

Optimizing Vegetable Waste-Derived Biochar: Thermal Conversion for Sustainable Soil Fertility

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ABSTRACT

Biochar is a carbon-rich material made by heating organic matter, and it can improve soil health while helping the environment. In this study, we looked at how different pyrolysis temperatures (350°C, 450°C, and 550°C) affect biochar made from onion, banana, and orange peels. We also tested how these biochars influenced soil properties and the growth of chili (*Capsicum annuum*) and brinjal (*Solanum melongena*) plants. Vegetable waste with high lignocellulose content proved to be a good source for making biochar. Our results show that the pyrolysis temperature strongly affects both the amount and chemical makeup of the biochar. Lower temperatures (350°C) gave higher yields, retained more nutrients like phosphorus (0.40% in onion peel biochar), and preserved important functional groups such as -OH and -COOH. Adding biochar to soil raised the pH and made more nutrients available. Onion peel biochar made at 350°C had a more positive effect on plant growth, producing the tallest chili (2.47 cm/week) and brinjal (2.33 cm/week) plants. These findings highlight that lower pyrolysis temperatures (350°C) provide the greatest benefit from vegetable waste biochar and support sustainable farming.

Keywords: Biochar, Vegetable Waste, Pyrolysis, Temperature, Nutrient Retention, *Capsicum annuum*, *Solanum melongena*.

1. Introduction

Biochar is a type of charcoal made by heating plant material with little oxygen¹. It has a large surface area, is porous, and holds water well. As managing organic waste like vegetable peels, stems, and leaves becomes harder, researchers are exploring pyrolysis as a sustainable way to turn this waste into biochar².

Augmenting biochar into soil enhances water retention, improves aeration, and supports nutrient cycling, boosting plant growth and reducing environmental impact³. Biochar also helps to store carbon in the soil for long periods. Conditions, particularly pyrolysis temperature, affect biochar properties. Elevated temperatures typically decrease biochar yield due to increased volatilization, but enhance carbon content, structural stability, and adsorption capacity. Biochar produced at moderate temperatures, approximately 400°C, often exhibits higher cation exchange capacity, which facilitates nutrient retention and supports soil fertility.

Understanding the influence of feedstock type (e.g., vegetable waste) and pyrolysis temperature on biochar characteristics is important to determine how the type of starting material (like vegetable waste) and the temperature used during pyrolysis affect biochar, so we can make the best biochar for soil improvement⁴.

2. Materials and Methods

In this study, we examined the physical and chemical properties of biochar made from onion, banana, and orange peels at different temperatures and tested their effects on soil and plant growth. The study was conducted in the Kalladikod area of Mannarkkad taluk, Palakkad district. The collected peels were dried in a hot air oven. Carbon content was calculated based on the residual carbon remaining after ignition. Five grams of each biochar sample were weighed into a crucible and put in a muffle furnace for 30 minutes at the respective pyrolysis temperatures (350°C, 450°C, 550°C). The final weight of the crucible with the black powdered ash was used to calculate the carbon percentage. Flame photometry was used to determine the presence and concentration of elements found crucial for soil fertility and plant growth, such as potassium (K), sodium (Na), calcium (Ca), organic carbon (OC), nitrogen (N), iron (Fe), and phosphorus (P).

We used Fourier Transform Infrared spectroscopy to identify the functional groups that affect cation exchange capacity and adsorption⁵. We prepared soil samples as KBr pellets and recorded their spectra. Before adding biochar, we measured the basic properties of the loamy soil. We determined soil texture using the hydrometer method⁵. We measured pH and electrical conductivity (EC) in a 1:2.5 soil-to-water mix using a pH meter and a conductivity meter⁶. Organic carbon (OC) was measured with the Walkley-Black method, and available potassium (K) was measured with a flame photometer after extraction with ammonium acetate⁷.

We used a completely randomized design (CRD) with nine biochar treatments (three peel types and three temperatures) and a control group (soil without biochar), for a total of 10 treatments. Each treatment was repeated ten times, for 100 experimental units. We added 2.5g of biochar to the soil and mixed it well. We left the mixtures for 7 days to allow the biochar and soil to interact. Chili (*Capsicum annuum*) and brinjal (*Solanum melongena*) were used as test plants⁸. Trays with 25g of the soil-biochar mix were watered with deionized water to keep the soil at about 60% of field capacity, and no extra fertilizers were used⁹.

3. Results and Discussion

The study assessed plant growth for 30 days, documenting the germination rate of seeds that sprouted within 7 days, measuring plant height every 15 days, and counting leaves every 15 days. Pyrolysis temperature is a key factor in determining biochar properties. The result aligns with earlier studies showing that lower temperatures, such as 350°C, retain more volatile compounds and yield more biochar. Whereas higher temperatures (450°C and 550°C) lead to lower yields as more compounds break down¹⁰. Although higher temperatures usually increase carbon content and stability, the 350 °C samples showed the highest carbon percentages for all three peel types, as shown in Table 1. The temperature also changes the functional groups and surface chemistry of the biochar. FTIR analysis showed that biochar made at 350°C kept more oxygen-containing functional groups, such as O-H stretching (alcohols or phenols) at 3691.09, =C-H stretch at 910.53, and C-O bonds in alcohols or phenols at 1002.80, as shown in Fig. 1.

These functional groups are important because they help biochar hold and supply nutrients by increasing its cation exchange capacity (CEC). At 450°C, these groups became less intense, making the biochar more stable but less reactive. Lower pyrolysis temperatures (350°C) kept more nutrients in the biochar. For example, onion peel biochar made at 350°C had higher amounts of phosphorus (0.40%), nitrogen (0.19%), and potassium (2.08%), as shown in Table 2. The higher phosphorus in onion peel biochar at 350°C is because less phosphorus is lost at this temperature. The porous structure and functional groups at 350°C also supported microbes and improved nutrient cycling, leading to better growth. Of all the treatments, onion peel biochar at 350°C performed best, contributing to the tallest chili (2.47 cm/week) and brinjal (2.33 cm/week) plants. Orange peel biochar had a balanced nutrient profile but only moderate effects, which became weaker as pyrolysis temperature increased and more nutrients were lost.

The pyrolysis temperature affected the carbon content of the biochar. Lower temperatures led to higher carbon percentages across all peel types.

Table 1: Calculation of Carbon Percentage

Sample	Degree	Initial weight	Final weight	Carbon percentage
Banana	350	17.77	10.98	61.78
	450	13.99	7.20	51.46
	550	12.25	5.73	46.77
Orange	350	14.8	7.73	52.22
	450	13.13	6.06	46.15
	550	12.28	5.21	42.42
Onion	350	27.12	20.34	75.00
Onion	450	17.77	10.99	61.84
Onion	550	12.1	5.33	44.04

The results indicated that onion peel biochar produced at 350°C contained the highest carbon content (75%), followed by banana peel. The results showed that onion peel biochar made at 350°C had the highest carbon content (75%), followed by banana peel (61.78%) and orange peel (52.22%) at the same temperature. The chemical makeup of biochar at 350°C differed for each peel type, as shown in Table 2.

Table: 2 Chemical Composition of Biochar

Sample no	OC	N	P	K	Fe	Zn
Onion 350	7.16	0.19	0.40	2.08	811.20	434.06
Orange 350	3.11	0.25	0.15	1.25	970.40	369.70
Banana 350	4.20	0.18	0.33	4.63	755.80	87.88

Fig 1: FTIR Spectrum of the soil sample taken to mix with biochar

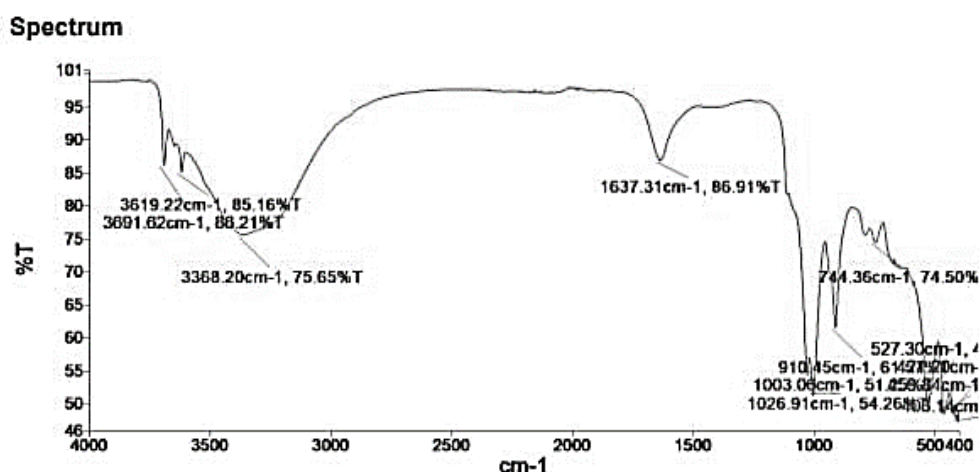


Table 3: Functional group FTIR Onion 350 °C

FTIR value	Functional group
3619.22 cm ⁻¹	O-H stretching vibration alcohol or phenols
3691.62 cm ⁻¹	O-H stretching vibration alcohol or phenols
3368.20 cm ⁻¹	N-H and O-H stretching vibration
1637.31 cm ⁻¹	C=C, C=O, N-H
744.36 cm ⁻¹	C-H out of plane bending in aromatic ring C-Cl stretch (halogens) present
527.30 cm ⁻¹	Metal oxygen bond, C-Br stretch
910.45 cm ⁻¹	Alkaline =C-H, substituted aromatic C-H
1003.06 cm ⁻¹	C-O stretching vibrations
1026.91 cm ⁻¹	C-O stretching vibrations

Table 4: Calculation of Average Plant Height and Std Deviation of Chilly Plant

height than onion peel biochar at 350°C (2.4/4 cm/week). For brinjal, banana peel biochar at 550°C (4.026

Biochar	Pyrolysis Temperature (°C)	Average plant height (cm/week)	Std Deviation	No. of trays
Onion peel	350	4.9125	0.10732	1
Orange peel	350	3.613636	0.62635	1
Banana peel	350	4.441667	0.10647	1
Orange peel + onion peel	350	4.358335	0.499226	1
Orange peel + banana peel	350	4.06087	0.481527	1
Onion peel + banana peel	350	4.675	0.530532	1
Combination	350	4.629167	0.556138	1
Control	Soil	4.458333	0.400201	1

cm/week) produced the tallest plants, much higher than onion peel biochar at 350°C (2.330 cm/week).

Table 5: Calculation of Average Plant Height and Std Deviation of Brinjal Plant

Biochar source	Pyrolysis Temp	Average plant height (cm/week)	Std Deviation	No of tray
Onion peel	350°C	2.330242	0.648438	10
Onion peel	450°C	3.514167	1.097562	10
Onion peel	550°C	1.313478	0.413737	10
Banana peel	350°C	1.49444	0.36197	10
Banana peel	450°C	0.73	0.181755	10
Banana peel	550°C	4.026087	0.943954	10
Orange peel	350°C	1.599034	0.42065	10
Orange peel	450°C	3.765217	0.838618	10
Orange peel	550°C	3.9	0.898989	10
Control	Soil	1.466222	0.634449	10

When we combined biochar, samples made at 350°C, the tallest chili plants grew with the mix of onion peel and banana peel biochar (4.675 cm/week). The treatment with all three biochars together was close behind (4.629 cm/week).

Fig 2: Graph showing average plant height and std Deviation of combination of biochar (Brinjal plant)

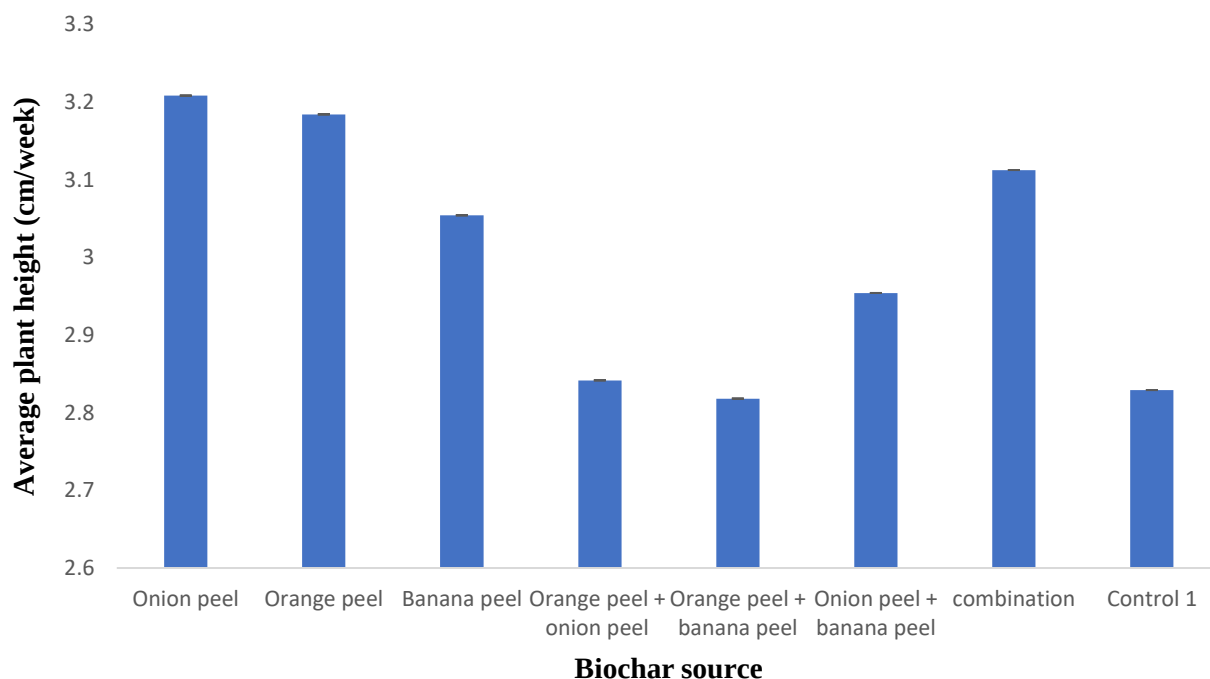
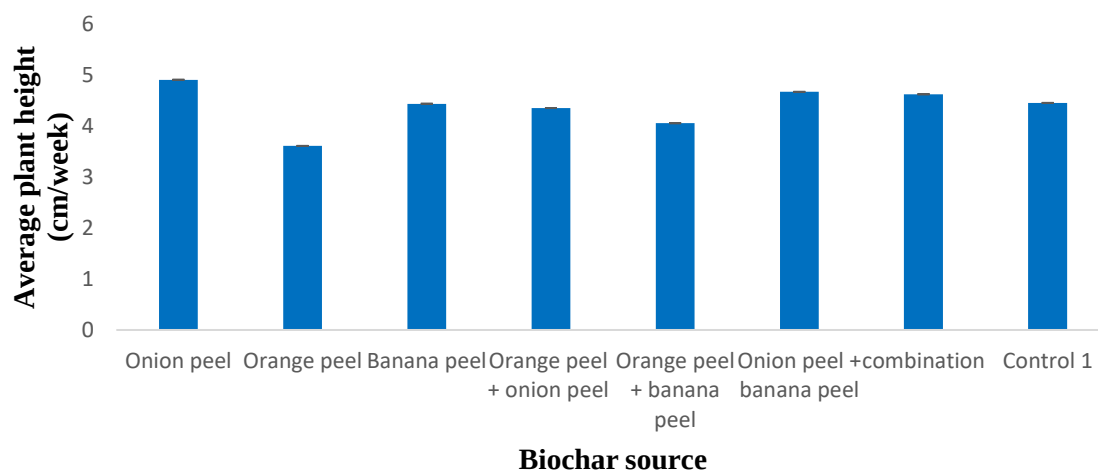


Table 6: Average Plant Height and Std Deviation (Combination of Biochar) Chilly Plant

Biochar source	Pyrolysis Temp	Average plant height (cm/week)	Std Deviation	No. of tray
Onion peel	350°C	4.9125	0.10732	1
Orange peel	350°C	3.613636	0.62635	1
Banana peel	350°C	4.441667	0.10647	1
Orange peel + onion peel	350°C	4.358335	0.499226	1
Orange peel + banana peel	350°C	4.06087	0.481527	1
Onion peel + banana peel	350°C	4.675	0.530532	1
Combination	350°C	4.629167	0.556138	1
Control	Soil	4.458333	0.400201	1

Fig 3: Graph showing average plant height and std Deviation of combination of biochar (chilly plant)



These findings match earlier research showing that lower pyrolysis temperatures keep more nutrients available for plants. The higher phosphorus retention and better plant growth seen with onion peel biochar agree with reports that biochar helps microbes and phosphorus cycling. The strong results from nutrient-rich biochar are similar to studies in which phosphorus-enriched biochar increased crop yields. The results also support concerns that high-temperature biochar can cause nutrient loss and create harmful compounds for plants.

4. Conclusion

This study examined biochar produced from onion, banana, and orange peels at three pyrolysis temperatures (350°C, 450°C, and 550°C) and tested its effects on soil fertility and plant growth. The results show that adding biochar improves soil quality, especially by elevating nutrient levels (NPK) and maintaining suitable pH. Pyrolysis temperature was critical, as lower temperatures (350°C) retained more functional groups and nutrients, making the biochar better for soil. Onion peel biochar at 350°C performed best, with higher phosphorus and more organic compounds, making it a cost-effective and eco-friendly way to support crop growth. Higher temperatures made the biochar more stable but with fewer nutrients. Overall, making biochar from vegetable waste at lower temperatures is a good way to support sustainable farming and better soil health.

5. References

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