Sustainability in Environment
ISSN 2470-637X (Print) ISSN 2470-6388 (Online)
Vol. 10, No. 2, 2025
www.scholink.org/ojs/index.php/se

Original Paper

Buffering and Mitigation of Soil Acidity by Biochar Produced at Varied Temperatures

RongHui Li[1], Yuan Cao[1], Liu Yang[2†], YuLan Chen[2], JunWen Zhao[1], DongLing Hu[1], Rong Huang[1], & Bing Li[1]

[1] College of Resources Sichuan Agricultural University, Chengdu 611130, China

[2] Sichuan Liangshan Prefectural Tobacco Company, Xichang Sichuan 615000, China

[†] Corresponding Author: Liu Yang (1985-), E-mail: 369507968cyl@sina.com

Received: February 23, 2025 Accepted: March 22, 2025 Online Published: April 12, 2025

doi:10.22158/se.v10n2p28 URL: http://dx.doi.org/10.22158/se.v10n2p28

Abstract

To investigate the effects of biochar application on the amelioration of acidified soil (Purple soil), biochar derived from cattle manure was prepared at low (300°C) and high (600°C) temperatures. The study utilized acidified soil with five experimental treatments including a control (CK), 1% low-temperature biochar (NF300-1), 2% low-temperature biochar (NF300-2), 1% high-temperature biochar (NF600-1), and 2% high-temperature biochar (NF600-2), over a 90-day indoor cultivation period. The results showed that the specific surface area of NF600 was 9.4 times that of NF300. Compared to NF300, NF600 exhibited an increased carbon content and decreased nitrogen, hydrogen, and oxygen contents. Ratios such as H/C, O/C, and (O+N)/C also decreased, ash content increased by 20.67%, carbonization rate decreased by 19.79%, pH increased by 19.48%, and mineral content increased slightly though the types remained largely unchanged. The application of biochar notably altered the soil's basic physicochemical properties; throughout the cultivation period, biochar addition notably increased soil pH and notably reduced the content of active aluminum, with the 2% high-temperature biochar (NF600-2) showing the most pronounced effects. By the 90th day, compared to the control, soil pH had increased by 23.69% and active aluminum content had decreased by 47.79%. Additionally, biochar application notably enhanced soil conductivity, although this effect diminished over time. Overall, the application of 2% biochar showed a notably better amelioration effect on acidic soils compared to 1%, and biochar produced at a pyrolysis temperature of 600°C was more effective than that produced at 300°C.

Keywords

Biochar, Soil Amendment, Biochar, Pyrolysis Temperature

1. Introduction

Soil acidification is a key manifestation of land degradation, having adverse effects on both the environment and biological systems. This process increases the concentration of soluble aluminum in soil while reducing soluble and exchangeable base cations. Consequently, the toxicity of aluminum to plants increases, leading to a reduction in the soil's nutrient retention capacity(Yuan & Xu, 2012). With the modernization of industrial and agricultural production influenced by human activities, the acceleration of soil acidification has become an urgent issue. The extensive use of nitrogen fertilizers in agriculture is a primary factor speeding up the acidification process in China. Research in environmental protection and sustainable agriculture focuses on how to mitigate soil acidification while enhancing the retention of soil nitrogen nutrients (Tilman et al., 2011).

Biochar has been identified as an effective means to alleviate soil acidification (Zhang et al., 2013). Biochar is a stable, carbon-rich material produced from biomass under anaerobic or low-oxygen conditions, characterized by a large specific surface area and high porosity. Its surface is rich in chemical functional groups, providing a strong adsorptive capacity (Ok et al., 2015; Wrobel-Tobiszewska et al., 2018). Studies have shown that adding biochar to soil can increase the pH and cation exchange capacity of acidic soils, as well as enhance the content of soil organic matter, available P, and total P, thereby increasing rice yields (Yang et al., 2020). Wang Fan and colleagues have found through soil column simulation experiments that biochar addition can improve soil pH and conductivity, reduce nutrient leaching caused by water, and thus mitigate nitrogen loss in soil (Wang et al., 2017). Research indicates that the yield of rice straw biochar and its pH and carbon content increase with the preparation temperature (Jian et al., 2016). Huang Tao and others have found that as the preparation temperature rises, the pH and ash content of bovine bone biochar increase, while its yield and volatile content decrease (Huang et al., 2023). These findings indicate that biochar produced from different materials and under different conditions can vary notably in its physicochemical properties and its effectiveness in soil improvement. Furthermore, the differences in the physicochemical properties of biochar are more pronounced at different preparation temperatures(Sun, 2023). Additionally, the rate and method of biochar application can also affect soil properties (Li et al., 2016).

Purple soil, a typical soil type in the Southwest region, currently faces significant acidification due to long-term excessive use of nitrogen fertilizers and acid deposition, which impedes agricultural development in this area (Zhang et al., 2017). Recently, the application of biochar for the amelioration of acidified soils has increasingly been recognized. To ascertain the ameliorative effects of biochar on acidified Purple soil, this study employs acidified Purple soil as its research subject and conducts laboratory-based pure culture experiments. It explores the impact of biochar produced under various pyrolysis temperature conditions and its application rates on soil acidity and fertility. This research aims to reveal the interaction between the ameliorative effects on acidified soil and the duration of biochar application, providing a theoretical reference for the improvement of acidified Purple soil in the Southwest region, the protection, restoration, and reconstruction of acidified poor soil ecosystems, and the formulation of scientifically effective arable soil management measures.

2. Materials and Methods

2.1 Experimental Materials

2.1.1 Test Soil

The sampling site is located in Leshan City, Sichuan Province (103.93'N, 28.87'E). The topsoil layer from 0-15 cm was selected as the test soil. The soil type is Purple soil with a gravelly sandy loam texture, a pH of 5.08, an active aluminum content of 31.17 mg/kg, and a soil conductivity of 154.36 μS/cm. After removing debris and naturally air-drying, the soil was ground and sieved through a 10-mesh screen, then mixed and reserved for further use.

2.1.2 Preparation of Biochar Materials

This experiment selected cow dung-derived biochar (NF300, NF600) based on differences in biochar Pyrolysis Temperatures and raw materials. The specific preparation process involved drying and crushing cow dung, then sieving it through a 100-mesh screen and storing it in wide-mouth bottles. Fifty grams of the biomass powder was placed into a crucible and compacted; the crucible was then placed into a muffle furnace under nitrogen atmosphere to ensure anaerobic conditions. The material was carbonized at a heating rate of 10 °C/min at temperatures of 300 °C and 600 °C for two hours each. After cooling to room temperature, the char was sieved through a 100-mesh screen and stored in sealed bags (Tang & Chen, 2018; Wang et al., 2017).

2.2 Experimental Design and Treatments

2.2.1 Experimental Design

The experiment was conducted using a "fertilizer-free, plant-free" pure cultivation method. Five treatments were established: (1) Control with no biochar added to the soil (CK); (2) Soil amended with 1% biochar (by mass, as with all subsequent biochar treatments) produced at 300°C from cattle manure (NF300-1); (3) Soil amended with 2% biochar produced at 300°C from cattle manure (NF300-2); (4) Soil amended with 1% biochar produced at 600°C from cattle manure (NF600-1); (5) Soil amended with 2% biochar produced at 600°C from cattle manure (NF600-2). Each treatment was replicated three times, totaling 15 cultivation bottles. The experimental containers were 500 ml plastic bottles, each filled with 50 g of air-dried soil mixed uniformly with the respective proportion of biochar. All samples were moistened to 70% of field capacity using deionized water and incubated at 25°C in a constant temperature incubator for 90 days. The water lost to evaporation was replenished periodically using a weighing method.

2.2.2 Sample Collection and Preparation

Destructive sampling was performed on days 0, 14, 60, and 90 of cultivation. Each sampling occasion involved collecting one set of replicate samples while maintaining the original soil moisture in the remaining replicates. The collected samples were air-dried for subsequent analysis of soil pH, active aluminum content, and soil conductivity among other parameters.

2.3 Parameter Measurements

2.3.1 Biochar Characterization

The pH of the biochar was measured using a pH meter after extraction with a char-to-liquid ratio of 1:10. The concentrations of carbon (C), hydrogen (H), and nitrogen (N) in the biochar were determined using a CHN elemental analyzer (Flash-EA112, Thermo Finnigan, Italy). The specific surface area of the biochar was measured primarily by nitrogen adsorption, using an automatic surface area and pore distribution analyzer. The biochar's X-ray diffraction spectrum was measured using an X-ray diffractometer (XRD). The ash content and yield of biochar were calculated based on the mass changes before and after pyrolysis.

2.3.2 Soil Basic Physicochemical Properties

Soil pH was measured with a pH meter after uniform mixing with water at a soil-to-water ratio of 1:2.5. Soil conductivity was measured using a conductivity meter at a soil-to-water ratio of 1:5. Ammonium nitrogen and nitrate nitrogen in the soil were first extracted with calcium chloride solution, then analyzed using a flow analyzer. Total nitrogen, available K, available P, total K, total P, and natural organic matter were determined according to the methods in "Soil Agrochemical Analysis." Active aluminum in the soil was quantified using a modified continuous grading extraction method developed by Qiu (Qiu, 2024).

2.4 Data Processing

Data analysis was performed using Microsoft Office Excel 2019 and SPSS 23.0. Charts and graphs were created using Microsoft Office Excel 2019. Differences among treatments were tested for statistical significance using the LSD test ($P<0.05$).

3. Results and Analysis

3.1 Variations in Biochar under Varying Pyrolysis Temperature Conditions

3.1.1 Elemental Composition of Biochar at Diverse Pyrolysis Temperatures

The elemental composition and atomic ratios of biochar produced at varying Pyrolysis Temperatures (300°C, 600°C) differ notably (Table 1). With higher temperatures in pyrolysis, the C content in cattle manure-derived biochar also rises, whereas the contents of N, H, and O decrease. The elemental percentages are ordered as C > O > H > N. The atomic ratios in biochars prepared at different temperatures show variations, with those produced at higher temperatures (NF600) having notably lower H/C, O/C, and (O+N)/C ratios compared to those produced at lower temperatures (NF300). Specifically, as the temperature increases, the H/C ratio decreases from 1.584 to 0.493, the O/C ratio from 0.919 to 0.390, and the (O+N)/C ratio from 0.995 to 0.417.

Table 1. Elemental Composition of Biochar under Various Pyrolysis Temperature Conditions

Sample name	Elemental percentage (%)				Atomic ratios		
	N	C	H	O	H/C	O/C	(O+N)/C
NF300	1.98	22.16	2.93	27.14	1.584	0.919	0.995
NF600	0.81	25.57	1.05	13.28	0.493	0.390	0.417

3.1.2 Physicochemical Properties of Biochar under Varying Pyrolysis Temperature Conditions

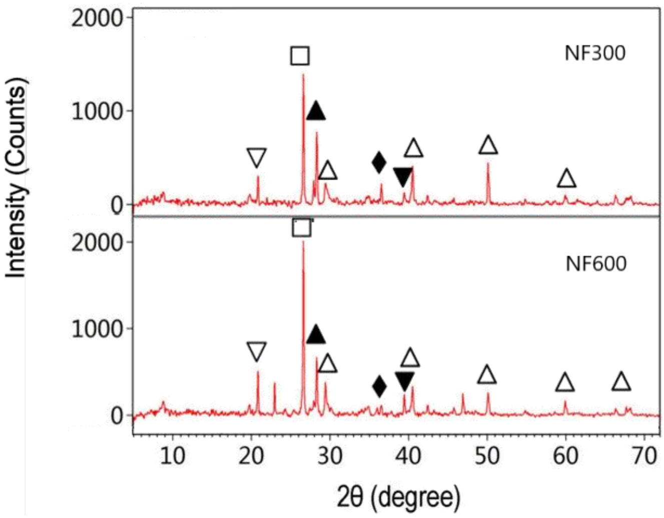
As indicated in Table 2, changes in Pyrolysis Temperature notably impact the specific surface area, ash content, and carbonization rate of biochar. With an increase in Pyrolysis Temperature, the specific surface area of biochar increases, with NF600 having a specific surface area 9.4 times greater than NF300. An examination of ash content reveals that with higher temperatures in pyrolysis from 300°C to 600°C, the ash content in NF600 increases by 20.67%, while the carbonization rate decreases by 19.79%. These changes indicate that biochar produced at higher temperatures contains higher carbon content and a larger specific surface area. Furthermore, the pH of biochar also exhibits a positive correlation with Pyrolysis Temperature, with the pH of NF600 being notably higher at 11.53 compared to 9.65 for NF300, representing a 19.48% increase.

Table 2. Physicochemical Properties of Biochar under Various Pyrolysis Temperature Conditions

Sample name	Specific surface area (m^2/g)	Ash content (%)	Carbonization rate (%)	pH
NF300	2.16	50.00%	76.30%	9.65
NF600	20.30	70.67%	56.51%	11.53

3.1.3 X-ray Diffraction Analysis of Biochar at Varying Pyrolysis Temperatures

The XRD patterns of biochar produced under various Pyrolysis Temperature conditions are presented in Figure 1. By comparing these results with standard reference cards, it is possible to identify the presence of various mineralogical phases such as hybridized carbon, quartz, $CaCO_3$, MgO, Fe_2O_3, and KCl. The mineral crystal types in biochar samples NF300 and NF600 are essentially the same. However, the peak intensities of the minerals in NF600 are higher than those in NF300. Additionally, a greater presence of KCl was detected in NF600, indicating that with higher temperatures in pyrolysis, the mineral content in cattle manure-derived biochar increases, although the types of minerals remain largely unchanged.



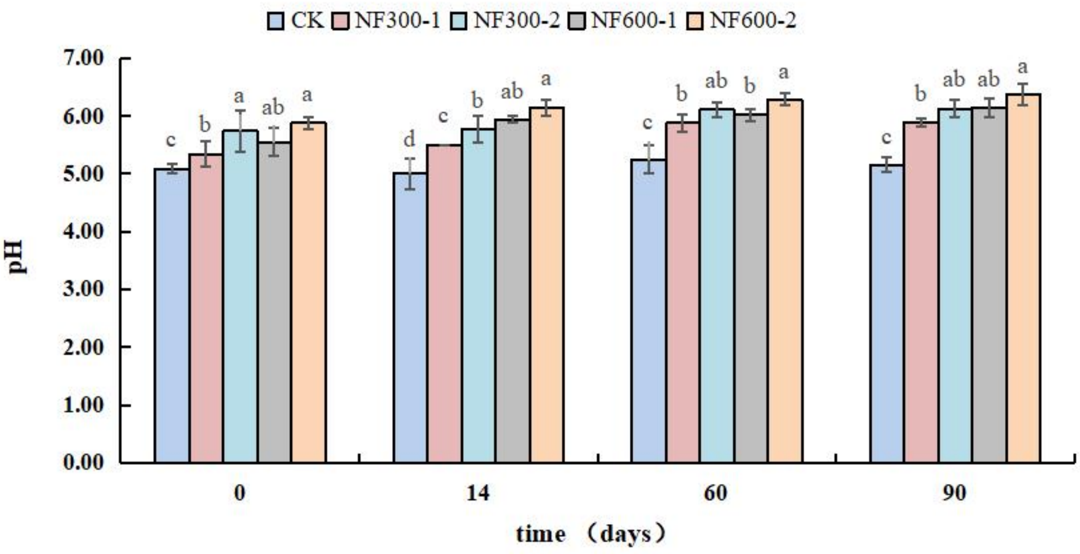
▽: Hybridized carbon; □: Quartz; ▲: $CaCO_3$; ◆: MgO; ▼: Fe_2O_3; △: KCl.

Figure 1. X-ray Diffraction Analysis of Cattle manure-derived Biochar (CB) at 300°C and 600°C

3.2 Effects of Biochar on Soil Acidity

3.2.1 Influence of Different Biochars on Soil pH

Cultivation experiments, as shown in Figure 2, reveal that adding biochar notably increases soil pH throughout the cultivation period compared to the control soil pH (5.00-5.25). This increase becomes more pronounced over time. By the 90th day, the soil pH in treatments NF300-1, NF300-2, NF600-1, and NF600-2 had increased by 0.73, 0.97, 0.99, and 1.22 units respectively, corresponding to increases of 14.17%, 18.83%, 19.22%, and 23.69%. At equivalent biochar dosages, the soil pH for NF600-1 was higher than NF300-1, and NF600-2 was higher than NF300-2, demonstrating that biochars produced at higher temperatures are more effective in raising soil pH. Furthermore, within the same temperature treatments, the pH increase was greater with higher biochar dosages. Overall, the application of cattle manure-derived biochar effectively raises soil pH, with the treatment NF600-2 showing superior performance.

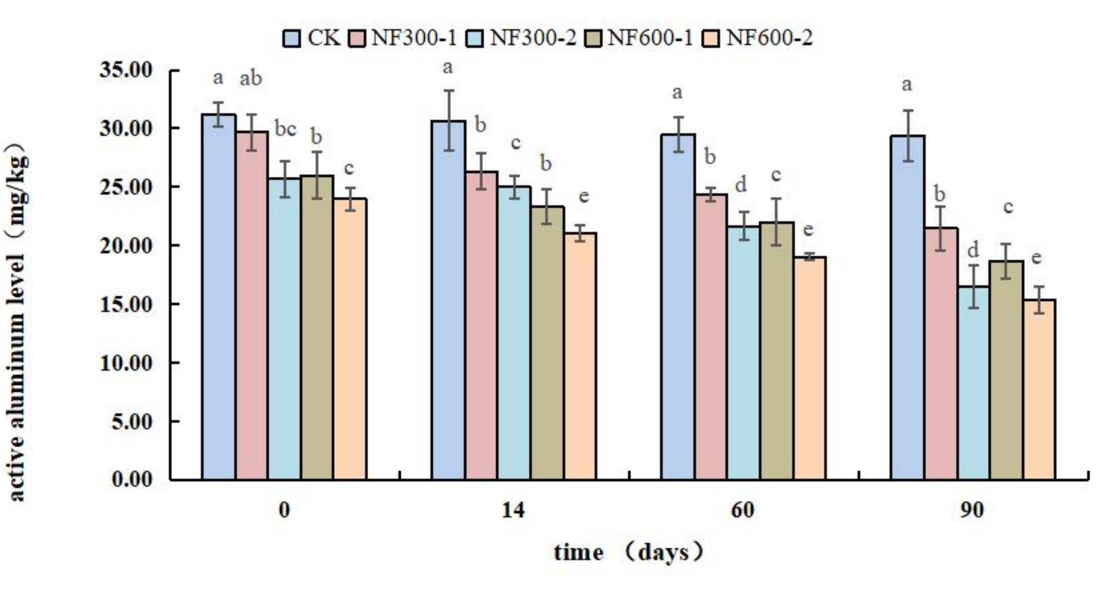


Note: Distinct lowercase letters denote important differences (P<0.05).

Figure 2. Effect of Biochar Addition on Soil pH

3.2.2 Impact of Different Biochars on Soil Active Aluminum Content

As illustrated in Figure 3, the introduction of biochar consistently reduces the content of active aluminum in the soil over the cultivation period. By the 90th day, the active aluminum content in treatments NF300-1, NF300-2, NF600-1, and NF600-2 had decreased by 7.91, 12.86, 10.69, and 14.03 mg/kg, respectively, representing reductions of 26.94%, 43.80%, 36.41%, and 47.79%. The active aluminum content was lower in treatments prepared at higher temperatures (NF600) compared to those at lower temperatures (NF300), and lower in treatments with higher dosages of the same temperature-prepared biochar. These results indicate that the application of biochar notably reduces the soil's active aluminum content, with both the preparation temperature and the biochar amount showing a significant negative correlation with active aluminum levels.

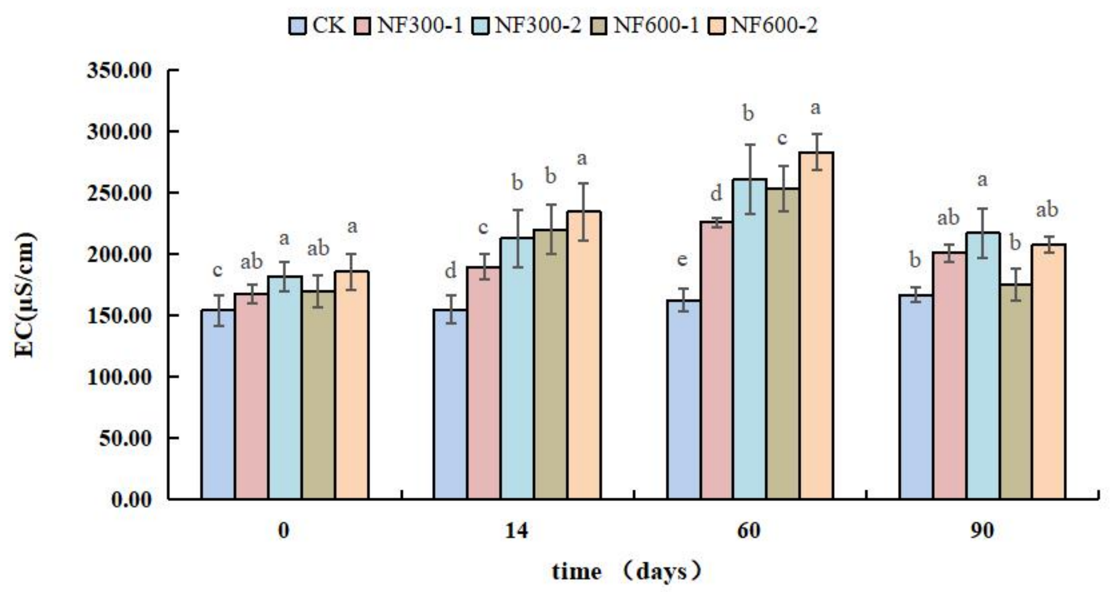


Note. Distinct lowercase letters denote important differences (P<0.05).

Figure 3. Impact of Biochar Addition on Soil Active Aluminum Content

3.2.3 The Impact of Different Biochars on Soil Conductivity

The influence of various biochars on soil EC is depicted in Figure 4. The addition of biochar consistently enhanced soil conductivity throughout the cultivation period. Compared to the CK range of 154.36-166.79 µS/cm, the conductivity showed an initial increase followed by a decrease as the cultivation time extended. Specifically, the conductivity trended upwards from 0 to 60 days, with NF600-1 and NF600-2 showing higher values than NF300-1 and NF300-2 respectively, and NF300-2 being higher than NF300-1, and NF600-2 higher than NF600-1. At day 60, the peak soil conductivity was observed in NF600-2, reaching 283.33 µS/cm, which represents a 74.31% increase as contrasted with the control. However, from 60 to 90 days, a decreasing trend was noted, with reductions in soil conductivity for NF300-1, NF300-2, NF600-1, and NF600-2 by 10.99%, 16.92%, 30.92%, and 26.70%, respectively, compared to the values at day 60. These results indicate that while adding biochar to soil notably boosts its conductivity, the effect of biochar diminishes over time.



***Note*. Distinct lowercase letters denote important differences (P<0.05).**

Figure 4. Impact of Biochar Addition on Soil Conductivity

4. Discussion

Biochar has a wide range of raw materials and various preparation methods. Research indicates significant variation in the properties of biochar produced from different materials and Pyrolysis Temperatures, with the differences attributed mainly to the Pyrolysis Temperature being more pronounced. This study characterizes biochar differences under various Pyrolysis Temperatures in terms of elemental composition, physicochemical properties, and mineral crystal structure. Pyrolysis of biochar is a complex thermochemical process involving dehydration and carbonization(Hossain et al., 2011). The study finds that with higher temperatures in pyrolysis, the content of C in biochar increases, whereas the contents of N, O, and H decrease, consistent with the findings of Zhu.(Zhu et al., 2021). The ratios of H/C and O/C indicate the degree of carbonization of biochar, while the (O+N)/C ratio indicates its polarity, both of which decrease with higher temperatures in pyrolysis. This suggests an enhancement in the carbonization degree and a reduction in polarity (Chun et al., 2004), aligning with the results of other scholars (Wang et al., 2016; Xing et al., 2022). With increasing Pyrolysis Temperature, both the ash content and specific surface area of biochar notably increase, mainly determined by its porosity. Additionally, the Pyrolysis Temperature affects the pore structure of biochar. Higher temperatures lead to the opening of numerous micropores on the surface of biochar, which drastically increases its specific surface area (Dai & Liu, 2013). The pH of biochar rises with increasing Pyrolysis Temperature, primarily because at lower temperatures, the biochar surface contains abundant oxygen-containing functional groups which form acidic substances that gradually volatilize under high temperatures, raising the pH value (Fidel et al., 2017). Research (Yu et al., 2017) indicates that the ash contains alkaline substances, and higher temperatures lead to an increase in ash content, thereby also increasing the pH value of biochar within a certain range (Chun et al., 2004). This study finds that the mineral crystal types in biochar prepared at two different Pyrolysis Temperatures are essentially the same, consistent with the findings of Ma (Ma, 2019) that different Pyrolysis Temperatures do not notably affect the mineral composition of biochar.

Adding biochar can enhance soil pH due to the presence of alkaline functional groups on its surface and its high porosity, which allows for the adsorption of a significant amount of H^+. Studies have also shown that the ability of biochar to amend soil pH is related to its content of nitrates and organic acids (Wu et al., 2014). During the incubation process, the decrease in active aluminum content may be due to the exchange reactions between the basic cations in biochar and exchangeable aluminum in the soil, resulting in reduced levels of exchangeable aluminum (Jiang et al., 2014). Furthermore, the porous structure and the abundant oxygen-containing functional groups on the surface of biochar provide a strong adsorptive capacity for heavy metals and can alleviate aluminum toxicity in acidic soils, consistent with previous research findings (Lin et al., 2017; Zhu et al., 2015). This study indicates that the application of biochar increases soil conductivity, in line with findings by Zhang et al. (Zhang et al., 2020). This increase may be due to the aging of biochar over time, which could reduce soil conductivity (Li et al., 2021).

5 Conclusion

When the Pyrolysis Temperature of biochar production is increased from 300°C to 600°C, the carbon content in biochar increases while the contents of nitrogen, hydrogen, and oxygen decrease. This results in an enhanced degree of carbonization and reduced polarity; the specific surface area, ash content, and pH of the biochar increase, while the yield decreases, and the mineral content increases though the types of minerals remain largely unchanged. Cultivation tests reveal that the application of biochar effectively improves soil pH, reduces the concentration of active aluminum, and increases soil conductivity. Overall, the application of 2% biochar in acidic soil shows a notably better improvement than 1%, and biochar produced at a Pyrolysis Temperature of 600°C has a superior effect on amending acidic soils compared to that produced at 3201700°C. However, further research and analysis are needed to understand the specific mechanisms and processes involved.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Key Science and Technology Projects of Sichuan Tobacco Company (Grant No. SCYC202515). All authors made equal contributions to this study, and there are no conflicts of interest or property rights disputes associated with the publication.

References

Chun, Y., Sheng, G., Chiou, C. T., & Xing, B. (2004). Compositions and Sorptive Properties of Crop

Residue-Derived Chars. *Environmental Science & Technology*, *38*(17), 4649-4655. https://doi.org/10.1021/es035034w

Dai, J., & Liu, Y. S. (2013). Research progress on the properties of biochar and its application in soil environment. *Chinese Journal of Soil Science*, *44*(06), 1520-1525. https://doi.org/10.19336/j.cnki.trtb.2013.06.042

Fidel, R. B., Laird, D. A., Thompson, M. L., & Lawrinenko, M. (2017). Characterization and quantification of biochar alkalinity. *Chemosphere*, *167*, 367-373. https://doi.org/https://doi.org/10.1016/j.chemosphere.2016.09.151

Hossain, M. K., Strezov, V., Chan, K. Y., Ziolkowski, A., & Nelson, P. F. (2011). Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. *Journal of Environmental Management*, *92*(1), 223-228. https://doi.org/https://doi.org/10.1016/j.jenvman.2010.09.008

Huang, T., Hu, L. C., Wu, J. N., Zhang, W. Y., & Mao, L. Q. (2023). Characteristics of biochar derived from cattle bone at different pyrolysis temperatures and its adsorption of Cd^{2+}. *Journal of Agro-Environment Science*, *42*(07), 1632-1644. https://link.cnki.net/urlid/12.1347.S.20230420.1700.005

Jian, M. F., Gao, K. F., & Yu, H. P. (2016). Effects of different pyrolysis temperatures on biochar production and properties from rice straw. *Acta Scientiae Circumstantiae*, *36*(05), 1757-1765. https://doi.org/10.13671/j.hjkxxb.2015.0657

Jiang, J. J., Guo, R., & Chen, L. L. (2014). Research progress on the improvement effect of biochar on acidic and saline-alkali soils. *Agricultural Development & Equipments*, (11), 30-32. https://link.cnki.net/urlid/32.1779.th.20141202.1048.029

Li, S. L., Wang, X., Wang, S., Zhang, Y. W., Wang, S. S., & Shangguan, Z. P. (2016). Effects of biochar application methods and rates on soil water infiltration and evaporation. *Transactions of the Chinese Society of Agricultural Engineering*, *32*(14), 135-144. https://kns.cnki.net/kcms2/article/abstract?v=Kk8bzUe9ukqGY4-ByFZAFnveY8dyekpdvqz3pvYqa5AXZiRUT81UE2wiDuf_-RGrlkDjzWifpXt41VInmaTgqHdGa41FgyrTEOAB4yygJ0zwYGmAwDVgZDVMHxH2Ht3PBgBI4I0iP_n-SzBA4cunlH5FmOZrV6pbycUmZAX_YLhFav-IJnB3aN7FsGMTI7hoSXdHhD9Ups0=&uniplatform=NZKPT&language=CHS

Li, X., Zhang, X. Q., Qi, Y. L., Zhang, C., Ren, D. J., Ye, J., & Zhang, S. Q. (2021). Effects of biochar on soil improvement in tea gardens of western Hubei. *Environmental Science and Technology*, *34*(06), 26-31+36. https://doi.org/10.19824/j.cnki.cn32-1786/x.2021.0082

Lin, Q. Y., Ying, J. G., Zhang, M. Y., Peng, S. A., & Jiang, C. C. (2017). Effects of biochar on different aluminum forms in red soil and the growth of pakchoi. *Journal of Shenyang Agricultural University*, *48*(04), 445-450.

Ma, J. C. (2019). *Characteristics of lobster shell biochar at different pyrolysis temperatures and its adsorption mechanism for heavy metals* [Master's thesis, University of Anhui].

Ok, Y. S., Chang, S. X., Gao, B., & Chung, H.-J. (2015). SMART biochar technology—A shifting paradigm towards advanced materials and healthcare research. *Environmental Technology & Innovation*, *4*, 206-209. https://doi.org/https://doi.org/10.1016/j.eti.2015.08.003

Qiu, H. H. (2024). *Mechanism of red soil aluminum transformation regulated by different organic materials* (Master's thesis, Chinese Academy of Agricultural Sciences). https://link.cnki.net/doi/10.27630/d.cnki.gznky.2024.000298

Sun, J. (2023). *Study on the improvement effect and mechanism of biochar and organic fertilizer on white soil* (Doctoral dissertation, Guangxi University). https://link.cnki.net/doi/10.27536/d.cnki.gccdy.2023.000008

Tang, X. C., & Chen, J. L. (2018). Research progress on the effects of biochar on soil physical, chemical, and microbial properties. *Ecological Science*, *37*(01), 192-199. https://doi.org/10.14108/j.cnki.1008-8873.2018.01.026

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci U S A*, *108*(50), 20260-20264. https://doi.org/10.1073/pnas.1116437108

Wang, F., Qu, Z. Y., Li, C. J., Jia, B., & Sun, G. F. (2017). Experimental study on the effect of biochar on nitrogen leaching in sandy loam. *Journal of Irrigation and Drainage*, *36*(07), 71-74. https://doi.org/10.13522/j.cnki.ggps.2017.07.013

Wang, T. T., Wang, X. L., Ren, Z. S., & Zheng, J. Y. (2017). Morphological structure and surface properties of biochars derived from different raw materials. *Environmental Science & Technology*, *40*(01), 42-48.

Wang, Z. Y., Qiu, M. Y., Yang, Y., & Sun, K. (2016). Characteristics and mechanisms of acetochlor adsorption by different biochars. *Journal of Agro-Environment Science*, *35*(01), 93-100. https://link.cnki.net/urlid/12.1347.s.20160126.1124.002

Wrobel-Tobiszewska, A., Boersma, M., Sargison, J., Adams, P., Singh, B., Franks, S., . . . Close, D. C. (2018). Nutrient changes in potting mix and Eucalyptus nitens leaf tissue under macadamia biochar amendments. *Journal of Forestry Research*, *29*(2), 383-393. https://doi.org/10.1007/s11676-017-0437-0

Wu, Y., Xu, G., Lü, Y. C., & Shao, H. B. (2014). *Research progress on the effect of biochar on soil physicochemical properties* (Publication Number 01)

Xing, L. B., Cheng, J., Geng, Z. C., Zhang, H. W., Liang, H. X., Wang, Q., . . . Li, Y. (2022). Physicochemical properties of biochars from different raw materials and their potential as slow-release carriers for biochar-based fertilizers. *Environmental Science*, *43*(05), 2770-2778. https://doi.org/10.13227/j.hjkx.202108023

Yang, C. D., Zong, Y. T., & Lu, S. G. (2020). Dynamic effects of different biochars on properties of acidic farmland soil and crop yield. *Environmental Science*, *41*(04), 1914-1920. https://doi.org/10.13227/j.hjkx.201910102

Yu, X. N., Zhang, X. F., Li, Z. P., Zhou, H. J., Fu, Z. Y., Meng, Q., & Ye, X. F. (2017). Effects of pyrolysis temperature on biochar yield and some physicochemical properties of peanut shell biochar. *Journal of Henan Agricultural University*, *51*(01), 108-114. https://doi.org/10.16445/j.cnki.1000-2340.2017.01.019

Yuan, J. H., & Xu, R. K. (2012). Research progress on the improvement of acid soil by biochar. *Soil*, *44*(04), 541-547. https://doi.org/10.13758/j.cnki.tr.2012.04.010

Zhang, X., Wang, D., Jiang, C. C., & Peng, S. A. (2013). Research progress on biochar and its improvement of acidic soil *Hubei Agricultural Sciences*, *52*(05), 997-1000. https://doi.org/10.14088/j.cnki.issn0439-8114.2013.05.037

Zhang, Y. N., Guo, W., Zhao, Q., Liu, G. G., Dai, B. Y., & Meng, Q. F. (2020). Effects of 600 ℃ straw biochar addition on physicochemical properties of typical black soil. *Territory & Natural Resources Study*(06), 52-54. https://doi.org/10.16202/j.cnki.tnrs.2020.06.013

Zhang, Y., de Vries, W., Thomas, B. W., Hao, X., & Shi, X. (2017). Impacts of long-term nitrogen fertilization on acid buffering rates and mechanisms of a slightly calcareous clay soil. *Geoderma*, *305*, 92-99. https://doi.org/https://doi.org/10.1016/j.geoderma.2017.05.021

Zhu, P., Ying, J. G., Peng, S. A., & Jiang, C. C. (2015). Effects of biochar on physicochemical properties of acidic red soil under simulated precipitation conditions. *Scientia Agricultura Sinica*, *48*(05), 1035-1040. https://link.cnki.net/urlid/11.1328.S.20150302.0251.021

Zhu, Q. L., Cao, M., Zhang, X. B., Tao, K., Ke, Y. C., & Meng, L. (2021). Analysis of physicochemical properties of biochar from gramineous plants at different pyrolysis temperatures. *Biomass Chemical Engineering*, *55*(04), 21-28.