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VALORIZATION OF AGRICULTURAL WASTES INTO DENSIFIED BIOCHAR PELLETS: IMPLICATIONS FOR SOIL HEALTH AND SUSTAINABLE CROP PRODUCTION

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agricultural waste valorization; densified biochar pellets; soil health; sustainable crop production; pyrolysis; soil fertility; nutrient availability; organic farming; biochar pelletization; climate-resilient agriculture.

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Abstract

The increasing accumulation of agricultural residues presents significant environmental challenges while simultaneously offering opportunities for sustainable resource utilization. This study investigated the valorization of locally available agricultural wastes into densified biochar pellets and evaluated their implications for soil health and sustainable crop production. Specifically, the study developed and characterized biochar pellets produced from rice hulls, corn cobs, coconut husks, sugarcane bagasse, and peanut shells through pyrolysis and pelletization; assessed their effects on soil chemical properties, organic matter dynamics, and nutrient availability; and examined their influence on the growth and yield performance of major cereal, legume, vegetable, and root crops. A laboratory-experimental and field research approach was employed using pyrolysis for biochar production, greenhouse incubation experiments, and field trials arranged in a Randomized Complete Block Design (RCBD) with three replications. Soil and biochar samples were analyzed for pH, organic matter, organic carbon, nitrogen, phosphorus, potassium, and selected micronutrients using standard laboratory procedures. Results revealed that all biochar formulations possessed alkaline properties and contained appreciable levels of essential macro- and micronutrients. Peanut shell biochar exhibited the highest organic matter, organic carbon, nitrogen, phosphorus, and iron contents, whereas corn cob biochar contained the highest potassium, zinc, and manganese concentrations. Application of pelleted biochar significantly improved soil pH, organic matter, nutrient availability, and soil fertility, with sugarcane bagasse and corn cob biochars demonstrating superior performance in enhancing soil chemical properties. Crop evaluation further showed that biochar treatments improved yields across various crops, while combining pelleted biochar with recommended or reduced rates of inorganic fertilizer consistently produced the highest yields, indicating improved nutrient-use efficiency and reduced dependence on synthetic fertilizers. Overall, the findings demonstrate that densified biochar pellets derived from agricultural wastes represent an effective and sustainable soil amendment capable of enhancing soil quality, increasing crop productivity, promoting agricultural waste valorization, and supporting climate-resilient organic farming systems. The study highlights the potential of integrating biochar technology into sustainable agricultural management strategies to improve long-term soil health and food production while contributing to environmental conservation.

INTRODUCTION

The province of Isabela, known as one of the country's top agricultural producers, generates large volumes of agricultural residues such as rice husks, corn cobs, coconut shells, and sugarcane bagasse. Improper disposal of these wastes not only contributes to environmental pollution but also leads to the loss of valuable organic resources that could otherwise be used to enhance soil fertility. Compounding this issue, continuous land cultivation and the excessive use of chemical fertilizers have degraded soil quality, resulting in declining crop yields and increased production costs for farmers. In response, the Philippine Organic Agriculture Act (RA 10068) was enacted to promote organic farming practices that enrich soil fertility, boost productivity, and mitigate environmental degradation.

One promising solution is biochar, a carbon-rich material produced through the pyrolysis of organic matter. As a soil amendment, biochar improves soil quality by sequestering carbon, enhancing nutrient retention, and fostering beneficial microbial activity. Compared with compost and manure, biochar provides more stable, long-term fertility benefits due to its high surface area, complex pore structure, and resistance to decomposition (Aggangan et al., 2019). Biochar application has been shown to raise soil pH, increase cation exchange capacity, improve water retention, and stimulate plant growth by enhancing nutrient uptake efficiency (Chan et al., 2007).

Despite these benefits, traditional loose biochar poses practical challenges. Studies report that up to 30% can be lost to wind and 25% during field application, while dust particles pose respiratory hazards to farmers. Pelletization offers a viable solution by compressing biochar into durable, uniformly sized pellets using binders. This improves handling, storage, transport, and application while reducing losses. Biochar pellets also enhance soil aeration and porosity, making them more effective for crop production.

By improving the usability of biochar, pelletization encourages broader adoption among farmers. This innovation not only supports sustainable organic farming but also promotes waste valorization, improved soil health, and long-term agricultural productivity.

Objectives

1. Develop and characterize ISU biochar pellets using locally available agro-wastes via pyrolysis and pelletization.
2. Evaluate the effect of biochar on soil chemical properties, organic matter dynamics, and nutrient availability.
3. Assess its impact on crop growth and yield performance across cereals, legumes, vegetables, and root crops

METHODOLOGY

Biochar Production & Pelletization

Biomass (feedstocks) were collected within the community surrounding the university. Materials which are hardly decomposable plus the availability were the major considerations in selecting the type of feedstock. Five agri-waste materials were utilized in the production of biochar – rice hull, corn cobs, sugarcane bagasse, coconut and peanut shells. Before the carbonization process, the prepared feedstock materials were cut into small pieces (average length of 5 - 10 cm) and air dried for one-week until moisture contents were reduced to about 10-15%. Each of the organic wastes were mixed with poultry manure, then the mixture is placed inside the kiln made up of big and small drums. The various feedstocks are subjected to chemical decomposition (pyrolysis) for 3 hours at terminal temperature of 500ºC under limited oxygen. The produced biochar was washed with tap water, dried to 10 to 15% moisture ground and sieved through a 3.175 mm mesh screen. Pelletization can improve mass and energy density of pellets and can also extend storage time for seasonal crops. The pulverized biochars were blended with cementing agents (molasses, corn starch, oil, rice bran) for 5 minutes and moistened with tap water. The biochar was densified using a pelletizing machine.

The biochar derived from the various substrate combinations were assessed in terms of chemical (pH, organic carbon), physical properties and nutrient content. One-half kilogram sample of the each of the biochar products were brought to DA Regional Soil Analytical Laboratory for analysis of pH, organic matter content, total nitrogen, available phosphorus, exchangeable potassium and other micronutrients using standard procedures.

Greenhouse Incubation Trials

The effects of the pelleted biochar on the soil chemical properties were examined through a soil-biochar incubation experiment. One-half kilogram air-dried soil was weighed and put in different polyethylene plastics and pelleted biochar were added at 15 % (w/w) of biochar (corn cobs/stalks, rice straw/hull, peanut shell, sugar cane bagasse, coconut husk) and were thoroughly homogenized. A no biochar soil was used as the control/reference check. Three replicates of each treatment were prepared, randomly placed and incubated in the greenhouse at ambient temperature for 60 days. The moisture content of the soil-biochar mixture was maintained at field capacity throughout the incubation period, by adding distilled water whenever necessary. At the end of 3 months, soil samples (about 100 g) were removed from all the treatments and were analyzed for pH, organic matter content, and nutrients using standard methods.

Field Trials

Field experiments were conducted to determine the effect of pelleted biochar as additional nutrient source for rice, corn, pepper, radish and lettuce as test crops. The study was laid-out in Randomized Complete Block Design with 3 replications. The treatments included pelleted biochar (corn cobs/stalks, rice straw/hull, peanut shell, sugar cane bagasse, coconut husk) at the rate of 3.0 tons/ha^{-1} with an untreated control. Field experiments were conducted to determine the effect of pelletized biochar as organic fertilizers on the growth and yield of cereal (rice and corn), fruiting vegetable (eggplant, pepper), lettuce and root crop (radish).

RESULTS AND DISCUSSION

Nutrient Composition

The combination of decomposed poultry manure and biomass (feedstock) at a ratio of 60:40 was found the most optimal mixture and was used in the biochar production. Five kinds of biochar - corn cobs biochar, sugarcane bagasse biochar, rice hull biochar, peanut shell biochar and coconut shell biochar were produced. Table 1 presents the chemical properties of the 5 formulations of biochar prior to pelletization. A ratio of one kilogram of biochar blended to 90 grams of corn starch (binder) moistened with 880 ml of water resulted in better pellet durability.

Table 1. Chemical properties of 5 formulations of biochar

Parameters	Biochar (Peanut shell)	Biochar (Corn cobs)	Biochar (Coconut husk)	Biochar (Rice hull)	Biochar (Sugarcane bagasse)
pH	10.27	10.36	10.22	9.73	10.39
Total N (%)	2.62	1.94	2.18	2.02	2.43
OM (%)	52.3	38.77	43.63	40.33	48.5
OC (%)	30.34	22.49	24.56	22.59	28.13
Available P (%)	3.75	3.46	2.88	3.72	2.93
Exchangeable K (%)	3.29	4.5	3.7	3.92	3.29
Zn (ppm)	238.96	415.94	241.25	142.71	217.61
Cu (ppm)	44.69	38.96	33.23	31.88	32.61
Mn (ppm)	322.09	358.96	307.29	331.98	320.84
Fe (ppm)	1711.25	879.07	748.86	1088.44	1275

The pH values of the biochar of various composition ranged from 9.73 (rice hull biochar) to 10.39 (sugarcane bagasse biochar), indicating that all biochar are alkaline. The alkalinity of these biochar is beneficial for acidic soils as it helps neutralize soil pH, reducing soil acidity and improving nutrient availability. Sugarcane bagasse biochar (10.39) and corn cob biochar (10.36) exhibit the highest alkalinity, making it the most effective in counteracting soil acidity. The nitrogen content ranges from 1.94 percent (corn cobs biochar) to 2.62 percent (peanut shell biochar). Peanut shell biochar has the highest nitrogen content at 2.62 percent, making it potentially beneficial for nitrogen-deficient soils. Corn cob biochar indicated the lowest nitrogen content at 1.94 percent, which when applied may require supplementation with additional nitrogen sources.

Organic matter content of the biochar varies from 38.77 percent (corn cobs biochar) to 52.3 percent (peanut shell biochar). Peanut shell biochar has the highest organic matter with 52.3 percent, making it the best for improving soil organic matter. Corn cob biochar with 38.77 percent has the lowest OM content, indicating it might provide less improvement in soil organic content than other biochar. Organic matter is an essential component that enhances soil structure, moisture retention, and microbial activity. In terms of organic carbon content which is crucial for carbon sequestration, microbial activity, and soil fertility, it ranges from 22.49 percent (corn cobs biochar) to 30.34

percent (peanut shell biochar). Peanut shell biochar (30.34%) has the highest organic carbon, indicating its superior ability to store carbon and improve soil health, while corn cob biochar has the lowest organic carbon (22.49%), suggesting it may have lower long-term soil fertility benefits.

Phosphorus is vital for plant root development, flowering, and fruiting. The available P varies from 2.88 percent (coconut husk biochar) to 3.75 percent (peanut shell biochar). Peanut shell biochar and rice hull biochar with 3.72 percent have the highest P content, making these biochars ideal for phosphorus-deficient soils. Coconut husk biochar has the lowest phosphorus content; hence it may require supplementation for P-deficient soils. For potassium, K levels range from 3.29 percent (peanut shell and sugarcane bagasse biochar) to 4.50 percent (corn cobs biochar). Corn cob biochar has the highest K content, making it a valuable soil amendment for potassium-deficient soils. Peanut shell and sugarcane bagasse biochars (both at 3.29 percent) have the lowest K content, which might require additional potassium supplementation. Potassium is essential for plant growth, improving drought tolerance, and enhancing crop yields.

The micronutrient contents varied from among the five biochar formulations. Zinc levels range from 142.71 ppm (rice hull biochar) to 415.94 ppm (corn cob biochar). Corn cob biochar (415.94 ppm) contains the highest Zn, making it particularly beneficial for zinc-deficient soils. Rice hull biochar has the lowest Zn content (142.71 ppm), indicating that it may not be the best biochar choice for Zn-deficient soils. Copper, on the other hand, is highest in peanut shell biochar (44.69 ppm), making it useful for soils lacking copper. Rice hull biochar has the lowest Cu (31.88 ppm), which may require additional copper fertilization. Corn cob biochar has the highest Mn content (358.96 ppm), making it effective for Mn-deficient soils. Coconut husk biochar has the lowest Mn (307.29 ppm), meaning it may be less effective in correcting Mn deficiencies. Fe levels vary from 748.86 ppm (coconut husk biochar) to 1711.25 ppm (peanut shell biochar). Peanut shell biochar has the highest Fe content (1711.25 ppm), making it highly beneficial for Fe-deficient soils. Coconut husk biochar has the lowest Fe (748.86 ppm), which may require supplementation for Fe-deficient conditions.

Based on the result of the analysis, peanut shell biochar has the highest organic matter, organic carbon, nitrogen, phosphorus, and iron, making it an excellent soil amendment for improving soil fertility and nutrient retention. However, corn cob biochar contains the highest potassium, zinc, and manganese, making it beneficial for soils needing these nutrients. Coconut husk biochar has relatively balanced nutrient levels but the lowest available phosphorus and iron, making it less effective in soils requiring high Fe and P inputs. Rice hull biochar has the lowest pH and the least amount of zinc and copper, making it potentially less effective in Zn-deficient soils. Sugarcane bagasse biochar has good overall properties, especially in pH and organic matter, making it useful in improving soil structure and neutralizing acidic soils.

Effect of Pelleted Biochar on Soil Properties and Organic Matter Content

Incubation Study 1. Table 2 presents the chemical properties of soil after a 60-day incubation period with different biochar treatments. It compares soil without biochar (control) against soils treated with biochar pellets derived from mixture of PM and five feedstocks. The data provides insights into the effect of biochar on soil nutrients, all of which are crucial for soil fertility and plant growth.

Table 2. Chemical properties of incubated soil with and without biochar pellets

TREATMENTS	Soil pH	OM (%)	N (%)	P (ppm)	K (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)
Soil (No biochar)	4.36 c	1.60 b	0.08 b	9.40 d	419	1.78 c	3.76	125.93	93.53 a
Corn Cobs Biochar	6.06 ab	2.36 a	0.12 a	140.27 a	871	7.27 a	2.98	128.87	45.60 b
Rice Hull Biochar	5.66 b	2.27 a	0.11 a	104.53 c	979	3.78 b	3.4	126.87	53.00 b
Peanut Shell Biochar	5.97 ab	2.25 a	0.11 a	126.00 ab	1013	4.29 b	3.21	112.53	50.40 b
Sugarcane Bagasse Biochar	6.43 a	2.39 a	0.12 a	125.07 b	1114	4.77 b	3.19	115.67	48.67 b
Coconut Husk Biochar	6.09 ab	2.28 a	0.11 a	121.93 b	882	5.07 b	3.13	139.32	46.37 b
C.V. (%)	3.75	5.71	7.14	5.27	39.68	14.8	10.4	9.66	7.68

The initial soil (without biochar) has a highly acidic pH of 4.36, which can hinder nutrient availability and plant growth. All biochar treatments significantly increase soil pH, making the soil less acidic. Sugarcane bagasse biochar (pH 6.43) has the highest pH, followed by coconut husk biochar (pH 6.09) and corn cob biochar (pH 6.06). Rice hull biochar results in the lowest pH increase (5.66), though still higher than the control. This demonstrates that biochar application helps neutralize acidic soils, promoting better conditions for microbial activity and plant nutrient uptake. Organic matter (OM) improves soil structure, water retention, and microbial diversity. The control soil (without biochar) has the lowest OM (1.60 percent). All biochar treatments significantly increase OM, with sugarcane bagasse biochar (2.39 percent) and corn cob biochar (2.36 percent) showing the highest OM content. The higher OM content in biochar-treated soils suggests improved soil fertility, as biochar enhances organic material decomposition and nutrient retention.

The control soil has the lowest nitrogen content (0.08 percent), while all biochar-treated soils have significantly higher nitrogen levels. Corn cob biochar (0.12 percent) and sugarcane bagasse biochar (0.12 percent) provide the highest nitrogen content. The nitrogen enhancement is likely due to biochar’s ability to retain nutrients, reduce nitrogen leaching, and support nitrogen-fixing microbes. Phosphorus is necessary for root development, flowering, and fruiting. The control soil has very low phosphorus levels (9.40 ppm), making it phosphorus deficient. Biochar significantly improves phosphorus availability, with corn cob biochar (140.27 ppm) showing the highest increase, followed by peanut shell biochar (126 ppm). The enhanced phosphorus content indicates biochar's role in binding and slowly releasing phosphorus, making it more available to plants. Potassium (K) is vital for plant growth, enhancing resistance to diseases and drought. The control soil has 419 ppm of potassium, which is much lower compared to the biochar-treated soils. Sugarcane bagasse biochar (1114 ppm) and peanut shell biochar (1013 ppm) show the highest potassium content. This suggests that biochar application can help in replenishing soil potassium levels, reducing leaching, and maintaining soil fertility.

The control soil has the lowest zinc content (1.78 ppm), indicating a deficiency. Corn cob biochar significantly increases Zn to 7.27 ppm, the highest among treatments. Other biochar also improves Zn levels, though less than corn cobs. This indicates that biochar application, especially from corn cobs, can correct Zn deficiencies in the soil. Copper is essential for plant metabolism and enzyme functions. There is no significant difference in Cu levels among treatments, as all values remain within a small range (2.98 to 3.76 ppm). Biochar application maintains Cu levels, preventing deficiencies but not drastically increasing it. Manganese levels range from 125.93 ppm (control) to 139.32 ppm (coconut husk biochar). Coconut husk biochar results in the highest Mn content (139.32 ppm), suggesting its effectiveness in improving Mn availability. Other biochars show moderate Mn levels, indicating that biochar helps maintain Mn but does not cause excessive accumulation. Iron is essential for chlorophyll production and energy transfer in plants. Interestingly, the control soil has the highest Fe content (93.53 ppm), while biochar-treated soils have lower Fe levels. Corn cob biochar (45.60 ppm) results in the lowest Fe content. This suggests that biochar may bind excess iron, reducing its availability in soils where Fe toxicity is an issue. However, for Fe-deficient soils, supplementation may be required when applying biochar.

From the findings, biochar pellets significantly increases soil pH, reducing acidity and improving nutrient availability. Soil organic matter improves across all biochar treatments, with sugarcane bagasse and corn cobs leading in OM enhancement. Nitrogen content increases with biochar pellet application, especially with corn cobs and sugarcane bagasse. Phosphorus availability is drastically improved, with corn cob and peanut shell biochar providing the highest P levels. Potassium content increases significantly, with sugarcane bagasse biochar contributing the most. Corn cob biochar is the best for increasing zinc levels, while coconut husk biochar enhances manganese availability. Iron levels decrease with biochar, indicating that biochar may help regulate excess Fe in the soil.

Incubation Study 2: Table 3 presents the chemical composition of soil before and after incubation with corn cob biochar, highlighting changes in soil pH, organic matter, organic carbon, nitrogen, phosphorus, and potassium.

Table 3. Chemical Composition of Soil after Incubation with Biochar (Corn Cobs)

Chemical Properties	Before	After	SD	$t_{0.05}$	Pr(>|t|)
Soil pH	5.40	5.94	0.382	21.00*	0.0303
Organic Matter (%)	1.44	2.17	0.516	4.95^{ns}	0.1270
Organic Carbon (%)	0.84	1.25	0.290	5.10^{ns}	0.1233
Nitrogen (%)	0.07	0.11	0.028	4.50^{ns}	0.1392
Available P (ppm)	5.70	12.40	4.738	2.70^{ns}	0.2257
Exchangeable K (ppm)	269.00	450.00	127.986	3.97 *	0.0570

* significant ns – not significant

The soil pH increased from 5.40 to 5.94, with a significant *t*-value of 21.00 (p = 0.0303), showing that the application of corn cob biochar significantly reduced soil acidity. This pH improvement is essential for enhancing nutrient availability and creating a more favorable environment for microbial activity, particularly in acidic soils.

The organic matter) content increased from 1.44 percent to 2.17 percent, and organic carbon rose from 0.84 percent to 1.25 percent. However, the statistical analysis indicates that these changes are not significant (ns, $p > 0.05$). Although the increases in OM and OC suggest that biochar contributes to soil organic matter enrichment, the lack of statistical significance may be due to variability in soil conditions or the duration of incubation.

Nitrogen content also increased from 0.07 percent to 0.11 percent, reflecting biochar's ability to retain nitrogen and reduce leaching losses. However, the statistical test shows no significant difference (t = 4.50, p = 0.1392), suggesting that while biochar can enhance nitrogen levels, its immediate effect might not be substantial enough to be statistically conclusive.

A notable improvement was observed in available phosphorus, which increased from 5.70 ppm to 12.40 ppm. Despite this increase, the *t*-value (2.70) and probability (p = 0.2257) indicate that the change is not statistically significant. This result suggests that while biochar can enhance phosphorus availability by retaining and slowly releasing it, the short incubation period may not have been sufficient to show a strong statistical impact.

The most significant change was in exchangeable potassium, which increased from 269 ppm to 450 ppm. The statistical test confirms that this change is significant (t = 3.97, p = 0.0570). This indicates that corn cob biochar effectively improves potassium levels, likely due to its high K content and ability to reduce nutrient leaching. Increased potassium availability is beneficial for plant growth, particularly in soils that are deficient in this essential nutrient.

Overall, the data demonstrates that corn cob biochar positively influences soil properties, particularly in raising soil pH and increasing potassium availability. Although changes in organic matter, organic carbon, nitrogen, and phosphorus are observed, they are not statistically significant in the short-term incubation period. These results suggest that while biochar can contribute to soil fertility, its effects may become more pronounced over a longer period or when applied in larger quantities. Future research should focus on long-term field trials to assess biochar's sustained impact on soil health and crop productivity.

Incubation Study 3. Table 4 presents the chemical composition of soil after two months of incubation with two types of biochar: Poultry manure-corn cobs biochar and poultry manure-coconut shell biochar.

Table 4. Chemical Composition of Soil after Incubation with Biochar for 2 months

Chemical Properties	Before	After	SD	$t_{0.05}$	Pr(>|t|)
Biochar 1: Poultry manure-corn cobs biochar					
Soil pH	7.28	7.23	0.035	290.20*	0.00
Organic Matter (%)	2.89	3.46	0.403	11.14*	0.05
Organic Carbon (%)	1.67	2.01	0.240	10.82*	0.05
Nitrogen (%)	0.14	0.173	0.023	9.48 ^{ns}	0.06
Available P (ppm)	17.98	34.83	11.914	3.13 ^{ns}	0.19
Exchangeable K (ppm)	322.15	354.52	230.976	2.97 ^{ns}	0.20
Biochar 2: Poultry manure-coconut shell biochar					
Soil pH	7.28	7.43	0.106	98.06*	0.00
Organic Matter (%)	2.89	3.09	0.141	29.90*	0.02
Organic Carbon (%)	1.67	1.79	0.848	28.83*	0.02
Nitrogen (%)	0.14	0.15	0.007	29.00*	0.02
Available P (ppm)	17.98	42.60	17.408	2.46 ^{ns}	0.24
Exchangeable K (ppm)	322.15	648.80	22.889	20.90 *	0.03

* significant ns – not significant

Effects of Poultry Manure-Corn Cobs Biochar on Soil Properties

For the Poultry manure-corn cobs biochar, the soil pH slightly decreased from 7.28 to 7.23, with a highly significant t-value of 290.20 (p = 0.00). This slight decrease in pH indicates that although biochar is generally alkaline, the combination with poultry manure may have moderated its effect on soil acidity, making the pH more balanced for nutrient availability.

The organic matter increased from 2.89% to 3.46%, with a statistically significant change (t = 11.14, p = 0.05), suggesting that biochar application effectively improves soil organic content. Similarly, organic carbon increased from 1.67% to 2.01%, also with a significant result (t = 10.82, p = 0.05), confirming biochar's role in enhancing soil carbon storage and organic material retention.

Nitrogen content increased from 0.14% to 0.173%, but the change was not significant (ns, p = 0.06). While biochar contributes to nitrogen retention, the lack of significance may indicate that more time is required to observe stronger effects. Similarly, available phosphorus increased from 17.98 ppm to 34.83 ppm, but the change was not statistically significant (t = 3.13, p = 0.19), likely due to variability in phosphorus release. Exchangeable potassium also showed an increase from 322.15 ppm to 354.52 ppm, but the change was not significant (t = 2.97, p = 0.20), suggesting that more incubation time may be needed for biochar to release potassium effectively.

Effects of Poultry Manure-Coconut Shell Biochar on Soil Properties

For the Poultry manure-coconut shell biochar, the soil pH increased from 7.28 to 7.43, a statistically significant change (t = 98.06, p = 0.00). This suggests that coconut shell biochar, combined with poultry manure, had a stronger alkalizing effect on the soil compared to corn cobs biochar.

The organic matter increased from 2.89 to 3.09 percent, and organic carbon increased from 1.67 to 1.79 percent, both of which were statistically significant (OM: t = 29.90, p = 0.02; OC: t = 28.83, p = 0.02). These results confirm that coconut shell biochar, like corn cobs biochar, enhances organic matter and carbon content in the soil, improving soil structure and microbial activity.

Nitrogen content showed a slight increase from 0.14 to 0.15 percent, and this change was significant (t = 29.00, p = 0.02), suggesting that coconut shell biochar was more effective in improving nitrogen retention compared to corn cobs biochar. Available phosphorus also increased significantly from 17.98 ppm to 42.60 ppm, but the result was not statistically significant (t = 2.46, p = 0.24), indicating that biochar's ability to improve phosphorus availability may take longer to manifest fully.

The most significant change was observed in exchangeable potassium, which increased from 322.15 ppm to 648.80 ppm, with a highly significant result (t = 20.90, p = 0.03). This suggests that Poultry manure-coconut shell biochar is particularly effective in increasing soil potassium, which is vital for plant growth, disease resistance, and drought tolerance.

Comparison of the Two Biochar Treatments

Both types of biochar positively impacted soil fertility, but with some differences in effectiveness: Poultry manure-corn cobs biochar slightly reduced soil pH, while Poultry manure-coconut shell biochar increased it. Both biochar significantly increased organic matter and organic carbon, improving soil organic content. Coconut shell biochar had a greater effect on nitrogen retention, while corn cobs biochar showed a higher phosphorus increase (though not statistically significant). Coconut shell biochar significantly improved exchangeable potassium, making it the best option for potassium-deficient soils.

The results indicate that both types of biochar improve soil quality by increasing organic matter, organic carbon, and nitrogen, while also affecting phosphorus and potassium availability. Coconut shell biochar is particularly effective for increasing soil potassium and nitrogen retention, making it beneficial for nutrient-poor soils. Meanwhile, corn cobs biochar contributes more to phosphorus availability and slightly lowers soil pH, making it more suitable for alkaline soils needing phosphorus enhancement.

These findings suggest that biochar application, especially when combined with poultry manure, is a viable strategy for enhancing soil fertility in organic farming. However, longer incubation periods and field trials are necessary to determine the full extent of biochar's effects on soil and crop productivity.

Crop Yield Performance

Table 5 presents the effect of different types of pelleted biochar on the yield of rice, corn, peanut, eggplant, and honeydew. The treatments include various biochar sources (rice hull, corn cobs, coconut shell, sugarcane bagasse, and peanut shell), compared against the standard recommended rate of NPK fertilizer (T1 – RR NPK).

Table 5. Effect of pelleted biochar on yield of various crops

TREATMENTS	Rice (t/ha)	Corn (t/ha)	Peanut (t/ha)	Eggplant (t/1000 m^2)	Honeydew (t/ha)
T_1 – RR NPK	8.75 a	7.75	3.69 c	1.18	28.68
T_2 – rice hull biochar	6.69 c	8.61	4.68 b	1.29	14.72

T_3 – corn cobs biochar	8.07 b	8.71	4.68 b	1.12	15.25
T_4 – coconut shell biochar	8.19 b	8.38	4.70 ab	1.25	16.00
T_5 – sugarcane bagasse biochar	8.55 ab	9.10	4.77 a	1.16	15.10
T_6 – peanut shell biochar	7.10 c	8.80	4.67 b	1.32	17.05
CV (%)	2.15	2.34	0.56	10.35	3.09

For rice, the highest yield was observed with T1 – RR NPK (8.75 t/ha), which indicates that conventional fertilizer still provides optimal growth conditions. However, sugarcane bagasse biochar (T5) recorded a comparable yield of 8.55 t/ha, showing that it can be an effective alternative soil amendment. Corn cobs biochar (8.07 t/ha) and coconut shell biochar (8.19 t/ha) also showed good performance, suggesting their potential in enhancing soil fertility for rice cultivation. On the other hand, rice hull biochar (T2 – 6.69 t/ha) and peanut shell biochar (T6 – 7.10 t/ha) resulted in lower yields, indicating their lower efficiency in improving soil productivity for rice.

For corn, all biochar treatments outperformed the conventional fertilizer. The highest yield was observed in sugarcane bagasse biochar (T5 – 9.10 t/ha), followed by peanut shell biochar (T6 – 8.80 t/ha) and corn cobs biochar (T3 – 8.71 t/ha). These results suggest that biochar enhances soil conditions for corn growth, potentially due to its ability to improve soil moisture retention and nutrient availability.

In peanut, sugarcane bagasse biochar (T5 – 4.77 t/ha) performed best, followed by coconut shell biochar (T4 – 4.70 t/ha). Conventional fertilizer (T1 – 3.69 t/ha) had the lowest yield, highlighting that biochar has a significant positive impact on peanut cultivation. This may be due to biochar's ability to enhance soil aeration and increase organic matter, both crucial for legume growth.

For eggplant, peanut shell biochar (T6 – 1.32 t/1000 m²) and rice hull biochar (T2 – 1.29 t/1000 m²) led to the highest yields. This suggests that these biochar types contribute positively to soil quality for eggplant growth, likely by improving nutrient availability and soil structure. The lowest yield was recorded for corn cobs biochar (T3 – 1.12 t/1000 m²), indicating that not all biochar types are equally effective across different crops.

For honeydew, the highest production was observed in T1 – RR NPK (28.68 t/ha), demonstrating that conventional fertilizer is still highly effective for honeydew farming. However, peanut shell biochar (T6 – 17.05 t/ha) and coconut shell biochar (T4 – 16.00 t/ha) produced moderately high yields, indicating their effectiveness in maintaining soil fertility for honeydew. On the other hand, rice hull biochar (T2 – 14.72 t/ha) had the lowest yield, suggesting it may be less suitable for honeydew cultivation.

Overall, the results suggest that sugarcane bagasse biochar (T5) consistently performed well across multiple crops, making it one of the most effective biochar treatments. While conventional fertilizers still provide the highest yields, biochar-based treatments offer a viable alternative, particularly for peanut and corn production. The variation in performance across different biochar types indicates that their effectiveness depends on crop-specific nutrient requirements and soil conditions.

Table 6 presents the yield performance of different crops (sweet corn, pepper, carrot, and radish) under various biochar treatments, including combinations of biochar with NPK fertilizer. The treatments include full-rate NPK (T2), reduced-rate NPK (T3), biochar-only applications (T6), and biochar combined with NPK (T4 and T5).

Table 6. Yield of various crops with pelleted biochar as nutrient supplement

TREATMENTS	Sweet Corn		Pepper (t/ha)	Carrot (kg/1000 m2)	Radish (kg/1000 m2)
	With Husk	Without Husk			
T_1 - Control	5.51 e	4.35 e	6.30	396.00 c	1806.90

T_2 - RR NPK	10.69 bc	8.58 bc	10.60	539.52 b	2612.37
T_3 – 0.5RR NPK	9.10 c	7.42 c	9.40	524.48 b	2257.37
T_4 – RR NPK plus biochar	12.99 a	10.52 a	12.50	775.36 a	3008.25
T_5 – 0.5NPK plus biochar	12.20 ab	9.82 ab	10.30	750.72 a	2962.89
T_6 - Pelleted Biochar (3 t ha^{-1})	7.32 d	6.00 d	6.50	478.72 bc	2143.27
CV (%)	5.93	5.84	8.13	5.47	4.66

For sweet corn, measured both with husk and without husk, the highest yield was observed in T4 – RR NPK plus biochar (12.99 t/ha with husk, 10.52 t/ha without husk), indicating that combining biochar with full-rate NPK leads to the best crop performance. T5 – 0.5NPK plus biochar (12.20 t/ha with husk, 9.82 t/ha without husk) also resulted in high yields, showing that even with a reduced fertilizer rate, biochar improves crop productivity. On the other hand, the lowest yield was observed in T1 – Control (5.51 t/ha with husk, 4.35 t/ha without husk), confirming that biochar and fertilizers significantly enhance sweet corn yield.

For pepper, the highest production was again seen in T4 – RR NPK plus biochar (12.50 t/ha), demonstrating the synergistic effect of biochar with fertilizers. T5 – 0.5NPK plus biochar (10.30 t/ha) also performed well, suggesting that biochar allows for fertilizer reduction while maintaining productivity. The lowest yield was recorded for T1 – Control (6.30 t/ha), indicating that biochar or fertilizers are necessary for optimal pepper production.

For carrot, the highest yield was achieved with T4 – RR NPK plus biochar (775.36 kg/1000 m²), followed closely by T5 – 0.5NPK plus biochar (750.72 kg/1000 m²). This suggests that biochar contributes positively to carrot growth by enhancing soil structure and nutrient availability. T1 – Control (396.00 kg/1000 m²) had the lowest yield, confirming the importance of nutrient supplementation.

For radish, the highest production was also observed in T4 – RR NPK plus biochar (3008.25 kg/1000 m²), followed by T5 – 0.5NPK plus biochar (2962.89 kg/1000 m²). The lowest yield was recorded in T1 – Control (1806.90 kg/1000 m²). The results suggest that radish, like other root crops, benefits from biochar's ability to enhance soil aeration and nutrient retention.

The findings indicate that combining biochar with NPK fertilizer provides the best crop yields, particularly in sweet corn, pepper, carrot, and radish production. The most effective treatment was T4 (RR NPK plus biochar), demonstrating that biochar enhances nutrient efficiency when used with conventional fertilizers. Additionally, T5 (0.5NPK plus biochar) achieved comparable yields to full-rate NPK treatments, suggesting that biochar can allow farmers to reduce chemical fertilizer use while maintaining high productivity.

The performance of T6 (Pelleted Biochar alone, 3 t/ha) was lower than NPK-based treatments but still improved yields compared to the control. This suggests that while biochar alone provides some benefits, it is more effective when supplemented with fertilizers.

CONCLUSION

Conclusion

The findings of the study demonstrate that densified biochar pellets produced from locally available agricultural wastes are an effective and sustainable soil amendment capable of improving soil health and enhancing agricultural productivity. The conversion of agricultural residues such as rice hulls, corn cobs, coconut husks, sugarcane bagasse, and peanut shells into biochar pellets provides a practical solution to the growing problem of agricultural waste disposal while simultaneously transforming these residues into value-added products that contribute to sustainable farming. The study further established that the application of pelleted biochar significantly improved key soil chemical properties, including soil pH, organic matter content, nutrient availability, and overall soil fertility. Different biochar feedstocks exhibited distinct nutrient profiles, making them suitable for specific soil conditions and crop requirements. Moreover, the incorporation of biochar into the soil enhanced nutrient retention and improved the efficiency of nutrient utilization, thereby creating favorable conditions for crop growth and development. These improvements translated into increased yield performance across several cereal, legume, vegetable, and root crops, particularly when biochar was integrated with recommended or reduced rates of inorganic fertilizers.

The results also indicate that integrating pelleted biochar into existing fertilizer management practices can reduce dependence on synthetic fertilizers while maintaining or even improving crop productivity. This integrated nutrient management approach promotes efficient resource utilization, lowers production costs over time, minimizes nutrient losses, and reduces the environmental impacts associated with excessive chemical fertilizer application. Furthermore, biochar contributes to long-term soil improvement through carbon sequestration, enhanced microbial activity, increased water-holding capacity, and improved soil structure, making it a valuable component of climate-resilient agricultural systems.

Hence, the study confirms that biochar pellet technology represents a promising innovation for sustainable agriculture. By simultaneously addressing agricultural waste management, soil degradation, nutrient efficiency, and crop productivity, densified biochar pellets offer an environmentally sound and economically viable strategy for promoting sustainable crop production. Their adoption can significantly support organic farming initiatives, strengthen climate-smart agricultural practices, and contribute to long-term food security and environmental sustainability. These findings underscore the importance of expanding research, production, and field application of biochar technology as part of integrated soil fertility management and sustainable agricultural development programs.

RECOMMENDATIONS

Based on the findings, the use of biochar pellets is highly recommended as a sustainable soil amendment to improve soil fertility and crop productivity while reducing dependence on chemical fertilizers. To maximize its benefits, farmers should be trained through on-farm demonstrations and capacity-building programs in partnership with LGUs, cooperatives, and extension agencies. Further research should focus on optimizing biochar formulations for specific soils and crops and conducting long-term field trials to validate its effectiveness under different conditions. Scaling up production through collaborations with government agencies, private enterprises, and farmer groups is encouraged to make the technology widely available and affordable. Finally, policy support should be strengthened by integrating biochar technology into national programs like the Philippine Organic Agriculture Act (RA 10068) to promote wider adoption, environmental sustainability, and climate-resilient farming.

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STATEMENTS AND DECLARATIONS

No Conflict of Interest

The author declare that he had no known competing interests or personal relationships that could appear to have influenced the work reported in this paper".

Ethics Approval and Consent to Participate

This study did not involve any human participants, animals, or clinical trials that would require ethical approval. Prior informed consent was obtained from all farmer-respondents before conducting the surveys and interviews.

Consent for Publication

The author confirms that all participants provided their consent for the publication of data and findings included in this manuscript.

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interests

The author declares no competing financial or non-financial interests relevant to this study.

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Authors' Contributions

- Artemio A. Martin Jr., PhD — Conceived and designed the study, coordinated project implementation, supervised fieldwork, analyzed the data, and wrote the manuscript.