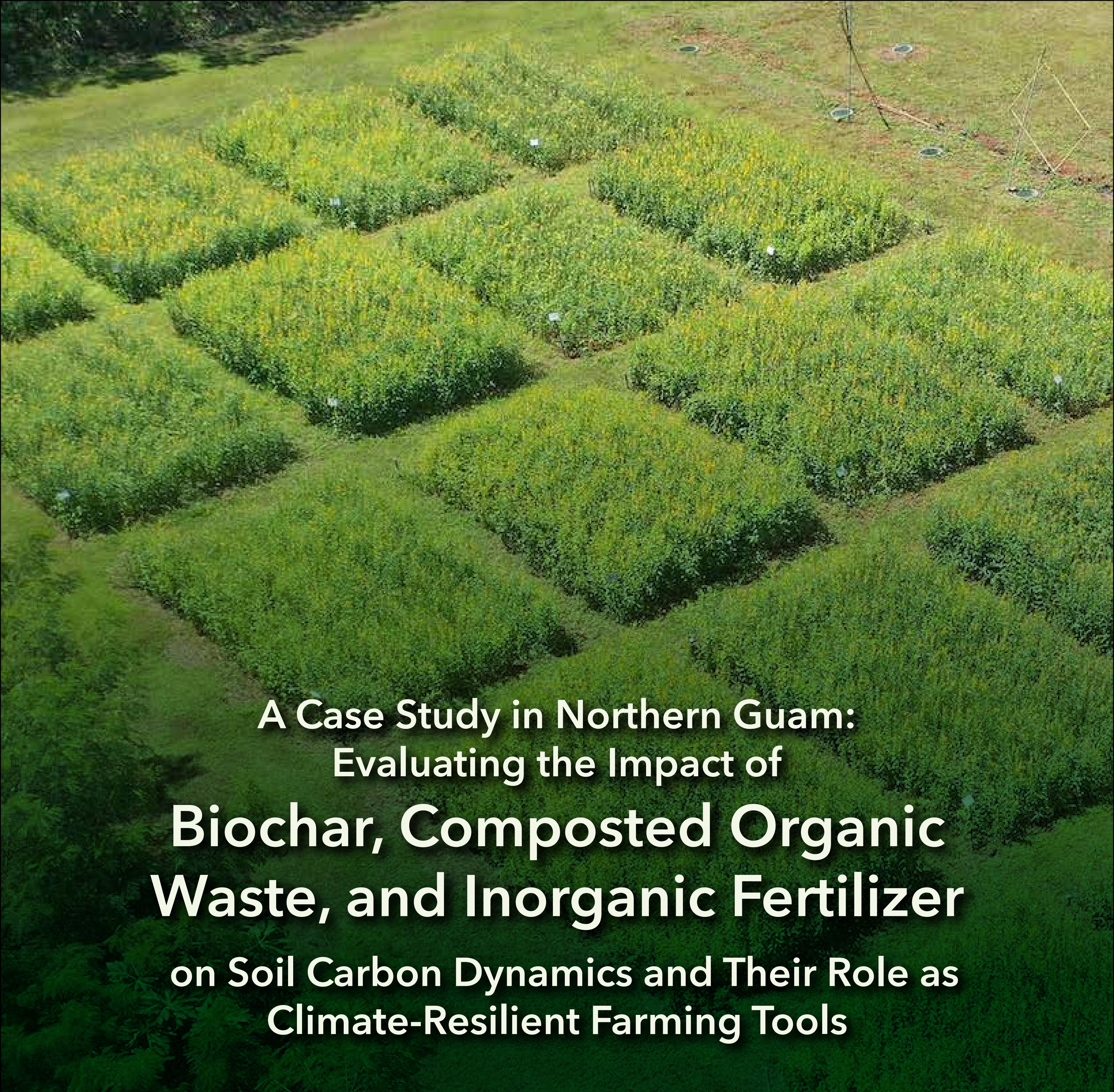

A Case Study in Northern Guam: Evaluating the Impact of Biochar, Composted Organic Waste, and Inorganic Fertilizer on Soil Carbon Dynamics and Their Role as Climate-Resilient Farming Tools

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UNIVERSITY OF GUAM
WESTERN PACIFIC TROPICAL
RESEARCH CENTER

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Table of Contents

LIST OF FIGURES.................... 4

LIST OF TABLES.................... 5

SECTION 1: ABSTRACT.................... 6

SECTION 2: INTRODUCTION 6

SECTION 3: OBJECTIVES.................... 7

SECTION 4: GOAL 7

SECTION 5: MATERIALS AND METHODS 7

Section 5a. Experimentation Site.................... 8

Section 5b. Experimental Field Design.................... 8

SECTION 6: TREATMENTS.................... 8

Section 6.1: Treatment 1: Compost 9

Section 6.2: Treatment 2: Biochar.................... 10

Section 6.3: Treatment 3: Biochar and Compost Mix.................... 10

Section 6.4: Treatment 4: Inorganic Commercial Fertilizer 11

SECTION 7: APPLICATION RATES 11

SECTION 8: SUNN HEMP.................... 11

SECTION 9: SOIL ANALYSIS.................... 12

SECTION 10: CO_2 EFFLUX 13

SECTION 11: WEATHER STATION DATA LOGGER AND IRRIGATION SYSTEM 13

SECTION 12: CROP PRODUCTION 13

SECTION 13: RESULTS 14

SECTION 14. CARBON AND NITROGEN RATIO (C:N).................... 17

SECTION 15: SOIL ORGANIC MATTER (SOM).................... 17

SECTION 16. SOIL NUTRIENTS (K, MG, P (PO_4), CA) 19

SECTION 16: THE POTENTIAL OF HYDROGEN (PH) 20

SECTION 17: CATION EXCHANGE CAPACITY (CEC).................... 21

SECTION 18: SOIL BIOLOGICAL ACTIVITY LAB TEST.................... 22

SECTION 19: SOIL INCUBATION 23

SECTION 20: CARBON DIOXIDE (CO_2) EFFLUX.................... 26

SECTION 21: CROP YIELD 27

SECTION 22: THE CONSEQUENCES OF INSECT DAMAGE 27

SECTION 23: DISCUSSION 27

SECTION 24: CONCLUSION 28

SECTION 25: REFERENCES.................... 29

LIST OF FIGURES

Figure 1. Location of the experimental site 7

Figure 2. Experimental plots grouped into blocks or replicates........ 8

Figure 3. Compost windrow turning 9

Figure 4. Biochar made from woodchips 10

Figure 5. Biochar production demonstration. 11

Figure 6. Sunn hemp grown in the experimental plots as a rotation crop 12

Figure 7. Thermo Scientific FlashSmart Elemental Analyzer 12

Figure 8. Sodium hydroxide-filled (NaOH) Erlenmeyer flasks placed above the soil surface........ 13

Figure 9. Weather station data logger 13

Figure 10. Total carbon content of the soil for the duration of the experiment (2020-2022) 14

Figure 11. Total nitrogen of the soil for the duration of the experiment (2020-2022) 16

Figure 12. Soil organic matter (SOM) throughout the cropping seasons. 18

Figure 13. Nutrient analysis of potassium (K), magnesium (Mg), and phosphorus (P) in the form of phosphate ... 19

Figure 14. Data by Desamito (2020) for comparison. 19

Figure 15. Nutrient analysis of Ca. 20

Figure 16. Chart of nutrient availability based on pH levels 21

Figure 17. Soil-test biological activity (STBA) data. 23

Figure 18. Cumulative C mineralization in 24 days 24

Figure 19. Soil density 24

Figure 20. Soil-Test Biological Activity (STBA) data 25

Figure 21. Basal Soil Respiration (BSR) data 25

Figure 22. Cumulative C mineralization in 24 days 26

Figure 23. CO_2 efflux throughout the cropping seasons 26

Figure 24. Crop yield (2021-2022) 27

LIST OF TABLES

Table 1. Statistical comparisons (T-test) for soil total carbon between experimental treatments 15

Table 2. Soil organic carbon (SOC) content (%) 15

Table 3. Soil inorganic carbon (SIC) content (%) 15

Table 4. Statistical analysis (T-test) *p-value* of total nitrogen. 16

Table 5. Carbon to nitrogen ratio (C:N) throughout the cropping seasons....17

Table 6. Statistical analysis (T-test): *P-value* of SOM 18

Table 7. *P-values* of crop yield 22

Table 8 . Crop yield (kg/plot) and SEM 27

LIST OF APPENDICES

Appendix 1. Total carbon and total nitrogen 32

Appendix 2. Nutrient analysis (K, Ca, Mg, and P as PO_4) 32

Appendix 3. Soil organic matter (SOM)....33

Appendix 4. Biological activity in-lab tests....33

Appendix 5. Crop yield and statistical data 34

Section 1: Abstract

The purpose of this study was to evaluate how different soil amendments, such as biochar, compost, a combination of biochar and compost, and inorganic fertilizer affect crop productivity, soil health, and carbon dioxide (CO_2) emission in the cobbly clay soils situated in northern Guam.

The soil plots analyzed had an average total carbon (TC) range of 8% to 12% and a total nitrogen (TN) range of 0.3% to 0.7% throughout each cropping season. The compost-only and compost/biochar mix plots had the highest carbon (C) levels, with biochar-treated plots surpassing both the fertilizer and control treatments.

Despite the lower nitrogen levels in compost and compost/biochar mix during soil testing, both produced similar or satisfactory crop production during most of the cropping season, comparable to the plots treated with fertilizers. The fertilizer-treated plots had lower yields during the wet season, likely due to the lack of soil organic matter (SOM) or the leaching caused by intense rainfall. During the dry season, the compost/biochar mix had significantly lower CO_2 emissions compared to compost-only plots. However, during the wet season, the emissions were similar. Compost and compost/biochar mix treatments had the highest response in basal soil response (BSR), according to lab tests.

Section 2: Introduction

Soil organic carbon (SOC) is the largest carbon pool in soils and plays a crucial role in carbon (C) storage and exchange of CO_2 in the atmosphere (Follett, Ronald., 2001; Kutsch, W., *et al.*, 2010). According to Lorenz and Lal (2018) and Lal (2011), crop intensification through methods such as soil tillage, fertilization, irrigation, and liming has affected SOC dynamics, leading to a significant loss of terrestrial C estimated at 98.4 Pg from 1850 to 2015. Intense tilling increases aerobic micro-organisms, which consume soil C and release greenhouse gases like CO_2 and methane (CH^4). In addition, changes in weather conditions (e.g., increase in soil temperature and moisture) also affect microbial activities contributing to soil C emissions and nutrient cycles (He, L., *et al.*, 2021).

Soil respiration, as reported by NOAA (2023) and Bond-Lamberty and Thomson (2010), is a significant contributor to CO_2 emissions, ranking second to fossil fuel burning and cement manufacturing. It has been on the rise over the past few decades and is predicted to continue increasing as the weather warms. Warmer tropical soils are also highly vulnerable to intensive soil disturbance that can accelerate CO_2 emissions and loss of SOC. A two-year study in the tropical forest soil of Panama revealed that the increase in temperature caused a 55% rise in CO_2 emissions, indicating that SOC in tropical forests is impacted by warming temperatures (Nottingham *et al.*, 2017).

Challenges with soil and crop management are prevalent in Guam and other Pacific islands, particularly in the northern regions of Guam, where calcareous soils have low SOM content (Golabi *et al.*, 2004). Furthermore, more than 300 plant pathogens have been reported on Guam since 1905, mainly affecting vegetable and fruit crops (Schlub, 2018). Consequently, farmers struggle to produce quality and high-yield crops.

To address these problems, farmers employ large quantities of agricultural chemicals, such as commercial fertilizers, pesticides, and herbicides. However, this practice can lead to increased farm production expenses and negative environmental impacts, such as contamination of drinking water as well as harming the marine life. Therefore, innovative approaches to increase crop production with minimal environmental impact are critical for improving agricultural production for food security (Matson *et al.*, 1997).

An environmentally friendly alternative to commercial inorganic fertilizer is the land application of composted organic waste, or compost. Soil is a mixture of inorganic (e.g., sand, silt, and clay) and organic materials (e.g., living and dead organisms), water, and air (SSSA, 2023). When compost is added to the soil, it increases the SOM, which provides vital nutrients for plants, nourishes soil organisms, enhances soil structure, and boosts the capacity to retain nutrients and water (University of Minnesota Extension, 2021). Compost also stores more global carbon than plants and the atmosphere combined (Jackson *et al.*, 2017).

A compost-to-soil application study was conducted for southern and northern Guam, resulting in improved soil health and crop yield (Golabi *et al.*, 2007 and 2017). However, in large-scale and short-term farming, composting alone may not be cost-effective for crops that require large amounts of nutrients.

Additionally, to reduce greenhouse gases, researchers are studying biochar. This carbonated organic material is rich in carbon and produced in a controlled environment of high temperatures with limited or no oxygen, called pyrolysis (Lehmann *et al.*, 2006). Compared to regular charcoal, it contains about 65% or more C. The C content, however, depends on the feedstock type and pyrolysis conditions (Gaskins *et al.*, 2008).

Section 3: Objectives

1. Investigate biochar's C sequestration potentials and compare them to composted organic waste (compost) and commercial fertilizer (inorganic).
2. Evaluate corn (maize) yield and quality.
3. Conduct soil testing to manage crop nutrition.
4. Verify if biochar can sequester carbon in northern Guam's calcareous and poor soil conditions.

Section 4: Goal

Determine if applying biochar to farmlands can improve soil quality by increasing microbial activity and crop health and limiting CO_2 emissions according to the following soil quality indicators:

1. Physical: Improved soil structure and water retention.
2. Chemical: Increased nutrient availability, nitrogen (N), and phosphorus (P) solubility and cycling, and improved nutrient cation exchange capacity (CEC).
3. Biological: Increased microbial activity and pathogen suppression.

Section 5: Materials and Methods

Section 5a: Experimentation Site

This project was conducted at the University of Guam's Yigo Research & Education Center (Figure 1) in northern Guam,

Figure 1. Location of the experimental site at the Yigo Research & Education Center. Left photo: Kaya Taitano, University of Guam Drone Corps. Right photo: Google Maps.

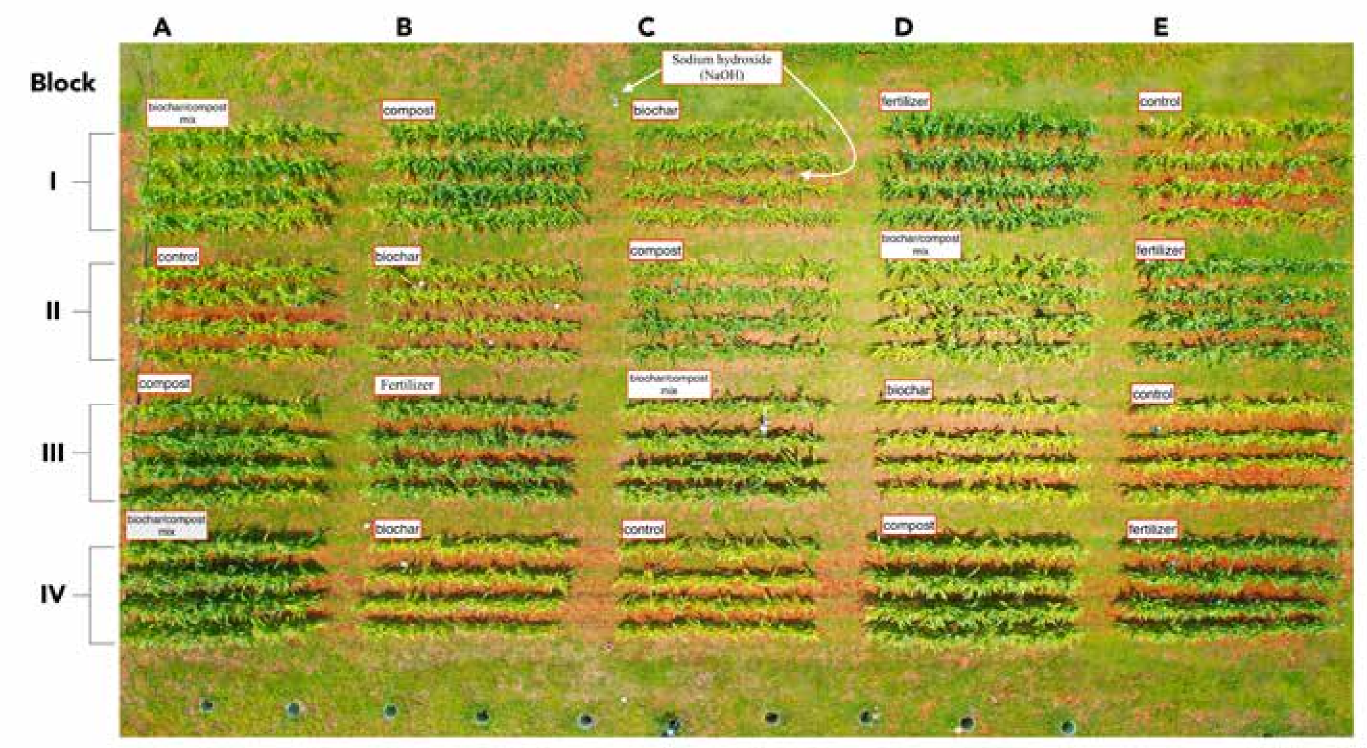

Figure 2. Similar experimental plots are grouped into blocks or replicates.
Photo: Chieriel Desamito

at latitude13°25′ 51.302″ N and longitude 144° 48′ 5.218″ E and 145 m to 155 m elevation above sea level. Northern Guam is relatively flat with no surface drainage as all rainfall percolates directly into the permeable limestone (Soil Survey of Territory of Guam, 1984). Guam has a mean annual rainfall of approximately 2540 mm, with a distinct dry season from January to June, with an average rainfall of approximately 800 mm (Lander, 1994). The mean annual temperature is 26°C, and the monthly temperature range varies approximately ±2°C from the mean (Karolle, 1991).

The soil underlying the site is the Guam soil series (clayey, gibbsitic, nonacid, isohypothermic lithic ustorthents) formed in sediment over porous coralline limestone (Young and Nakamura, 1988). Soils in northern Guam are typically nutrient deficient and high in calcium carbonate.

Section 5b: Experimental Field Design

A randomized complete block design (RCBD) with four replications per treatment was used. The experimental field (Figure 2) was divided into 20 plots (10-by-20 feet, or 3-by-6 meters). Conventional tillage and drip irrigation were implemented in all plots. Drip irrigation was used to minimize water evaporation and leaching of nutrients. A t-test statistical analysis was performed to compare treatments and determine significant differences in paired measurements.

Section 6: Treatments

We used compost and non-composted organic material (biochar) and synthetic fertilizers at comparative rates as soil amendments. Biochar, compost, and compost/biochar treatments were integrated into the topsoil at 0-8 inches (0-20 cm) depth. Commercial inorganic fertilizer (triple 16) was applied using the side dressing method. Triple 16 fertilizer

Figure 3. Compost windrow turning at the University of Guam Yigo Research & Education Center.

contains 16% nitrogen (N), phosphorus (P), and potassium (K).

Section 6.1: Treatment 1: Compost

Composting (Figure 3) is an alternative method for developing effectual plant nutrient and waste management. In Guam and other islands in the Pacific, most agricultural lands are small-scale farming; therefore, composting may benefit local farmers because of the soil's poor fertility and low organic matter (Golabi *et al.*, 2004).

Composting organic waste promotes soil health by increasing organic matter, biological activity, soil water content, and nutrient exchange capacity. Biologically active soil promotes natural food webs for microorganisms by increasing organic material and maintaining ideal soil structure (Hoorman, 2010).

Because compost releases nutrients slowly in the soil compared to commercial fertilizer, compost amendment may prevent excess nutrients (e.g., N and P) from infiltrating and contaminating the groundwater of northern Guam. A study by Galsim ***et. al.*** (2021), indicated that land application of composted organic waste may reduce nitrate leaching into the groundwater that supplies 80% of Guam's drinking water. In addition, Guam is working on a Zero Waste Plan policy from the U.S. Department of Defense Office of Economic Adjustment as part of the alternative waste management needed by the relocation of 5,000 Marines and 1,300 dependents from Okinawa (Johnston, 2014).

Although applying compost improves soil health and crop production, it may not be a complete substitute for fertilizer on high nutrient–demand crops (i.e., maize, wheat, and most leafy green vegetables). Compost's average macronutrient content is approximately 1.5%, almost seven times less than an all-purpose inorganic fertilizer (Pugliese, 2022). Compared to 16 pounds of triple 16 commercial inorganic fertilizer, 112 pounds of dry compost is needed per application.

Composting also produces and releases significant amounts of CO_2 and other greenhouse gases in the atmosphere that may have negative environmental and health impacts. Each time microbes consume C as their energy source, two-thirds is given off as CO_2. At the same time, the remaining third is stored in the microbe cells or part of the mature compost (Trautman *et al.*, n.d). The long-term application of compost provides lasting nutrients to tropical soil, but an alternative treatment is recommended to sequester C and reduce greenhouse gas emissions. Woodchips and vetiver grass were the primary sources of C, while chicken manure and green material provided N in the compost production, as shown in Figure 3.

Section 6.2: Treatment 2: Biochar

An alternative to improving C storage in the soil is the application of biochar. Biochar (Figure 4) is a thermally decomposed biomass from organic material, such as wood, crop residues, and other biological wastes under pyrolysis (Ciolkosz *et al.*,2023). This carbon-rich material is combusted in elevated temperatures up to 700°C with very low to no oxygen (USDA Climate HUBS, 2023). Depending on the type of biomass, this porous and lightweight charcoal-like material contains around 70% carbon and other elements such as N, H, O, and minerals in the ash (Spears, 2023; Rawat *et al.*, 2018).

Biochar technology is being studied to mitigate greenhouse gas emissions by sequestrating or capturing CO_2 in the atmosphere, as some C-containing greenhouse gases may contribute to warmer climates (USGS, 2023). Due to its hydrophilic nature, biochar helps to improve soil water and nutrient retention and increase CEC. This may lead to better crop health and yield.

Figure 4. Biochar made from woodchips. The black color in biochar results from incomplete combustion, indicating high carbon content.

Section 6.2.1: Other Benefits of Biochar in Soil

- High porosity and surface area
- Potential microbial carrier for agricultural and environmental applications
- Enriched with organic carbon, N, P, and nutrients for microorganisms (Bolan *et al.*, 2023)
- Increases water and nutrient holding capacity due to the adsorption of hydrated ions (Batista, E.M.C.C., *et al.*, 2018)
- Cation exchange capacity (CEC)
- Retains soil nutrients, reduces fertilizer runoff, and improves soil water retention (Gyanendra *et al.*, 2019)
- Buffering capacity
- Maintains soil organic matter content and base cations (Y Yu *et al.*, 2016)
- Disease suppression
- The changes in soil microbiota can affect pathogen motility and colonization (Poveda *et al.*, 2021).

The biochar used in this project was purchased off-island. Efforts are ongoing to develop large-scale production of biochar in Guam. In this regard, University of Guam students are learning

Figure 5. Dr. Mohammad Golabi (bottom left) demonstrates biochar production to UOG agriculture students. Once the fire starts, the top of the furnace is covered to eliminate oxygen.

biochar production basics (Figure 5).

Section 6.3: Treatment 3: Biochar and Compost Mix

Plots with compost and biochar mixtures were compared for crop yields and CO_2 emissions. Corn plants were also monitored for the presence of diseases.

Section 6.4: Treatment 4: Inorganic Commercial Fertilizer

An all-purpose slow-dissolving granular fertilizer with equal percentages of nitrogen (N), phosphorus (P), and potassium (K) was applied to the plots using the side-dressing method to reduce nitrate release in groundwater.

Section 7: Application Rates

Five treatments were applied with three replications for each treatment using a randomized complete block design as follows:

Treatment 1: Compost only - 60 t/a compost application*
Treatment 2: Biochar only - 15 t/a 'biochar' *
Treatment 3: Compost and biochar mix - 60 t/a compost and 15 t/a biochar
Treatment 4: Fertilizer only - equivalent rates of nitrogen to compost*
Control: No additional nutrients were added to the soil (0 t/a)

**The application rates are based on the results evaluated from the previous experiment at the Yigo research station for optimum yield production. These application rates provide estimated equivalent rates of 0 and 130 kg/ha of total nitrogen applied. The fertilizer application rate used by local farmers ranges from 120 to 150 kg/ha of nitrogen-based fertilizers.*

Section 8: Sunn Hemp

Corn *(Zea mays L.)* was the main crop throughout the planting seasons (Figure 6). However, due to negative drawbacks of monoculture farming (i.e., depletion of soil nutrients and intensive use of agricultural chemicals), sunn hemp *(Crotalaria juncea L.)* was incorporated in the soil between cropping seasons as a cover crop to help suppress invertebrate pests (e.g., plant-parasitic nematodes) that can cause severe damage to corn or other crops.

Sunn hemp is an annual legume commonly used in rota-

Figure 6. Dr. Mohammad Golabi stands among sunn hemp that was grown in the experimental plots as a rotation crop between planting seasons.

tion to the main crop. It forms a symbiotic relationship with N-fixing bacteria by taking N gas from the atmosphere and converting it to nitrate in the soil. It can suppress pests, particularly plant-parasitic nematodes (roundworms) that take away energy and nutrients by attacking the roots. As a cover crop, it effectively controls weeds (USDA NRCS, 2023). However, residual effects can be short-term. Thus, it was continually planted between cropping seasons.

In northern Guam, the soil is porous and lacks organic matter. However, sunn hemp offers a solution to this problem. With its rapid growth and fibrous stalks, it can produce more than 5,000 lb. of biomass and 100 lb. of nitrogen per acre (USDA, 1999). By increasing organic matter and nitrogen in the soil, farmers can reduce water use and fertilizer application. Additionally, using sunn hemp can minimize the use of pesticides, herbicides, and fertilizers that could potentially contaminate Guam's aquifer — the primary source of drinking water for 80% of the island's population. Therefore, both local farmers as well as the public stand to benefit from incorporating sunn hemp into their farming practices.

Section 9: Soil Analysis

The study plots were examined for changes in soil composition before and after applying composted organic waste, biochar, and fertilizer.

Figure 7. The Thermo Scientific FlashSmart Elemental Analyzer, located in UOG's Soil Lab, was used to determine total carbon (TC) and total nitrogen (TN) to evaluate soil quality.

Soil samples were taken from 0- to 8-inch depths and tested for plant nutrients, pH levels, carbon content, and organic matter (OM). The FlashSmart Analyzer instrument (Figure 7) was utilized to accurately measure the total carbon (TC) and total nitrogen (TN) present in both the soil and compost.

Section 10: CO_2 Efflux

Intensive soil tilling in agricultural ecosystems releases greenhouse gases (GHG) into the atmosphere. A study conducted in southern Guam compared the effects of no-tillage farming and biochar application with volcanic soils. Previous results (Golabi *et al.*, 2014 and 2023) indicated that biochar-amended soils and no-tillage practices have low CO_2 efflux measured from the soil surface using sealed containers with sodium hydroxide (Figure 8). The CO_2 captured from soil respiration was determined using the titration method. The concentration of CO_2 was determined using the titration method based on the following formula:

Mass of CO_2 =
volume of titrant (L) x
molarity of standard acid x
molecular weight of CO_2

Figure 8. Sealed containers with 3M of sodium hydroxide-filled (NaOH) Erlenmeyer flasks were placed above the soil surface to capture CO^2 efflux in 24 hours.

Figure 9. A weather station data logger (circled) was used for efficient irrigation.

Section 11: Weather Station Data Logger and Irrigation System

A weather station was used to monitor precipitation, humidity, soil moisture, and temperature to detect the overwatering or underwatering of crops (Figure 9). Drip irrigation emitters also provided a gradual water supply to plant roots (Figure 9).

Section 12: Crop Production

Crop production, or crop yield, refers to the weight of grain harvested from a specific land area during a single growing season. It is commonly measured as yield per unit area, such as metric tons per hectare (t/ha) (Oxford Reference 2023). Corn was collected from three of five rows per plot for this project.

Section 13: Results

Carbon (C) and Nitrogen (N)

Soil samples from study plots were analyzed for total carbon (TC) and total nitrogen (TN) (Figures 10 and 11). Soil organic carbon (SOC) is derived from organic matter, such as plant residues (Table 1). SOC was estimated based on the assumption that SOM is 58% C. In contrast, soil inorganic carbon (SIC) (Table 2) is from inorganic carbonates, like calcium carbonate or lime (Harold van Es. *et al.*, 2020).

Although inconsistent, biochar-treated plots generally had higher carbon content than the fertilizer and control plots.

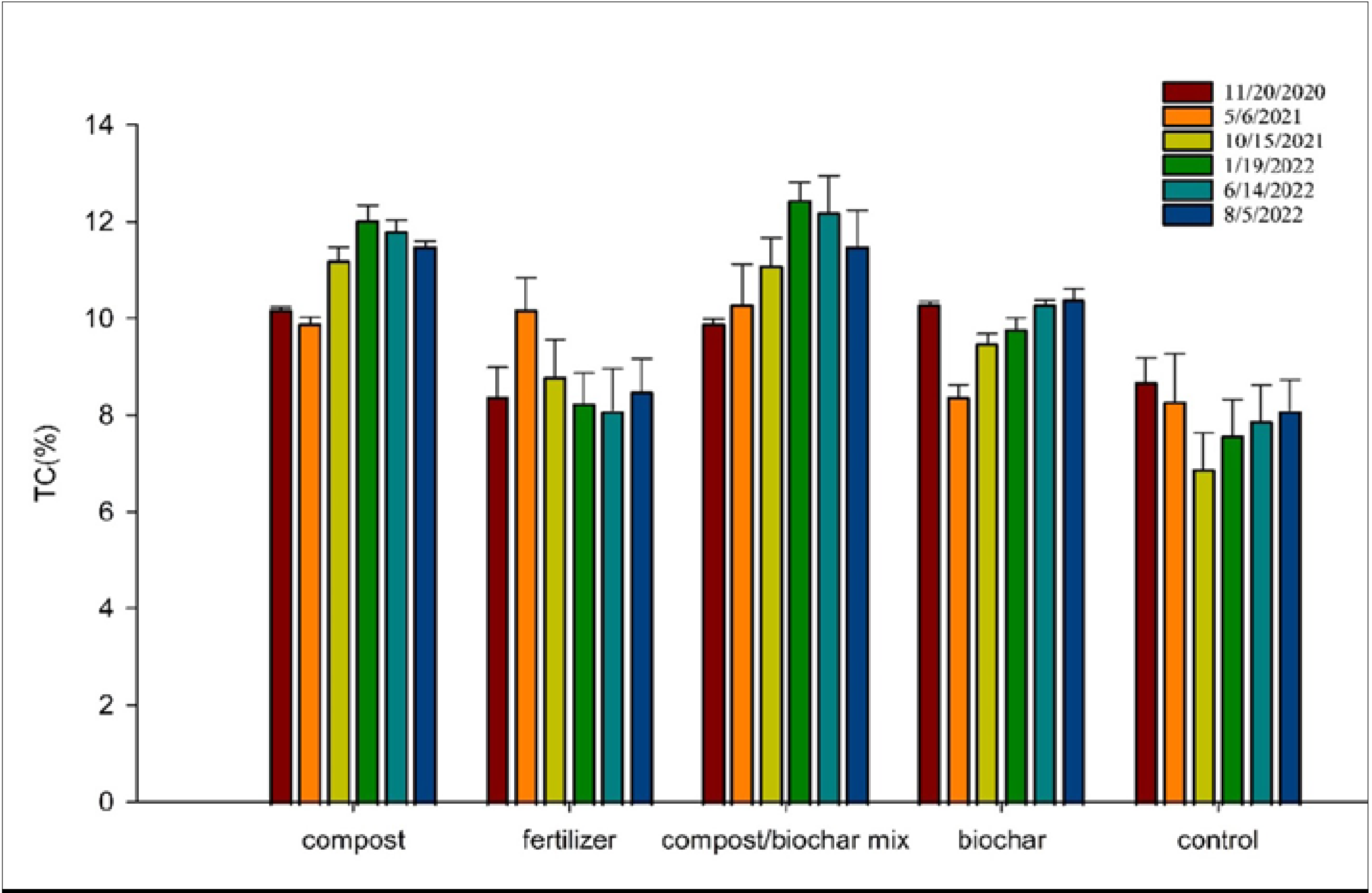

Figure 10. Total Carbon Content (TC) of the Soil for the Duration of the Experiment (2020-2022)

Table 1. Statistical Comparisons (T-test) for Soil Total Carbon (TC) Between Experimental Treatments

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
compost vs fertilizer	**0.0032**	**0.0261**	**0.019**	**0.004**	**0.0202**	**0.0190**
compost vs compost/biochar mix	**0.0094**	0.589	0.912	0.419	0.626	0.999
compost vs biochar	0.40	**0.0240**	**0.003**	**0.001**	**0.00511**	**0.00844**
compost vs control	**0.024**	**0.0000016**	**0.010**	0.006	**0.00852**	**0.0103**
fertilizer vs mix	**0.042**	**0.0100**	**0.015**	**0.003**	**0.0122**	**0.0226**
fertilizer vs biochar	**0.0030**	**0.0417**	0.138	0.086	0.0914	0.0566
fertilizer vs control	0.074	0.246	0.646	0.517	0.858	0.670
compost/biochar mix vs biochar	**0.0037**	0.0835	**0.043**	0.005	0.0769	0.238
compost/biochar mix vs control	**0.015**	**0.0075**	**0.007**	**0.004**	**0.00594**	**0.0121**
biochar vs control	**0.039**	**0.00042**	0.064	0.055	**0.0462**	**0.0257**

Note: Compost, biochar-compost mix, and biochar-only treatments had higher carbon contents compared to fertilizer and control, and the difference was statistically significant. Although not statistically different, the carbon content in control plots was higher than in the fertilizer plots.

Table 2. Soil Organic Carbon (SOC) Content (%)

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
compost	5.71	5.70	6.76	6.83	6.40	5.97
fertilizer	4.62	4.04	4.83	4.16	4.19	3.82
compost/biochar mix	5.44	5.85	5.91	8.15	6.87	6.55
biochar	5.43	4.40	4.43	4.62	4.30	4.26
control	4.33	3.97	4.04	4.01	3.82	3.91

Table 3. Soil Inorganic Carbon (SIC) Content (%)

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
compost	4.57	4.20	4.44	5.37	5.40	5.53
fertilizer	3.78	6.16	3.97	3.64	3.91	4.68
compost/biochar mix	4.46	4.45	5.19	3.35	5.33	4.95
biochar	4.87	4.00	5.07	4.98	6.00	6.14
control	4.37	4.33	2.86	2.89	4.08	4.19

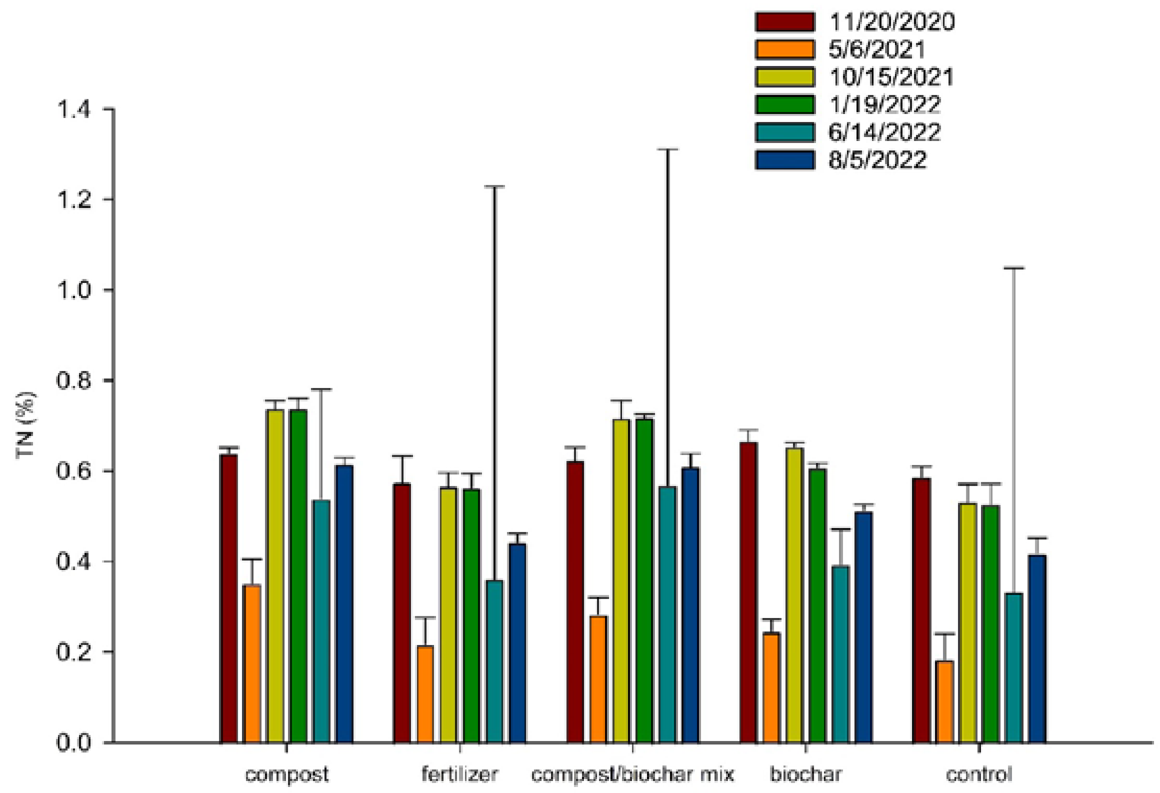

Figure 11. Total Nitrogen (TN) of the Soil for the Duration of the Experiment (2020-2022)

Table 4. Statistical Analysis (T-test): P-value of TN

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
compost vs fertilizer	0.32	0.136	**0.0045**	**0.0050**	**0.0187**	**0.000502**
compost vs compost/biochar mix	0.75	0.1364	0.64	0.71	0.456	0.860
compost vs biochar	0.48	0.1379	**0.0075**	**0.0053**	**0.00408**	**0.00158**
compost vs control	0.12	0.0706	**0.0077**	**0.0108**	**0.00117**	**0.00486**
fertilizer vs mix	0.18	0.3767	**0.022**	**0.029**	**0.0103**	**0.00401**
fertilizer vs biochar	0.**0030**	0.6775	0.054	0.255	0.524	**0.0264**
fertilizer vs control	0.074	0.6949	0.51	**0.02**	0.605	0.559
compost/biochar mix vs biochar	**0.0037**	0.4347	0.19	0.08	**0.00369**	**0.0344**
compost/biochar mix vs control	**0.015**	0.1927	**0.014**	**0.021**	**0.000833**	**0.00466**
biochar vs control	0.039	0.369	0.048	0.170	0.0981	0.**0557**

Note: P-values in bold are statistically different (P<0.05)

Section 14: Carbon and Nitrogen Ratio (C:N)

Maintaining the optimal ratio of C to N in agricultural soils is crucial for ensuring healthy crop growth and microbial activity. Experts suggest a ratio of 10:1 as the ideal balance between these two essential nutrients in the soil (USDA, n.d). This ratio helps facilitate the breakdown of organic matter, which releases nutrients for plants to feed on while promoting the growth of beneficial soil microorganisms. For long-term maintenance of soil health and to achieve maximum crop yield, it is highly recommended to follow the appropriate ratio. Table 1 shows the C:N ratio of the soil plots throughout the cropping seasons.

Table 5. Carbon to Nitrogen Ratio (C:N) throughout the Cropping Seasons

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
Compost	16:1	17:1	15:1	16:1	24:1	19:1
Fertilizer	15:1	16:1	15:1	14:1	20:1	19:1
Compost/biochar mix	16:1	15:1	16:1	16:1	20:1	19:1
Biochar	15:1	14:1	15:1	16:1	26:1	20:1
Control	15:1	14:1	14:1	12:1	26:1	19:1

Section 15: Soil Organic Matter (SOM)

The content of organic matter from both the compost and compost/biochar mix was significant compared to the rest of the treatments.

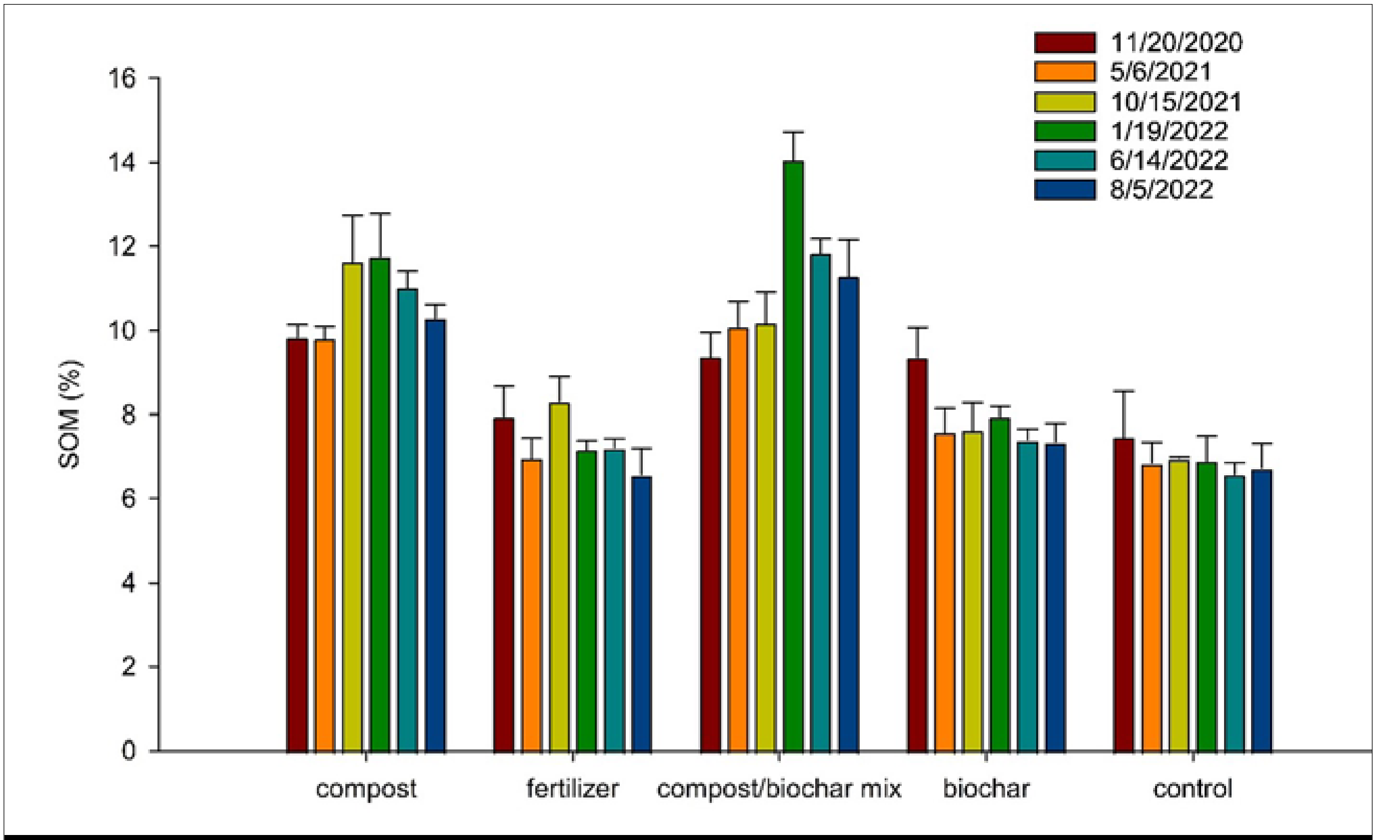

Figure 12. Soil Organic Matter (SOM) throughout the Cropping Seasons

Table 6. Statistical Analysis (T-test): *P-value* of SOM

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022
compost vs fertilizer	**0.004**	0.046	**0.018**	**0.00057**	**0.013**
compost vs mix	0.70	0.31	0.110	0.14	0.33
compost vs biochar	**0.018**	**0.024**	**0.029**	**0.00048**	**0.0066**
compost vs control	**0.0039**	**0.022**	**0.010**	**0.00017**	**0.0036**
fertilizer vs mix	**0.0081**	0.099	**0.0012**	**0.000053**	**0.0071**
fertilizer vs biochar	0.44	0.44	**0.048**	0.67	0.36
fertilizer vs control	0.81	0.10	0.71	0.11	0.86
compost/biochar mix vs biochar	**0.023**	**0.040**	**0.0014**	**0.000017**	**0.0079**
compost/biochar mix vs control	**0.0066**	**0.022**	**0.00023**	**0.000018**	**0.0065**
biochar vs control	0.33	0.37	0.18	0.076	0.19

Note: P-values *in bold are statistically different (P<0.05)*

Section 16. Soil Nutrients: K, Mg, P (PO_4), Ca

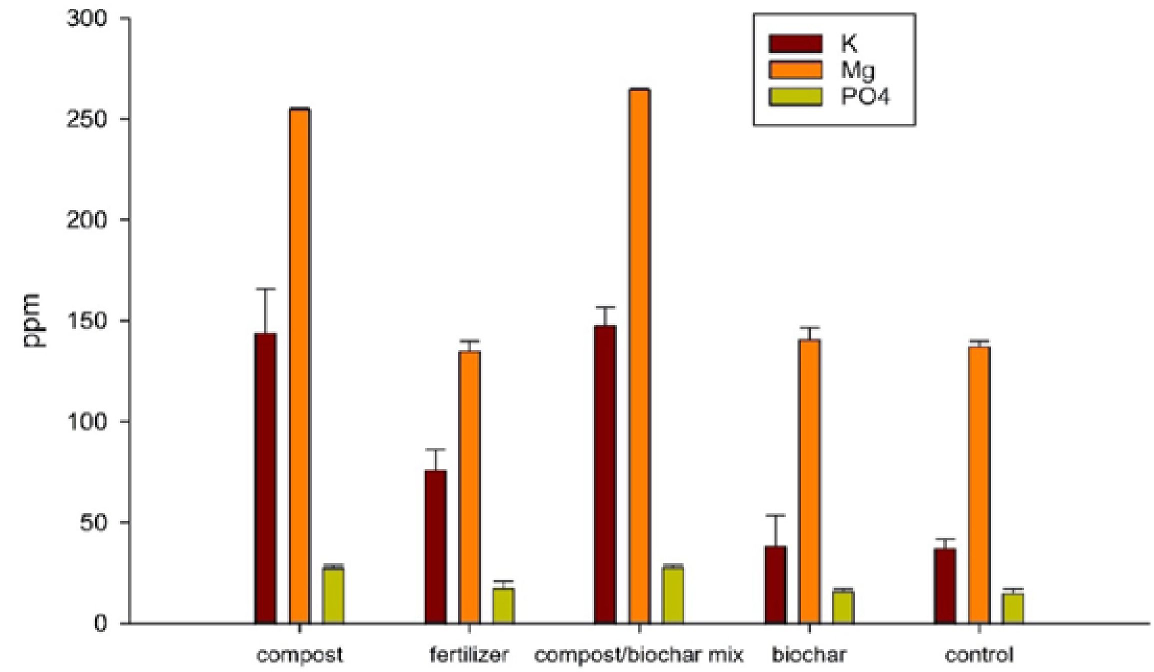

Figure 13. Nutrient Analysis of Potassium (K), Magnesium (Mg), and Phosphorus (P) in the Form of Phosphate (PO_4) (June 14, 2022)

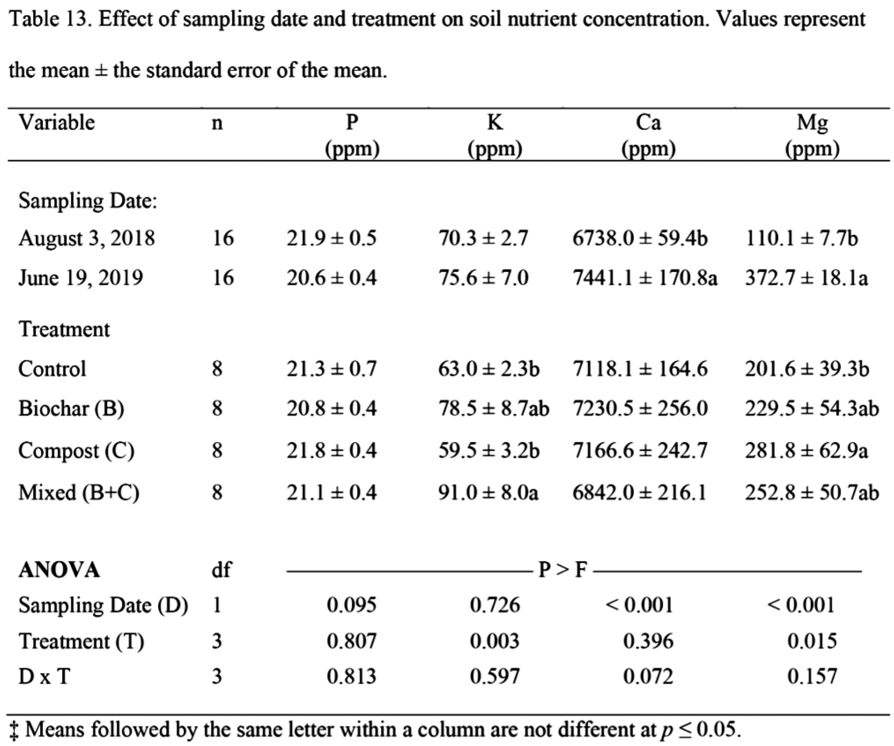

Table 13. Effect of sampling date and treatment on soil nutrient concentration. Values represent the mean ± the standard error of the mean.

Variable	n	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)
Sampling Date:					
August 3, 2018	16	21.9 ± 0.5	70.3 ± 2.7	6738.0 ± 59.4b	110.1 ± 7.7b
June 19, 2019	16	20.6 ± 0.4	75.6 ± 7.0	7441.1 ± 170.8a	372.7 ± 18.1a
Treatment					
Control	8	21.3 ± 0.7	63.0 ± 2.3b	7118.1 ± 164.6	201.6 ± 39.3b
Biochar (B)	8	20.8 ± 0.4	78.5 ± 8.7ab	7230.5 ± 256.0	229.5 ± 54.3ab
Compost (C)	8	21.8 ± 0.4	59.5 ± 3.2b	7166.6 ± 242.7	281.8 ± 62.9a
Mixed (B+C)	8	21.1 ± 0.4	91.0 ± 8.0a	6842.0 ± 216.1	252.8 ± 50.7ab
ANOVA	df	P > F			
Sampling Date (D)	1	0.095	0.726	< 0.001	< 0.001
Treatment (T)	3	0.807	0.003	0.396	0.015
D x T	3	0.813	0.597	0.072	0.157

‡ Means followed by the same letter within a column are not different at $p \leq 0.05$.

Figure 14. Data by Desamito (2020) for comparison. Desamito performed similar projects on the same study plots. However, the project did not include a fertilizer study.

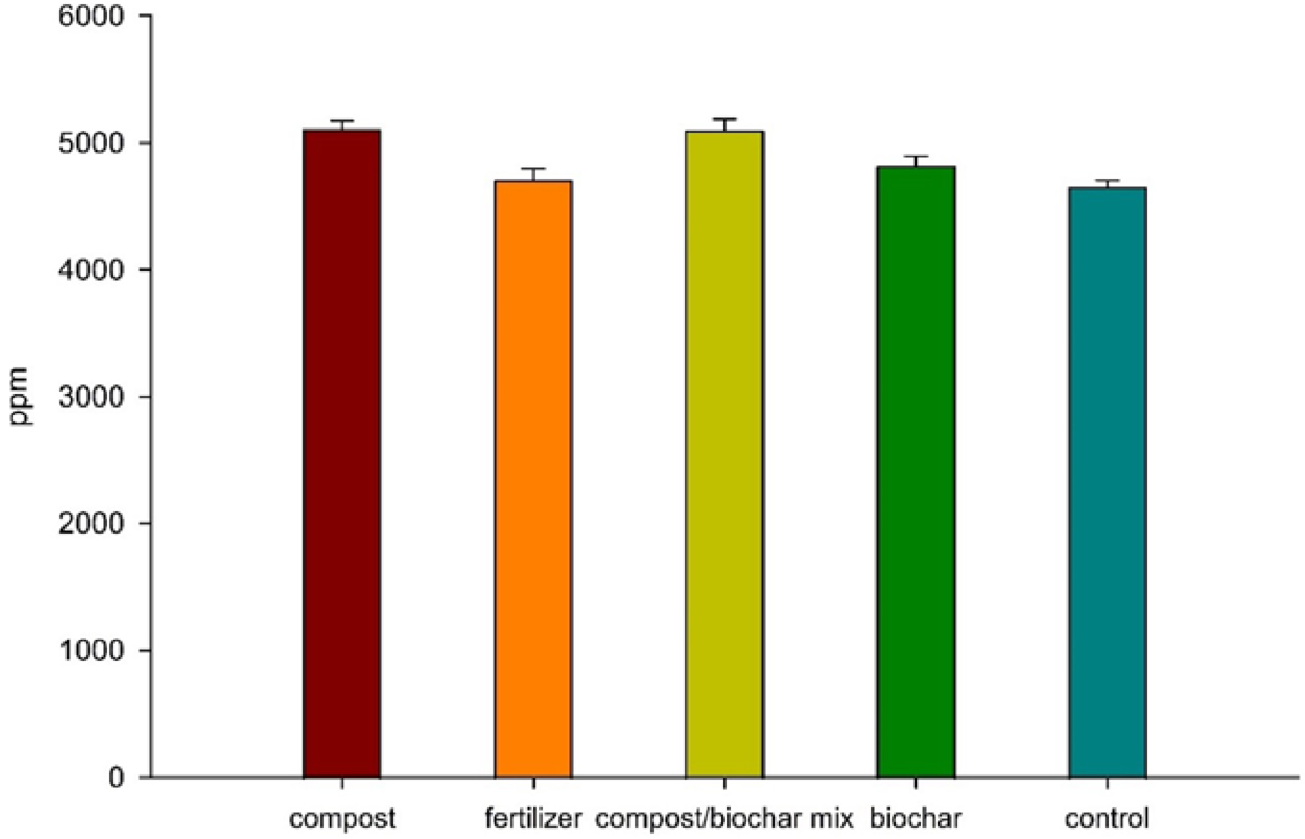

Figure 15. Nutrient Analysis of Ca. (June 14, 2022)

Section 16: The Potential of Hydrogen (pH)

A measure of acidity or alkalinity (pH) affects soil's biological, chemical, and physical properties as it also determines the availability of essential plant nutrients. Soil pH of 6.5 is considered optimum for nutrient availability for most crops (Cornell University, 2023). On June 14, 2022, the soil pH of all treatments ranged from 7.4 to 7.5.

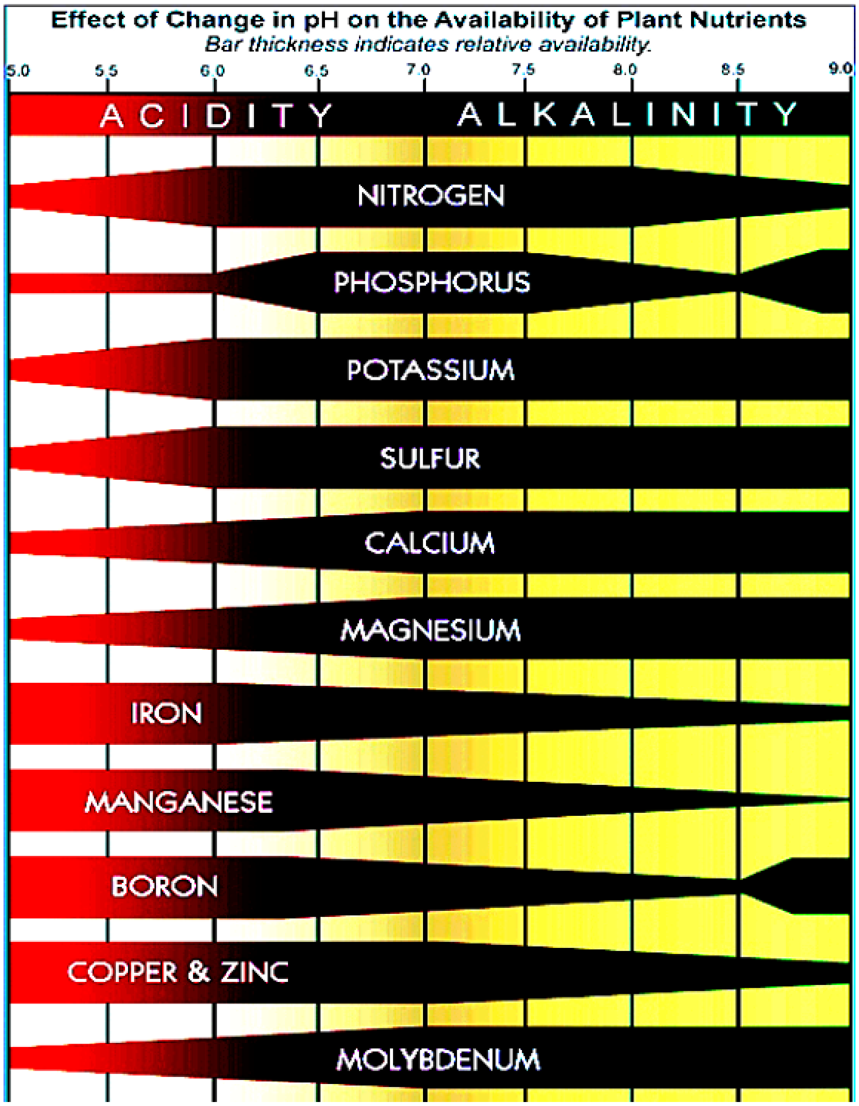

Figure 16. Nutrient Availability Based on pH Levels
Source: New Enterprise Stone & Lime Co.

Section 17: Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) was estimated based on the following formula:

CEC = [2 (%OM) + 0.5 (%clay)]

The clay content of the study plots was based on Desamito's data collected in the same project area in 2020.

Table 7. CEC (meq/100g of soil) Based on the Clay Content of the Soil

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
compost	33.68	33.64	37.32	37.54	36.06	34.6
fertilizer	29.92	27.94	30.64	28.36	28.44	27.16
compost/biochar mix	32.76	34.18	34.38	42.1	37.7	36.6
biochar	32.72	29.18	29.28	29.92	28.82	28.7
control	28.94	27.7	27.94	27.82	27.18	27.48

Section 18: Soil Biological Activity Lab Test

One of the advantages of presenting our project's progress during conferences was initiating collaboration with other scientists in the field. This vision established a collaborative effort with a scientist from the U.S. Department of Agriculture (USDA) in North Carolina.

The term "soil microbial activity" refers to the various heterotrophic activities of macro-fauna, micro-fauna, and generally, the microorganisms that make up the soil food web, as Franzluebbers (2021) explained. By measuring the soil respiration (CO_2), we can quantify the efficient nutrient cycling and soil health, which is a fundamental heterotrophic process of reusing carbon in the soil to balance the autotrophic process of photosynthesis and carbon cycle (Franzluebbers, 1999; Chen and Zhang, 2003).

Understanding the impact of organic matter and nutrients on crops and the environment requires knowledge of potential carbon (C) and nitrogen (N) mineralization as well as soil microbial biomass C (SMBC). As microorganisms are the primary agents of decomposition, they account for more than 90% of heterotrophic respiration (Foissner, 1987). Additionally, the biological activity test serves as an indicator of total organic matter in the soil.

Section 19: Soil Incubation

Soil-test biological activity (STBA) may be an important indicator of soil N availability (Franzluebbers 2020). Testing was conducted to measure soil-test biological activity (STBA), cumulative carbon (C) mineralization (CMIN), basal soil response (BSR), and soil density (Figures 17 to 22) (Franzluebbers, 2021). STBA was measured through three days of aerobic incubation at 50% water-filled pore space and 25°C, while CMIN was measured through 24 days of aerobic incubation under the same conditions. Soil basal respiration (BSR) refers to the constant rate of respiration in soil that results from the breakdown of organic matter (Pell *et al.*, 2006). This rate can be determined by measuring the amount of CO_2 released or O2 consumed (Dilly and Zyakun, 2008).

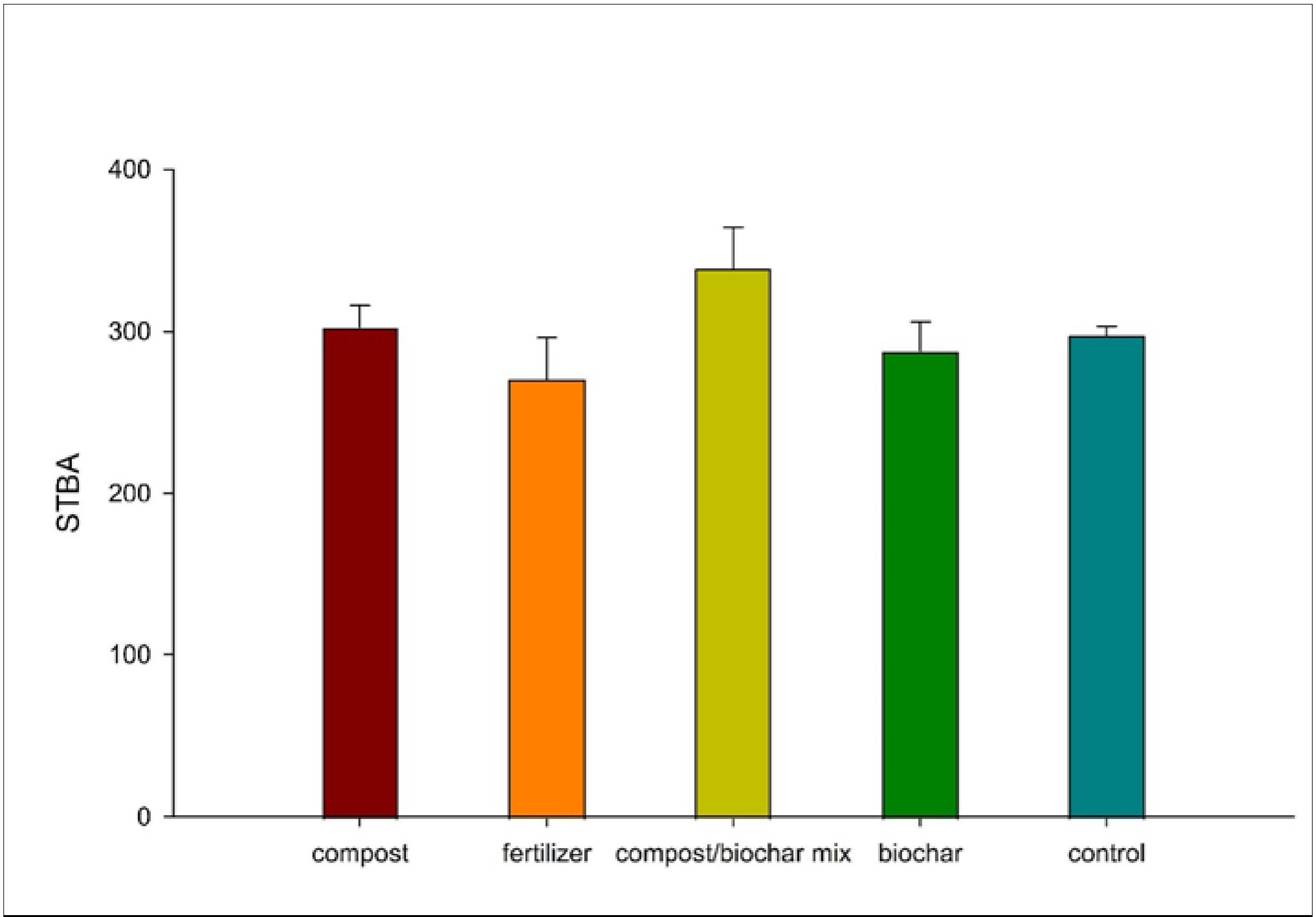

Figure 17. Soil-Test Biological Activity (STBA) Data (May 6, 2021)

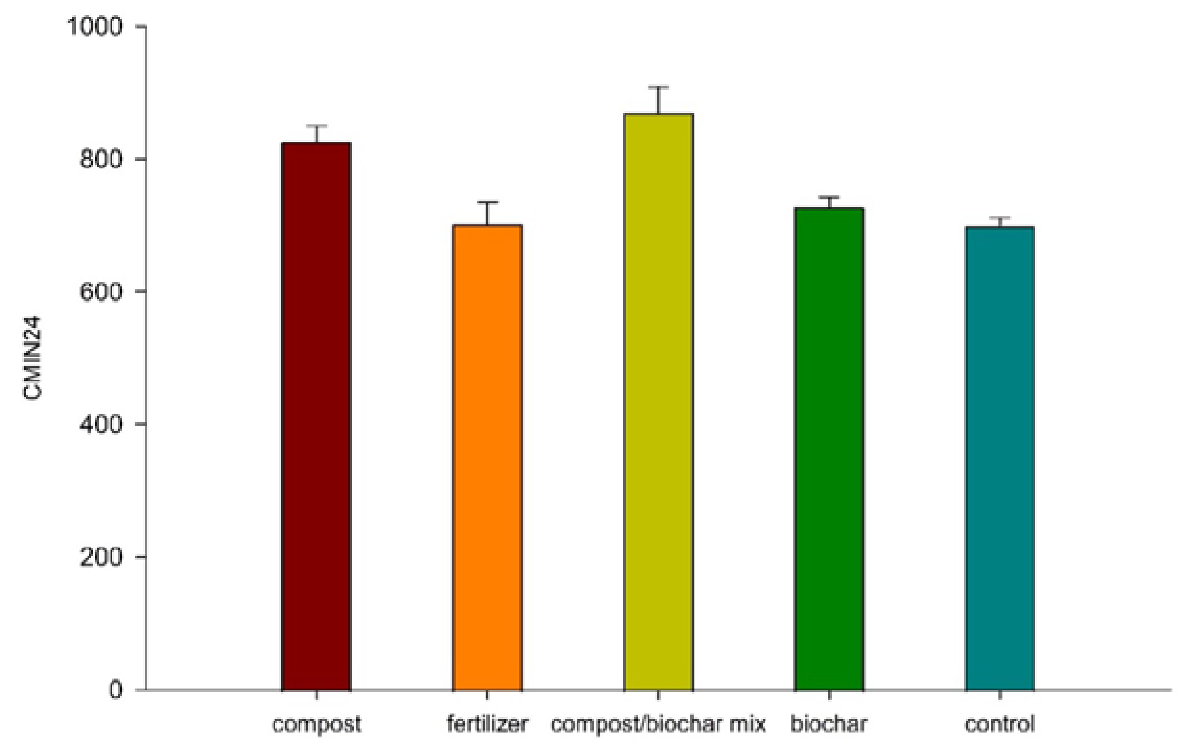

Figure 18. Cumulative C Mineralization in 24 Days (CMIN24) (May 6, 2021)

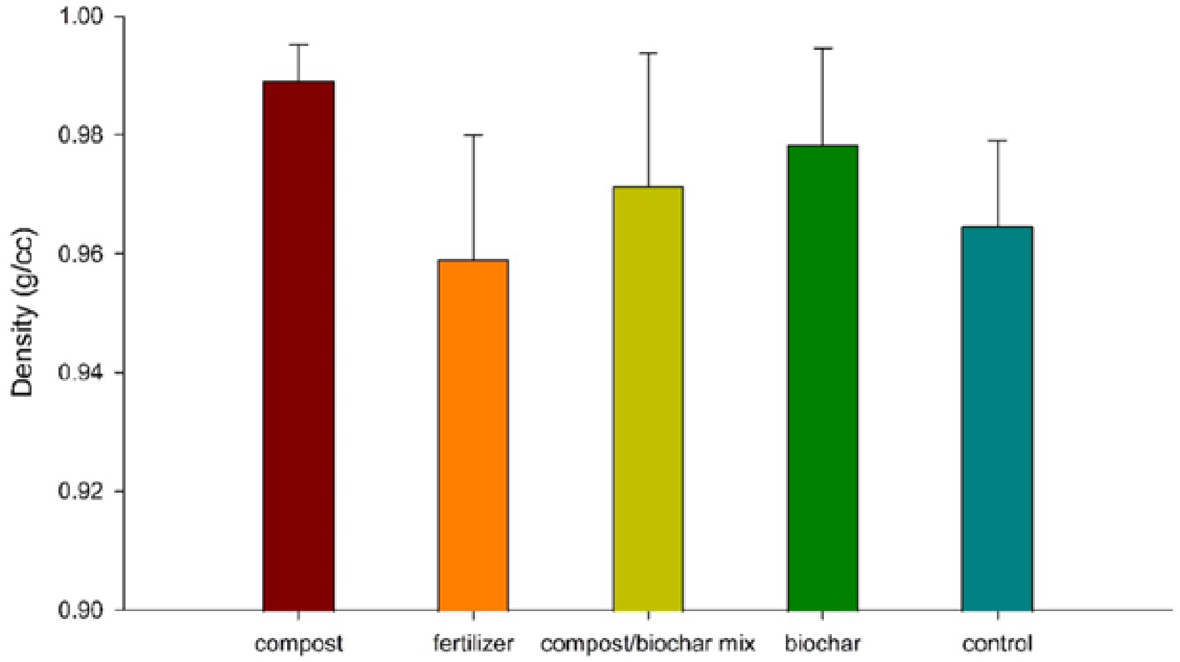

Figure 19. Soil Density (May 6, 2021)

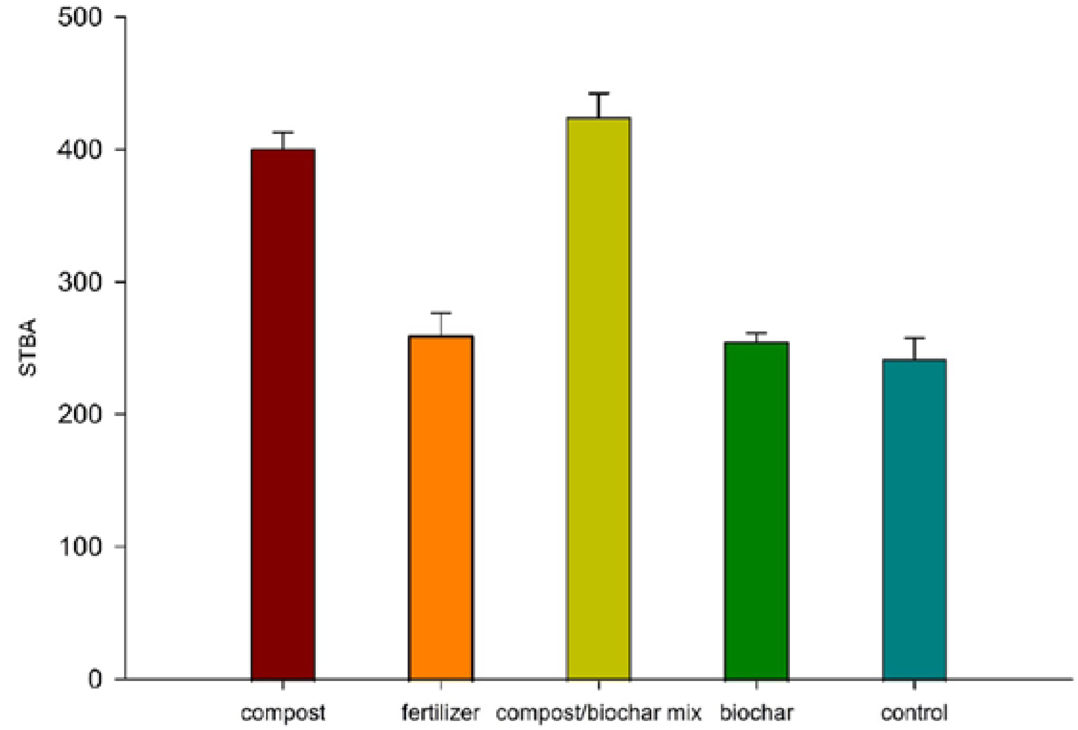

Figure 20. Soil-Test Biological Activity (STBA) Data (June 14, 2022)

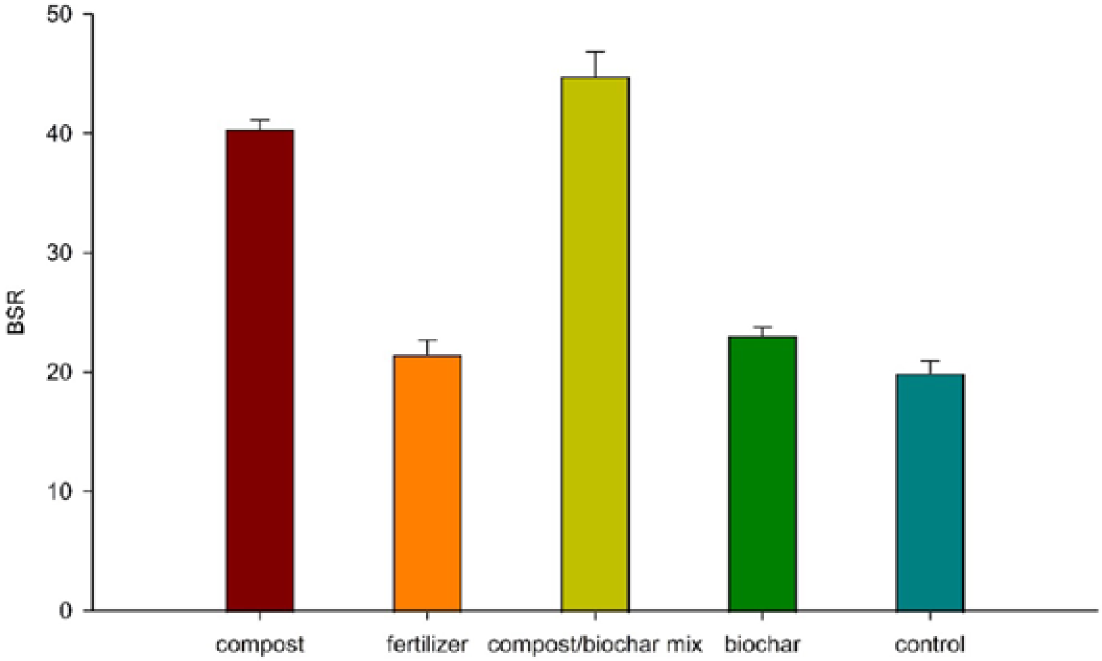

Figure 21. Basal Soil Respiration (BSR) Data (June 14, 2022)

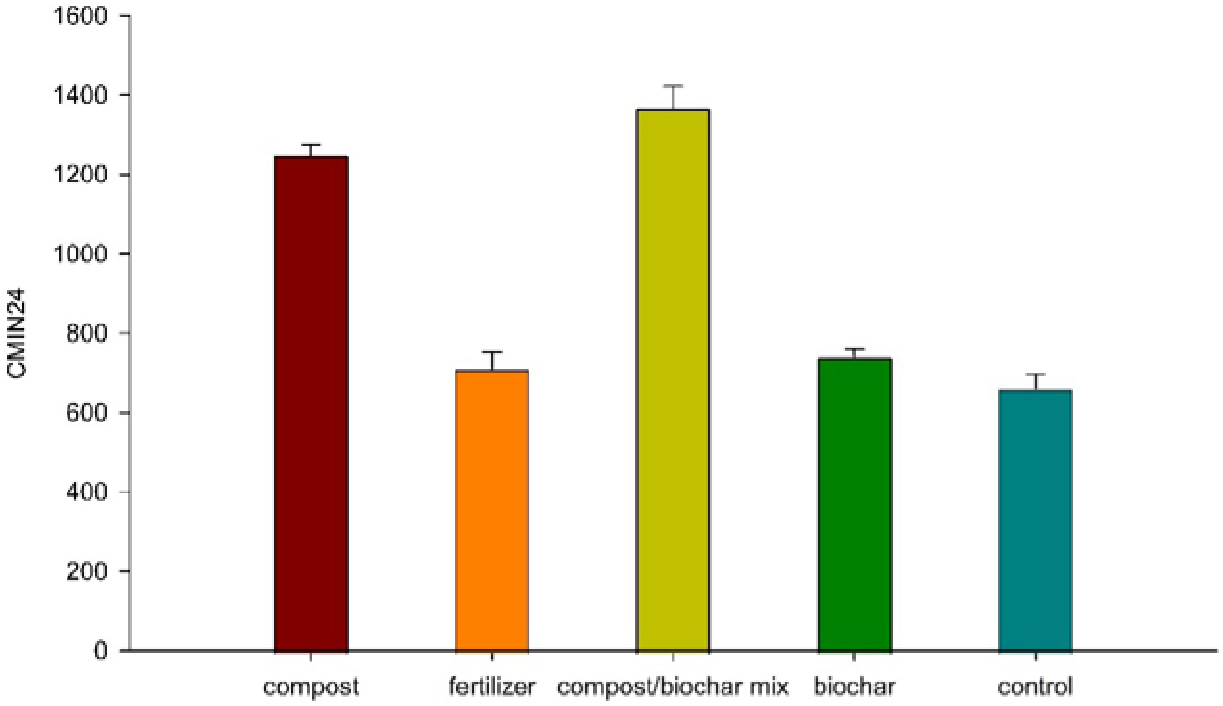

Figure 22. Cumulative C Mineralization in 24 Days (CMIN24) Data (June 14, 2022)

Section 20: Carbon Dioxide (CO_2) Efflux

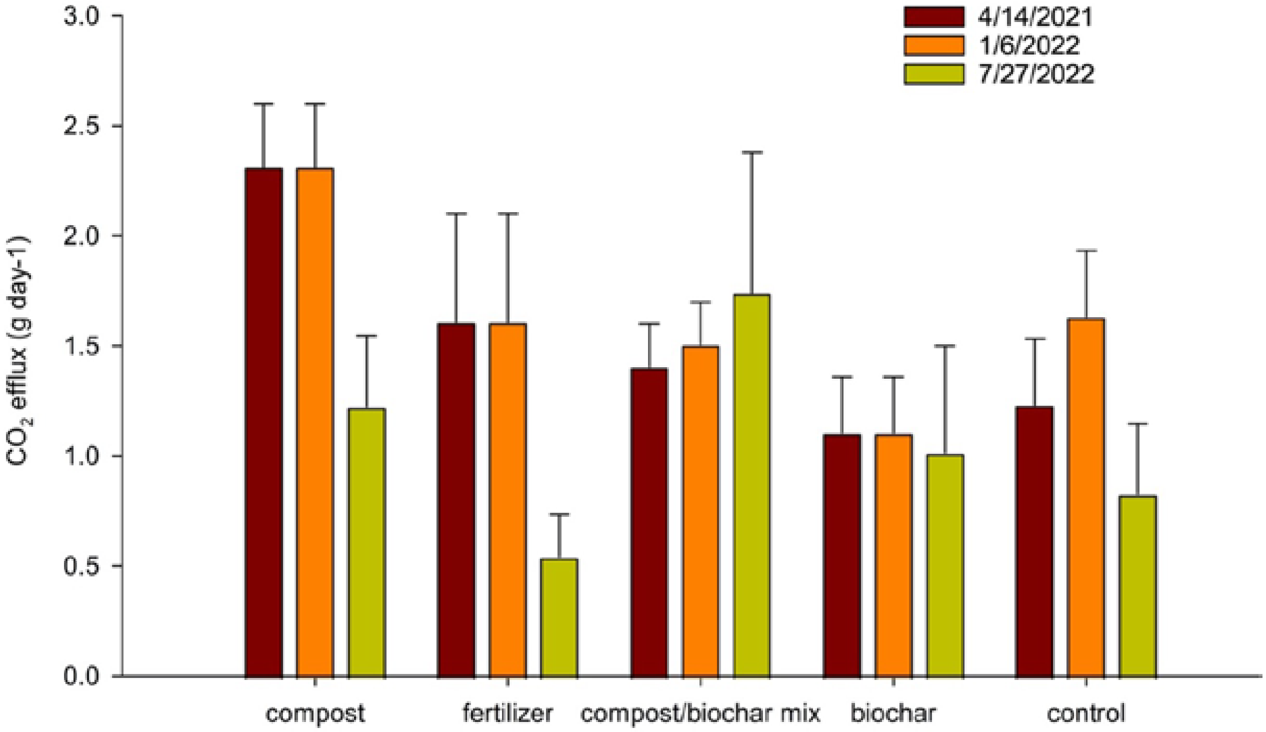

Figure 23. CO_2 Efflux throughout the Cropping Seasons

Table 8. CO_2 Efflux with P-values (T-test)

Treatment	4/13/2021	1/6/2021	7/27/22
compost vs fertilizer	**0.042**	**0.020**	**0.0000343**
compost vs mix	**0.004**	**0.002**	0.920
compost vs biochar	**0.005**	**0.001**	**0.000126**
compost vs control	**0.004**	**0.010**	**0.00140**
fertilizer vs mix	0.775	0.671	**0.00043**
fertilizer vs biochar	0.885	0.288	0.506
fertilizer vs control	0.485	0.801	0.339
mix vs biochar	0.278	0.146	**0.000400**
mix vs control	0.278	0.887	**0.003**
biochar vs control	0.491	0.253	0.235

Note: P-values *in bold are statistically different (P<0.05)*

Section 21: Crop Yield

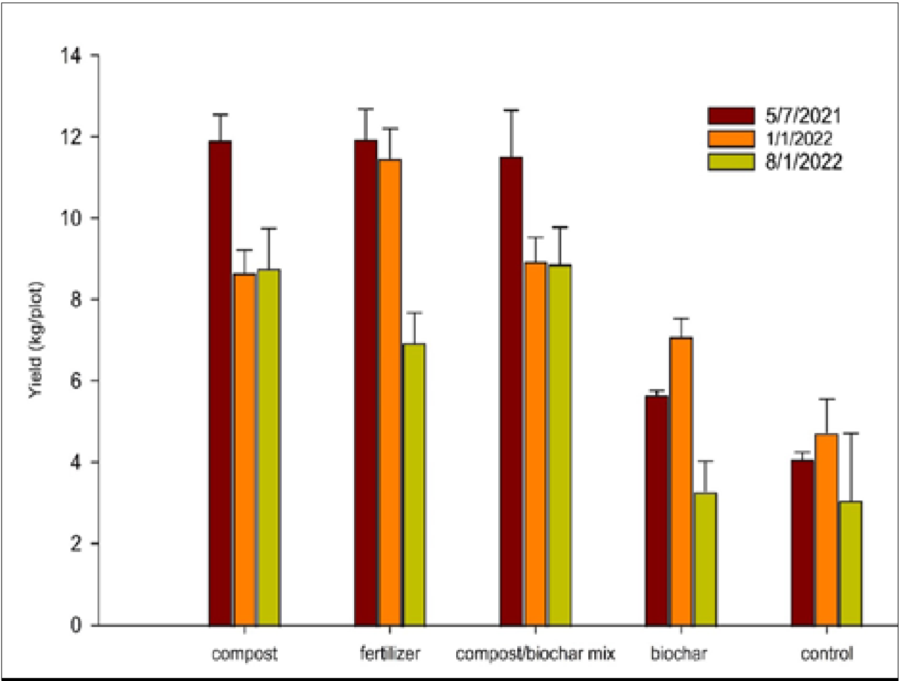

Figure 24. Crop Yield (2021-2022)

During Season 1 (May 7, 2021, Figure 24), the crop yield for compost, fertilizer, and compost/biochar mix treatments was equivalent. However, the biochar plot outperformed the control plot in terms of yield.

In Season 2 (Jan. 1, 2022), the crop yield from biochar plots was higher and statistically different from the control group. Fertilizer plots yielded significantly more than compost and compost/biochar mix groups. However, significant damage from insects and chickens likely impacted the data.

In Season 3, another dry season, the same experiment showed that the biochar and control groups did not yield statistically different results. Nevertheless, the biochar yielded greater results compared to the control group. There was a decrease in fertilizer plot yield during the rainy season. This is most likely due to leaching caused by heavy rain, which significantly impacts the porous soil in the northern region.

Section 22: The Consequences of Insect Damage

In January 2022 (Season 2, as indicated in Figure 24), 144 ears of corn were damaged by Japanese beetles and chickens. However, no cases of the disease were observed. In contrast, no plants went missing or damaged during Season 1. Eighteen plants were reported missing during Season 3. Damages caused by insects and other animals may have contributed to the unsatisfactory yield of both compost and compost/biochar mix, causing inconsistent data.

Section 23: Discussion

In this study, all soil plots exhibited a range of 8%-12%

Treatment	4/13/2021	1/6/2021	7/27/22
compost vs fertilizer	1.0	0.096	**0.04**
compost vs mix	0.35	0.70	0.93
compost vs biochar	**0.0037**	0.052	**0.01**
compost vs control	**0.0014**	0.050	**0.003**
fertilizer vs mix	0.36	0.70	0.93
fertilizer vs biochar	**0.0063**	0.052	**0.01**
fertilizer vs control	**0.0027**	**0.0055**	0.0035
compost/biochar mix vs biochar	**0.48**	**0.023**	**0.01**
compost/biochar mix vs control	**0.021**	**0.039**	**0.01**
biochar vs control	**0.0013**	0.12	0.64

Note: P-values *in bold are statistically different (P<0.05*

Table 7. *P-values* of Crop Yield

Treatment	5/7/2021	SEM	1/1/2022	SEM	8/1/2022	SEM
compost	11.916	0.625	8.655	0.556	8.773	0.967
fertilizer	11.940	0.744	11.465	0.733	6.942	0.733
compost/biochar mix	11.522	1.133	8.933	0.601	8.876	0.898
biochar	5.669	0.087	7.098	0.438	3.289	0.735
control	4.082	0.160	4.724	0.816	3.078	1.633

Table 8. Crop Yield (Kg/plot) and SEM

for TC and 0.3% to 0.7% for TN. Compost-enriched plots contained the highest levels of C, with biochar surpassing both fertilizer and control, which have comparatively lower rates. Compost and compost/biochar mix plots overall contained more N, as statistical data showed. Although compost and compost/biochar mix exhibited a low nitrogen level, they managed to produce similar or satisfactory crop yield during most of the cropping season, comparable to plots treated with fertilizers. However, fertilizer plots suffered lower yields during the wet season, likely due to the lack of SOM and/or leaching caused by intense rainfall.

During the dry seasons, the compost/biochar mix had lower CO_2 efflux than compost-only plots. Lab testing showed that the BSR of compost and compost/biochar mix had the highest response.

One of the concerns is the use of biochar in alkaline soils, such as those found in northern Guam, and its potential to increase soil pH and subsequently impact the availability of nutrients for plant growth. When the pH level is above 7, phosphate binds with calcium or calcium carbonate. This results in phosphorus becoming immobile and inaccessible for plants to use. However, compost proves to be particularly advantageous during wet seasons as it lessens the necessity for frequent application in contrast to inorganic fertilizer. On the other hand, over-application of inorganic fertilizer can harm the environment significantly. In addition, farmers will likely increase the use of other agricultural chemicals.

Section 24: Conclusion

To achieve sustainable and climate-resilient farming, it is crucial to prioritize soil fertility that fosters favorable chemical, physical, and biological conditions with minimal environmental harm. Incorporating biochar into soil and compost has the potential to contribute to these goals. Our findings demonstrate that using biochar, either on its own or as a mixture in conjunction with compost, can significantly decrease the amount of CO_2 emissions while enhancing crop production. However, biochar's long-term agronomical and environmental impact is unknown, and further study is recommended to reach a conclusive answer.

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Appendix 1. Total carbon (TC) and total nitrogen (TN)

Percent total carbon (TC)

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
Compost	10.2	9.9	11.2	12.2	11.8	11.5
Fertilizer	8.4	10.2	8.8	7.8	8.1	8.5
Compost/ biochar mix	9.9	10.3	11.1	11.5	12.2	11.5
Biochar	10.3	8.4	9.5	9.6	10.3	10.4
Control	8.7	8.3	6.9	6.9	7.9	8.1

Percent total nitrogen (TN)

Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
Compost	0.6	0.6	0.7	0.7	0.5	0.6
Fertilizer	0.6	0.6	0.6	0.6	0.4	0.4
Compost/ biochar mix	0.6	0.7	0.7	0.7	0.6	0.6
Biochar	0.7	0.6	0.6	0.6	0.4	0.5
Control	0.6	0.6	0.5	0.5	0.3	0.4

Appendix 2. Nutrient analysis (K, Ca, Mg, and P as PO_4)

Nutrient analysis for K, Ca, Mg, and P as PO_4 (June 14, 2022)

Treatment	K (ppm)	SEM	Ca (ppm)	SEM	Mg (ppm)	SEM	PO_4 (ppm)	SEM
Compost	144.2	21.5	5104.8	69.6	254.8	0.8	27.8	0.0
Fertilizer	76.2	9.8	4705.5	91.3	135.0	4.8	18.0	2.8
Compost/ biochar mix	147.4	9.2	5095.9	93.5	264.5	0.7	28.0	0.8
Biochar	38.6	14.9	4819.2	72.9	140.8	5.5	16.2	1.0
Control	37.6	4.2	4649.5	58.0	137.4	2.4	15.2	1.8

Appendix 3. Soil organic matter (SOM)

Soil organic carbon (SOM) content (%)						
Treatment	11/20/2020	5/6/2021	10/15/2021	1/19/2022	6/14/2022	8/5/2022
Compost	9.84	9.82	11.66	11.77	11.03	10.30
Fertilizer	7.96	6.97	8.32	7.18	7.22	6.58
Compost/ biochar mix	9.38	10.09	10.19	14.05	11.85	11.30
Biochar	9.36	7.59	7.64	7.96	7.41	7.35
Control	7.47	6.85	6.97	6.91	6.59	6.74

Appendix 4. Biological activity in-lab tests

Soil-test biological activity (STBA), C mineralization (CMIN24), and soil density (May 6, 2021)				
Treatment	STBA	BSR	CMIN24	Density (g/cc)
Compost	302.8	no data	826	0.99
Fertilizer	271.0	no data	702.5	0.96
Compost/biochar mix	339.0	no data	870.75	0.97
Biochar	288.0	no data	728.5	0.98
Control	298.0	no data	699.75	0.96
Density = sieved density in ¼ cup of soil				

Soil-test of biological activity (STBA) (June 14, 2022)			
Treatment	401.125	40.375	1249.125
Compost	260.35	21.525	712.125
Fertilizer	424.9	44.775	1365.7
Compost/biochar mix	255.425	23.1	740.625
Biochar	242.4	19.975	661.325
Control	298.0	no data	699.75

Appendix 5. Crop yield and statistical data

Percent total nitrogen (TN)						
Treatment	5/7/2021	SEM	1/1/2022	SEM	8/1/2022	SEM
Compost	11.916	0.625	8.655	0.556	8.773	0.967
Fertilizer	11.940	0.744	11.465	0.733	6.942	0.733
Compost/ biochar mix	11.522	1.133	8.933	0.601	8.876	0.898
Biochar	5.669	0.087	7.098	0.438	3.289	0.735
Control	4.082	0.160	4.724	0.816	3.078	1.633

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