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Article

Enhanced soil fertility through seaweed-derived biochar: Comparative analysis of commercial fertilizers

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SUMMARY

Decomposing seaweed waste in coastal regions releases toxic hydrogen sulfide gas, which poses environmental and health hazards. Researchers have demonstrated that biochar—a carbon-rich, porous material created through pyrolysis of organic biomass—serves as a sustainable soil amendment. In this study, we investigated seaweed-derived biochar as a dual-purpose solution for coastal waste management and soil enhancement. We transformed Gracilaria seaweed waste into biochar via pyrolysis and applied it to soil supporting spider plants (Chlorophytum comosum), with plant height, nutrient content, and water retention monitored over time. We compared two groups: spider plants grown with seaweed-derived biochar and a control group treated with commercially available fertilizer, both maintained under identical water, sunlight, and environmental conditions. The biochar-treated group consistently outperformed the control group across multiple parameters, exhibiting higher nutrient levels and visibly healthier plant development. The biochar-amended soil retained moisture significantly longer than the control soil, demonstrating markedly improved water retention capacity. Additionally, the greener leaf color in the biochar-treated plants indicated healthier development. These findings suggest that seaweed-derived biochar could serve as a foundation for future research into sustainable agriculture, particularly in regions facing soil degradation, limited fertilizer access, or water scarcity. Further studies may help translate this approach into scalable, low-cost solutions that support both crop productivity and carbon sequestration.

INTRODUCTION

The decomposition of seaweed waste along coastal regions creates significant environmental and public health concerns. Seaweed decomposition releases hydrogen sulfide (H_2S), a toxic gas that poses severe health risks (1). Direct exposure to hydrogen sulfide causes immediate respiratory distress, skin irritation, and persistent headaches (1). When hydrogen sulfide concentrations exceed 5 parts per million (ppm), as often occurs beneath accumulated seaweed piles, they can cause severe neurological and cardiovascular complications (1).

Coastal communities also face significant economic impacts. Tourism-dependent regions lose visitors and suffer reduced quality of life as the sulfurous odor permeates residential and recreational areas (2). This situation simultaneously threatens public health and local economies (1,2).

Researchers have developed an innovative solution to these challenges by converting seaweed waste into biochar. Producers create biochar, a carbon-rich, porous substance, by heating organic biomass such as plant material or seaweed in a low-oxygen environment through a process called pyrolysis (3). Researchers have explored seaweed-derived biochar for a variety of environmental applications, including wastewater treatment, heavy metal adsorption, and soil remediation. Among these, its use as a carbon-rich soil amendment is particularly promising, as it enhances soil fertility and water retention capacity while contributing to long-term carbon sequestration (3, 4, 5). Seaweed biochar improves acidic soils by increasing soil pH and enhancing macronutrient availability (4). Biochar produced from various seaweed species reduces heavy metal contamination and improves soil microbial activity, demonstrating strong potential for soil remediation (5). Seaweed derived biochar offers unique advantages compared to traditional biochar sources. Essential plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K) play key roles in vegetative growth, root development, and flowering. Calcium (Ca) and magnesium (Mg) are also critical for cell wall structure and photosynthesis. By increasing the availability of these macronutrients, soil enrichment directly improves plant health and productivity. In this study, we observed that seaweed-derived biochar contained higher nitrogen, phosphorus, potassium, calcium, and magnesium than the commercial fertilizer used. Although seaweed biochar contains less carbon, it provides higher concentrations of essential nutrients and exchangeable cations, especially potassium (9). Its pH range of 7–11 makes it suitable for diverse soil types. Additionally, its application in co-composting organic waste materials has demonstrated improvements in humification, the process by which organic matter is broken down into stable humus, along with better nitrogen retention and organic matter degradation (10). This combination of high nutrient content and beneficial physical properties makes seaweed biochar particularly valuable for improving degraded soils and enhancing agricultural productivity (11).

Previous research demonstrates that biochar application significantly improves soil properties through multiple mechanisms. Biochar application reduces soil bulk density by 5.8–9.6%, enhancing porosity and improving water retention by 22% (6). These structural improvements facilitate better movement of gases, water, and nutrients within the soil matrix. The porous structure of biochar creates an extensive

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surface area that functions as a reservoir for both water and nutrients (7). Studies show that biochar derived from brown algae enhances soil fertility by increasing cation exchange capacity and supporting beneficial microbial communities (8). This technology holds global implications, particularly for developing regions facing agricultural challenges. Unlike chemical fertilizers—which manufacturers often synthesize from non-renewable resources such as fossil fuels and mined minerals—seaweed biochar is produced from organic marine biomass through pyrolysis, making it an eco-friendly and potentially cost-effective alternative in areas with poor soil conditions, drought, and low crop yields (12). Biochar sequesters carbon and contributes to climate change mitigation efforts. Estimates indicate that sustainable biochar production can sequester up to 1.8 peta-grams (1.8 billion metric tons) of carbon dioxide equivalent (CO_2-Ce) per year when applied globally using available biomass (3). This highlights biochar's promising role in climate change mitigation when scaled appropriately. Integrating seaweed-derived biochar into a circular biorefinery model enhances sustainability by converting organic coastal waste into valuable agricultural products, minimizing waste, and maximizing resource efficiency. In this model, seaweed is not discarded but instead repurposed through processes like pyrolysis to create soil amendments—closing the loop between waste generation and productive reuse (13).

Despite these promising attributes, optimizing seaweed biochar production and application presents ongoing challenges. The effectiveness of nutrient enhancement and water retention varies depending on biochar type and soil conditions. While the high sodium content in seaweed biochar could potentially increase soil salinity, studies show that pre-treatment methods such as freshwater rinsing can mitigate this effect through pre-treatment methods such as freshwater rinsing of the biomass before pyrolysis. Proper management allows the positive impacts on soil fertility and crop productivity to outweigh these salinity concerns (5, 9). Additionally, pre-treatment methods such as washing and activation can further refine biochar properties, making it more effective in soil enhancement and water treatment applications (9).

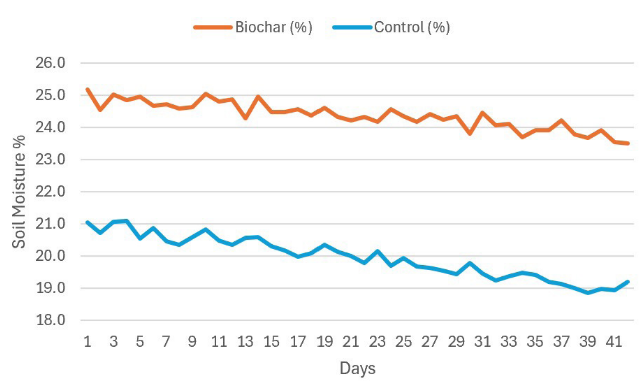

Figure 1: Soil moisture dynamics in experimental and control groups. This line graph displays the percentage soil moisture we measured daily in both the biochar treatment group (orange line) and the commercial fertilizer control group (blue line). The biochar-amended soil consistently maintained 22% higher average moisture levels (mean 24.4% with standard deviation 0.4%; range 23.5%–25.2%) throughout the experiment compared to the control group (mean 20.0% with standard deviation 0.6%; range 18.8%–21.1%). This sustained difference highlights the enhanced water-holding capacity of biochar-amended soil, likely due to improved soil structure and porosity, supporting its potential for drought resilience in agricultural applications.

We investigate seaweed-derived biochar as a dual-purpose solution for coastal waste management and soil enhancement. We compare seaweed-derived biochar with commercial fertilizers across multiple parameters, including plant growth, nutrient composition, and water retention, to demonstrate the viability of this sustainable approach to agricultural improvement and environmental protection.
Based on this objective, we hypothesized that soil amended with seaweed-derived biochar would exhibit superior soil fertility, nutrient retention, water retention, and plant growth compared to soil treated with Pure Gold Organic Natural All Purpose Plant Food, a commercially available fertilizer.

Our results supported this hypothesis: plants grown in biochar-treated soil demonstrated enhanced growth, improved water retention, and significantly higher macronutrient levels than those in the commercial fertilizer group. These findings highlight the potential of seaweed-derived biochar as a sustainable, low-cost alternative to synthetic fertilizers, especially in regions facing environmental or agricultural challenges.

We hypothesize that amending soil with seaweed-derived biochar increases soil fertility, greater nutrient retention, higher water-holding capacity, and improved plant growth compared to soil treated with commercial fertilizer. Specifically, we expected the biochar-treated group to exhibit higher concentrations of key macronutrients (nitrogen, phosphorus, potassium, calcium, and magnesium), greater soil moisture retention over time, and increased plant height over the 42-day study period. We base this prediction on biochar's porous structure, which enhances water and nutrient retention, and on prior research indicating that marine algae–derived biochar improves nutrient availability and supports beneficial soil microbial communities (5, 8).

RESULTS

We designed this study to evaluate whether seaweed-derived biochar could improve soil fertility, water retention, and plant growth compared to commercially available fertilizer. We tested this by conducting a controlled 42-day experiment using spider plants (*Chlorophytum comosum*) grown in two soil conditions: one amended with seaweed-derived biochar and the other treated with a commercial organic fertilizer. We monitored plant growth, soil moisture, and nutrient composition to compare performance between the two treatments.

We used calibrated moisture sensors to measure water retention for both the biochar-amended and control soil pots. We measured moisture levels daily over the 42-day period. The seaweed biochar-amended soil maintained significantly higher moisture levels throughout the study period (mean 24.4% with standard deviation 0.4%) compared to the control group (mean 20.0% with standard deviation 0.6%), representing a 22% improvement in water retention (p = 0.01, independent t-test). The biochar treatment exhibited consistently higher water retention across all measurement days, with moisture values ranging from 23.5% to 25.2% in the biochar group compared to 18.8% to 21.1% in the control

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group **(Figure 1)**. We produced seaweed-derived biochar through a multi-step process, starting with the collection and drying of *Gracilaria* seaweed, followed by loading the seaweed into a pyrolysis reactor for high-temperature heating. We cooled the resulting char, crushed it into fine particles, and sieved it to ensure uniformity. This controlled pyrolysis process produced a carbon-rich biochar with high surface area, which we subsequently applied to the experimental soil to test its effects on fertility and water-holding capacity. We sieved all resulting biochar to a particle size of less than 2 mm for consistency across all experimental samples. We chose this fine particle size based on prior literature indicating that smaller biochar particles improve soil integration and retention properties due to increased surface area, though we did not directly compare different particle sizes in this study (6, 7). (**Figures 2 and 3**).

Our soil analysis revealed significantly higher nutrient concentrations in the seaweed biochar-amended soil compared to the control soil treated with commercial fertilizer. Specifically, the biochar-amended soil exhibited a 62% increase in nitrogen, a 49% increase in phosphorus, and a 25% increase in potassium compared to the commercial fertilizer–amended soil. Calcium and magnesium levels increased even more—by 99% and 73%, respectively (**Figure 4**). The biochar-amended soil showed higher nutrient concentrations compared to the control soil.

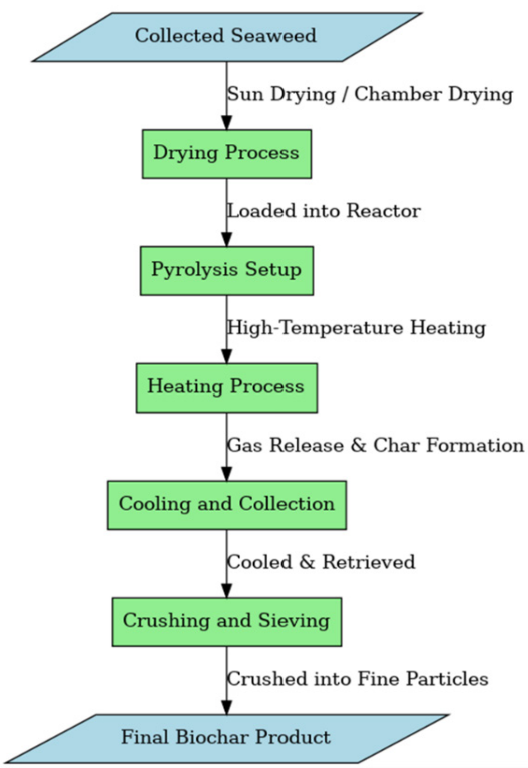

Figure 2: Seaweed biochar production process. Flowchart outlining the preparation of seaweed-derived biochar used in this study. We collected, rinsed, and air-dried Gracilaria seaweed for 48 hours, then pyrolyzed at 450 °C for 2 hours under limited oxygen. We cooled and crushed the resulting char to a fine particle size using a mortar and pestle. We used only fine-particle biochar; no uncrushed or variable sizes were tested.

Figure 3. Final stages of seaweed biochar production. (A) Filtering seaweed-derived biochar particles using a fine-mesh sieve to ensure particle size uniformity. (B) The resulting fine biochar, used for soil amendment in this study. Although not directly compared to larger particle sizes, We did not test uncrushed or variable particle sizes in this study. Instead, we sieved all biochar to <2 mm for consistency. We based our choice of fine particle size on prior findings that smaller particles improve soil integration and retention, though we did not directly compare this in our experiment.

We calculated descriptive statistics to summarize the nutrient concentrations, soil pH, and plant growth across treatment groups. On average, biochar-treated soil exhibited higher concentrations of nitrogen, phosphorus, potassium, calcium, and magnesium compared to the control soil, as summarized in Table 1. Nutrient increases ranged from 25% to 99%, with calcium and magnesium showing the greatest improvements. Plant growth was also greater in the biochar group, with a mean final height of 3.22 cm versus 2.85 cm in the control. Soil pH remained more stable in the biochar-treated soil (range = 6.0–6.1) compared to the control (range = 5.8–6.2).

The biochar-amended soil demonstrated lower bulk density compared to the control, with a reduction of approximately 5.8% to 9.6% ($p < 0.01$, independent t-test), as shown in (**Figure 5 A**). This reduction is associated with increased porosity and improved water infiltration capacity. Although we did not record quantitative measurements of soil aggregation, visual inspection suggested better soil structure in the biochar group (**Figure 5 B**).

Plants in the biochar-treated group consistently exhibited healthier appearance, darker green coloration and fewer visible signs of nutrient deficiency (e.g., chlorosis or wilting) compared to the control group. Multiple observers consistently confirmed our qualitative assessments. Our quantitative measurements confirmed that by Day 42, biochar-treated plants had a significantly greater mean height (3.22 ± 0.13 cm) than the control group (2.85 ± 0.16 cm; $p < 0.01$, Student's t-test. Plant height varied less in the biochar group (SD 0.13 cm vs. 0.16 cm), indicating more uniform growth conditions (**Figure 6**).

We performed unpaired t-tests to assess the significance of observed trends by comparing water retention, soil pH, and plant height between the biochar-treated and control groups. The tests yielded p-values of 0.01 (water retention), 0.042 (soil pH), and 0.005 (plant height). These results suggest potential differences between treatments, but the small sample size (n=5 per group) limits strong interpretation. We emphasize descriptive comparisons to highlight consistent trends without overinterpreting the statistical findings.

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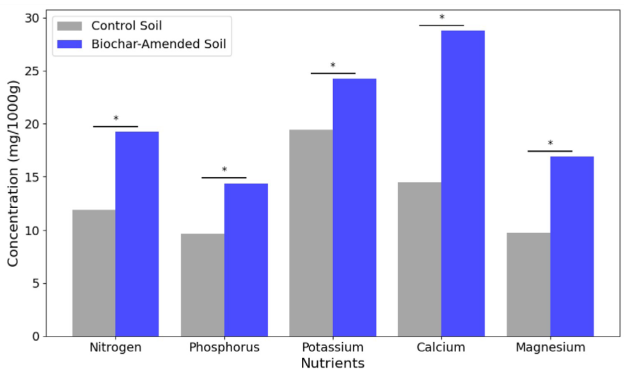

Figure 4: Nutrient composition comparison between biochar-amended and control soil. The concentrations of key nutrients—Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), and Magnesium (Mg)—are shown for soil treated with biochar (blue bars) and a control soil treated with commercial fertilizer (gray bars). Biochar amendment resulted in significantly higher nutrient levels across all measured parameters. Notably, Calcium concentration increased by [insert absolute value and units], a 99% increase over the control, while Magnesium increased by [insert absolute value and units] (73% increase), and Nitrogen increased by [insert absolute value and units] (62% increase). The asterisk (*) indicates a statistically significant difference ($p < 0.05$), as determined by independent t-tests.

We used an exploratory one-way ANOVA to compare macronutrient concentrations between the biochar and control groups. The analysis yielded a high F-statistic ($F = 391.90$), indicating substantial variation between treatments across all five nutrients measured: nitrogen, phosphorus, potassium, calcium, and magnesium. These statistical findings reinforce the observed percent increases—such as 26.7% higher nitrogen and 39.4% higher potassium—in biochar-treated soils. While the small sample size limits the strength of inferential conclusions, the consistency of these trends suggests a potential enhancement of soil nutrient composition by seaweed-derived biochar.

By the end of the 42-day growth period, plants in the biochar-treated group reached an average final height of 3.22 cm, approximately 13% taller than those in the control group (2.85 cm), indicating enhanced growth under biochar amendment. Biochar-treated plants consistently showed darker green leaves, a visual indicator often correlated with increased chlorophyll levels and overall plant vitality. These findings suggest that the improved growth may result from the combined effects of greater nutrient availability, superior water retention, and a more supportive rhizosphere environment (**Figure 6**).

Although the limited sample size restricts the statistical power of this study, the consistent trends observed across replicates—combined with preliminary statistical analyses—strongly support the conclusion that seaweed-derived biochar positively influences soil nutrient composition. These findings align with visual observations and percent improvements in key macronutrients, reinforcing the potential of biochar as an effective soil amendment. Future studies with expanded replicates are needed to confirm these results and strengthen inferential conclusions.

DISCUSSION

We demonstrated that seaweed-derived biochar improved soil fertility and plant growth compared to commercial fertilizer. We find increased water retention, enhanced nutrient availability (particularly nitrogen, phosphorus, potassium, calcium, and magnesium), and slightly more stable soil pH. Plants grown in biochar-treated soil also exhibited greater height and darker green coloration over the 42-day observation period.

These results support the hypothesis that seaweed-derived biochar can serve as an effective soil amendment. This approach provides a sustainable way to repurpose coastal seaweed waste, contributing to both environmental management and regenerative farming practices.

We observed a 16% greater plant growth rate the biochar-treated group suggests that seaweed-derived biochar fosters

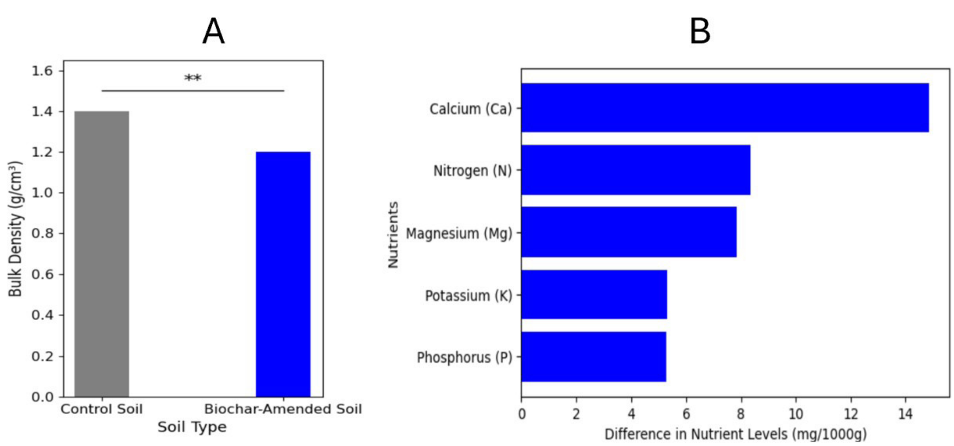

Figure 5: Soil structure and nutrient improvement in biochar-amended soil. This figure presents two comparative analyses: (A) a bar chart showing a statistically significant reduction in soil bulk density in the biochar-amended soil (blue) compared to the control (gray), with $p < 0.01$; and (B) a horizontal bar chart showing increases in nutrient concentrations (mg/1000 g) for Calcium (Ca), Nitrogen (N), Magnesium (Mg), Phosphorus (P), and Potassium (K) in the biochar-treated group relative to the control. All values are displayed as absolute concentrations, and color coding reflects treatment group (blue = biochar-amended, gray = control). We assessed statistical significance using independent t-tests, and we mark nutrients with ** to indicate $p < 0.01$.

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a more favorable soil environment for plant development than commercial fertilizer. Biochar's high cation exchange capacity and porous structure likely cause this advantage by improving nutrient availability and water retention—critical factors for plant health and root development (10, 13). Biochar not only supplies nutrients but also enhances the soil's ability to retain them, enabling more efficient uptake over time. This mechanism, in conjunction with improved soil structure and microbial activity, may underlie the superior plant performance observed.

Biochar stabilizes soil pH, which has important implications for long-term soil health and nutrient availability. At the start of the experiment, the biochar-treated soil had a slightly higher pH (~6.7) compared to the control (~6.5). Over the 42-day period, the control group's pH declined more noticeably, reaching approximately 6.0, while the biochar-amended soil maintained a relatively stable pH, declining only to ~6.1. This smaller change suggests that biochar possesses a mild buffering capacity that resists acidification trends commonly observed in cultivated soils. Although the absolute pH difference between groups at day 42 was modest (0.1 unit), the steadier pH trajectory in the biochar group suggests greater chemical stability over time. These patterns may be better appreciated visually, and a line graph showing pH over time for both treatments has been added to highlight the stabilization effect.

Several mechanisms likely contributed to the enhanced performance observed in the biochar-treated soil. The high porosity and surface area of seaweed-derived biochar create favorable microhabitats for beneficial microbial communities, which in turn promote nutrient cycling and root–microbe symbiosis (6, 7). In addition, biochar's porous matrix improves air circulation and water infiltration within the soil profile, supporting healthier root development and enhancing oxygen availability for aerobic microbial activity. The reduction in bulk density also facilitates deeper root penetration and more efficient moisture and nutrient transport. These structural improvements likely contributed to the superior plant growth and higher nutrient concentrations observed. Furthermore, the enhanced water retention capacity in biochar-amended soils suggests greater drought resilience, a trait especially beneficial in arid and semi-arid agricultural zones (7, 11).

While prior studies using biochar derived from sources such as wood or crop residues have also shown improvements in soil structure and moisture retention, our findings indicate that seaweed-derived biochar may offer comparable—if not superior—benefits due to its inherently higher mineral content and potential to buffer pH. Future studies directly comparing seaweed-derived biochar to other biochar sources under controlled conditions would be valuable in isolating these differences.

While we find the results promising, we must consider some limitations. Using spider plants (*Chlorophytum comosum*), while practical for this study, may not fully represent the response of agricultural crops. Additionally, the 42-day observation period, though informative, may not capture long-term effects or seasonal variations. Future research should focus on extending the study duration and testing with various agricultural crops to validate these findings across different plant species.

This study has one limitation: we used the LaMotte Garden Soil Test Kit, which is designed for educational use and provides semi-quantitative estimates rather than precise laboratory-grade measurements. The kit sufficiently detects relative differences in macronutrient levels between groups, but it limits the resolution of nutrient concentration data.

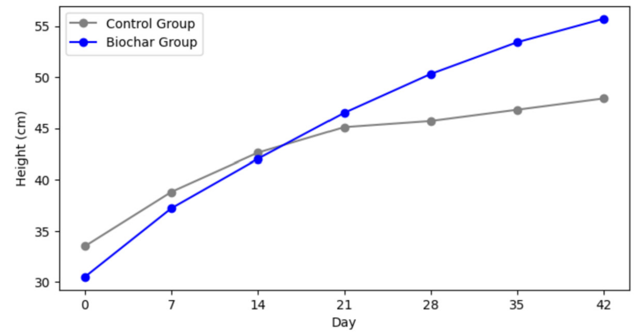

Figure 6: Plant growth over time in biochar-amended versus control soil. This line graph shows plant height (measured in centimeters) over a 42-day period in biochar-amended soil (blue) compared to control soil (gray). Plants grown in the biochar-treated soil exhibited a 16% faster growth rate relative to those in the control group, indicating improved conditions for plant development in the biochar-amended environment.

Another important limitation of this study is the small sample size within each treatment group, which constrains the statistical power and limits the appropriateness of formal hypothesis testing. We performed exploratory t-tests and ANOVA to gain initial insights, but we emphasize descriptive statistics such as means, medians, and percentage differences to illustrate key trends. In addition, because this experiment only compared biochar to one commercial fertilizer, more research is needed to evaluate how biochar performs against other soil amendments, such as compost or synthetic blends. Future studies should also include a no-fertilizer control group to better isolate and understand biochar's unique effects (6, 7, 12). These modifications will help generate more robust and generalizable conclusions.

We used only fine-particle biochar (<2 mm) and did not compare uncrushed or larger particle sizes. Particle size can strongly influence porosity, soil integration, nutrient release, and water retention. Future research should directly compare biochar fractions of varying sizes to determine whether the benefits observed here are consistent across particle sizes or unique to fine-particle biochar.

Despite the study's limitations, the implications of these findings extend beyond agricultural applications. The successful conversion of seaweed waste into beneficial biochar addresses both waste management and soil fertility challenges. This dual-purpose solution could particularly benefit coastal communities struggling with seaweed waste while providing a sustainable alternative to chemical fertilizers. Furthermore, the carbon sequestration potential of biochar contributes to climate change mitigation efforts, offering additional environmental benefits.

Biochar derived from *Gracilaria* seaweed offers a sustainable solution to improving soil fertility and mitigating environmental challenges in agriculture. Biochar production utilizes organic waste materials, such as seaweed biomass, which are often underutilized or discarded (5, 13). By converting this biomass into biochar through pyrolysis, we

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not only sequester carbon but also reduces greenhouse gas emissions compared to traditional organic matter decomposition (6). Biochar enhances soil health by improving nutrient retention, reducing leaching, and stabilizing soil pH, thereby decreasing the need for chemical fertilizers (7). This aligns with sustainable agricultural practices by promoting circular economy principles, reducing dependency on synthetic inputs, and supporting long-term soil productivity (5, 13). The integration of biochar into farming systems represents a viable pathway toward achieving global sustainability goals in food security and environmental conservation.

We see biochar's relevance extending globally, particularly to developing countries facing agricultural crises due to poor soil health and climate change (11, 12). While industrial-scale pyrolysis equipment may be inaccessible in low-resource regions, farmers can still use simplified low-cost reactors such as metal barrel kilns or pit methods to produce biochar effectively at the local level. In countries like India, where declining soil fertility and drought conditions have led to widespread farmer distress and suicides, biochar could offer a viable alternative to improve soil productivity and reduce dependency on expensive chemical fertilizers (11). In Sub-Saharan Africa, where soil degradation limits food production, biochar-enhanced soils could help restore fertility and sustain long-term agricultural productivity. Future studies should investigate optimal biochar application rates across different soil types and climatic conditions. Researchers should conduct economic viability analyses to assess the scalability of seaweed biochar production for commercial applications. Developing standardized production methods would also help ensure consistent quality and performance in agricultural applications.

These findings support our hypothesis and align with existing research showing that biochar can improve soil fertility by helping the soil hold on to nutrients, reducing nutrient loss through leaching, and slowly releasing nutrients over time. In this study, biochar-treated soil showed higher levels of calcium, nitrogen, and magnesium nutrients highlighted in the tornado diagram.

METHODS

Soil Collection and Preparation

Untreated garden soil collected from Cedar Park, TX was carefully screened to remove debris and contaminants. Two identical pots were prepared, each containing 1000 g of soil measured using a kitchen scale. Both pots included proper drainage holes to ensure consistent water movement throughout the experiment.

Biochar Production Process

Gracilaria seaweed was manually collected from Galveston and Corpus Christi beaches in Texas. The seaweed was rinsed with clean water to remove sand, salt, and debris, then air-dried for several days. A custom-built pyrolysis chamber was constructed using a nested metal-can design: a smaller inner can (500 mL) with vent holes for the biomass and a larger outer can (1 L) filled with wood chips as fuel. The setup was heated in an open fire pit, maintaining 450–500°C for three hours. After cooling, the resulting biochar was crushed with a mallet and sieved to a particle size of <2 mm to ensure uniformity before mixing with soil.

Soil Amendment and Plant Setup

Both the control and experimental pots used the same base soil collected from Cedar Park, TX. The experimental pot received a 5% biochar amendment (50 g of biochar per 1000 g of soil). The control pot was amended with Pure Gold Organic Natural All Purpose Plant Food, with 2 teaspoons (approximately 10 g) added per pot, following the manufacturer's recommended dosage for container gardening. No other soil differences were introduced, ensuring that only the type of amendment varied between the two groups. Two identical spider plants (*Chlorophytum comosum*) were planted, one in each pot. Both plants received identical conditions for water (50 mL daily), sunlight (6 hours), and temperature exposure throughout the 42-day testing period.

Monitoring and Data Collection

Plant growth was measured weekly using a metric ruler, recording plant height as the primary growth indicator. Soil moisture levels were monitored three to four times per week (morning at 8 AM and evening at 8 PM) using calibrated Sonkir Soil pH/Moisture meters. Three soil samples were collected from each pot at a 2-inch depth every seven days for nutrient analysis using a LaMotte Garden Soil Test Kit.

Statistical Analysis

Growth rate was calculated as the percent increase in plant height from initial to final measurements. Nutrient retention was assessed by comparing macronutrient concentrations in soil samples between the two treatment groups using LaMotte soil test kits. Water retention was assessed through moisture meter readings recorded at 12-hour intervals. Python-based statistical analysis was performed using the following packages: Python v 3.8.19, NumPy v 1.24.4, Pandas v 2.0.3, Matplotlib v 3.7.5, SciPy v1.10.1, and Basemap (mpl_toolkits.basemap) v 1.4.1. These tools supported descriptive statistics, hypothesis testing, trend analysis, and graphical plotting throughout the study.

Due to the limited number of replicates per group, formal parametric testing (such as t-tests or ANOVA) may not provide robust results. For nutrient analysis, soil samples were collected every 7 days over the 42-day testing period, resulting in 7 total measurements for each group ($n = 7$ for biochar-treated soil; $n = 7$ for control soil). While each timepoint represents a composite sample rather than true biological replicates, this approach effectively captures temporal trends but limits statistical generalizability.

Before applying statistical tests, the dataset was assessed for key statistical assumptions. The independence of observations was ensured by separately measuring nutrient levels for biochar-treated and control soil samples. The normality assumption was considered valid due to the sample size, while variance between groups was checked to confirm comparability.

To compare the mean nutrient concentrations between the two treatment groups (biochar-amended and commercial fertilizer), independent t-tests were conducted for nitrogen, phosphorus, potassium, calcium, and magnesium. A one-way ANOVA was also performed to evaluate overall nutrient variability across groups. Additionally, a one-sided sensitivity bar chart was used to examine the relative responsiveness of individual nutrients to biochar treatment.

The study was conducted at Vista Ridge High School (Cedar Park, TX) over a 42-day period under consistent environmental conditions. All plants were grown in identical plastic containers placed in the same outdoor area, receiving approximately 6 hours of natural sunlight per day and 150 mL of water daily. The soil used in both treatment groups was a commercial loamy mix, initially pH-balanced around 6.5. Each group contained four replicate pots. The experimental group received seaweed-derived biochar mixed into the top 5 cm of soil, while the control group received a measured dose of a conventional commercial fertilizer according to manufacturer instructions. Environmental factors such as light exposure, watering frequency, container size, and ambient temperature were held constant across all replicates to isolate the effect of the treatment variable. The key outcome metrics included water retention, soil nutrient levels, soil pH, and plant height.

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