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Recycling Agricultural Waste to Enhance Sustainable Greenhouse Agriculture: Analyzing the Cost-Effectiveness and Agronomic Benefits of Bokashi and Biochar Byproducts as Soil Amendments in Citrus Nursery Production

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Abstract: Applying bokashi (Bok) at 10% volume/volume (*v*/*v*), biochar (BC) at 10% *v*/*v*, and their combination (Bok_BC) as soil amendments significantly enhances citrus nursery production, improving plant growth and soil health, alongside offering notable economic benefits. Our greenhouse experiment evaluated these treatments across two fertilizer doses, at half (700 µS/cm) and full (1400 µS/cm) electrical conductivity (EC) levels, compared to a control mix, demonstrating improved nutrient availability, water retention, growth rates, and potential for carbon sequestration. Based on the results of this experiment, a cost–benefit analysis was performed; the BC treatment yielded substantial savings, particularly in large nurseries where BC at 700 µS/cm electrical conductivity (EC) saved USD 1356.38 per day and the same treatment at 1400 µS/cm EC saved USD 1857.53. These savings stem from increased nutrient contents (N, P, and K) and improved water retention, reducing irrigation; shortened growth cycles due to enhanced growth rates were observed, indirectly suggesting reduced electricity costs for greenhouse operations. Additionally, the increased carbon content within the soil points toward long-term benefits from carbon sequestration, further contributing to the sustainability and economic viability of these practices. These findings highlight the economic advantage of incorporating Bok and BC into soil mixes, providing a cost-effective strategy for enhancing greenhouse agriculture sustainability.

Keywords: soil amendments; resource use efficiency; economic sustainability; carbon sequestration; nutrient management

1. Introduction

The intensification of agriculture has led to a dependency on synthetic fertilizers, significantly contributing to CO_2 and non-CO_2 greenhouse gas emissions [1–3]. Conversely, carbon-based nutrients from agricultural and food wastes offer a promising alternative, potentially increasing crop yield through the slow release of nutrients [4–6]. This approach also helps in reducing environmental harm associated with conventional fertilizer use [7]. The efficiency of these organic amendments, however, is contingent upon their mineralization by soil microorganisms, a process that can vary widely [8–10]. Aerobic composting and anaerobic processing, such as bokashi (Bok) fermentation, stand out as two principal methods for processing agricultural waste, each with distinct benefits and drawbacks [11–13]. Composting, which supports soil health and waste reduction, is a relatively slow process and can result in greenhouse gas emissions [14]. In contrast, Bok fermentation, which utilizes microbial inoculants, provides a quicker, low-emission alternative, albeit with specific technical needs. Biochar (BC) represents another alternative. BC, derived from organic waste through pyrolysis, improves soil fertility by enhancing nutrient retention, water-holding capacity, and microbial diversity. It acts as a long-term carbon sink, mitigating greenhouse gas emissions and promoting sustainable agriculture [15,16]. BC reduces reliance on synthetic fertilizers, potentially decreasing nutrient runoff and environmental contamination [17]. Integrated strategies with other soil amendments optimize pyrolysis processes, effectively revitalizing low-fertility soils and enhancing crop yields [18]. Economic analyses suggest that BC can reduce carbon emissions and enhance farm profitability, particularly when the market price of BC is low and a C offset trading system is in place [19]. The synergistic use of Bok and BC could potentially provide the immediate nutrient supply and microbial advantages of Bok with the long-term soil structure and carbon sequestration benefits of BC.

Various studies consistently demonstrate the positive impacts of Bok on plant growth, survival, and soil health. For example, Bok significantly enhances the survival and growth rates of reforestation species, while also improving overall crop productivity through enhanced soil nutrient levels [20,21]. Bok applications enhance microbial activity, soil fertility, and root growth via lactic acid bacteria, further improving chlorophyll levels, biomass, and crop yield compared to chemical fertilizers [22–24]. Compared to chemical fertilizers, Bok increases the panicle number, ripened grain percentage, and grain yield in rice under specific planting conditions [25]. Additionally, Bok compost promotes robust vegetative growth in tomato plants [26] and sustains beneficial microbes within citrus plant systems [27]. Studies also demonstrate the effectiveness of Bok in increasing essential soil nutrients, such as nitrogen, phosphorus, and potassium, which are crucial for healthy plant development [28–30]. Pagliaccia et al. (2024) revealed that the combined use of Bok and BC can significantly substitute for synthetic fertilizers, improving soil levels of nitrogen, phosphorus, and calcium, as well as improving the soil's carbon content and potassium levels, especially when applied in specific doses [31]. These research findings underline the role of organic-waste-derived amendments in promoting the sustainability of indoor agriculture, offering valuable insights for integrating these practices into sustainable farming strategies.

Following the positive impacts of organic amendments like Bok and BC on plant growth and soil health, it is equally important to consider their economic viability. Studies examining the costs and returns of such amendments have begun to shed light on their financial benefits. A comprehensive cost–benefit analysis on recycling agricultural wastes demonstrated that such recycling not only mitigates waste pollution but also generates economic benefits for the agricultural sector [32]. Various composting models for recycling agricultural waste have been analyzed using cost–benefit analyses, showcasing the economic viability of organic waste composting systems through the lens of time-driven activity-based costing [33]. A comparative cost–benefit analysis of conventional and organic fertilizers highlights the higher unitary prices of organic fertilizers but also their long-term benefits in sustainable cultivation practices [34]. A cost–benefit analysis for the agricultural use of coal ash as a soil amendment outlines a methodology for estimating costs and benefits to farmers, emphasizing the broader economic considerations required in the adoption of alternative soil amendments [35]. These findings suggest that while upfront costs may exist for the transition to organic amendments, the long-term returns through improved yield, soil health, and potential market benefits for organic waste could outweigh initial investments. Therefore, integrating organic waste byproducts into farming strategies not only aligns with sustainable agricultural practices but also offers a promising avenue for greater economic viability.

This paper uses a partial budget approach to evaluate the economic viability of Bok and BC as sustainable soil amendments in greenhouse nursery production, focusing on their role as alternatives to synthetic fertilizers. Leveraging experimental data, insights from agricultural supply retailers, and a survey of California nurseries, this study assesses the financial and agronomic impacts of integrating these organically derived nutrient resources in comparison with traditional soil mixes that are predominantly composed of chemical fertilizers. Our analysis covers operational costs, such as seeds, containers, trays, fertilizers, water, labor, electricity, and soil, along with expenses specific to Bok and BC treatments, like citrus waste, bokashi bran, anaerobic fermentation bins, and BC. Emphasizing the potential cost savings and environmental benefits, we highlight their role in reducing chemical input dependency, improving nutrient efficiency, and conserving water. This paper not only reaffirms the agronomic advantages of Bok and BC amendments but also stresses their significant contributions to improving soil health, boosting plant vitality, and facilitating the diversion of organic waste from landfills. Through this extensive evaluation, our research contributes to the evolving conversation on sustainable soil management practices, advocating for approaches that are both environmentally friendly and economically viable in greenhouse agriculture. This shift toward sustainable amendments like Bok and BC presents a compelling case for rethinking traditional agricultural inputs, offering a pathway to more sustainable and financially sound greenhouse nursery production.

2. Materials and Methods

2.1. Cost–Benefit Analysis Approach

A cost–benefit analysis approach was utilized in this study to evaluate the economic impact of using BC and Bok at 10% *v/v* compared to conventional fertilizers. Models of typical nurseries were developed by integrating data from greenhouse nursery experiments, agricultural supply retailer insights, and surveys and expert consultations from citrus nurseries throughout California (Supplementary Survey S1). The focus was placed on the assessment of monetary gains and costs associated with changes in water and nutrient (N, P, and K) usage facilitated by these anaerobically generated nutrient resources. The economic valuation of carbon sequestration was also determined as a possible revenue source. The experiments were conducted in temperature-controlled greenhouses (20–32 °C) at the University of California, Riverside, from February to June 2023. Carrizo citrange (X *Citroncirus* sp.) was used as the crop, and the soil composition was a mixture of equal parts perlite, peat moss, and fine coco coir. In the greenhouse experiments, eight treatment groups were analyzed to assess the effectiveness of the BC and Bok amendments. These included control soils with and without fertilizer doses of 1400 and 700 electrical conductivity (EC; measured as micro siemens per centimeter (μS/cm)), soils amended with 10% *v*/*v* Bok or BC at both fertilizer levels, and combinations of both Bok and BC with each fertilizer dose. See Pagliaccia et al. (2024) [31] for more details on the materials, experimental design, analyses, and sampling. Furthermore, nurseries were categorized by size based on annual plant production, as follows: small (100,000 plants), medium (250,000 plants), and large (350,000 plants). This categorization was crucial in tailoring the cost–benefit analysis to different nursery operations scales, thus providing insights into the economic feasibility of using Bok and BC across varied nursery sizes.

2.2. Nitrogen, Phosphorus, and Potassium Data

The nitrogen (N), phosphorus (P), and potassium (K) contents of the plants were collected during prefertilization, immediately postfertilization, and when the plants were 7, 14, 21, 28, 42, 56, 70, and 84 days old. The percentage difference in the N contents for each treatment was relative to the control treatment of a 1400 μS/cm EC fertilizer dosage at the same point in time. The percentage differences were then multiplied by the fertilizer cost to determine the cost of N per gallon of water applied at different fertilizer dosages of 700 and 1400 μS/cm EC (Supplementary Table S1). We evaluated the potential cost savings per gallon in N by grouping the distinct timepoints for each treatment over the 84-day period. The same approach was adopted for P (Supplementary Table S2) and K (Supplementary Table S3). The cost of fertilizer was evaluated based on the price of Peter’s Excel Fertilizer (21-5-20); it was first calculated per cone (Supplementary Table S4), and the results were then adapted for different nursery sizes (Supplementary Tables S5–S7).

2.3. Irrigation and Water Content Data

Water content data from the greenhouse nursery experiments were continuously recorded using sensors throughout the duration of the experiment. The analysis specifically concentrated on three one-week periods selected to ensure uniformity in external temperature conditions. These recordings enabled the calculation of variations in the water content among the different treatments. Combined with data from the literature, this allowed for the determination of potential savings in water and irrigation labor that could be achieved by different-sized nurseries through the use of BC, Bok, or their combination. Table 1 summarizes the costs and the quantities related to water usage and irrigation labor needed for a one-acre greenhouse in Southern California (wage information was sourced from a literature survey and adjusted for inflation to 2023 US dollars).

Table 1. Cost and quantity summary for water usage and labor per a one-acre greenhouse in Southern California.

Parameter	Value	Source
Water Cost per 1000 Gallons (Southern California)	USD 2.59	[36]
Number of Gallons of Water Used per Day	22,000	[37]
Number of Gallons of Water Used per Hour	917	
Average Hourly Wage for Irrigation Worker	USD 19.80	[38]

The calculated results for a one-acre greenhouse are compiled and presented in Supplementary Tables S8–S13. Supplementary Table S14 details the adjustments necessary for applying these data to nurseries of various sizes (small, medium, and large), highlighting the daily water usage in gallons for each size category. Supplementary Table S15 displays the outcomes of these calculations, specifying the annual water (i.e., material) costs for small, medium, and large nurseries. Finally, Supplementary Table S16 outlines the calculations used to determine the annual irrigation labor hours required for nurseries of each of these three sizes.

2.4. Germination and Seedling Growth Data

The number of germinated seeds was recorded between 4 and 10 weeks after sowing. The germination rate (%) was calculated according to the following equation: germination rate (%) = (number of seeds germinated/total number of seeds sown) × 100. In order to ensure an adequate number of seedlings per replicate, 28 cell pots per replicate/cell pot were dedicated for germination and seedling growth evaluation. Four months after seeding, the heights (cm) of the seedlings were measured from the media surfaces to the tips of the seedlings. See Pagliaccia et al. (2024) [31] for more details on the methods for sampling.

Data from the experiment were analyzed to assess the effects of Bok and BC on germination rates and seedling growth. Germination rates and seedling growth data from various treatments at different time intervals were compared with data from the control treatment, which included a fertilizer dosage of 1400 µS/cm. See the seed germination rate data in Figure 8 and plant height data in Figure 9 in Pagliaccia et al. (2024) [31].

2.5. Total C Changes in the Potting Soil

For this analysis, 24 soil samples were collected at the beginning of 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 the control, Bok solid 10%, BC 10%, Bok solid 10% + BC 10%, at both fertilizer doses (700 or 1400 µS/cm). See Pagliaccia et al. (2024) [31] for more details on the methods for sampling.

To assess the potential revenue for nurseries via enhanced carbon sequestration with Bok and BC, the C content data in the plants recorded throughout the experiment for all of the different treatments and at various time points were compared with those from the control treatment, for which the fertilizer dosage was set at 1400 µS/cm. The percentage of organic C (Wt.% OC) in the soil was utilized to calculate the C content in each cone. This calculation was based on the total weight of the soil blend, which was 33,940 mg. The soil blend, measured during the experiment, consisted of equal parts perlite, coco coir, and peat moss. The differences in C mass between various treatments and the control with a fertilizer dosage of 1400 µS/cm were identified. These differences were then scaled according to the annual output of small, medium, and large nurseries and converted from milligrams to US tons. To estimate the potential revenue per ton of carbon (C) stored by a greenhouse, the total number of tons was multiplied by the 2023 California carbon price of USD 29.84 per ton, as reported by the World Bank [39].

2.6. Economic Analysis of Treatments: Costs and Benefits

After determining the cost savings from water and fertilizer when using Bok and BC, we calculate the difference in the costs of the soil mixes to estimate the net benefits (benefits minus costs) when using Bok and BC rather than the control, which represents a conventional soil mix. For the control soil mix, we accounted for the cost of Carrizo seeds, cone expenses (with two seeds per cone) tray expenses, fertilizer cost (Peters Excel 21-5-20, at the following two concentrations: 700 µS/cm EC and 1400 µS/cm EC), irrigation water expenses, labor expenses for irrigation, and the cost of the soil blend, comprising equal parts coco coir, peat moss, and perlite (Supplementary Tables S17–S19).

For the Bok treatments, the cost of the soil mix was similar to the cost of the control. It also included expenses related to bokashi bran and anaerobic fermentation bins. Similarly, for the BC treatment, apart from the expenses listed for the control, the cost assessment included expenses for BC and aerobic fermentation bins. Additionally, it was presumed that citrus waste used in the treatments incurred no cost. Expenses related to waste collection and transport labor were not included as well. These expenses may not be realized because a grove takes on the costs of the collection and transportation or the waste material is generated onsite and would need to be collected and removed regardless. For the Bok_BC treatment, the cost included those for the BC treatment and Bok treatment. Table 2 lists the daily costs of the soil mix, while Supplementary Tables S17–S28 provide details on the annual expenses.

Table 2. Summary of average daily costs for the control (CK700 and CK1400), biochar, and bokashi treatments at two different fertilizer dosages (700 µS/cm EC and 1400 µS/cm EC) across various nursery sizes.

Treatment	Cost/Day		
	Small	**Medium**	**Large**
CK700	USD 103.49	USD 224.95	USD 423.96
CK1400	USD 106.31	USD 231.99	USD 433.83
Bok700	USD 121.17	USD 298.24	USD 486.56
Bok1400	USD 122.58	USD 301.77	USD 491.49
BC700	USD 104.09	USD 255.53	USD 426.77
BC1400	USD 106.91	USD 262.58	USD 436.63
Bok_BC700	USD 121.78	USD 300.45	USD 489.36
Bok_BC1400	USD 123.19	USD 303.97	USD 494.30

The total benefits for each treatment and nursery size were determined by summing the cost savings for reduced water and fertilizer use. Subsequently, these total benefits were compared to the additional costs for each treatment relative to the control to determine net benefits, which were then used to determine which treatments were preferred to the control.

3. Results

3.1. Nitrogen

The savings in costs achieved by lowering the N usage in the treatments, compared to the control, are illustrated in Supplementary Table S29. Over the 84-day period, the

BC1400 treatment resulted in an average 27.34% increase in the N content, yielding a cost saving of USD 0.0015 per gallon of water used. This translates to average daily savings of USD 41.66 for a small nursery, USD 104.15 for a medium-sized one, and USD 291.61 for a large nursery. The BC700 exhibited an average 15.03% increase in the N level, leading to savings of USD 0.0004 per gallon of water, corresponding to average daily savings of USD 11.45 for a small nursery, USD 28.63 for a medium one, and USD 80.16 for a large nursery. The Bok_BC1400 approach demonstrated an average 64.49% increase in the N content, resulting in cost savings of USD 0.0035 per gallon, equating to daily savings of USD 98.26 for a small nursery, USD 245.64 for a medium one, and USD 687.80 for a large nursery on average. The Bok_BC700 treatment showed an average 51.39% increase in the N level, yielding savings of USD 0.0014 per gallon, with average daily savings of USD 39.15 for a small nursery, USD 97.87 for a medium-sized one, and USD 274.03 for a large nursery. Bok1400 produced an average 34.7% increase in the N content, leading to savings of USD 0.0019 per gallon of water, generating average daily savings of USD 52.86 for a small nursery, USD 132.16 for a medium one, and USD 370.05 for a large nursery. Bok700 resulted in an average 18.64% increase in the N level, leading to savings of USD 0.0005 per gallon, which corresponds to average daily savings of USD 14.20 for a small nursery, USD 35.51 for a medium one, and USD 99.42 for a large-sized nursery.

3.2. Phosphorus

The cost savings generated by reducing P for the treatments relative to the control are displayed in Supplementary Table S30. Over the 84-day period, the outcomes revealed an average increase of 33.81% for the BC1400 treatment, resulting in cost savings of USD 0.0004 per gallon of water used, corresponding to average daily savings of USD 12.26 for a small nursery, USD 38.89 for a medium-sized nursery, and USD 42.93 for a large nursery. The BC700 treatment showed an average increase of 4.59% in the P level, which led to cost savings of USD 0.00003 per gallon of water, which translates into average daily savings of USD 0.83 for a small nursery, USD 2.64 for a medium nursery, and USD 2.92 for a large nursery. The Bok_BC1400 treatment displayed a significant 106.33% change in the P quantity, which is average savings of USD 0.001 per gallon of water, leading to average daily savings of USD 38.57 for a small nursery, USD 122.30 for a medium one, and USD 134.99 for a large nursery. In comparison, the same treatment with a fertilizer dosage of 700 exhibited an average 88.63% change in the P quantity, which is a saving of USD 0.0006 per gallon of water, translating into average daily savings of USD 16.08 for a small nursery, 50.97% for a medium-sized nursery, and USD 56.26 for a large nursery. Bok1400 led to a 94.11% average change in the P quantity, which is a saving of USD 0.001 per gallon of water, leading to average daily savings of USD 34.14 for a small nursery, USD 108.25 for a medium nursery, and USD 119.48 for a large nursery. The Bok700 treatment showed a 25.76% average increase in the P quantity, equating to a saving of USD 0.0002 per gallon of water. This results in average daily savings of USD 4.67 for a small nursery, USD 14.81 for a medium nursery, and USD 16.35 for a large nursery.

3.3. Potassium

The cost savings from reductions in K are provided in Supplementary Table S31. Over the 84-day period, the findings reveal that in the case of the BC1400 treatment, there was an average increase of 16.47% in the K levels, leading to a cost saving of USD 0.0009 per gallon of water applied. This translates to average daily savings of USD 23.90 for a small nursery, USD 59.75 for a medium-sized nursery, and USD 167.29 for a large nursery. Similarly, BC700 exhibited an average change of 14.65% in the K levels, resulting in a cost saving of USD 0.0004 per gallon of water. This equates to average daily savings of USD 10.63 for a small nursery, USD 26.58 for a medium-sized one, and USD 74.42 for a large nursery. The Bok_BC1400 treatment displayed a substantial 16.75% shift in the K quantity, resulting in an average saving of USD 0.0009 per gallon of water, amounting to average daily savings of USD 24.31 for a small nursery, USD 60.77 for a medium one, and USD 170.16 for a large nursery. In contrast, the same treatment with a fertilizer dosage of 700 showed an average 9.75% adjustment in the K quantity, resulting in a saving of USD 0.0003 per gallon of water, and daily savings of USD 7.07 for a small nursery, USD 17.68 for a medium one, and USD 49.49 for a large nursery. Bok1400 resulted in a 13.71% average alteration in the K quantity, leading to a saving of USD 0.0007 per gallon of water, and daily savings of USD 19.90 for a small nursery, USD 49.75 for a medium-sized one, and USD 139.29 for a large nursery. The Bok700 treatment exhibited an average 3.47% increase in P quantity, which translated into an average saving of USD 0.0001 per gallon of water, equivalent to average daily savings of USD 2.52 for a small nursery, USD 6.29 for a medium one, and USD 17.62 for a large nursery.

3.4. Water Content and Water Irrigation Labor

The calculations for the water cost savings are shown in Supplementary Tables S32–S37, where a summary of the changes in the water usage percentages and daily cost savings for nurseries of small, medium, and large sizes is presented. Additionally, these tables include the average daily savings in irrigation labor for nurseries in each of these size categories, considering various treatments. In the three-week analysis against CK1400, Bok700 had a 4.86% higher water content than the control, resulting in daily water savings of USD 3.51, USD 8.66, and USD 24.60 for small, medium, and large nurseries, respectively. It also saved USD 29.30, USD 72.19, and USD 205.08 in water irrigation labor, leading to overall savings of USD 32.81, USD 80.85, and USD 229.68, accordingly for each size. Conversely, Bok1400 experienced a 3.58% reduction in water content, leading to daily water losses of USD 2.58, USD 6.37, and USD 18.09 and labor cost reductions of USD 21.55, USD 53.10, and USD 150.83, summing up to total losses of USD 24.13, USD 59.47, and USD 168.93 for small, medium, and large nurseries. BC700, compared to CK1400, increased the water content by 25.53%, saving USD 18.45, USD 45.47, and USD 129.16 daily in water costs and USD 153.83, USD 379, and USD 1076.79 in labor costs for small, medium, and large nurseries. These amounted to total savings of USD 172.28, USD 424.52, and USD 1205.95 for the three nursery sizes, respectively. BC1400, with a 28.64% water content increase, saved USD 20.70, USD 51.01, and USD 144.90 daily in water and USD 172.57, USD 425.24, and USD 1208 in labor for small, medium, and large nurseries, totaling USD 193.27, USD 476.25, and USD 1352.90 in savings. Additionally, Bok_BC700, with a 13.62% water content increase, achieved daily savings of USD 9.85, USD 24.26, and USD 68.92 in water and USD 82.08, USD 202.26, and USD 574.57 in labor for small, medium, and large nurseries, leading to total savings of USD 91.93, USD 226.52, and USD 643.49, respectively. However, Bok_BC1400, showing a 10.1% decrease in water content, resulted in water losses of USD 7.30, USD 17.98, and USD 51.07, but saved USD 60.82, USD 149.88, and USD 425.77 in labor, culminating in net losses of USD 68.12, USD 167.86, and USD 476.85 for small, medium, and large nurseries.

3.5. Germination and Seedling Growth Data

When analyzing changes in the germination rates relative to the control treatment (CK1400), the results, averaged across seven time points, reveal significant improvements. Bok700 led to a 66.99% enhancement in the germination rate, Bok1400 achieved a 65.03% increase, BC700 resulted in a 54.57% improvement, BC1400 saw a 60.78% boost, Bok_BC700 showed a 53.59% rise, and Bok_BC1400 recorded a 55.55% increase. Supplementary Table S38 summarizes these results.

When analyzing changes in the plant heights relative to the control treatment (CK1400), with the results averaged over several measurements, the data reveal significant improvements. Bok700 led to a 29.66% increase in plant height, Bok1400 achieved a 21.98% rise, BC700 resulted in a 20.69% improvement, and BC1400 saw a 32.10% boost. Additionally, Bok_BC700 showed a 6.62% increase, and Bok_BC1400 recorded a 16.36% increase. The results are summarized in Supplementary Table S39.

The data on changes in both the germination rates and plant heights, while providing clear insights into the biological improvements across different treatments, did not include data related to financial aspects. As a result, it was not possible to quantify the potential economic benefits of these improvements.

3.6. Carbon Sequestration

Table 3 presents the average percentage change in the C content relative to the control treatment with a fertilizer dosage of 1400 µS/cm (CK1400) across various treatments throughout the experiment at the points when the C data were recorded and the correspondent average revenue per ton for CO_2 sequestration in California at the three different nursery size levels (i.e., small, medium, and large).

Table 3. Percentage change in the C content and potential revenue per ton for CO_2 sequestration (in USD) for biochar and bokashi treatments at two different fertilizer dosages (700 µS/cm EC and 1400 µS/cm EC) compared to the control treatment (CK1400) at the 2023 C price of USD 29.84 per ton in California across various nursery sizes in California.

Treatment	**Percentage Change in C Content**	**Average Revenues/Ton**		
		Small	**Medium**	**Large**
Bok700	2.43%	USD 0.53	USD 1.32	USD 1.84
Bok1400	−1.13%	USD −0.46	USD −1.15	USD −1.61
BC700	31.45%	USD 8.58	USD 21.45	USD 30.03
BC1400	41.55%	USD 12.24	USD 30.60	USD 42.85
Bok_BC700	37.36%	USD 11.07	USD 27.67	USD 38.73
Bok_BC1400	37.45%	USD 10.71	USD 26.77	USD 37.48

Under Bok700, there is a 2.43% increase in the C content, corresponding to potential revenues of USD 0.53 per ton for small nurseries, USD 1.32 for medium-sized nurseries, and USD 1.84 for large nurseries. Bok1400 shows a decrease in the C content of −1.13%, resulting in negative revenues of USD −0.46, USD −1.15, and USD −1.61 per ton for small, medium, and large nurseries, respectively. BC700 exhibits a notable 31.45% increase in the C content, with potential revenues of USD 8.58, USD 21.450, and USD 30.03 per ton for small, medium, and large nurseries, respectively. Meanwhile, the BC1400 treatment demonstrates a substantial 41.55% increase in the C content, generating revenues of USD 12.24, USD 30.60, and USD 42.85 per ton for small, medium, and large nurseries, respectively. Both Bok_BC700 and Bok_BC1400 display significant increases in the C content at 37.36% and 37.45%, respectively; they yield revenues of USD 11.07 and USD 10.71 per ton for small nurseries, USD 27.67 and USD 26.77 for medium-sized nurseries, and USD 38.73 and USD 37.48 for large nurseries.

3.7. Total Benefits

Table 4 presents a comparison of daily savings in terms of the N, P, K, water content, and water irrigation labor costs, measured in 2023 USD, across different treatments in nurseries of varying sizes when compared to the CK1400 treatment. For a small nursery, the saving per day with the Bok700 treatment amounts to USD 54.20, whereas the Bok1400 treatment offers a saving of USD 82.77. The BC700 and BC1400 treatments provide greater savings of USD 195.19 and USD 271.09, respectively. The Bok_BC700 treatment provides a saving of USD 154.22, and Bok_BC1400 yields USD 93.01. In a medium-sized nursery, the Bok700 treatment saves USD 137.47 per day, and Bok1400 more than doubles this at USD 230.69. The BC700 treatment offers substantial savings of USD 482.37, and BC1400 further increases this to USD 679.03. The mixed treatments, Bok_BC700 and Bok_BC1400, save USD 393.04 and USD 260.85 per day, respectively. For a large nursery, the savings are even more pronounced. The Bok700 treatment results in daily savings of USD 363.07, and Bok1400 increases this to USD 459.90. The BC700 treatment leads to a significant saving of USD 1363.44 per day, and the BC1400 treatment tops this with a saving of USD 1854.72. The mixed treatments, Bok_BC700 and Bok_BC1400, contribute to savings of USD 1023.27 and USD 516.11 per day, respectively.

Table 4. Summary of total benefits in terms of nitrogen, phosphorus, potassium, water content, and water irrigation labor (in USD) for biochar and bokashi treatments at two different fertilizer dosages (700 µS/cm EC and 1400 µS/cm EC) compared to the control treatment (CK1400) across various nursery sizes in Southern California.

Treatment	Savings/Day Compared to the CK1400 Control		
	Small	**Medium**	**Large**
Bok700	USD 54.20	USD 137.47	USD 363.07
Bok1400	USD 82.77	USD 230.69	USD 459.90
BC700	USD 195.19	USD 482.37	USD 1363.44
BC1400	USD 271.09	USD 679.03	USD 1854.72
Bok_BC700	USD 154.22	USD 393.04	USD 1023.27
Bok_BC1400	USD 93.01	USD 260.85	USD 516.11

3.8. Difference in Net Benefits between Treatments and Control

Table 5 shows the net benefits of the different treatments in nurseries of different sizes relative to the CK1400 treatment, measured in USD per day. In a small nursery, the Bok700 treatment shows a saving of USD 69.07 per day, while the Bok1400 treatment increases to USD 99.04. The BC700 and BC1400 treatments offer higher savings of USD 192.98 and USD 271.70, respectively. The combined treatments, Bok_BC700 and Bok_BC1400, result in daily savings of USD 169.69 and USD 109.89. For medium-sized nurseries, the Bok700 treatment yields a daily saving of USD 203.72, and the Bok1400 treatment enhances this to USD 300.46. The BC700 treatment leads to savings of USD 505.91 per day, and the BC1400 treatment outperforms with savings of USD 709.63. The mixed treatments, Bok_BC700 and Bok_BC1400, contribute to savings of USD 461.49 and USD 332.83 per day, respectively. In large nurseries, the savings are even more significant. The Bok700 treatment achieves a daily saving of USD 415.80, and the Bok1400 treatment increases this to USD 517.56. The BC700 treatment shows a remarkable saving of USD 1356.38 per day, and the BC1400 treatment tops the list with a saving of USD 1857.53. The mixed treatments, Bok_BC700 and Bok_BC1400, also yield substantial savings of USD 1078.81 and USD 576.58, respectively.

Table 5. Summary of total average daily net benefits (in USD) for biochar and bokashi treatments at two different fertilizer dosages (700 µS/cm EC and 1400 µS/cm EC) compared to the control treatment (CK1400) across various nursery sizes in Southern California.

Treatment	Savings/Day Compared to the CK1400 Control		
	Small	**Medium**	**Large**
Bok700	USD 69.07	USD 203.72	USD 415.80
Bok1400	USD 99.04	USD 300.46	USD 517.56
BC700	USD 192.98	USD 505.91	USD 1356.38
BC1400	USD 271.70	USD 709.63	USD 1857.53
Bok_BC700	USD 169.69	USD 461.49	USD 1078.81
Bok_BC1400	USD 109.89	USD 332.83	USD 576.58

All results presented thus far are representative of a Southern Californian nursery. Notably, one of the primary differences between Southern and Northern California is the cost of water. Based on interviews conducted with nurseries in both regions, it has been determined that the price of water in Northern California is approximately USD 0.83 per 1000 gallons, whereas in Southern California, it is USD 2.59 for the same amount [36]. Consequently, the calculated average price of water for the state of California is USD 1.71 per 1000 gallons. Adjusting solely for this variable, the revised estimates of cumulative daily savings are detailed in Table 6 below.

Table 6. Summary of total average daily net benefits (in USD) for biochar and bokashi treatments at two different fertilizer dosages (700 µS/cm EC and 1400 µS/cm EC) compared to the control treatment (CK1400) across various nursery sizes in California.

Treatment	Savings/Day Compared to the CK1400 Treatment		
	Small	**Medium**	**Large**
Bok700	USD 67.87	USD 200.78	USD 407.44
Bok1400	USD 99.92	USD 302.63	USD 523.71
BC700	USD 186.71	USD 490.47	USD 1312.50
BC1400	USD 264.66	USD 692.30	USD 1808.30
Bok_BC700	USD 166.34	USD 453.25	USD 1055.39
Bok_BC1400	USD 112.37	USD 338.94	USD 593.93

4. Discussion

Despite their undeniable contribution to global food production increases, synthetic fertilizers pose substantial environmental risks, including leaching, greenhouse gas emissions, and the depletion of postrenewable resources. The discussion of this research sheds light on the economic and environmental viability of utilizing Bok and BC as sustainable soil amendments in citrus nursery production, juxtaposed with traditional soil mixes and synthetic fertilizers. The cost–benefit analysis, while drawing on a review of the existing literature, a survey of nurseries, and primary experimental data, underscores the potential for these organic amendments to significantly alter nutrient management practices within greenhouse agriculture. The observed increases in essential nutrients—nitrogen (N), phosphorus (P), and potassium (K)—through the application of Bok, BC, and their combined use not only bolster soil quality and plant health but also translate into marked cost savings. These savings are particularly crucial against the backdrop of the escalating need to transition away from synthetic fertilizers.

This study reveals that Bok and BC amendments significantly enhance the levels of key nutrients—N, P, and K—in greenhouse soils, yielding considerable cost savings and underscoring their potential as sustainable alternatives to synthetic fertilizers. For example, applying BC at a 1400 fertilizer dosage markedly increased N by 27%, P by 34%, and K by 16%, resulting in daily savings of up to USD 32.85, USD 7.74, and USD 18.84 per acre (See Supplementary Table S16 for comparison of nursery sizes in terms of acreage), respectively. The combination Bok_BC was particularly effective, with a 1400 dosage boosting N by 64%, P by 106%, and showing significant effects on K relative to the control, leading to daily savings of USD 77.47, USD 30.41, and USD 19.17 per acre, respectively. The increases in the N, P, and K levels demonstrate the efficacy of BC amendments in optimizing nutrient management and suggest a synergistic effect that could significantly contribute to sustainable agricultural practices.

This study also explores the impacts of Bok and BC treatments on carbon (C) sequestration and water content management in greenhouse conditions, providing valuable insights into sustainable agricultural practices. The findings demonstrate that the Bok and BC treatments significantly enhanced C retention in the soil, with a notable 41% increase in the C content for the BC1400 treatment, suggesting a potential for reducing atmospheric C release. The price of C sequestration was reported at USD 29.84 per ton [40]. However, because of the unknown timeframe for C storage, integrating this potential revenue into the cost–benefit analysis alongside the daily savings from the water content and N, P, and K benefits is challenging. These savings were calculated on a per day basis, and without a precise estimate of daily C sequestration, the corresponding potential revenue cannot be determined. Additionally, stringent procedures are involved in C storage, which may incur costs exceeding the potential benefits. Consequently, the ultimate results of the cost–benefit analysis do not account for the potential revenue from C sequestration. Similarly to C, the water content management results indicate that BC treatments can significantly improve water efficiency, leading to substantial cost savings in water expenses and irrigation labor. For instance, the BC1400 treatment consistently outperformed the control treatments in increasing water content, resulting in an average daily saving of USD 21.99 per acre in water and irrigation labor costs (See Supplementary Table S16 for a comparison of the nursery sizes in terms of acreage).

The analysis of the daily savings across various treatments in nurseries of different sizes, when compared to the CK1400 control, reveals significant financial benefits from Bok and BC amendments. The data demonstrate that small to large nurseries can achieve considerable cost savings on nutrients (N, P, and K), water content, and water irrigation labor by implementing these sustainable soil amendments. The comparison between the total benefits and costs further underscores the economic efficiency of the BC treatments, with BC700 and BC1400 showing the most substantial savings across all nursery sizes. This economic efficiency not only highlights the direct financial benefits of adopting BC amendments but also suggests a broader implication for sustainable agricultural practices by reducing operational costs and enhancing environmental sustainability.

We did not account for electricity costs in our evaluation of the treatments. However, factoring in these costs would reinforce our findings, as faster growth rates in plants, as we observed, imply a shorter duration for each plant's growth cycle. Consequently, this would lead to a decrease in electricity usage, thus lowering the associated costs. This connection between accelerated growth rates and reduced electricity costs could result in substantial cost savings.

Our findings align with the growing body of research emphasizing the importance of organic amendments in enhancing soil health and sustainability in agriculture [41–44]. Our study contributes to existing knowledge by demonstrating substantial nutrient management improvements and cost efficiencies not previously reported with such magnitudes in citrus nursery settings. While some studies report modest improvements in nutrient levels with organic amendments [45], our results show significant enhancements, especially in the nitrogen content, which suggests a potentiated effect of combining Bok with BC. The ability of BC treatments and organic amendments, such as Bok byproducts, supports more sustainable agricultural practices by enhancing carbon sequestration and water efficiency [46,47]. In addition, BC-compost is also effective in improving soil conditions, mitigating nutrient deficiencies, promoting sustainable soil management, enhancing soil health, and increasing crop productivity by improving nutrient availability and reducing contaminants [48,49].

In evaluating the economic viability of Bok and BC as organic fertilizers, it is essential to consider a range of factors beyond their agronomic benefits. The timing and conditions of storage, transportation costs, application methods, and labor expenses play crucial roles in determining their overall feasibility in agricultural settings [50,51]. While our study has primarily focused on demonstrating the agronomic advantages within controlled greenhouse nursery environments, where variables such as application methods, crop prices, substrate types, climate conditions, and irrigation practices are standardized, we recognize the significance of these logistical factors in broader agricultural applications. To address these considerations, future research efforts should incorporate comprehensive cost analyses that encompass these logistical challenges.

Moreover, organic fertilizers like Bok and BC are particularly cost-effective in intensive farming systems, such as greenhouse cultivation, hydroponics, aquaponics, and irrigated agriculture. These controlled environments optimize the application and benefits of organic amendments, reducing input costs and supporting sustainable soil management. In contrast, open farming without irrigation faces challenges such as fluctuating environmental conditions and higher operational costs, which can limit the economic benefits of these fertilizers [20,52]. Therefore, while Bok and BC can improve soil fertility and reduce pollution in these settings, their application must be carefully managed [16,21]. Our study emphasizes the strategic use of organic fertilizers in settings where they provide the most economic and environmental benefits, highlighting the importance of tailored management practices based on farming system characteristics. By focusing on intensive farming systems with optimized irrigation practices, organic fertilizers not only reduce input costs but also support sustainable soil management and environmental conservation.

Furthermore, it is essential that long-term studies over multiple growing seasons are conducted to thoroughly understand the sustained impact of Bok and BC on soil health and crop yields. Such studies should focus on evaluating the long-term benefits of these amendments on soil structure, microbial activity, nutrient availability, and crop productivity. This will provide deeper insight into the lasting advantages and potential limitations of these soil amendments and on how these amendments contribute to carbon sequestration and other environmental benefits over time.

Additionally, investigating how different waste sources used in producing Bok influence nutrient release and carbon sequestration capabilities is also crucial, offering insights into optimizing Bok production and identifying the most beneficial raw materials to enhance its positive effects. While the research outlines opportunities for enhancing the application of these organic amendments, it also sheds light on the importance of broadening our understanding across diverse agricultural settings. The study's insights into greenhouse environments pave the way for future investigations in varied agricultural contexts (indoor and field studies), ensuring the applicability and generalizability of our findings. However, the variability in outcomes, especially concerning the carbon sequestration and nutrient release capabilities of Bok from specific waste types like citrus waste with suboptimal C/N ratios underscores the complexity of these amendments' effectiveness and the need to test different raw materials. Indeed, Bok byproduct can be produced from a variety of organic substrates, including but not limited to wheat, oats, and other crop residues and brewery, juice processing facility, and preconsumer grocery wastes [20]. Although the specific microflora formed during the Bok process depends significantly on the microorganisms present in the Bok inoculum (primary microorganisms include Lactobacillus species, Saccharomyces cerevisiae, Rhodopseudomonas palustris, and Actinomycetes) that collectively contribute to the effective anaerobic fermentation of organic materials, each of these substrates supports the cultivation of distinct microbial taxonomic groups that characterize the Bok byproducts [28]. These variations can lead to differences in nutrient release rates and the ability of the Bok to enhance soil fertility and structure [21]. Additionally, the presence of particular microbes with specific ecological functions can influence the carbon sequestration capabilities of Bok, further affecting its long-term benefits for soil health and its economic viability [31]. Therefore, to ensure the broadest benefits and to cater to varying agricultural needs, it is crucial to explore the impact of these microbial communities in detail. This means conducting controlled experiments to compare the effects of Bok produced from different raw materials. Such research should aim to determine optimal compositions and taxonomic microbial profiles that maximize nutrient availability, improve soil health, and increase crop yields, thereby enhancing the economic returns from Bok application. Understanding these dynamics will enable farmers and agricultural producers to make more informed decisions about which type of Bok is best suited for their specific soil types and crop requirements. This tailored approach to Bok production not only informs farmers about the optimal use of locally available safe waste materials but also supports the broader adoption of this practice. By elucidating the specific impacts of various waste byproduct materials and their optimal dosages (% v/v), we can underscore the importance of customizing organic amendments based on available resources, thereby maximizing their environmental and economic advantages. On the other hand, BC derived from a single type of waste, such as almond waste, offers a more uniform byproduct, potentially simplifying its use in downstream applications. This uniformity can make it easier for farmers to predict and rely on the amendment's effects on soil health and crop growth.

In addition, assessing the carbon footprint and promoting decarbonization in agricultural production are critical considerations for advancing the adoption of organic fertilizers such as Bok and BC. These fertilizers offer the potential to sequester carbon during production and application, contributing to carbon accumulation in soils over time [19,31]. The concept of establishing a "carbon fund" through prolonged carbon storage in granular dry fertilizers further underscores their environmental benefits. While our study has highlighted the immediate agronomic advantages of Bok and BC in greenhouse nursery environments, the long-term implications of carbon sequestration deserve more detailed examination. Future research should comprehensively assess the carbon footprint of organic fertilizers throughout their lifecycle, integrating carbon sequestration metrics into economic analyses to better evaluate their sustainability and promote global adoption. Another important area for exploration is the integration of potential revenue from carbon credits into cost–benefit analyses. Although our study highlights the difficulties in estimating the duration of carbon storage, future research should address these issues and develop methods to accurately quantify the economic gains from carbon credits.

This study emphasizes the importance of tailored approaches in applying these amendments, considering the unique conditions and requirements of each nursery operation. Future research directions should focus on optimizing the application of Bok and BC to enhance both environmental sustainability and economic efficiency by exploring their long-term effects and potential scalability across various agricultural systems and climates. Scaling the use of organic fertilizers presents challenges that must be addressed, including standardization issues, variability in storage conditions and durations, application methods, and the calculation of profitability considering crop types, growing substrates, climate variations, and irrigation practices. Successful implementation in closed production cycles may not always translate to specialized enterprises purchasing organic fertilizers from the market, where profitability can vary significantly. Moreover, forecasting should account for the increased costs associated with water resources, irrigation, and potential restrictions on electricity use amidst global climate change and diminishing arable land. These factors underscore the importance of comprehensive studies that evaluate the broader economic and environmental impacts of organic fertilizers. By addressing these complexities, future research can provide valuable insights into optimizing the scalability and sustainability of bokashi and biochar applications in diverse agricultural contexts.

5. Conclusions

This study highlights the significant role of Bok and BC amendments in promoting sustainable soil management within citrus nursery production, highlighting their environmental and economic benefits. By showcasing potential cost savings and improved nutrient management, water retention, plant growth, and carbon sequestration, Bok and BC amendments emerge as viable substitutes for synthetic fertilizers, aligning with the shift toward environmentally responsible farming practices. While the findings are promising, they pave the way for future research to refine Bok and BC application methods and investigate their impacts across various conditions. This work supports the broader adoption of sustainable agricultural practices, suggesting that integrating Bok and BC amendments can enhance both the environmental and economic aspects of greenhouse agriculture. The continued exploration of these amendments' potential is essential for advancing sustainable farming, ensuring it meets global sustainability and productivity goals.

Supplementary Materials: The following supporting information can be downloaded at, https://www.mdpi.com/article/10.3390/su16146070/s1, Survey S1, Open- and closed-ended questions presented to California nurseries utilizing online surveys and direct in-person interviews; Table S1, Fertilizer Peters Excel 21-5-20, nitrogen (N) costs (in USD) per gallon at different dosages; Table S2, Fertilizer Peters Excel 21-5-20, phosphorous (P) costs (in USD) per gallon at different dosages; Table S3, Fertilizer Peters Excel 21-5-20, potassium (K) costs (in USD) per gallon at different dosages; Table S4, Cost calculation (in USD) summary for Peters Excel fertilizer per cone; Table S5, Annual fertilizer cost calculations (in USD) for a small nursery; Table S6, Annual fertilizer cost calculations (in USD) for a medium nursery; Table S7, Annual fertilizer cost calculations (in USD) for a large nursery; Table S8, Water content average percentage variations for various treatments over different weeks; Table S9, Average cost savings (in USD) per 1000 gallons of water for various treatments over different weeks; Table S10, Average daily cost savings (in USD) in water per one-acre greenhouse for various treatments over different weeks; Table S11, Average daily irrigation labor hours savings per one-acre greenhouse for various treatments over different weeks; Table S12, Average daily irrigation labor cost savings (in USD) per one-acre greenhouse for various treatments over different weeks; Table S13, Average daily water and irrigation labor cost savings (in USD) per one-acre greenhouse for various treatments over different weeks; Table S14, Calculations of plant density, cones, and daily water usage in small, medium, and large nurseries; Table S15, Annual water cost (in USD) calculations for small, medium, and large nurseries; Table S16, Nursery sizes and yearly labor hours per acre; Table S17, Costs (in USD) for a small nursery using the control treatment; Table S18, Costs (in USD) for a medium nursery using the control treatment; Table S19, Costs (in USD) for a large nursery using the control treatment; Table S20, Costs (in USD) for a small nursery using the bokashi treatment; Table S21, Costs (in USD) for a medium nursery using the bokashi treatment; Table S22, Costs (in USD) for a large nursery using the bokashi treatment; Table S23, Costs (in USD) for a small nursery using the biochar treatment; Table S24, Costs (in USD) for a medium nursery using the biochar treatment; Table S25, Costs (in USD) for a large nursery using the biochar treatment; Table S26, Costs (in USD) for a small nursery using the bokashi and biochar treatments; Table S27, Costs (in USD) for a medium nursery using the bokashi and biochar treatments; Table S28, Costs (in USD) for a large nursery using the bokashi and biochar treatments; Table S29, Daily nitrogen (N) savings (in USD) across various nursery sizes for each treatment compared to the CK1400 treatment; Table S30, Daily phosphorous (P) savings (in USD) across various nursery sizes for each treatment compared to the CK1400 treatment; Table S31, Daily potassium (K) savings (in USD) across various nursery sizes for each treatment compared to the CK1400 treatment; Table S32, Average percentage change in water content and daily savings derived from water (in USD) for a small nursery for each treatment compared to the CK1400 treatment; Table S33, Average daily savings derived from water content (in USD) for a medium nursery for each treatment compared to the CK1400 treatment; Table S34, Average daily savings derived from water content (in USD) for a large nursery for each treatment compared to the CK1400 treatment; Table S35, Average daily savings derived from water irrigation labor (in USD) for a small nursery for each treatment compared to the CK1400 Treatment; Table S36, Average daily savings derived from water irrigation labor (in USD) for a medium nursery for each treatment compared to the CK1400 treatment; Table S37, Average daily savings derived from water irrigation labor (in USD) for a large nursery for each treatment compared to the CK1400 treatment; Table S38, Average germination rate and percentage change for each treatment compared to the CK1400 treatment; Table S39, Average plant heights (in cm) and percentage change for each treatment compared to the CK1400 treatment. Reference [53] is cited in the supplementary materials.

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