Feasibility Study of Biochar Prepared by Low-temperature Pyrolysis of Traditional Chinese Medicine Residue

Qian Deng[a], Aijun Li[b] and Yangwei Wu[c]
School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

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Abstract: This study focused on the evaluation of biochar prepared by low-temperature pyrolysis from traditional Chinese medicine residue, which providing feasibility demonstration for the construction of the industrial chain in circular economy of Chinese medicinal resources. We found that biochar produced by low-temperature pyrolysis at 400℃ and 550℃ showed preferable feasibility and fine foreground, and the scheme of low-temperature pyrolysis at 400℃ is better than that at 550℃. The market of biochar has a relatively large impact on the evaluation indexes, which can easily lead to the fluctuation of profits or losses.

1 INTRODUCTION

With the rapid development of Chinese medicine and the extension of the related resource based industrial chains, the yield of Chinese medicinal residue is increasing year by year. The annual discharge of Chinese medicinal residue in China is as high as 30 million tons in 2015, among which the production of Chinese patent medicine takes up the largest part, accounting for about 70% of the total (Na et al., 2016). Traditional Chinese medicine residue contains a certain amount of active ingredients and a large amount of cellulose, hemicellulose, lignin, protein and other rich organic ingredients. In recent years, it has been reported that traditional Chinese medicine residue is used for edible fungus cultivation, feed additives, pyrolysis and gasification (Chen, Tan, Wang, & Wang, 2012; Duan, Su, Sheng, Pei, & Wu, 2013; Wang, Cai, & Zhang, 2020), partly realizing its resource-oriented utilization. However, due to the long fermentation cycle, complex composition, difficult separation, and some may contain toxic and harmful substances, the utilization of the residue as feed and fertilizer is still under restriction. Therefore, how to realize the effective disposal and resource utilization of Chinese medicinal residue has become an unavoidable problem in the green development of Chinese medicinal resource industry and constructing the industrial chain in circular economy of Chinese medicinal resource (Duan, 2015; Zhang, Su, Guo, & Wu, 2015).

Biochar is a substance with high carbon content formed by pyrolysis and carbonization of biomass under anoxic conditions at high temperature (Lehmann, Gaunt, & Rondon, 2006). In recent years, agricultural straw and garden waste have been widely used in the preparation of biochar, showing broad application prospects in soil improvement and environmental protection (Chen, Zhang, & Meng, 2013; Qian et al., 2016). To a certain extent, Chinese medicine residue showed high similarity with agricultural and forestry wastes, which is characterized by high carbon content and easy to collect, and also can be used to prepare biochar. Due to its unique physical and chemical properties such as high porosity and large specific surface area, biochar is considered as a potential improver to accelerate the composting process and improve the final composting quality (Godlewska, Schmidt, Ok, & Oleszczuk, 2017). High-temperature composting can kill pathogenic bacteria, insect eggs and weed seeds to the maximum extent. What's more, it can rapidly degrade easily biodegradable organic substances into stable humus, and finally transform them into organic fertilizer. It's commonly applied in the transformation

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[a] https://orcid.org/0000-0001-6507-3268
[b] https://orcid.org/0000-0003-3738-2308
[c] https://orcid.org/0000-0002-0688-3209

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of organic solid waste into fertilizer at home and abroad. Biochar plays a role in increasing the organic matter content of fertilizers, so it lays a foundation for the development of high-temperature aerobic fermentation for organic fertilizer preparation technology based on the synergistic enhancement of "bacteria / mud/ carbon". Therefore, the techno-economic evaluation of biochar production from Chinese medicinal residue is of great significance to produce organic fertilizer.

In this study, the material flow and energy flow of Chinese medicine residue pyrolysis system were accounted by regarding Chinese medicine residue as conventional biomass. We analyzed the economic performance of the pyrolysis system of traditional Chinese medicine residue to prepare biochar by techno-economic analysis method. The detailed techno-economic evaluation of the project was carried out from the perspectives of production cost, profitability, sensitivity analysis and so on.

2 MATERIALS AND METHODS

2.1 Materials

The Chinese medicine residue analyzed in this article is based on the research of Guo(Guo, 2013) from Henan Wanxi Pharmaceutical Co., Ltd. The wet base industrial analysis, dry base elemental analysis and low heating value (LHV) are shown in table 1.

Table 1: Industrial analysis, elemental analysis and LHV of Chinese medicine residue (Guo, 2013).

Industrial analysis (wt% wet basis)				Elemental analysis (wt% dry basis)					LHV (MJ/kg)
M	FC	V	A	C	H	O	N	S	
12.5	12.41	72.62	2.47	42.4	6.2	47.39	1.06	0.15	14.90

The pyrolysis system of Chinese medicinal residue was divided into four units: raw material pretreatment, pyrolysis, separation and cooling. The heat of the pyrolysis system was released by the combustion of pyrolysis gas. The three-state yield was estimated according to formulas (1)(2)(3) (Guo, 2013). In order to obtain stable quality biochar, the high-temperature solid products from pyrolysis were cooled by cooling air and water. The input of cooling air was mainly reflected in the power consumption. The power consumption in the pyrolysis system was mainly used in blower and water pump, and the most important consumption is the blower. The cooling water and power consumption during pyrolysis can be calculated according to formula (4) (5)(Wei, 2018).

$$\mathrm{Y_{Gas}} = 0.09\mathrm{T} - 27.9(400℃ \le T \le 900℃) \quad (1)$$

$$\mathrm{Y_{Tar}} = -1.5 \times 10^{-4}\mathrm{T}^2 + 0.13\mathrm{T} + 7.58(400℃ \le T \le 900℃\,) \quad (2)$$

$$\mathrm{Y_{Char}} = 4.8 \times 10^{-5}\mathrm{T}^2 - 0.09\mathrm{T} + 67.6(400℃ \le T \le 900℃） \quad (3)$$

$$\mathrm{Power(T)} = 1.25 \times 10^{-6}\mathrm{T}^3 - 1.96 \times 10^{-3}\mathrm{T}^2 + 1.03\mathrm{T} - 140 \quad (4)$$

$$\mathrm{Cooling\ water(T)} = -4.2 \times 10^{-5}\mathrm{T}^3 + 6.2 \times 10^{-2}\mathrm{T}^2 - 29\mathrm{T} + 4742 \quad (5)$$

2.2 Methods

To assess the economic values of preparing biochar by low-temperature pyrolysis, profitability of the project was analyzed based on estimation of total investment and cost. The sensitivity analysis was carried out by considering two key factors of selling price and operating cost. The economic benefit and anti-risk ability of the project were reasonably evaluated, which provides a theoretical basis for its industrialization.

The total investment of this project is composed of fixed capital investment (FCI), interest during construction and working capital. The equipment purchase and installation cost of pyrolysis system were estimated by the production scale index method, which can be formulated as below.

$$I_2 = I_1(\frac{P_2}{P_1})^n \times C_F \quad (6)$$

$$C_F = ER \times \sigma \quad (7)$$

in which, I_1, P_1 are the investment amount and production scale of similar projects or production facilities that have been completed, $I_2\,, P_2$ are the investment amount and production scale of proposed projects or production facilities, n represents the production scale index, and C_F illustrates price adjustment index. ER and σ mean the exchange rate between US dollar and RMB in reference year and price index of fixed assets investment in reference year compared with that in 2019. σ is based on the data published in China Statistical Yearbook. The equipment involved in this study was designed according to the current technical state, and the production scale index, purchase cost and installation coefficient of the equipment can be found from the actual equipment data(Dutta, Sahir, & Tan, 2015;

Huang, 2015; Jones, Valkenburg, Walton, Elliott, & Czernik, 2009).

Working capital represents cash kept on hand for day-to-day plant operations like accounts receivable, cash on hand, raw material and product inventory, which is recouped in the last year of the analysis(Du, 2012). In this study, working capital is assumed to equal a fixed percent of FCI, which is taken as 5%(Bond et al., 2014).

The interest during the construction period was calculated according to formula (8).

$$q_j = (P_{j-1} + \frac{1}{2}A_j)i \tag{8}$$

in which, q_j is interest accrued in year j of the construction period, P_{j-1} means the sum of accumulated loan amount and interest amount in year (j-1), A_j represents the loan amount in year j of construction period, and i illustrates annual interest rate.

According to the capital cost method developed by Peters et al.(Peters & Timmerhaus, 1958), the total capital investment can be estimated by the total cost of the purchased equipment. The accuracy of the estimation based on this method is usually less than 30%.

Cost estimation was analyzed from three aspects: variable operating costs, fixed operating costs and cost analysis. Profitability was carried out from three aspects of time-based evaluation index, value-based evaluation index and ratio-based evaluation index. The static investment payback period, net present value (NPV) and internal rate of return (IRR) were selected to evaluate the profitability. The calculation formula is as follows.

P_t = (Year of positive cumulative cash flow)-1+ (The absolute value of cumulative net cash flow last year/ Net cash flow of the year) (9)

$$NPV = \sum_{t=0}^{n}(CI - CO)_t(1 + i_c)^{-t} \tag{10}$$

$$NPV = \sum_{t=0}^{n}(CI - CO)_t(1 + IRR)^{-t} = 0 \tag{11}$$

In this study, the project investment cash flow table was used to evaluate the project from the perspective of pre-financing. The total investment of the project was used as calculation basis to reflect the cash flow and outflow during operation, so as to calculate the economic indicators of the project.

3 RESULTS & DISCUSSION

When the design capacity of disposal amount of Chinese medicine residue for low-temperature pyrolysis in this study is 10 ton per hour, the three-state yield and energy consumption at different temperatures were calculated as table 2. Biochar was the main product of pyrolysis system, and the by-product were bio-oil and bio-gas. Bio-oil was sold while bio-gas were burned for heating.

Table 2: Three-state yield and energy consumption at different temperatures.

Temperature (°C)	Output			Input	
	Bio-gas (wt%)	Bio-oil (wt%)	Biochar (wt%)	Power (kWh)	Cooling water (kg)
400	8.1	35.58	39.28	384	3740
550	21.6	33.71	32.62	416	5592

3.1 Investment Estimation

According to the above estimation methods of FCI and working capital, their values can be obtained respectively, as shown in table3.

Table 3: Estimation of total investment and production cost.

—	TDC[a]	TIC[b]	FCI	Working Capital	Loan interest	TCI[c]
Cost (10^4¥)	8758.51	5255.11	14013.62	700.68	367.25	15081.55

[a] TDC = Total direct capital.
[b] TIC = Total indirect capital.
[c] TCI = Total capital investment.

3.2 Cost Estimation

Due to the different operating parameters, the quality of biochar will change. It is necessary to set the corresponding selling price according to the heating value of the product. The selling price of biochar is 1200 ¥/t at 400°C and 1500 ¥/t at 550°C(Du, 2012). A summary of operating costs is given in Table 4, the cost of biochar per ton at 400°C is 857.37 yuan, and the cost of biochar per ton at 550°C is 1079.27 yuan. As temperature rising, the power and cooling water required in the pyrolysis process are increased. Meanwhile, the yield of biochar is reduced, resulting in an increase in unit operation cost.

Table 4: Summary of operating costs.

Project	—	Cost (10^4¥)	
		400°C	550°C
Production cost	Operation cost	36114.59	38528.01
	Depreciation expense	14013.62	14013.62
Financial cost	—	3055.52	3055.52
Unit cost	—	857.37 ¥/t	1079.27 ¥/t

According to the detailed cost analysis, we found that the financial cost only accounts for 5.75% of the total cost, and the production cost accounts for 94.25% in the low-temperature pyrolysis. The largest proportion of production costs is raw material costs, accounting for 29.97% of the total cost, followed by depreciation and maintenance costs, accounting for 26.35% and 15.81%, respectively. Reducing costs can be achieved by reducing raw material costs or increasing production. In the low-temperature pyrolysis at 550°C, the financial cost accounts for 5.5% of the total cost, and the production cost accounts for 94.5%. The largest proportion of production costs is still raw material costs, followed by depreciation and maintenance costs, which is similar to the result at 400°C.

3.3 Profitability Analysis

According to the analysis of cash flow, the NPV of low-temperature pyrolysis at 400℃ and 550℃ are respectively 15.65 million yuan and 15.04 million yuan, both of which showed high economic benefits. The IRR is greater than the benchmark rate of return 8%, and the two values are the same. The payback periods are 6.78 and 6.88 years, respectively, that is, 6.78 and 6.88 years after putting into production can be profitable, which are less than the benchmark payback period of eight years. The results indicate that the low-temperature pyrolysis at 400°C is better than that at 550°C.

3.4 Sensitivity Analysis

Sensitivity analyses were conducted to evaluate the sensitivity of financial performance (i.e., NPV, IRR and payback period) of the pyrolysis operation to biochar selling price and operating cost. The range of each variable from -20 to +20 percent of the baseline value was used in the sensitivity analyses while the other variables remained constant. According to the sensitivity analysis results of the selling price and operating cost, the impact of price change on the three indicators is greater than the operating cost, indicating that the selling price of biochar is the most influential variable for the financial performance.

4 CONCLUSIONS

In this study, the economic benefits and production cost of low-temperature pyrolysis of Chinese medicine residue to produce biochar were comprehensively studied, and the sensitivity analysis of some typical variables was carried out. The main conclusions are as following:

(1) Through technical and economic analysis, the total capital investment of the biochar preparation project was calculated to be 150.82 million yuan, and the production costs of biochar at 400℃ and 550℃ were 857.37 ¥/t and 1079.27 ¥/t, respectively. The production costs were increased with temperature. In addition, raw material cost, depreciation cost and maintenance cost were the top three cost components.

(2) Through the analysis of project cash flow, it is found that the production projects of biochar at 400°C and 550°C showed fair profitability and economic benefit, and the economic benefit at 400°C was higher. However, the payback period in the two cases was 6.78 and 6.88 years, respectively, showing the relatively poor anti-risk ability.

(3) Through the sensitivity analysis of operating costs and selling price, the selling price of biochar has a relatively large impact on economic benefit, which can easily lead to high profits and losses.

In this article, the by-product of pyrolysis bio-oil was sold and bio-gas were used for combustion heating. The utilization method is simple and we ignored the influence of bio-oil price. In addition to direct sale, bio-oil can also improve economy through quality rectification. To this end, the market for bio-oil is deserving of more attention in future studies.

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