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ISSN 2959-6157

Rice Straw Preparation of Biochar Process and Its Prospective Data Analysis

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Abstract:
With the development of global agriculture, the annual output of rice straw, one of the crop wastes, exceeds 700 million tons. However, traditional treatment methods pollute the environment and waste resources. Therefore, the preparation of biochar from rice straw has become a hot research topic. This study aims to analyze the process of preparing biochar from rice straw, to explore the effects of pyrolysis process parameters on the characteristics of biochar, and to give a prediction of the yield of biochar under ideal conditions. On the basis of available data, this study found that the biochar produced under 200°C and 1 h pyrolysis condition has the highest yield and carbon content, which is an ideal soil conditioner; the biochar produced under 400°C and 1 h condition has high carbon content and good stability, which is more suitable for long-term carbon storage. In addition, biochar is effective in improving soil quality, increasing agricultural production, and reducing greenhouse gas emissions. This study opens up new ideas for the high-value utilization of rice straw, which can help promote the sustainable development of agriculture and realize the synergistic development of efficient resource utilization and environmental protection.

Keywords: Rice straw, Biochar, Pyrolysis, Soil conditioner, Carbon storage.

1. Introduction

With the continuous development of global agricultural production, rice, as one of the world's major food crops, is widely planted and has a huge output. Correspondingly, the annual output of rice straw, as one of the major crop wastes, has exceeded 700 million tons [1]. However, traditional straw treatment methods, such as open burning or landfilling, not only lead to serious environmental pollution, which increases CO_2 and PM2.5 emissions, but also cause a huge waste of resources. In this context, how to efficiently and environmentally friendly utilize rice straw has become an important issue for sustainable agricultural development.

Biochar is produced from biodegradable wastes through advanced thermochemical processes such as pyrolysis, and it has tremendous environmental benefits due to its carbon-rich composition and wide range of applications [2]. Biochar made from rice

ISSN 2959-6157

straw has multiple benefits such as carbon sequestration and emission reduction, soil improvement and pollution remediation, and in recent years, the technology of preparing biochar from rice straw has attracted a lot of attention. Varkolu et al [3] in their article discussed, pyrolysis, roasting, gasification, hydrothermal liquefaction and solvent thermal liquefaction as the various methods of preparing biochar, bio-oils, and synthesis gases and gave the specific data and analyses, and also provided a review of the bio At the same time, the recent progress of biochar production technology and its applications across various fields such as adsorption, nutrient supply, soil improvement, plant disease mitigation, etc., were comprehensively analyzed, and it was concluded that the characteristics and applications of biochar largely depend on the production method and the type of organic feedstock used. Tang Yufei et al. in [4] also gave data on the characteristics of biochar prepared under different conditions and finally concluded that the performance of biochar is affected by the preparation method and raw material type, pyrolysis temperature, heating rate, residence time and other factors and that through the regulation of the above conditions and a series of modifications, biochar can be prepared to meet the needs of different applications, such as water purification, soil remediation, carbon sequestration, catalytic activation, energy storage and so on, Biochar can be prepared by regulating the above conditions and a series of modification means to meet the needs of different applications, such as water purification, soil remediation, carbon sequestration, catalytic activation, energy storage, etc. Biochars with specific properties have a promising future in promoting environmental sustainability.

In view of the practical dilemma of rice straw treatment and the broad prospect of biochar application in various fields, many scholars have carried out in-depth research on biochar preparation technology and performance influencing factors. However, most of the existing studies focus on a single technology or application scenario, and lack the systematic integration and optimization analysis of the biochar preparation process for rice straw as a specific raw material. In this regard, this paper aims to integrate data from multiple sources to hypothesize an optimal process for preparing biochar from rice straw, and to project the yield and predict the prospects and benefits of the process in combination with its yield. First, this paper summarizes the current research status of rice straw biochar preparation technology. Then, this paper combines specific experimental data and analytical models to explore the correlation mechanism between the influencing factors and the performance of biochar. Finally, based on the better process, the yield of biochar is accurately projected, and its application prospects and benefits are predicted from the environmental, economic, social and other dimensions, with a view to providing theoretical basis and practical reference for the high-value utilization of rice straw.

2. Rice straw preparation of biochar process

The current methods for preparing biochar include pyrolysis, gasification, and hydrothermal carbonization, with pyrolysis and hydrothermal carbonization being relatively more mature. Pyrolysis decomposes biomass in an anaerobic environment to produce biochar, while bio-oil can be produced [3].Hydrothermal Carbonization (HTC), also known as wet roasting, is a technique for the preparation of hydrochar [4]. Through processes such as combustion, pyrolysis, or gasification, rice husk can be converted to energy, and Herrera et al [5] noted that pyrolysis demonstrated high yield advantages in the production of liquid bio-oil, gaseous fuels, and solid bio-char, and was the most promising conversion method among them. Correspondingly rice straw is also applicable, which generally has a lower moisture content than dry and is more suitable for biochar preparation by pyrolysis, while the preparation of biochar should take into account the product properties and the cost of preparation. Varkolu et al. [3] reported only the effect of microwave power (100-600 W) on the biochar yield of wheat straw (24.25%) -74.66%), but did not specify the key parameters such as pyrolysis temperature and heating rate, which made the results difficult to reproduce or compare with other studies. In fact, the production of biochar is significantly affected by a variety of factors, which include the type of feedstock, pyrolysis temperature, heating rate, and residence time, etc. These key parameters must be considered comprehensively during the preparation of biochar to ensure that the final biochar produced has the desired physicochemical properties [4]. In contrast, Tang Yufei et al [4] systematically analyzed the relationship between biochar yield and physicochemical properties by studying the control of pyrolysis temperature and residence time of straw feedstock (Fig. 1). From Fig. 1, it can be seen that the biochar yield, carbon content, ash content, and C/H and C/O ratios showed significant changes under different pyrolysis temperatures and residence times, where higher pyrolysis temperatures and extended residence times usually led to a decrease in the biochar yield and an increase in the carbon content, which was accompanied by an increase in the ash content and C/H and C/O ratios.

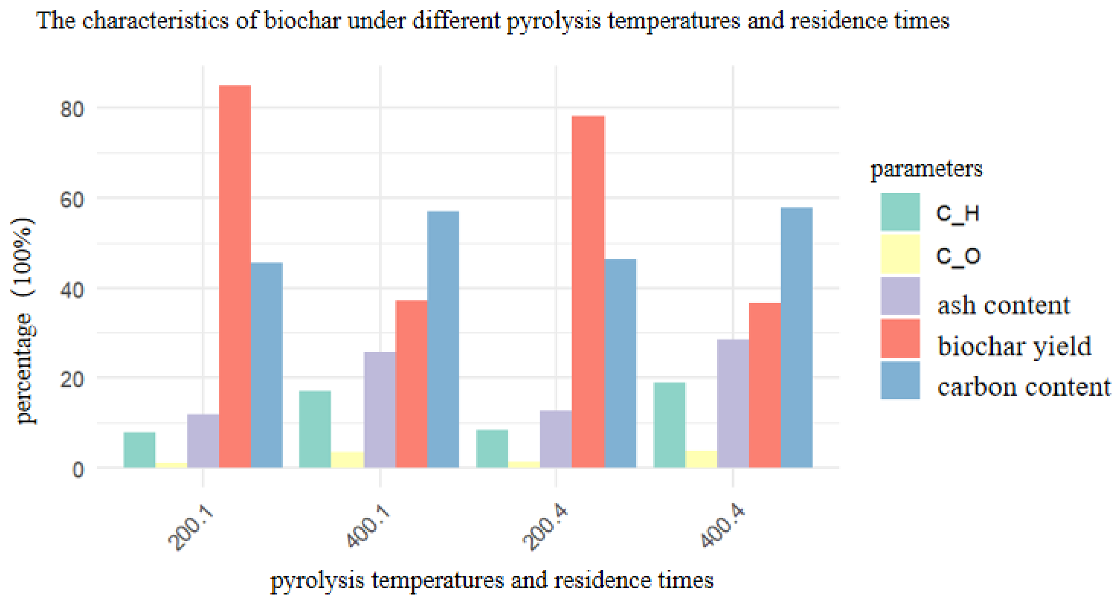

Fig. 1 The characteristics of biochar under different pyrolysis temperatures and residence times

By analyzing the characteristics of biochar and taking into account the cost of preparation, it is possible to speculate on the conditions under which biochar is prepared that are suitable for use as a soil conditioner and for long-term carbon storage. The use of biochar as a soil amendment requires four considerations: biochar yield, ash content, carbon content, and hydrogen-to-carbon ratio. As a soil amendment, a higher biochar yield means that more biochar can be obtained from the same amount of feedstock, which helps to reduce the cost of soil amendment per unit area. Lower ash content means that there are fewer inorganic impurities in the biochar, which may help to minimize negative impacts on soil structure. In addition, higher carbon content usually means that biochar has higher energy density and adsorption capacity, which is beneficial for soil amendment. Higher C/H ratios are usually associated with higher calorific values, while lower C/O ratios may indicate less oxidizability, which contributes to the stability of biochar in the soil. In contrast, if biochar is to be used as a long-term carbon store only the carbon content (C) and C/O ratio need to be considered. Higher carbon content contributes to carbon storage because it means that more carbon is immobilized in the biochar, and lower C/O ratios may indicate less oxidizability, which contributes to the long-term stability of the biochar in the soil, and thus to long-term carbon storage.

Taken together, biochar produced at a pyrolysis temperature of 200°C and a residence time of 1 h is more suitable as a soil amendment because it has the highest biochar yield and carbon content, as well as the lowest ash content and C/O ratio, which contributes to soil fertility and cost reduction. In contrast, biochar with a pyrolysis temperature of 400°C and a residence time of 4 h had a lower yield but possessed the highest carbon content and higher C/H ratio, which may help to improve its stability in the soil, making it more suitable as a long-term carbon store. However, in terms of cost-effectiveness, the difference in carbon content and stability between biochar with a pyrolysis temperature of 400°C and a residence time of 1 hour and biochar with a pyrolysis temperature of 400°C and a residence time of 4 hours is not significant, and choosing the option with a shorter residence time may be more reasonable. A shorter residence time reduces energy consumption and thus costs, while still yielding biochar with high stability. Therefore, biochar with a pyrolysis temperature of 400°C and a residence time of 1 hour may be a more cost-effective option when considering the balance between cost and performance.

3. Forecasting the yield analysis of biochar prepared from rice straw

Xie Guanghui et al [6] in their research results showed that the harvest index and straw coefficient of rice have a national average of 0.50 and 1.00 in China respectively. This paper is based on Tang Yufei et al [4] who mentioned the method of straw yield measurement, based on the economic yield of crops and straw coefficients, and derived the formula for the measurement of the yield of crop straw as:

$$W_S = W_P \times S_G \quad (1)$$

ISSN 2959-6157

In formula W_S, crop straw yield t; W_P, crop economic yield, t; S_G, straw coefficient.

Since the straw coefficient of rice is 1.00, the straw yield of rice is equal to the economic yield of rice (i.e., paddy). Economic yield of rice = rice yield × harvest index of rice. Fig. 2 is a data plot of the economic yield of rice, integrated by the rice production in China from 2015 to 2023 obtained from FAO, from which the data shows that China's rice straw production from 2015 to 2022 is more than 104 million tons, and its rich organic matter (cellulose, lignin, etc.) can be converted into biochar through pyrolysis technology. As a soil conditioner, biochar can reduce the amount of chemical fertilizer by 15%-20%, and its selling price in the field of activated carbon and battery materials can be 8-10 times of straw (e.g., RMB 3,000/ton), and the use of only 10% of straw can create more than RMB 3 billion of direct output value, with both economic and environmental benefits.

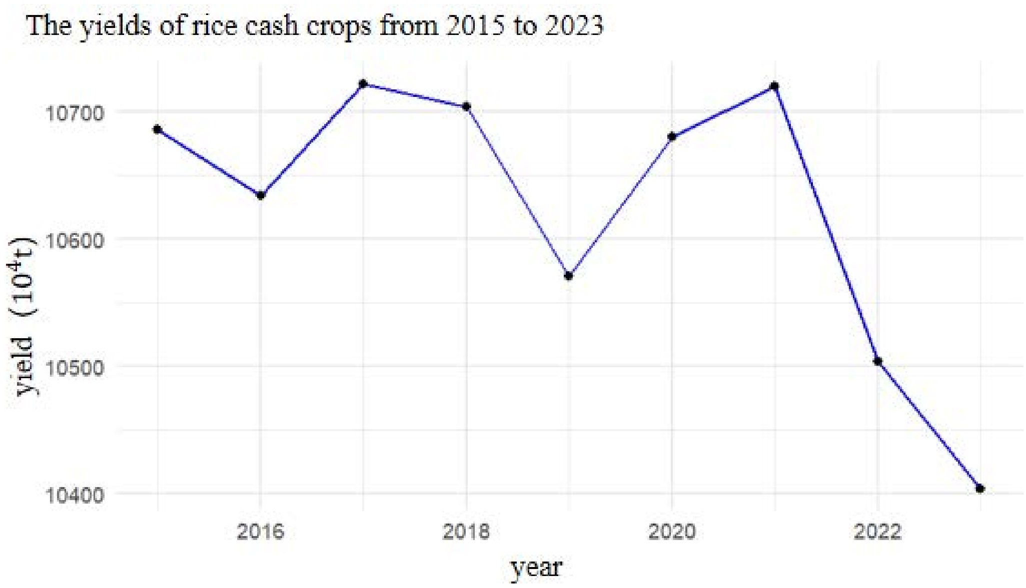

Fig. 2 The yields of rice cash crops from 2015 to 2023

Combined with the process of preparing biochar from rice straw, as mentioned in the process, if the biochar produced is used as soil improvement and long-term charcoal storage, the most suitable production conditions are pyrolysis temperature of 200°C and residence time of 1 hour, and pyrolysis temperature of 400°C and residence time of 1 hour, respectively, and the corresponding yields are 84.95% and 37.30%. Combined with the data in Fig. 2, the corresponding yield of biochar that can be produced from rice straw from 2015 to 2023 can be calculated, rice straw is used for the preparation of soil-improving biochar as biochar 1, and used for the preparation of long-term charcoal storage as biochar 2, and Fig. 3 shows the soil-improving biochar 1, with a yield of 84.95%, and an annual output of more than 88.3 million tons, and the sequestered carbon biochar 2, with a yield of 37.30%, the annual output can be over 38.8 million tons. Under ideal conditions, the yield of rice straw made into biochar is huge, showing good economic value and benefits.

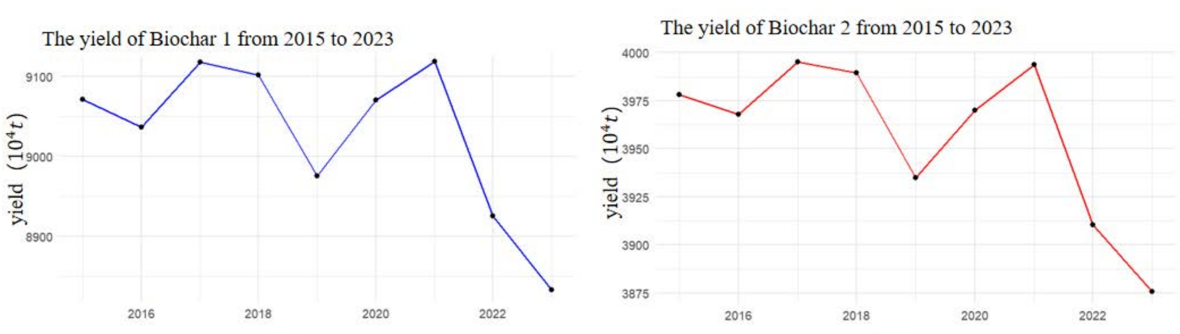

Fig. 3 The yield of Biochar 1 from 2015 to 2023 and The yield of Biochar 2 from 2015 to 2023

4. Specific applications of rice straw biochar

Biochar, as a carbon-rich material produced by pyrolysis of biomass, has become the subject of much attention due to its potential applications in the fields of sustainable agricultural development, integrated environmental management, and climate change mitigation [7].

4.1 The role of biochar in enhancing soil health and improving agricultural productivity

The use of biochar in rice production system not only reduces its carbon footprint but also brings higher economic returns to the production [8]. According to Kartika et al [9], the use of biochar can reduce the constraints on root elongation, volume and surface area under water stress conditions. So rice straw biochar can help plants to survive under poorer moisture conditions.Waheed et al [8] mentioned in their study that biochar can play a positive role in both soil structure improvement, enhancement of nutrient and water retention, and soil microbial activity, especially in degraded soils such as acidic, sandy, and infertile soils, which are often faced with water retention difficulties and nutrient loss. Moreover, biochar is effective in enhancing crop yield. According to Waheed et al [8], crop yield in poor soils can be increased up to 30% with the help of biochar. According to Kartika et al [9], the addition of biochar to the soil was found to be effective in increasing the water holding capacity of the soil and improving a number of soil properties including soil pH, cation exchange capacity (CEC), effective phosphorus level and cation exchange capacity.Mohammadi et al [7] stated that the use of biochar in rice systems was found to be effective in reducing the emission of greenhouse gases from the soil, increase soil carbon (C) storage and enhance nitrogen (N) retention, while improving soil function and crop productivity.

4.2 Environmental impacts of biochar

The interaction of biochar with soil and plants encompasses mechanisms at the physical, chemical, and biological levels These mechanisms work synergistically to enhance soil fertility, promote plant growth and development, and contribute to environmental sustainability [8]. According to Herrera et al [5], rice husk biochar, with the advantages of low cost and easy accessibility, has shown strong adsorption capacity when dealing with emerging pollutants such as high molecular weight antibiotics, and its application is promising. Accordingly, biochar made from rice straw should also have strong adsorption potential. Waheed et al [8] mentioned that biochar has the ability to sequester carbon for centuries, which can significantly reduce greenhouse gas emissions, such as reducing nitrous oxide emissions by up to 50%, and can also effectively mitigate water pollution by adsorption of excess nutrients and heavy metals.Mohammadi et al [7] showed that Environmental Life Cycle Assessment (E-LCA) integrates the addition of biochar to a wide range of soil-related emission sources to quantify the system-level impacts of terrestrial carbon stocks and atmospheric greenhouse gas concentrations, and published E-LCA studies have found that biochar has the potential to mitigate the carbon footprints of agricultural systems through a variety of mechanisms.Mohammadi et al. [7] suggested that suppressing soil methane emissions is an important pathway to mitigate climate change in rice production. Mohammadi et al [7] suggested that suppressing soil methane emissions in rice production is an important pathway to mitigate climate change, and that biochar addition plays a key role in this, contributing 40 - 70% of the total. Biochar can be categorized as a negative-emission technology given its ability to fix atmospheric carbon into the soil, bringing atmospheric GHG concentrations into the “safe” range.

5. Limitations and prospects

Biochar has shown remarkable potential in the field of agricultural quality and efficiency improvement and ecological environmental protection, but there are still many bottlenecks that need to be broken through from the laboratory to large-scale industrialized application.

At the mechanism level, the effect of biochar on crop yield is highly complex and uncertain, and Lehmann et al. [10] demonstrated that soil type cannot be used as a key indicator to accurately predict the response of crops to biochar addition, and their is no significant correlation between the response and the response of crops to inorganic fertilizers, which makes it difficult to apply the traditional assessment system based on soil fertility and fertilizer effect to the effect of biochar. This makes it difficult to apply the traditional evaluation system based on soil fertility and fertilizer effect to predict the effect of biochar. Nevertheless, the long-term value of biochar in improving soil structure and promoting nutrient cycling should not be ignored.

At the industrialization level, the large-scale application of biochar faces a triple obstacle: Waheed et al. [8] pointed out that the effect of biochar varies significantly under different soil types and climatic conditions, which makes it difficult to quantify its performance in the field; the energy consumption of pyrolysis and the transportation cost of raw materials involved in the production process remain high, which significantly undermines the

ISSN 2959-6157

economic competitiveness of the product; and at the same time, there is a lack of uniform standards for raw material selection, preparation process specification, and the lack of a unified system to predict the effect of biochar on soil structure and nutrient circulation. At the same time, there is a lack of uniform raw material screening standards, preparation process specifications and quality testing system in the industry, and there are large differences in the pore structure, carbon content and other key indicators of biochar produced by different processes, which further exacerbates the complexity of the application.

Future research should focus on optimizing the production process of biochar, reducing the production cost, and exploring the best conditions for its use in different application scenarios in practice. Meanwhile, more cost-effective transportation and application methods need to be developed to improve the market competitiveness of biochar. In addition, standardizing the production process and quality standards of biochar will help to increase its wide application in agriculture and the environment. Through these efforts, biochar is expected to play a greater role in sustainable agricultural development and environmental protection.

6. Conclusion

In this paper, the effects of pyrolysis process parameters on biochar characteristics were investigated by comprehensively analyzing the process of preparing bi In this paper, the effects of pyrolysis process parameters on biochar characteristics were investigated by comprehensively analyzing the process of preparing biochar from rice straw and its application prospects. The study employed experimental data analysis and literature review to systematically analyze the biochar yield, carbon content, ash content, and C/H and C/O ratios at different pyrolysis temperatures and residence times under ideal conditions. It was found that biochar produced under pyrolysis conditions at 200°C and 1 h had the highe ochar from rice straw and its application prospects. The study employed experimental data analysis and literature review to systematically analyze the biochar yield, carbon content, ash content, and C/H and C/O ratios at different pyrolysis temperatures and residence times under ideal conditions. It was found that biochar produced under pyrolysis conditions at 200°C and 1 h had the highest yield and carbon content, making it suitable for use as a soil conditioner, whereas biochar produced at 400°C and 1 h was more suitable for long-term carbon storage due to its higher carbon content and stability. In addition, biochar showed significant effects in enhancing soil health, improving agricultural productivity, and reducing greenhouse gas emissions.

Looking ahead, research should further optimize the production process of biochar to reduce costs and explore its potential application under different environmental conditions. At the same time, more cost-effective transportation and application methods need to be developed to improve the market competitiveness of biochar. Standardizing the production process and quality standards of biochar will help to improve its wide application in agricultural and environmental fields. The significance of this study is to provide a theoretical basis and practical reference for the high-value utilization of rice straw, which will help promote sustainable agricultural development and environmental protection, and achieve efficient utilization of resources and environmental sustainability. Through careful selection of pyrolysis parameters, biochar products can be produced to meet different demands, providing a new idea for the treatment and utilization of agricultural waste.

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