phillips et al., 2022). Fortunately, the slow release of N from organic amendments can be beneficial in maintaining a steady supply of nutrients to plants over a longer period than conventional fertilizers, reducing the risk of leaching and N losses to the environment (Cameron et al., 2013; Rashid et al., 2021; Wang et al., 2022).

Aerobic composting is a prevalent method for generating organic soil amendments, offering the dual benefits of enhancing soil health and diverting waste from landfills, thus mitigating methane emissions (Pérez et al., 2023). It offers an economical solution for farmers and local communities while reducing reliance on synthetic fertilizers (Farhidi et al., 2022). Despite its merits, composting does present challenges. Although composting diverts waste and lowers methane emissions, it still has an associated carbon footprint. Composting necessitates meticulous management and takes time, often several months, to yield compost. It also has limitations on the types of waste it can process, excluding meat and dairy products. Moreover, if not managed optimally, it has the potential to produce significant greenhouse gas emissions (Nordahl et al., 2023).

Bokashi fermentation, an anaerobic process using microbial inoculants, has gained attention as an alternative for composting agricultural and food waste (Dutta et al., 2021). It employs specific microorganisms like lactic acid bacteria, yeasts, and actinomycetes which metabolize organic matter to produce acidic byproducts like lactic acid, lowering the pH to around 3–3.5, stabilizing the bio-waste, and preserving nutrients (Lew et al., 2021; Kovačić et al., 2022). This process can substantially reduce greenhouse gas emissions and produce nutrient-rich, microbially active digestates that boost plant growth and productivity (Quiroz and Céspedes, 2019; Phooi et al., 2022). When the bokashi digestate (2nd aerobic phase) is mixed into the soil, it improves soil structure and increases water retention (Olle, 2021). Moreover, the process promotes beneficial soil and root microbiomes. The liquid residue can be used for fertigation or foliar application (Christel, 2017; Pagliaccia et al., 2020). Despite its benefits, the process may require special equipment and temperature control, limiting its application to certain waste types (Gashua et al., 2022).

Published research suggests that at the end of the 2nd phase of bokashi aerobic fermentation with soil, the most likely form of mineral N present is ammonium (NH₄⁺) (Yamada and Xu, 2001; Christel, 2017; Quiroz and Céspedes, 2019). However, the rate at which bokashi composts supply nutrients to plants compared to other amendments and synthetic fertilizers has not been determined and needs further investigation (Quiroz and Céspedes, 2019). Bokashi by-products can have varying nitrate content, ranging from 3 to 10 % weight, and can provide a steady or slower supply of nutrients than other amendments (Arumugam et al., 2022; Quiroz and Céspedes, 2019). Research examining

the impact of bokashi application on soil and subsequent plant growth reveals diverse outcomes. Several studies have documented enhanced plant growth parameters in a variety of plants, including medicinal plants, parsley, ginger, citrus, and spinach, when bokashi amendments were applied to the soil (Quiroz and Céspedes, 2019; Pagliaccia et al., 2020; Ramlan, 2022). However, not all outcomes were positive; other studies reported plant nutrient deficiency symptoms in radishes following bokashi application (Quiroz and Flores, 2018).

Understanding bokashi-derived N behavior in greenhouse conditions, which differ from field settings, is essential. Factors like temperature, soil mix, and co-amendments like biochar may influence nutrient release rates and availability to plants (Brtnicky et al., 2019; Allohverdi et al., 2021). Greenhouses, an emerging trend in plant production, offer a unique platform for this study. Grasping how bokashi-derived N behaves in such controlled environments allows for tailored soil recommendations to maximize crop yield and cost-benefit while minimizing nutrient leaching (Urre et al., 2019). Biochar improves soil structure, nutrients, water retention, and crop yield, while bokashi provides short-term organic matter and nutrients (Brtnicky et al., 2019; Allohverdi et al., 2021; Zhang et al., 2021; Sales et al., 2022). Their combination enhances soil microbial health, which is critical for nutrient cycling (Rawat et al., 2019; Phooi et al., 2022). However, effectiveness varies with biochar and bokashi types and local soil conditions (Ndoung et al., 2021).

In this study, we evaluated the effectiveness of carbon-based amendments like bokashi and biochar, derived from agri-food waste, in enhancing soil functions and plant health for indoor citrus nurseries (Du et al., 2018; Chia et al., 2020; O'Connor et al., 2021; Rombel et al., 2022). Soil analyses were conducted to assess carbon and nitrogen dynamics changes with full (1400 electrical conductivity, EC) or half fertilizer doses (700 EC). We also studied their preliminary impact on Carrizo citrange rootstock growth parameters. Our hypotheses include improvements in soil carbon, nitrogen, available nutrients, and plant growth, which could offer a sustainable alternative to synthetic fertilizers.

2. Materials and methods

2.1. Materials

Two organic amendments were compared in a greenhouse-based experiment: bokashi-derived solid digestate by-product (Bok) and almond shells-derived biochar (BC). Bok, obtained from citrus waste, and BC, derived from California almond shells waste (Corichar™, Coriging LLC.), were used alone and combined as amendments to the potting soil mix. Potting soil mix comprised equal amounts of perlite, peat moss, and fine coco coir. Citrus waste for the bokashi fermentation and almond shell-derived biochar were selected because they are commonly available agricultural wastes in central and southern California. Both wastes also represent uniform feedstocks and uniform by-products (i.e., stable nutrient supply), which is important for commercial indoor and field plant production. Two-week-old citrus waste digestate was produced under a controlled anaerobic bokashi-like fermentation technology under controlled conditions (Pagliaccia et al., 2020). The 2-week-old digestate was blended at 30 % (Vol/Vol) into the soil mix two weeks before use and kept in aerobic condition inside the greenhouse. At the beginning of each greenhouse experiment trial, the bokashi-treated soil was diluted to a final concentration of 10 % (Vol/Vol), and biochar was blended directly into the soil at a final concentration of 10 % (Vol/Vol).

2.2. Plant growing systems, analyses, and sampling

Experiments were conducted in temperature-controlled greenhouses (20–32 °C) using 24 separate plant-growing units. Each growing unit (located on a bench ca. 40 centimeters (cm) above ground level)

consisted of one RL98 tray holding up to 98 'Ray leach Cone-tainers', SC-10 (Stuewe and Sons, Inc., Corvallis, OR, USA) cell pots, with a 3.8 cm diameter × 21 cm depth and 163 cm³ vol and placed inside small flow trays where excess nutrient solution drained. Carrizo citrange (*X Citroncirus* spp. Rutaceae, Parentage *Citrus sinensis* × *Poncirus trifoliata*) seeds (Lynn Citrus) were used as a host plant to assess the effect of bokashi and biochar by-product amendments on plant growth and development. Two seeds were hand sown in treatment media in each cell pot. Seeded cell-pots were top irrigated manually (Around 30 ml each), 3 times per week in the first month and 1–2 times per week in the following months. For each irrigation, fresh nutrient solution was prepared at a pH of 5.8 ± 0.4 (adjusted with H₃PO₄ and KOH) and electrical conductivity-EC at 1.4 ± 0.05 or 0.7 ± 0.05 mS/cm² (equivalent to 0.1 and 0.05 kg of fertilizer per 100 liters of water) using Peters Excel 21-5-20 fertilizer formulation (ICL group). The final element concentrations in the nutrient solution at 1.4 EC were as follows: Total nitrogen (N) 221.5 µg/ml, (Ammoniacal nitrogen (NH₄) 77.1 µg/ml, nitrate nitrogen (NO₃) 132.9 µg/ml, and urea nitrogen around 11.5 µg/ml), phosphate (P₂O₅), 52.8 µg/ml; potassium oxide (K₂O), 211.1 µg/ml; boron (B), 0.28 µg/ml; copper (Cu), 0.28 µg/ml, Iron (Fe), 1.1 µg/ml, manganese (Mn) 0.56 µg/ml, molybdenum (Mo), 0.13 µg/ml; and Zinc (Zn), 0.56 µg/ml. In each experiment, the soil mixes were amended with different treatments and irrigated with 2 fertilizer doses (half dose at 700 micro siemens per centimeter uS/cm and full dose at 1400 uS/cm), with a total of 8 treatments, as described in Table 1. The experimental design was a randomized complete block with 2 factors (amendments treatments and fertilizer doses).

Each treatment consisted of 147 total cell-pots (49 cell-pots for each replication). For each 49 cell pots replicate, 28 cell pots were dedicated to germination and seedling growth evaluation, 21 cell pots were used to assess changes over time in total C, total N, and C:N Ratio, and NH₄-N (ammonium), NO₃-N (nitrate) + NO₂-N (nitrite), and elemental composition changes in the potting soil.

Soil samples were collected weekly for the first month, then bi-weekly for the rest of the experiment duration, with a total of 10 sampling points. In the first sampling date (time zero-Tm0), the treated soil mixes were sampled twice, before and after receiving the appropriate fertilizer doses. The eight subsequent dates represent time points, post-irrigation, at weeks 1, 2, 3, 4, 6, 8, 10, and 12, from each of the three replicates for control, Bok solid 10 %, biochar 10 %, Bok solid 10 % + biochar 10 %, and both fertilizer doses.

2.3. Total C, N, and C:N ratio changes in the potting soil

For this analysis, 24 soil samples were collected at the beginning of

Table 1

Treatment groups utilized in the study. Each of the eight treatment groups is characterized by a unique combination of soil amendment type and fertilizer dose (Electrical conductivity (EC) measured in micro siemens per centimeter, uS/cm). 'Control' refers to the non-amended soil mix, 'Bok solid 10 %' represents soil amended with 10 % volume Bokashi compost, 'Biochar 10 %' represents soil amended with 10 % volume biochar, and 'Bok solid 10 % + Biochar 10 %' represents soil amended with both 10 % volume Bokashi compost and 10 % biochar.

Treatment Acronym	Soil Amendment	Fertilizer Dose (EC uS/cm)
1400CK	Control (None)	1400
700CK	Control (None)	700
1400Bok	Bokashi solid 10 %	1400
700Bok	Bokashi solid 10 %	700
1400BC	Biochar 10 %	1400
700BC	Biochar 10 %	700
1400Bok_BC	Bokashi solid 10 % + Biochar 10 %	1400
700Bok_BC	Bokashi solid 10 % + Biochar 10 %	700

the experiment (Time 0), before and after receiving the appropriate fertilizer doses, and again at the end of weeks 1, 2, 3, 4, 6, 8, 10 and 12, from each of the three replicates for control, Bok solid 10 %, biochar 10 %, Bok solid 10 % + biochar 10 %, at both fertilizer doses (700 or 1400 uS/cm). On each sampling date, soil from one cell-pot container seeded with Carrizo rootstock seeds (around 35 g soil) was taken from each replicate, placed in a plastic Ziplock, and placed at −80 °C until further processing. The material was freeze-dried overnight (Labconco Free Zone 2.5 Plus), and subsamples were ground in 5 ml tubes with stainless steel balls (Geno Grinder Spex Samples Prep) using three cycles of 30 s with a 30-second pause in between to obtain a fine material. About 30 micrograms of dried, ground/ball milled samples were placed into a small aluminum tin dish and tightly folded for analysis of total C, total N, and C:N using a Costech ECS 4010-Delta V Plus Isotope Ratio Mass Spectrometer. These standards were used: Acet, Glycine, Peach, EM Soil, USGS64, and USGS66, and samples were combusted completely in EA at 88 % content CO₂ and 1020 °C combustion T set.

2.4. NH₄-N (Ammonium), NO₃-N (Nitrate) and NO₂-N (Nitrite) changes in the potting soil

NH₄⁺-N and NO_x (NO₃⁻-N + NO₂⁻-N) were determined with potassium chloride (KCl) extraction by mixing 3 g of fresh sampled soil with 30 mL of a 2 M KCl solution, shaken for 30 min on a rocking shaker, and filtered through Whatman No. 42 110 mm diameter filter paper. Liquid extractant was analyzed for NH₄⁺-N and NO_x-N via an AQ2 Discrete Analyzer (Seal Analytical, Mequon, WI). The gravimetric soil moisture content was determined by subsampling 5–8 g of fresh soil and oven drying at 105 °C for 24 h and used to express N nutrient concentration on an oven-dry weight basis (µg N g_{dry}⁻¹).

2.5. Elemental composition changes in the potting soil

Soil samples were collected at multiple time points, and the levels of P, K, Ca, Mo, Mg, Se, Cl, Fe, Mn, S, and Zn were analyzed using X-ray fluorescence spectroscopy (XRF). Soil samples were taken from each of the three soil replicates for all treatments at the beginning of the experiment (time 0), before and after receiving the appropriate fertilizer doses, and again at the end of weeks 4, 8, and 12. Collected soil material for each of the eight treatments (Table 1) was oven dried for 24 h at 70 °C in triplicate, and dried subsamples were ground in a Kleco Tissue Pulverizer (Kleco, Visalia, California, USA) for 45 s in a 2 mL snap-top centrifuge tube (Eppendorf) to obtain a fine powdered material. About 5 grams of dried and milled sample was used for analysis by XRF to determine the elemental composition of treatment soils and to quantify changes in the content of relevant elements over time with treatment.

2.6. Germination and seedling growth evaluation

The number of germinated seeds was recorded between 4 and 10 weeks after sowing. Germination rate (%) was calculated according to the following equations: Germination Rate (%) = (Number of Seeds Germinated / Total Number of Seeds Sown) × 100. In order to have an adequate number of seedlings per replicate, 28 cell pots per replicate/cell pot were dedicated for germination and growth evaluation. Four months after seeding, the height (cm) of the seedlings was measured from the media surface to the tip of the seedling.

2.7. Statistical methods

All statistical analyses were performed by Sigma Plot 15.0 software. All treatments were replicated for three experimental plots as described above. A three-way analysis of variance (ANOVA) was performed to assess the effects of treatment, fertilizer dosage, and time, as well as their interactions on total C, N, C:N ratio, NO_x-N (NO₃⁻-N + NO₂⁻-N), NH₄⁺-N, P, K, Ca, Mo, Mg, Se, Cl, Fe, Mn, S, and Zn, Na, Al, Co, Cu, Hg, Pb, V, Cr,

As, Cd and seed germination rate. Pairwise comparisons among treatments were conducted using Student-Newman-Keuls with an alpha set at 0.05. The power of performed tests was assessed for each factor and their interactions. Least square means were calculated for each category within each factor and for their interactions. One-way ANOVA was carried out on data from NO_x-N (NO₃⁻-N + NO₂⁻-N), NH₄⁺-N, P, K, and Ca to determine the effect of the eight treatments (Table 1) at each time point. The effects of the eight treatments on plant height four months after seeding were also analyzed using one-way ANOVA. Prior to conducting the ANOVA, the data were examined for normality and homogeneity of variance using the Shapiro-Wilk and Brown-Forsythe tests, respectively. A Kruskal-Wallis one-way ANOVA on ranks was utilized for data that did not have a normal distribution ($P < 0.050$). For all one-way ANOVA, multiple comparisons versus the control group (Holm-Sidak method) were used to determine significant differences between the 700CK, 1400Bok, 700BC, 1400BC, 1400Bok_BC, 700Bok_BC treatment groups (Table 1) versus the control group 1400CK, except for the height data for which Dunn's multiple comparison method was used. All statistical analyses were performed using an alpha level of 0.05. Statistically significant differences are shown by different alphabets. The data are reported as means with their standard errors.

3. Results

3.1. Total C, N, and C:N ratio changes in soil

3.1.1. Total C changes in the soil

The three-way ANOVA revealed significant effects of soil treatment ($F(3160) = 196.732, p < 0.001$) and time point ($F(9160) = 2.117, p = 0.031$) on total carbon (% C by weight) content in the soil. There was also a significant interaction between the type of soil treatment and fertilizer concentration ($F(3160) = 6.761, p < 0.001$), indicating that the effect of soil treatment on the total carbon content depends on the fertilizer concentration used. No significant effect was observed for fertilizer treatment alone ($F(1160) = 1.092, p = 0.298$). The interaction of time point with either fertilizer treatment ($F(9160) = 0.685, p = 0.722$) or soil treatment ($F(27,160) = 0.489, p = 0.984$) was also not significant. The three-way interaction between time point, fertilizer treatment, and soil treatment was not significant ($F(27,160) = 0.946, p = 0.546$). This indicates that the effects of soil treatment and fertilizer concentration on the total carbon content in the soil are consistent over time. As shown in

Fig. 1, at the beginning of the experiment (Tm0), the Bok_BC and BC treatments at both 700 $\mu\text{S}/\text{cm}$ and 1400 $\mu\text{S}/\text{cm}$ showed a higher total C content than the CK treatment, indicating an immediate effect of stable biochar organic matter on the soil's carbon content. The total carbon content of the BC and Bok_BC treatments consistently exceeded that of the CK treatment, with BC at 700 $\mu\text{S}/\text{cm}$ at 32.6 %, while CK was at 27.8 %. Similarly, Bok_BC at 1400 $\mu\text{S}/\text{cm}$ showed 34.5 %, compared to CK at 27.0 %. Throughout the mid-time points (Tm7-Tm42), the BC and Bok_BC treatments maintained higher total carbon content than CK. At Tm42, BC at 700 $\mu\text{S}/\text{cm}$ displayed 35.5 %, whereas CK had 27.2 %. Bok_BC at 1400 $\mu\text{S}/\text{cm}$ showed 34.1 %, compared to CK at 26.1 %. Towards the end of the study (Tm56-Tm84), BC and Bok_BC treatments continued to surpass CK. At Tm84, BC at 700 $\mu\text{S}/\text{cm}$ exhibited 34.5 %, whereas CK had 24.4 %. Bok_BC at 1400 $\mu\text{S}/\text{cm}$ showed 35.6 %, compared to CK at 25.1 %. The Bok treatment did not significantly change the total C content in the soil, remaining relatively consistent with the CK treatment. This aligns with the understanding that when used alone, bokashi by-products generally do not significantly alter the total carbon (C) content in the soil. The carbon pool in the soil is known to be slow to respond to immediate soil management changes, including the addition of bokashi by-products. Overall, the addition of biochar-derived organic matter (Bok_BC and BC) significantly increased the total C content of the soil compared to the CK treatment, and this effect was evident from the beginning of the experiment and maintained throughout the study period.

3.1.2. Total N changes in soil

Our investigation focused on the impact of various soil treatments on the total nitrogen (% N by weight) content in soil over multiple time points. The 3-way ANOVA showed a significant effect of time point ($F = 4.567, P < 0.001$), fertilizer treatment ($F = 25.969, P < 0.001$), and soil treatment ($F = 155.164, P < 0.001$) on total nitrogen levels. Interaction effects between time points and soil treatment were also significant ($F = 2.399, P < 0.001$). Other interaction effects were not significant. At the beginning of the experiment (Time 0), the total nitrogen content for Bok, BC, and Bok_BC treated soils was significantly higher than the control treatment. As shown in Fig. 2, the mean values for Bok, BC, and Bok_BC at 700 $\mu\text{S}/\text{cm}$ were 0.80, 0.57, and 0.85, respectively, compared to 0.51 for CK at the same fertilizer concentration. The trend was similar for 1400 $\mu\text{S}/\text{cm}$, with mean values for Bok, BC, and Bok_BC being 0.76, 0.62, and 0.88, respectively, while CK was at 0.492. During the mid-time

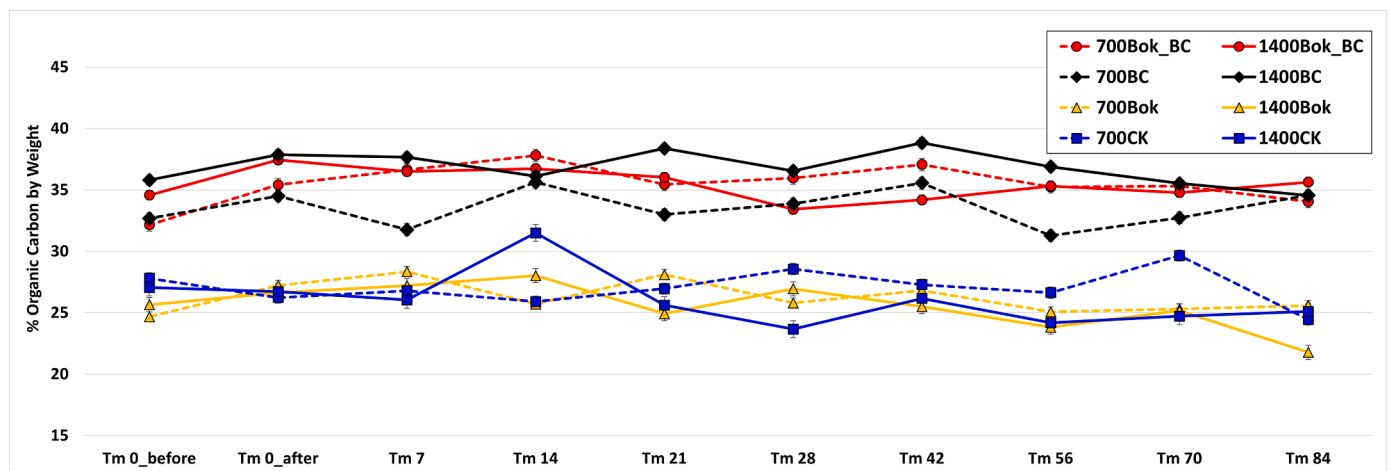


Fig. 1. Chart representing the influence of various soil amendments and fertilizer doses on total carbon (C). The x-axis represents the time points (days) sampled (Tm 0 - Tm 84), while the y-axis indicates the total nitrogen content expressed as weight percentage (wt.% N). Different color lines correspond to the eight treatments: CK1400 in solid blue with square marker, CK700 in blue with dashes with square marker, Bok1400 in solid yellow with triangle marker, Bok700 in yellow with dashes with triangle marker, Bok_BC1400 in solid black with diamond marker, Bok_BC700 in black with dashes with diamond marker, Bok_BC1400 in solid red with circle marker, and Bok_BC700 in red with dashes with circle marker. Error bars represent standard error of the mean (SEM). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

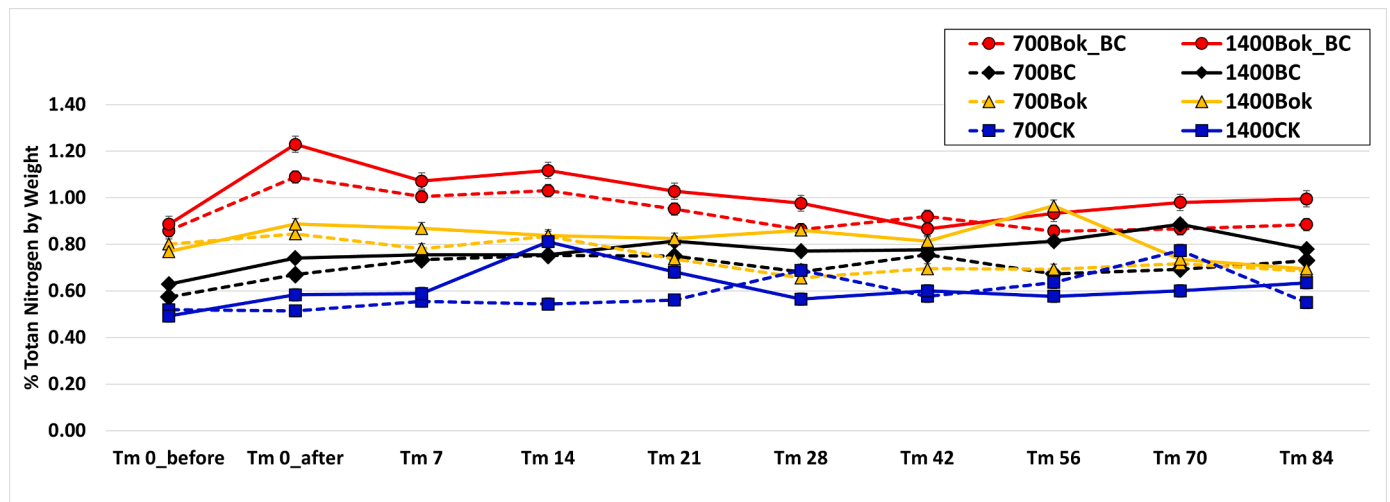


Fig. 2. Chart representing the influence of various soil amendments and fertilizer doses on total nitrogen (N) content. The x-axis represents the time points (days) sampled (Tm 0 - Tm 84), while the y-axis indicates the total nitrogen content expressed as weight percentage (wt.% N). Different color lines correspond to the eight treatments: CK1400 in solid blue with square marker, CK700 in blue with dashes with square marker, Bok1400 in solid yellow with triangle marker, Bok700 in yellow with dashes with triangle marker, BC1400 in solid black with diamond marker, BC700 in black with dashes with diamond marker, Bok_BC1400 in solid red with circle marker, and Bok_BC700 in red with dashes with circle marker. Error bars represent standard error of the mean (SEM). Error bars represent standard error of the mean (SEM). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

points (Tm7-Tm42), total nitrogen levels showed different patterns depending on the treatment. However, a higher total N level was generally observed in Bok, BC, and Bok_BC, with the combined treatment being the highest. This suggests that the combined effect of bokashi compost and biochar had a more profound impact on nitrogen levels. Towards the end of the study period (Tm56 - Tm84), some treatment groups showed a decrease in total nitrogen, while Bok BC treatment still demonstrated a higher mean total nitrogen level compared to the control. At Tm84 and a fertilizer concentration of 1400 $\mu\text{S}/\text{cm}$, Bok_BC had a mean nitrogen level of 0.99 compared to CK, with a mean of 0.63. Bok and BC treatments also showed higher total nitrogen levels than the control, but not as much as the combined treatment (Bok_BC). However, some treatments like BC1400 demonstrated an increase in nitrogen level from 0.81 N at Tm56 to 0.88 N at Tm70, indicating a possible time-dependent and treatment-dependent pattern in

nitrogen release. It is worth noting that starting from Tm 21, 700CK exhibited higher carbon (C) content than 1400CK. Overall, in comparison with the control treatment (CK), all three amendments, Bok, BC, and Bok_BC, significantly increased the total nitrogen level, providing clear evidence that the integration of composted organic matter, biochar, or their combination can effectively enrich the soil nitrogen content. These changes may have implications for soil fertility, nutrient availability to plants, and overall soil health, thereby supporting the use of such amendments for sustainable soil management.

3.1.3. Total C/N ratio changes in soil

The application of different treatments substantially influenced the C to N (C/N) ratio in the soil at various time points. The 3-way ANOVA showed significant main effects of timepoint ($F(9160)=5.732$, $p<0.001$), fertilizer treatment ($F(1160)=29.200$, $p<0.001$), and soil

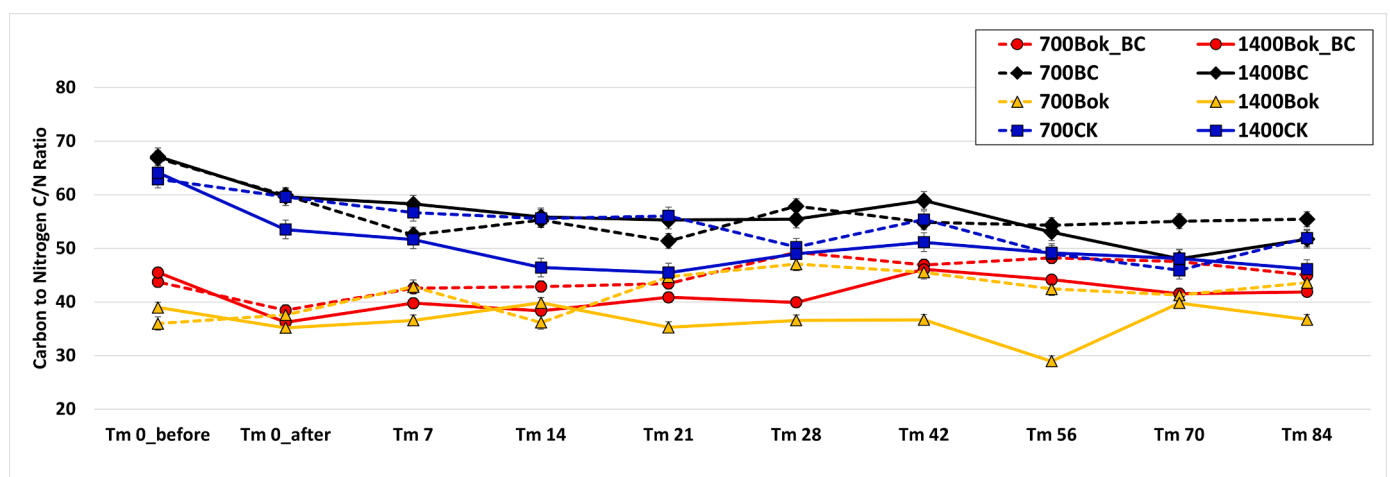


Fig. 3. Chart representing the influence of various soil amendments and fertilizer doses (Details in Table 1) on C:N ratio at different time points. The x-axis represents the time points (days) sampled (Tm 0 - Tm 84), while the y-axis indicates the total nitrogen content expressed as weight percentage (wt.% N). Different color lines correspond to the eight treatments: CK1400 in solid blue with square marker, CK700 in blue with dashes with square marker, Bok1400 in solid yellow with triangle marker, Bok700 in yellow with dashes with triangle marker, BC1400 in solid black with diamond marker, BC700 in black with dashes with diamond marker, Bok_BC1400 in solid red with circle marker, and Bok_BC700 in red with dashes with circle marker. Error bars represent standard error of the mean (SEM). Error bars represent the standard error of the mean (SEM). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

treatment ($F(3160)=191.874, p<0.001$) on the C:N ratio. We also found a significant interaction between time point and soil treatment ($F(27,160)=3.556, p<0.001$) and fertilizer treatment x soil treatment ($F(3160)=3.713, p=0.013$), indicating that the effect of soil amendments on the C:N ratio was contingent on both the time of sampling and the specific fertilizer treatment used. However, there was no significant interaction between time point and fertilizer treatment ($F(9160)=1.319, p=0.231$) or among timepoint, fertilizer treatment, and soil treatment ($F(27,160)=1.457, p=0.080$), indicating that fertilizer treatments did not affect the C:N ratio over time. Overall, as shown in Fig 3, the treatments with Bok and Bok_BC consistently resulted in significant changes in the C/N ratio, generally lowering the ratio compared to the control (CK) treatments. At the onset of the experiment (Time Point 0), the C/N ratios for CK1400 and CK700 were 63.4 and 64.1, respectively. At the end of the experiment, the Bok_BC1400 and Bok_BC700 treatments significantly lowered C/N ratios (45.4 and 43.7, respectively), as a result of elevated soil N content. On the other hand, the BC1400 and BC700 treatments presented comparable C/N ratios to CK at 67.1 and 66.8, respectively. Throughout the mid-time points (Tm7-Tm42), we observed an overall decreasing trend in the C/N ratios for all treatments. This decrease was more pronounced for treatments that included Bok and Bok_BC. For instance, at Tm42, the Bok_BC1400 and Bok_BC700 treatments had C/N ratios of 46.0 and 46.9, respectively, compared to 53.2 and 55.3 in CK1400 and CK700 treatments, respectively. This demonstrates a substantial decrease in the C/N ratio, suggesting the potential for faster nutrient release due to the incorporation of bokashi and biochar. Towards the end of the study period (Tm56-Tm84), the C/N ratios remained consistently lower for treatments with Bok and Bok_BC. At Tm84, the Bok_BC1400 and Bok_BC700 treatments exhibited C/N ratios of 41.8 and 44.9, respectively, again demonstrating lower ratios than the CK1400 and CK700 treatments (49.017 and 51.900), while the BC1400 and BC700 treatments exhibited a higher C/N ratio of 51.7 and 55.4, respectively. Overall, in terms of total C, treatments with biochar tended to exhibit moderately higher values than treatments without, reflecting biochar's role as a stable C source. As anticipated, all treatments involving composted organic matter (Bok and Bok_BC) significantly increased soil N content, contributing to the observed lower C/N ratios. In summary, our results demonstrate that the application of bokashi by-products alone and combined with biochar significantly alters the C/N ratio in soil, typically reducing this ratio relative to control

treatments and thus likely expediting nutrient release. Furthermore, our results suggest that biochar amendments contribute to higher soil carbon content, while bokashi amendments enhance N content. The overall results validate the addition of bokashi by-products and stable biochar organic matter as a viable strategy for increasing total carbon and nitrogen content in the soil while manipulating the C/N ratio to enhance nutrient availability and release, ultimately supporting plant growth and soil health.

3.2. $\text{NO}_x\text{-N}$ (Nitrite (NO_2^-) plus nitrate (NO_3^-)) and ammonium $\text{NH}_4^+\text{-N}$ levels change in the potting soil

The effects of different soil treatments, control (CK), biochar (BC), bokashi (Bok), and a mix of biochar and bokashi (Bok_BC) and fertilizer doses (700 $\mu\text{S/cm}$, 1400 $\mu\text{S/cm}$) on the levels of $\text{NO}_x\text{-N}$ and ammonium $\text{NH}_4^+\text{-N}$ in the soil over several time points were assessed via a three-way ANOVA. Results suggest that the type of soil treatment and synthetic fertilizer dose significantly affect the $\text{NO}_x\text{-N}$ and ammonium $\text{NH}_4^+\text{-N}$ levels over time. As shown in Fig. 4, at the beginning of the experiment (Time Point 0_Before), the average $\text{NH}_4^+\text{-N}$ levels for bokashi and the combination of bokashi and biochar (Bok_BC) were noticeably higher than the control and biochar-only group. For instance, the mean $\text{NH}_4^+\text{-N}$ levels for Bok at 700 and 1400 $\mu\text{S/cm}$ were 1224 and 1319, respectively, in stark contrast to CK with means of 19 and 41 at 700 and 1400 $\mu\text{S/cm}$. This pattern was consistent across the Bok and Bok_BC treatments, suggesting that the bokashi amendment significantly increased the soil's initial $\text{NH}_4^+\text{-N}$. The mid-time point (Tm42) showed that the highest mean levels of $\text{NH}_4^+\text{-N}$ were consistently recorded in the Bok1400 (1871 at Tm7 and 1979 at Tm14) and Bok_BC1400 treatments (1744 at Tm7 and 1929 at Tm14). The Bok, BC, and Bok_BC treatments with a reduced dose of 700 $\mu\text{S/cm}$, also maintained comparable or higher $\text{NH}_4^+\text{-N}$ levels than the CK with a full dose of 1400 $\mu\text{S/cm}$ (i.e., 809 and 876 at Tm7 and Tm14). Towards the end of the study period (Tm56-Tm84), a decreasing trend in $\text{NH}_4^+\text{-N}$ levels was observed across all treatments. Interestingly, we found a significant interaction effect between time points and treatments, indicating that the effectiveness of these treatments may vary over time.

Regarding $\text{NO}_x\text{-N}$ (Nitrite (NO_2^-) and nitrate (NO_3^-)), our analysis of the effects of eight different treatments on the level of $\text{NO}_x\text{-N}$ in soil revealed notable variations among treatments, time points, and their

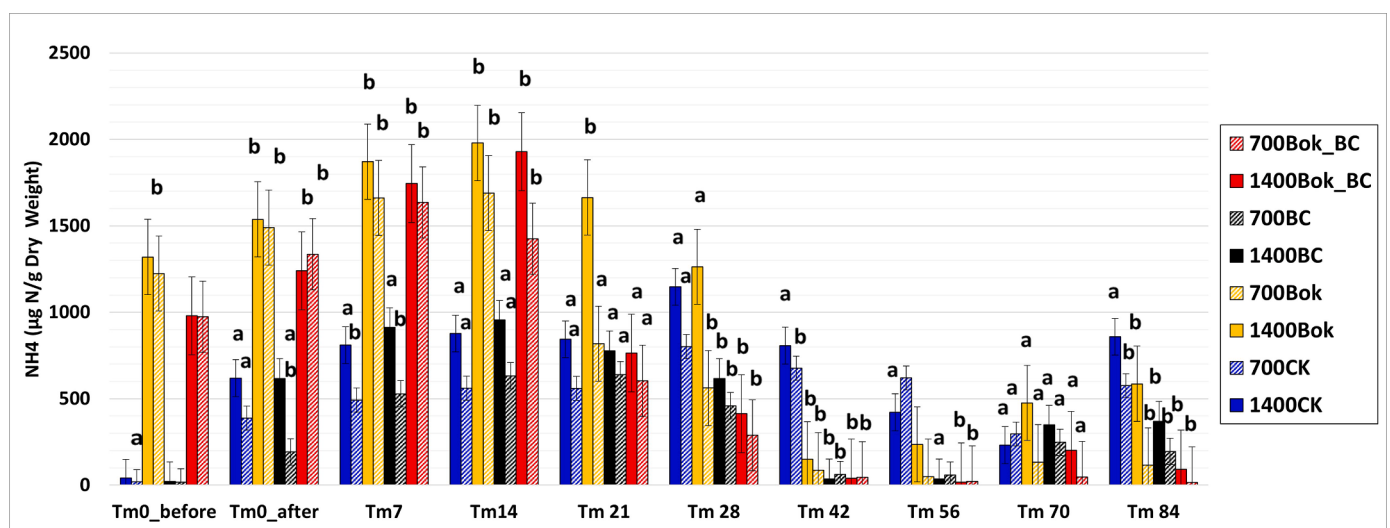


Fig. 4. Levels of ammonium ($\text{NH}_4^+\text{-N}$) in soil at different time points in different treatments (Details in Table 1). One-way ANOVA was performed at each time point to compare the means of different treatments at $p < 0.05$. Values followed by different letters indicate significant differences between the treatments. Different color bars correspond to the eight treatments: CK1400 in solid blue, CK700 in diagonal blue stripes, Bok1400 in solid yellow, Bok700 in diagonal yellow stripes, BC1400 in solid black, BC700 in diagonal black stripes, Bok_BC1400 in solid red, and Bok_BC700 in diagonal red stripes. Error bars represent the standard error of the mean (SEM).

interactions. NO_x-N concentrations were effectively just NO₃⁻ concentration as NO₂⁻ only levels were negligible and often below detection limits. At time point 0 (Tm0_before), the NO_x-N levels for all treatments were negligible to low values. This observation likely reflects the baseline condition before the application of treatments. As shown in Fig. 5, at Tm 0_after, the CK700 treatment displayed significantly higher NO_x-N levels (171) than the initial readings (Tm0_before), indicating an immediate response to the CK soil treatment at the lower fertilizer dose of 700 µS/cm. This trend was mirrored, albeit to a higher degree, in the CK1400 treatment, which registered a level of 364. Among the organic amendments, Bok BC700 (155) displayed a relatively comparable NO_x-N level to the CK700 treatment. As time progressed, differences in the NO_x-N levels became more apparent across treatment groups. Overall, for the mid-time points (Tm7 to Tm42), treatments with Bok, BC, and Bok_BC had variable effects on NO_x-N levels depending on the fertilizer dose. At 700 µS/cm, the bokashi treatment showed an increase from 240 (Tm7) to 400 (Tm42), which is a substantial improvement but still lower than the CK700 treatment, which ranged from 300 (Tm7) to 561 (Tm42). For the 1400 µS/cm dose, bokashi achieved the highest level at Tm42 (1251) compared to CK1400 (801). Interestingly, the combined Bok_BC treatment showed consistent results, with levels from 158 (Tm7) to 461 (Tm42) at 700 µS/cm and from 387 (Tm7) to 760 (Tm42) at 1400 µS/cm. Toward the end of the experiment (Tm56 to Tm84), remarkable increases were observed in the Bok-treated soil. For example, at Tm56 with 1400 µS/cm fertilizer, Bok-treated soil had a mean NO_x-N level of 2536, while CK-treated soil showed 865. Similarly, in Bok_BC treated soil, the NO_x-N level rose to 1284, suggesting that organic amendments such as bokashi and biochar can effectively elevate NO_x-N levels in the soil. Higher NO_x-N level in Bok BC treated soil compared to the control soils was also observed at Tm 70 and 84, indicating that biochar might help retain NO_x-N earlier and release it NO_x-N later.

3.3. Elemental composition changes (XRF) in the potting soil

Figs. 7 and 8 and supplemental Fig. S1 to S17 show the changes in the elemental composition of the soil solid phase collected at the beginning of the experiment before adding fertilized nutrient solution (Tm 0 Before) and after (Tm 0 After), at the end of week 4, 8 and week 12 (Tm 28, Tm 56, Tm 84). We categorized elements into two groups: Plant nutrients (P, K, Ca, Mo, Mg, Se, Cl, Fe, Mn, S, and Zn) and potentially toxic elements (Na, Al, Co, Cu, Hg, Pb, V, Cr, As, Cd).

3.3.1. Phosphorus soil levels

Phosphorus (P) is a crucial element for soil and plant health, playing a key role in energy transfer, photosynthesis, nutrient uptake, and other vital biochemical processes, thus contributing significantly to plant growth, development, and yield production. The results of the ANOVA indicated that fertilizer treatment, amendment treatment, timepoint, and all their interactions were significant ($p < 0.001$) for P. When comparing the µg N/g LS means of each treatment factor, Bok_BC (1238) had the highest phosphorus level among the soil amendments, followed by Bok (971), BC (715), and Control (455) (Fig. 6). For the fertilizer treatments, 1400 µS/cm (927) was higher than 700 µS/cm (762). Regarding the time points, Tm0_before (1088) had the highest phosphorus levels, followed by Tm0_after (1006), Tm28 (723), Tm56 (710), and Tm84 (696) (Fig. 6). Post-hoc analysis showed that the soil amendment treatments Bok, BC, and Bok_BC resulted in significantly increased phosphorus levels compared to control at all time points ($p < 0.05$). In terms of fertilizer treatments, for Bok, BC, and Bok_BC, the 700 µS/cm dose resulted in lower but comparable phosphorus levels to the 1400 µS/cm dose. For the combined treatments, the highest phosphorus level was observed with the combination of Bok_BC and 700 µS/cm fertilizer treatment at the Tm0_before timepoint (1888). The lowest phosphorus level was observed in the combination of Control and 700 µS/cm fertilizer treatment also at the Tm0_before timepoint (260). Overall, our results indicate that Bok, BC, and Bok_BC soil amendments significantly increase soil phosphorus levels compared to the Control. Additionally, a half dose of fertilizer (700 µS/cm) in combination with Bok, BC, and Bok_BC treatments could effectively replace the 1400 µS/cm and control soil amendment combination, supporting the potential for more sustainable soil management strategies.

3.3.2. Potassium soil levels

Potassium (K) is an essential macronutrient for plant health, playing a pivotal role in a wide range of physiological processes such as the regulation of water uptake and loss, the promotion of protein synthesis, and the activation of enzymes, thereby significantly enhancing plant growth, resistance to diseases, and overall crop quality and yield. Results from the three-way ANOVA statistical analysis reveal significant interactions between the time point, amendment treatment, and fertilizer treatment, indicating that the different treatments' effect on soil K levels varies depending on the time of application and the type of fertilizer used (p -value<0.0001). In terms of LS means for time points, the highest

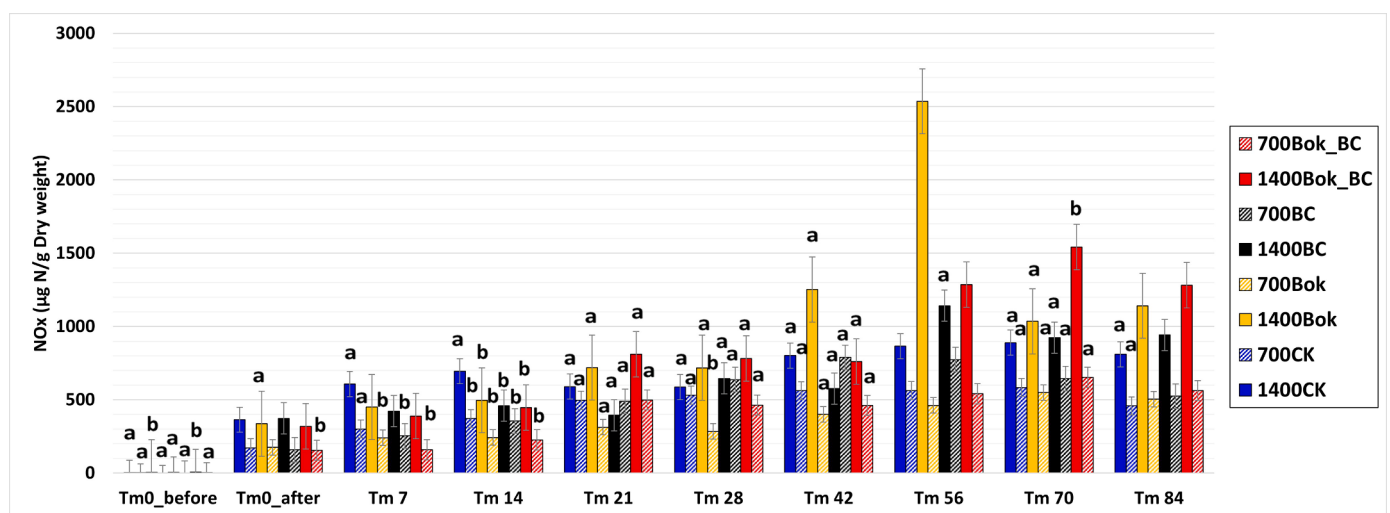


Fig. 5. Levels of Nitrate and Nitrite (NO_x (NO₃⁻-N + NO₂⁻-N)) in soil at different time points in different treatments (Details in Table 1). One-way ANOVA was performed at each time point to compare the means of different treatments at $p < 0.05$. Values followed by different letters indicate significant differences between the treatments. Different color bars correspond to the eight treatments: CK1400 in solid blue, CK700 in diagonal blue stripes, Bok1400 in solid yellow, Bok700 in diagonal yellow stripes, BC1400 in solid black, BC700 in diagonal black stripes, Bok_BC1400 in solid red, and Bok_BC700 in diagonal red stripes. Error bars represent the standard error of the mean (SEM).

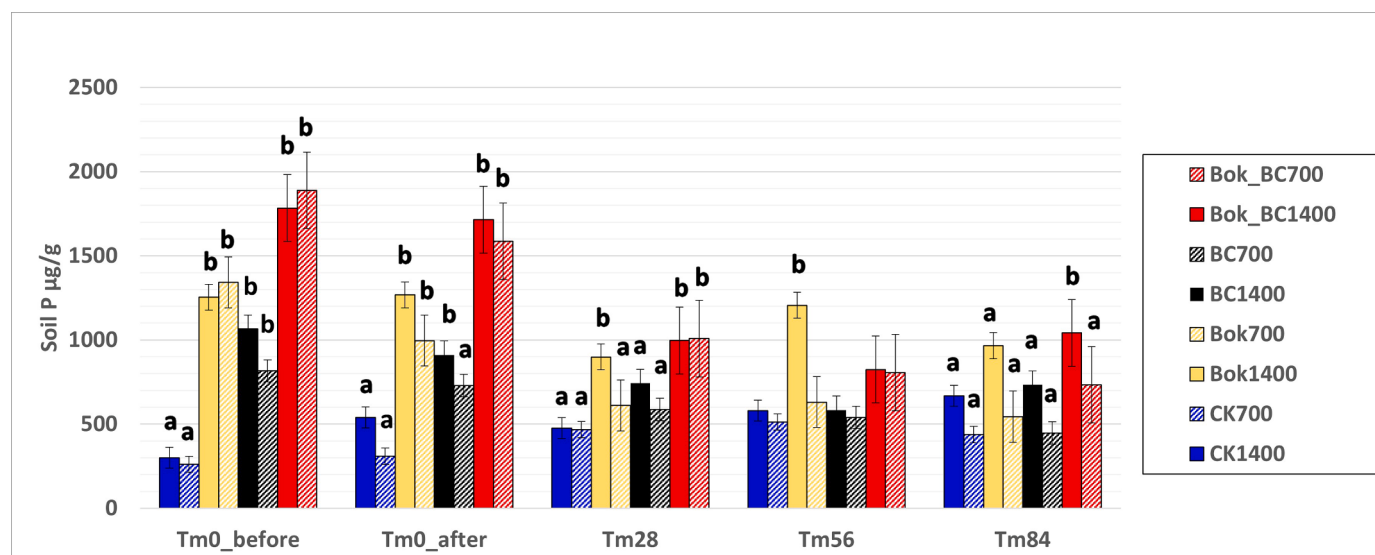


Fig. 6. Levels of phosphorus (P) in the soil at different time points in different treatments (Details in Table 1). One-way ANOVA was performed at each time point to compare the means of different treatments at $p < 0.05$. Values followed by different letters indicate significant differences between the treatments. Different color bars correspond to the eight treatments: CK1400 in solid blue, CK700 in diagonal blue stripes, Bok1400 in solid yellow, Bok700 in diagonal yellow stripes, BC1400 in solid black, BC700 in diagonal black stripes, Bok_BC1400 in solid red, and Bok_BC700 in diagonal red stripes. Error bars represent the standard error of the mean (SEM).

K level was observed at the Tm 0_before (36,163), and it gradually declined at later time points (Fig. 7). As for the soil amendment treatment, Bok_BC and BC had the highest means (32,522 and 32,508 respectively), surpassing the control, CK (25,928), suggesting that these amendments can potentially improve the soil K levels. In comparing the fertilizer treatment, the full 1400 fertilizer dose had a higher mean (30,455) but was comparable to the half 700 fertilizer dose (29,364).

The amendments Bok, BC, and particularly Bok_BC enhanced soil potassium levels compared to the control. Bok_BC and BC had the highest mean potassium levels among the Amendment Treatments. Furthermore, at the earliest time point, the BC and Bok_BC amendments, in conjunction with both low and high fertilizer doses, yielded the highest potassium levels (39,980, 45,296, 46,323, 44,220, respectively),

significantly outperforming the controls (27,063 and 25,436, respectively). This pattern was consistently observed even when analyzing the interaction between time points, soil amendment treatment, and fertilizer treatment.

3.3.3. Calcium (Ca), molybdenum (Mo), magnesium (Mg), selenium (Se), chlorine (Cl), iron (Fe), manganese (Mn), sulfur (S), zinc (Zn) soil levels

The XRF analysis revealed significant differences in element levels among the treatment groups. Bok, BC, and Bok_BC soil amendments showed comparable or increased Ca, Mo, Mg, Se, Cl, Fe, Mn, S, and Zn levels compared to the Control treatment (Fig. S1 to S9). The statistical power of the test varied for each element, with higher power observed for some elements (e.g., Mo, Cl, Fe, S) compared to others (e.g., Ca, Mg,

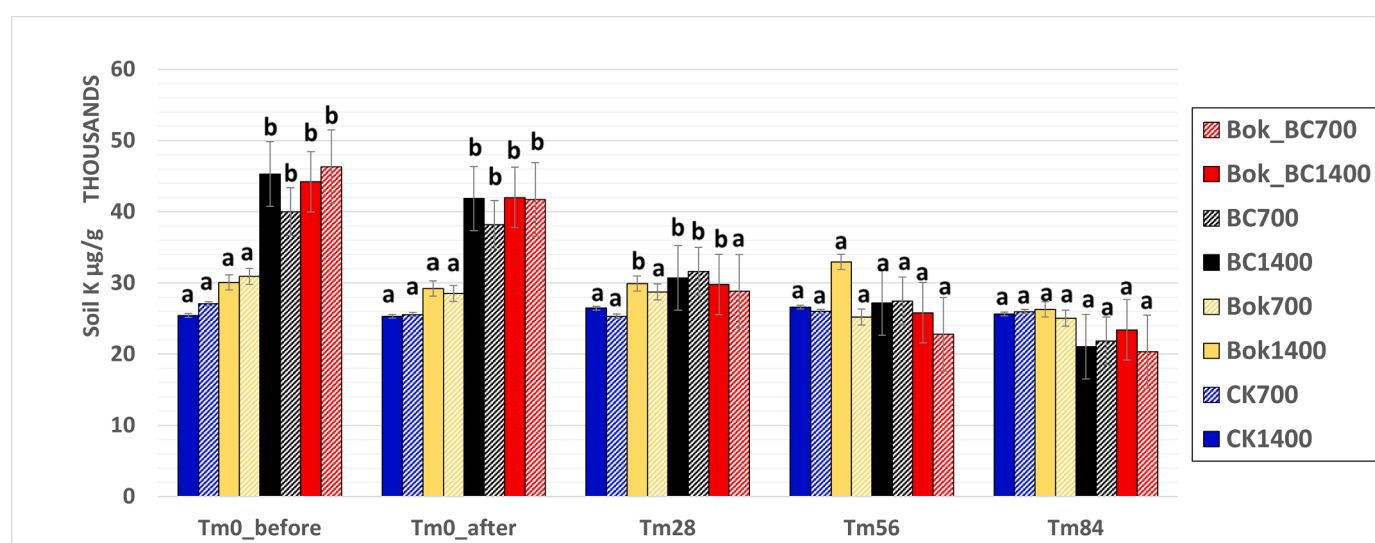


Fig. 7. Levels of potassium (K) in the soil at different time points in different treatments (Details in Table 1). One-way ANOVA was performed at each time point to compare the means of different treatments at $p < 0.05$. Values followed by different letters indicate significant differences between the treatments. Different color bars correspond to the eight treatments: CK1400 in solid blue, CK700 in diagonal blue stripes, Bok1400 in solid yellow, Bok700 in diagonal yellow stripes, BC1400 in solid black, BC700 in diagonal black stripes, Bok_BC1400 in solid red, and Bok_BC700 in diagonal red stripes. Error bars represent the standard error of the mean (SEM).

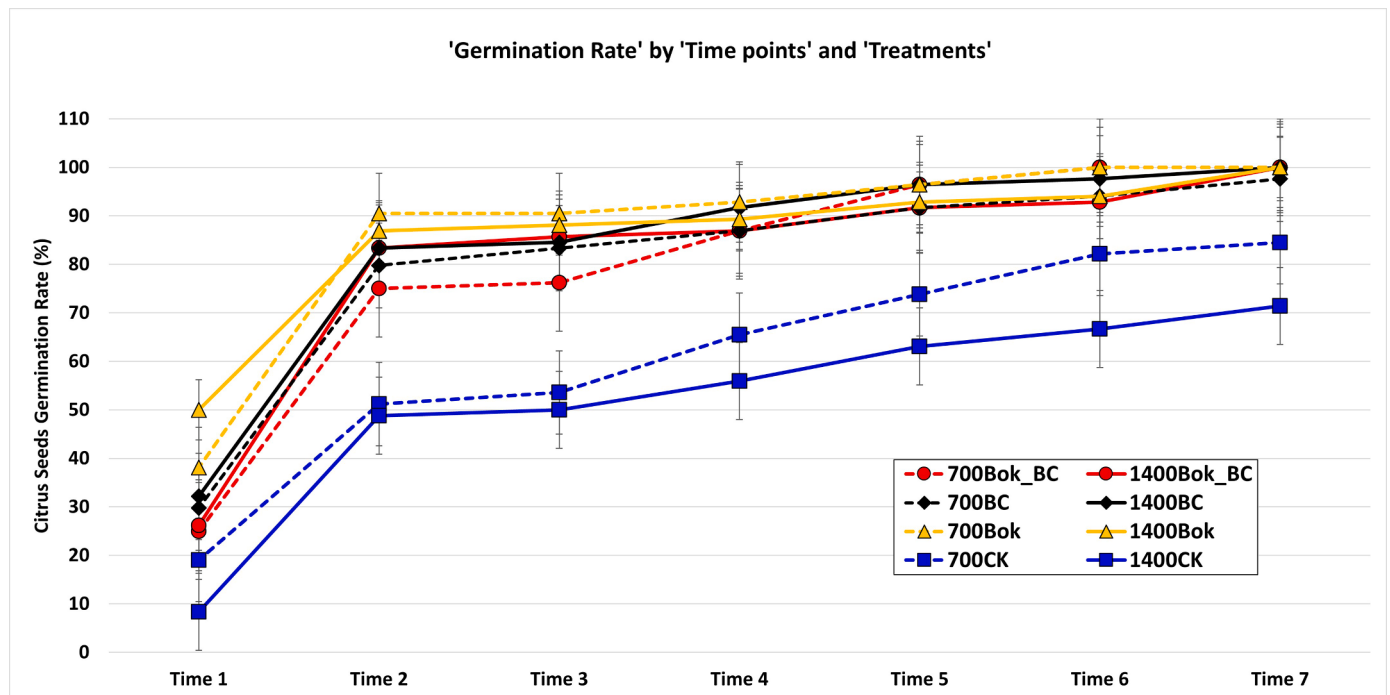


Fig. 8. Chart representing the influence of various soil amendments and fertilizer doses on seed germination rate at different time points, between 4 (Time 1) and 10 (Time 7) weeks after sowing. The x-axis represents the time points (weeks) sampled (Tm 0 - Tm 7), while the y-axis indicates the Germination Rate (%) = (Number of Seeds Germinated / Total Number of Seeds Sown) x 100. Different color lines correspond to the eight treatments: CK1400 in solid blue with square marker, CK700 in blue with dashes with square marker, Bok1400 in solid yellow with triangle marker, Bok700 in yellow with dashes with triangle marker, BC1400 in solid black with diamond marker, BC700 in black with dashes with diamond marker, Bok_BC1400 in solid red with circle marker, and Bok_BC700 in red with dashes with circle marker. Error bars represent standard error of the mean (SEM). Error bars represent the standard error of the mean (SEM). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Se) (Table S1). This suggests that the amendments Bok, BC, and Bok_BC can potentially increase or maintain adequate levels of these elements in the soil. Furthermore, the hypothesis was validated that a reduced fertilizer dose of 700 $\mu\text{S}/\text{cm}$ can be used with Bok, BC, and Bok_BC soil treatments to achieve comparable or increased element levels. The combination of a half fertilizer dose (700 $\mu\text{S}/\text{cm}$) with Bok, BC, or Bok_BC treatments resulted in element levels similar to or higher than those achieved with the full fertilizer dose (1400 $\mu\text{S}/\text{cm}$) in combination with Control treatment (Fig. S1 to S9). This indicates that reducing the fertilizer dosage while using appropriate soil amendments can be a viable approach to maintain or enhance levels of beneficial elements in our test soils. The analysis of the cumulative trend over time showed that the effects of the treatments on element levels were relatively stable across the tested time period. Although some elements showed fluctuations, overall, the amendments Bok, BC, and Bok_BC consistently maintained or increased beneficial element levels compared to the control treatment.

3.3.4. Sodium (Na), aluminum (Al), cobalt (Co), copper (Cu), mercury (Hg), lead (Pb), vanadium (V), and chromium (Cr) soil levels

In addition to the elements beneficial to plant growth that were discussed above, this work evaluated the impact of our soil and fertilizer treatments on the concentration of potentially toxic elements in the soil. The majority of the elements under study demonstrated decreased or comparable concentrations with the use of Bok, BC, and Bok_BC amendments (Fig. S10 to S17). Specifically, mercury (Hg), lead (Pb), vanadium (V), and chromium (Cr) levels (Fig. S14, S15, S16, and S17) did not increase significantly with the application of these amendments, suggesting their potential safety for use in sustainable agriculture. However, sodium (Na) (Fig. S10) levels increased with BC and Bok_BC treatments but not with Bok, implying that biochar might contribute to the surge of sodium in the soil. This requires further investigation to

understand its implications for soil and plant health. The results for aluminum (Al), cobalt (Co), and copper (Cu) (Fig. S11, S12, and S13) were less definitive. Some treatments showed potential increases in these elements' concentrations, but due to varied test power and lack of consistent trends, these results require further investigation. In summary, the soil amendments Bok, BC, and Bok_BC generally did not lead to a significant increase in potentially toxic elements. However, given the surge in sodium with BC and Bok_BC treatments and inconclusive results for aluminum, cobalt, and copper, further research is necessary to ensure the complete safety and efficacy of these amendments for sustainable agriculture.

3.4. Plant growth parameters (germination rate and plant height)

The effects of soil amendments (Bok, BC, Bok_BC) and fertilizer dose (700, 1400) on the germination rate (Bi-weekly for seven time points) were evaluated over various time points using a three-way ANOVA together with their interactions to provide an in-depth understanding of their combined effects. The average germination rate (Fig. 5) was significantly different among soil treatments, with Bok (24.2), BC (23.0), and Bok_BC (22.5) having higher germination rates compared to the control group CK (15.9) (LS means, Std Err = 0.419). Interestingly, the fertilizer dose did not significantly influence the germination rate, regardless of the soil amendment applied. This suggests that the increased germination rate was primarily due to the soil amendments rather than the fertilizer dose. The three-way interaction analysis confirmed the beneficial effects of Bok, BC, and Bok_BC soil amendments, as they consistently outperformed the control CK in terms of germination rate at all time points, regardless of the fertilizer dose used. These findings underscore the potential of Bok, BC, and Bok_BC soil amendments in improving soil germination rates over time. The Kruskal-Wallis one-way ANOVA test was utilized to ascertain whether the eight

different treatments affected plant height (4 months after seeding) (Fig. 6.). When compared to the full fertilized control group (1400CK), the 1400BC, 700Bok, 1400Bok, 700BC, and 1400Bok_BC treatments resulted in significantly higher plant heights compared to the control (all $P < 0.001$). The most considerable difference was seen in the 1400BC treatment, with a rank difference of 171 ($P < 0.001$). However, the 700Bok_BC and 700CK treatments did not differ significantly from the control group. These results suggest that the nature and dose of soil amendments, along with the level of fertilizer, significantly influence plant height (Fig. 9). The difference in results for different treatments indicates a complex interaction between these factors. Further analysis would be beneficial to identify the optimal combination for maximum plant growth.

4. Discussion

Carbon-based soil amendments have been suggested as a viable substitute for synthetic fertilizers to enhance soil fertility, quality, and ultimately, crop yield (Du et al., 2018; Chia et al., 2020; O'Connor et al., 2021; Rombel et al., 2022). In this study, we investigated the use of carbon-based soil amendments and fertilizers derived from agri-food waste and validated their use to enhance soil functions and improve plant health while achieving the diversion of organic waste from landfills. We examine the impact of organic soil amendments, specifically bokashi (Bok), biochar (BC), and their combination (Bok_BC), on key soil parameters such as total carbon, total nitrogen, the carbon to nitrogen (C:N) ratio, nutrients availability over time, influence on toxic elements, and impact on seeds' germination and plant growth. We also probe into their potential role in sustainable soil management, highlighting their capability to enhance soil fertility, nutrient availability to plants, and overall soil health, reducing reliance on synthetic fertilizers and mitigating their adverse environmental implications. Our results demonstrate the potential of agricultural and food waste organic-rich by-products in the form of Bok, BC, and Bok_BC to significantly alter the soil's total carbon, total nitrogen, and C:N ratio over time. This aligns with previous studies highlighting the potential of anaerobically digested organics and biochar treatments to enhance soil fertility, nutrient

availability to plants, and overall soil health, thereby supporting the use of such amendments for sustainable soil management (Agegnehu et al., 2016; Kizito et al., 2019; Pandit et al., 2019; Guo et al., 2020).

In our study, treatments with biochar (BC) and combined bokashi and biochar (Bok_BC) increased total soil carbon (C) to 35 %, compared to 26 % in the control, corroborating biochar's role in enhancing soil organic carbon and, consequently, soil health (Shi et al., 2020; Alkharabsheh et al., 2021). Similarly, nitrogen (N) content was significantly elevated in Bok and Bok_BC treatments at a 700 $\mu\text{S}/\text{cm}$ EC fertilizer dose, aligning with prior research showing that nitrogen-rich amendments improve soil N availability (Luo et al., 2018; Singh et al., 2020). Additionally, the treatments notably affected the soil's C:N ratio. Bok and Bok_BC lowered the C:N ratio to 36–44, compared to 50–54 in the control, indicating a relative nitrogen increase and faster nutrient release (Esmailzadeh and Ahangar, 2014). This supports the importance of maintaining an optimal C:N ratio for microbial activity and soil fertility.

Our study found significant effects of bokashi, biochar, and their combination (Bok_BC) on soil $\text{NO}_x\text{-N}$ and $\text{NH}_4\text{+N}$ levels. Bokashi notably increased $\text{NH}_4\text{+N}$, outperforming even full fertilizer doses. This points to a temporal aspect of nutrient release crucial for crop health while minimizing N loss (Gollany et al., 2004; Govindasamy et al., 2023). Moreover, biochar's role in the slow release of nitrified nitrogen highlights its potential in sustainable fertilization strategies (Wang et al., 2022). The rate at which $\text{NH}_4\text{+N}$ was released from bokashi by-products and their subsequent conversion into $\text{NO}_x\text{-N}$ was also notable. Our data showed that bokashi-treated soils at 1400 $\mu\text{S}/\text{cm}$ maintained high $\text{NH}_4\text{-N}$ levels, suggesting a sustained nutrient release, likely due to the high nutrient content of bokashi, where organic material is fermented with Effective Microorganisms (EM), which results in high mineral content and slow-release of nutrient sources to plants (Mayer et al., 2010; Joshi et al., 2019; Abo-Sido et al., 2021). Bok_BC1400 treatment showed higher $\text{NO}_x\text{-N}$ later in the study, indicating biochar's role in nutrient retention and release. Towards the study end, a decline in $\text{NH}_4\text{-N}$ was noted in Bok and BC treatments, hinting at possible nutrient exhaustion. The C/N ratio in our citrus bokashi material was higher than recommended, falling above the

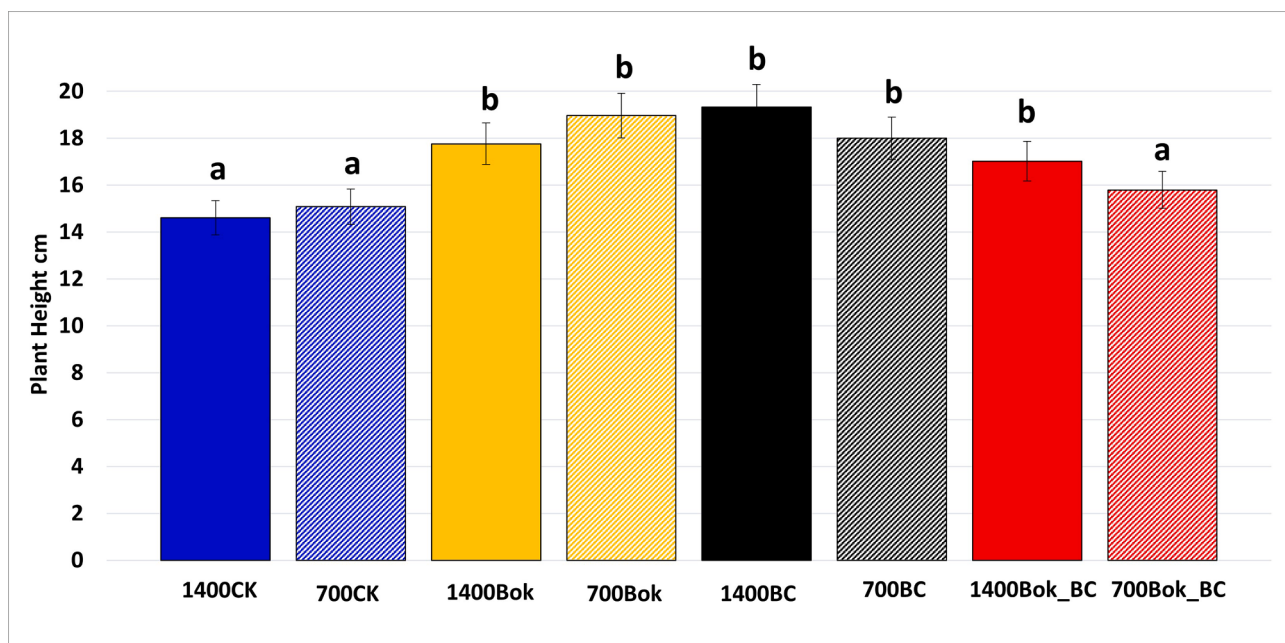


Fig. 9. Chart representing the influence of various soil amendments and fertilizer doses on seedlings height (cm) four months after seeding. Different color bars correspond to the eight treatments: CK1400 in solid blue, CK700 in diagonal blue stripes, Bok1400 in solid yellow, Bok700 in diagonal yellow stripes, BC1400 in solid black, BC700 in diagonal black stripes, Bok_BC1400 in solid red, and Bok_BC700 in diagonal red stripes. Error bars indicate the interquartile range (25th to 75th percentile). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

recommended range of 25–30. This could have led to a scenario where most of the synthetic nitrogen introduced with the lower fertilizer dose (700 EC), and a portion of the synthetic nitrogen introduced through the higher fertilizer dose (1400 EC), was utilized by soil microbes to mineralize the organic nitrogen (Quiroz and Céspedes, 2019; Du et al., 2018; O'Connor et al., 2021). Thus, adjusting raw material C/N ratios becomes crucial for effective nutrient balance. This aspect holds particular significance for the utilization of carbon-based fertilizers, as the nutrient contents (primarily N, P, and K) in the fermented digestate originate entirely from the feedstock. Finally, our study supports the synergistic effects of combining bokashi and biochar, especially if blended at the composting stage, for enhanced soil fertility. Several studies have shown that when combined with biochar at the composting step, digested organic material significantly improves biochar properties over time and overall soil fertility (Guo et al., 2020; Chia et al., 2020). Further studies are needed to elucidate the biochemistry underlying biochar's interaction with NH_4^+ and to confirm these findings.

Our results showed that initial nutrient spikes occurred in Bok and Bok_BC treated soil for phosphorus, potassium, calcium, and chlorine. This was followed by a gradual decline for phosphorus, potassium, and chlorine, indicating a possible slow nutrient release profile of the amendments, plant uptake, or a combination of both. At the same time, calcium maintained higher levels compared to the control soil throughout the experiment period. For other nutrient elements, including molybdenum (Mo), magnesium (Mg), selenium (Se), iron (Fe), manganese (Mn), sulfur (S), zinc (Zn), the Bok, BC, and Bok_BC soil amendments showed comparable or increased levels compared to the control treatment. These amendments maintained or enhanced element levels even with a reduced fertilizer dose, further reinforcing their potential for sustainable soil management strategies. Lastly, the study evaluated the concentration of potentially toxic elements in soil, including sodium (Na), aluminum (Al), cobalt (Co), copper (Cu), mercury (Hg), lead (Pb), vanadium (V), and chromium (Cr). Generally, the soil amendments Bok, BC, and Bok_BC did not lead to a significant increase in potentially toxic elements. However, given the surge in sodium with BC and Bok_BC treatments and inconclusive results for aluminum, cobalt, and copper, further research is necessary to ensure these amendments' complete safety and efficacy for sustainable agriculture. Our findings align with existing research, indicating that the amendments Bok, BC, and Bok_BC significantly boost germination rates compared to the control group (Kizito et al., 2019; Dangi et al., 2020; Murtaza et al., 2023). This improvement may result from alterations in soil structure, nutrient provision, or microbiome shifts (Dangi et al., 2020; Zhang et al., 2021). We also noted a time-dependent increase in germination from Time 1 to Time 7, possibly due to gradual nutrient release or microbial community establishment. Interestingly, fertilizer doses had no substantial impact on germination, emphasizing the importance of soil amendments over mere nutrient supplementation (Francioli et al., 2016). Our study raises questions about the specific components in Bok, BC, and Bok_BC that improve germination and calls for long-term studies on soil health.

The evolving regulatory landscape concerning fertilizer, water usage, and quality poses a growing challenge for the nursery industry. To remain sustainable and eco-friendly, the industry must explore innovative strategies and advanced technologies that efficiently utilize and manage alternative water and fertilizer sources while safeguarding production schedules and ensuring high crop quality (White et al., 2019). Our results revealed significant differences in plant height across the eight treatment groups, confirming that both soil amendments combined with half and full fertilizer doses positively impacted plant growth. Most notably, the 1400BC, 700Bok, 1400Bok, 700BC, and 1400Bok_BC treatments significantly enhanced plant height compared to the control group (1400CK). This finding highlights the promising potential of combining soil amendments (Bok and BC) with lower fertilizer doses to achieve comparable plant growth while minimizing the reliance on synthetic fertilizer inputs. However, the most significant

increase was observed with the 1400BC treatment, suggesting that a higher dosage of fertilizer (1400) combined with the BC amendment may be particularly beneficial. The findings corroborate previous research, hinting that higher fertilizer doses may amplify certain soil amendments' effects by increasing enzymatic activities (Sharma and Dhaliwal, 2019). However, treatments 700Bok_BC showed no significant difference from the 1400 full fertilizer control, highlighting plant-soil interaction complexity and the need for further research into the specific effects of different types of raw material, fertilizer doses, and % of amendment blended into the soil. Future studies should focus on understanding the mechanism of these soil amendments and their long-term impacts on soil health and plant growth. More in-depth research is recommended into the different combinations of soil amendments (made from different types of raw materials/wastes and having different C/N ratios) and fertilizer doses and their effect on other plant growth parameters. Future studies should focus on optimizing food waste conversion to biofertilizers through improved production efficiency, strict quality controls, smart distribution systems, and advanced technologies (Du et al., 2018; O'Connor et al., 2021).

5. Conclusion

In conclusion, our study underscores the efficacy of carbon-based soil amendments like bokashi and biochar in enhancing soil health and nutrient availability and fostering a healthier, more sustainable soil ecosystem for indoor plant production. This not only reduces dependency on synthetic fertilizers but also addresses their environmental shortcomings. When paired with reduced fertilizer doses, these amendments hold promise for maintaining soil nutrients, offering an avenue towards more sustainable agriculture. The positive impact on plant growth also supports their use in short-cycle crops and long-term nursery production. However, long-term field studies are needed for complete validation. These sustainable practices should be encouraged through policy and technological innovation to ensure wider adoption and a more sustainable agricultural future.

CRediT authorship contribution statement

Deborah Pagliaccia: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Michelle Ortiz:** Investigation, Methodology, Project administration. **Michael V Rodriguez:** Data curation, Formal analysis, Writing – original draft. **Sophia Abbott:** . **Agustina De Francesco:** Writing – original draft. **Madison Amador:** Formal analysis, Visualization, Data curation. **Valeria Lavagi:** Data curation, Resources. **Benjamin Maki:** Data curation. **Francesca Hopkins:** Conceptualization, Methodology, Resources, Validation, Writing – original draft. **Jonathan Kaplan:** Conceptualization, Writing – original draft. **Samantha Ying:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Georgios Vidalakis:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Samantha Ying reports financial support was provided by California Department of Food and Agriculture (CDFA) Specialty Crop Block Grant Program (SCBGP). Samantha Ying reports a relationship with California Department of Food and Agriculture (CDFA) Specialty Crop Block Grant Program (SCBGP) that includes: funding grants. NA

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.scienta.2023.112661](https://doi.org/10.1016/j.scienta.2023.112661).

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