Analysis of Economic and Environmental Benefits of Agricultural Straw Preparation for Biochar Returned to the Field: A Case Study at the County Scale in China

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Through field investigations and field experiments under different modes, the local cost composition and sources of income of agricultural straw carbonization and returning to the field in Xiangfen County, China, were analyzed, and an economic evaluation was carried out. The results showed that the preparation cost of biochar at the county scale was ¥ 1107/t, and it could be reduced to ¥ 507/t after excluding the straw cost. When considering only the income from yield increase, it is difficult to achieve profitability in both the mode of returning the field in batches with equal amounts and the mode of returning the field with a large dose at one time. However, when considering the combined income from yield increase, carbon sequestration, and emission reduction, the annual profit could reach up to ¥ 269/ha. If the straw is owned by farmers (the straw cost is not included), the highest annual income can reach ¥ 1241/ha. Although the upfront cost of agricultural straw carbonization and returning to the field is relatively high, in the long run, it has significant environmental benefits and economic potential in terms of increasing yields, sequestering carbon and reducing the use of chemical fertilizers.

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INTRODUCTION

Under the dual challenges of global climate change and sustainable agricultural development, China produces about 900 million tons of crop residues annually. Traditional direct return of crop residues to the field faces bottlenecks such as a long decomposition cycle, high risk of spreading pests and diseases, and destruction of soil structure; such practices also lead to large amounts of greenhouse gas emissions (Samomssa *et al.* 2024). On the other hand, as the global population continues to grow, the demand for food continues to increase. How to ensure food security while reducing the negative impacts of agricultural production on the environment and realizing the sustainable development of agriculture has become an urgent issue (Wang *et al.* 2019). The preparation of straw into biochar and its return to the field, as a technological innovation with both environmental benefits and agricultural yield potential, is promising to be an effective pathway to achieve straw resourcing, arable land quality enhancement, agricultural carbon sequestration, and emission reduction (Cordero-Lanzac *et al.* 2018).

Biochar, as a carbon-rich solid product obtained by pyrolysis of organic matter (*e.g.*, crop straw, animal manure, *etc.*) in a low-oxygen environment, is highly aromatic, refractory and stable (Daer *et al.* 2024). The use of agricultural straw for the production of biochar and its return to the field not only can increase the soil carbon pool and mitigate global climate change, but it also can improve the soil physicochemical properties and soil fertility. Specifically, the porous structure of biochar gives it a large specific surface area, which can increase the adsorption capacity of the soil for nutrients and water, improve the fertilizer utilization rate, and reduce nutrient leaching (Zhang *et al.* 2022). Biochar is alkaline, which can adjust the soil pH value and improve the acidic soil environment. In addition, biochar can provide soil microorganisms with a suitable habitat and carbon source, promote the growth and reproduction of microorganisms, and enhance the biological activity of soil (Li *et al.* 2024). In terms of carbon sequestration, biochar fixes carbon in biomass into a highly stable aromatic structure through pyrolysis, and its carbon sequestration cycle can reach hundreds to thousands of years, which is significantly better than the short-term carbon sequestration effect of traditional organic materials returned to the field. In terms of emission reduction, biochar reduces greenhouse gas emissions through multiple pathways. First, the porous structure of biochar can adsorb ammonium nitrogen in soil and inhibit nitrification, thus reducing nitrous oxide (N_2O) emissions. Secondly, the hydrophobicity and high specific surface area of biochar can change the soil water distribution and inhibit the activity of methanogenic bacteria. Although the beneficial effects of carbonizing agricultural straw and returning it to the field have been widely studied in various aspects, research on its economic analysis has been rarely reported.

Xiangfen County, Shanxi, as one of the important agricultural production areas in China, is characterized by typical northern dry farming. Its soil type is mainly brown soil, and soil fertility and water resource conditions have a large impact on agricultural production. In this context, this study measured the costs of agricultural straw purchase and transportation, charring equipment investment, and biochar application, *etc.*, through field research and field trials. The benefits of agricultural straw charcoal return to the field in terms of grain yield increase, soil carbon sequestration, and greenhouse gas emission reduction were analyzed in depth. To the best of our knowledge, this is the first economic analysis of agricultural straw and returning it to the fields charcoal fertilization on a county scale in China. This work provides a scientific basis and practical guidance for the wide application of charcoal fertilization in dry-crop agricultural areas.

EXPERIMENTAL

Measurement and Data Sources

Cost components

The cost of crop straw charring for field return generally includes the cost of feedstock acquisition, storage, and transportation (Table 1), biochar preparation cost (Table 2), and biochar application cost (Table 3). This is closely related to the distribution range of different feedstocks, charring conditions, charring equipment and its service life, biochar application methods, and other factors (Lachheb *et al.* 2002). In this work, wheat in Xiangfen County, China was selected for the study. In 2024, the wheat planting area in this county was 45,582 ha, wheat production was 225,127 tons, and wheat straw production was 275,736 tons, which is about 6 tons of straw per hectare of farmland. Xiangfen County is 39.3 km from north to south and 62.5 km from east to west. Thus, the cost of straw transportation was estimated as 3 Yuan (t-km), and the acquisition radius was taken as 15 km.

The cost measurement of biochar scale production comes from Xiangfen County Yonghe Agricultural Co. Among them, the investment in carbonization equipment is 1 million yuan, and the corresponding investment in ancillary equipment (plant weighbridge, forklift, transformer, truck, *etc.*) is 500,000 yuan. According to 10 years' wear and tear, the annual loss of fixed assets of the equipment is 150,000 ¥. Each set of charcoal furnace handles 6000 tons of straw per year, and the yield of biochar is listed as 30%. The annual electricity consumption of the company is 360,000 kWh, and the price of industrial electricity is 0. 8 yuan/kWh. The annual salary expenditure of workers is 696, 350 ¥.

Table 1. Costs of Agricultural Straw Purchase, Storage and Transportation

Item	Cost per ton of straw (¥)	Basis of measurement *
Straw purchase costs	180	local market transaction prices
Acquisition, baling	25	local market transaction prices
Storage (prior period)	4	local market transaction prices
Transportation	45	¥ 3 (t·km) ×15 km
Grand total	254	¥ 180+ ¥ 25+¥ 4+ ¥ 45
Deducting the cost of straw purchase	74	¥ 25+¥ 4+ ¥ 45

Table 2. Biochar Production Costs at Scale

Item	Cost per ton of biochar (¥)	Basis of measurement
Loss of equipment	83	¥ 150000 /（6000 t×30%）
Energy consumption	48	¥ 360000 kWh×¥ 0. 8/ kWh/6000 t
Labor	116	¥ 696350/6000 t
Wrap	10	Xiangfen Yonghe Agricultural Co.
Storage (late)	4	Xiangfen Yonghe Agricultural Co.
Grand total	261	¥ 83+ ¥ 48+ ¥ 116+ ¥ 10+¥ 4

Cost of Biochar Application

The biochar prepared from agricultural straw was returned to the field using two different modes. The batch equal-dose model of field return was equal to the amount of biochar produced from agricultural straw per hectare (6 t×30% = 1.8 t/ha), and it was guaranteed that field return was carried out every year. In the large-scale, high-dose, one-time return to field mode, 9 tons of biochar is added to each hectare of farmland at one time. It is assumed that biochar has a certain effect on improving farmland soil within 5 years. The labor cost for applying each ton of biochar is ¥ 150.

Table 3. Cost of Biochar Application

Item	Equal-dose batch return to the field		Large-dose one-time return to the field	
	Costs (¥ /ha)	Basis of measurement	Costs (¥ /ha)	Basis of measurement
Transportation	81	¥ 45×6 t/ha×30%	405	¥ 45×6 t/ha×30%×5
Labor	270	¥ 150×6 t/ha×30%	1350	¥ 150×6 t/ha×30%×5
Grand total	351	¥ 81+¥ 1270	1755	¥ 45×1.8 t+¥ 150×9 t

Economic Benefit

The annual economic benefits of agricultural straw charcoal return to the field mainly include increased food production, soil carbon sequestration, and greenhouse gas emission reduction (Arcibar-Orozco *et al.* 2019). The average carbon content of prepared biochar from agricultural straw used in this study was 50%. Wheat price (¥ 2300/t) and carbon trading price (¥ 92/t) were based on the current Chinese grain trading and carbon trading market prices. The increased wheat yield, carbon sequestration, and greenhouse gas (CH_4 and N_2O) emission reductions from batch equal-volume and large-dose one-time field return are sourced from the data of Xiangfen County experimental field. The experimental results of agricultural straw charred back to the field were compared with the blank control, respectively.

Table 4. Economic Benefits Per Year of Agricultural Straw Charring and Returning to the Field

Item	Equal-dose batch return to the field		Large-dose one-time return to the field	
	Earnings (¥ /ha)	Basis of measurement	Earnings (¥ /ha)	Basis of measurement
Yield increase	1725	(7. 24−6. 49) t/ha × ¥ 2300/t	12052	(8. 36−7. 43+8. 42−7. 51+8. 54−7. 27+8. 15−7. 19+8. 38−7. 21) t/ha × ¥ 2300/t
Benefits of carbon sequestration *	304	¥ 92/t×1. 8 t/ha × 50% × (1−2. 33×10−3) ×44/12	1509	¥ 92/t×9 t/ha × 50% × (1−6. 43×10−3) ×44/12
Emission reduction benefits	403	¥ 92/t× 25×(0. 437−0. 262) t/ha	151	¥ 92/t×(1. 453−1. 126) t/ha×5
Total benefit	2432	¥ (1725+304+403)/ha	2742	¥ (12052+1509+151) /ha /5

* Equation for carbon degradation rate of biochar $C_{BC\%}$=99. 87% × $(1-e^{-2.82\times10^{-6}\times t})$ + 0. 13% × $(1-e^{-0.047\times t})$ (t denotes biomass charcoal application time/d), calculated as 2.33×10^{-3} for the first year of biochar cloning and 6.43×10^{-3} for the five-year biochar degradation rate.

RESULTS AND DISCUSSION

Economic Analysis of Agricultural Straw Charcoal Returned to the Field

From the results in Tables 1 and 2, the cost of preparing wheat straw-based biochar at scale in Xiangfen County was ¥ 1107/t, which was lower than the price reported in the IBI (International Biochar Initiative) industry report (¥ 3194.8/t) and the local market trading price (¥ 1300 to 1600/t). This suggests that large-scale production and nearby utilization in the county can reduce the cost of transportation and marketing to a certain extent and improve the economy of biochar. In addition, the recycling of by-products (combustible gas, tar, waste heat, *etc.*) from the biochar preparation process and the upgrading and improvement of carbonization equipment can further reduce the cost of biochar preparation (Armanu *et al.* 2024). Considering that farmers' straw can be sold directly to the charcoal company as a commodity, the actual production cost can be reduced to ¥ 507/t by offsetting the straw purchase cost.

Currently, there are two main types of biomass charcoal soil application methods, one is annual charcoal return of biomass in equal doses with straw, and the other is a one-time large-dose return (Wang *et al.* 2018). The two methods are close to each other in terms of biochar application cost (Table 3). Comparative analysis revealed that, due to the higher biochar addition during one-time field return, its effect was more obvious in promoting wheat yield increase and carbon sequestration. However, there was some uncertainty in the GHG emission reduction effect. The average annual total benefit over 5 years of one-time field return (¥ 2742/ha) was greater than the total benefit at the beginning of batch field return (¥ 2742/ha) (Table 4). However, the environmental effects of biochar batch field return are cumulative and have a lag in performance, and the later effects in terms of yield increase and emission reduction may have greater potential and long-term cumulative effects. It is worth noting that the amount of biochar applied to the field in batches was much smaller than that of one-time large-dose field return, and the smaller cost investment is conducive to improving the motivation of farmers. In addition, batch field return is more compatible with the timing of agricultural cultivation than one-time large-dose field return.

Table 5. Economic Analysis of Agricultural Straw Charcoal Return to the Field Per Year

Item	Equal-dose batch return to the field		Large-dose one-time return to the field	
	Consideration of yield gains only (¥ /ha)	Gains from Yield Increase, Carbon Sequestration and Greenhouse Gas Emission Reduction (¥ /ha)	Consideration of yield gains only (¥ /ha)	Gains from Yield Increase, Carbon Sequestration and Emission Reduction (¥ /ha)
Total profit	−748	−41	−63	269
Basis of measurement	¥ 1725/ha −(¥ 254/t×5. 4 t/ha +¥ 261/t×1. 8 t/ha +¥ 351/t×1. 8 t/ha)	¥ 2432/ha −(¥ 254/t×5. 4 t/ha +¥ 261/t×1. 8 t/ha +¥ 351/t×1. 8 t/ha)	¥ 2410/ha −(¥ 254/t×5. 4 t/ha +¥ 261/t×1. 8 t/ha +¥ 351/t×1. 8 t/ha)	¥ 2742/ha −(¥ 254/t×5. 4 t/ha +¥ 261/t×1. 8 t/ha +¥ 351/t×1. 8 t/ha)
Total profit (net of straw cost)	224	931	909	1241
Basis of measurement	¥ 1725/ha −(¥ 74/t×5. 4 t/ha +¥ 261/t×1. 8 t/ha +¥ 351/t×1. 8 t/ha)	¥ 2432/ha −(¥ 74/t×5. 4 t/ha +¥ 261/t×1. 8 t/ha +¥ 351/t×1. 8 t/ha)	¥ 2410/ha −(¥ 74/t×5. 4 t/ha +¥ 261/t×1. 8 t/ha +¥ 351/t×1. 8 t/ha)	¥ 2742/ha −(¥ 74/t×5. 4 t/ha +¥ 261/t×1. 8 t/ha +¥ 351/t×1. 8 t/ha)

Although the environmental benefits of biochar are significant, there is still a considerable gap between the apparent economic benefits (yield increase benefits) of considering only the charred agricultural straw returned to the field and the current costs of biochar preparation and application. The economic gap per hectare reached ¥ 748 and ¥ 63 under the batch equal-volume and large-dose one-time return modes, respectively (Table 5). The average annual profit of the large-dose one-time return increased to ¥ 269/ha if yield increase, carbon sequestration, and emission reduction gains were also taken into account. However, the profit under the batch-equivalent return model was still negative (−¥ 41/ha). Due to the current immaturity of China's agricultural carbon trading market, it is still challenging to fully rely on corporatized operations to achieve profitability of agricultural straw field return (Wu *et al.* 2024). However, excluding the cost of straw, both yield gains and total returns under the two models turned out to be profitable. The average annual total return under the large-dose one-time return model could reach ¥ 1241/ha. Therefore, farmer-driven carbonization is a reasonable way to promote its application on a large scale and in a market-oriented manner.

To improve the agricultural, economic, and environmental benefits of agricultural straw carbonization, the following suggestions are given. (1) Quantify and market the carbon emission reduction effect of biochar application to motivate farmers and companies to participate in the promotion of the application. (2) Reduce the cost of harvesting, storing and transporting agricultural straw and the cost of biochar preparation through model optimization, equipment modification, *etc.* (3) Deep-process the biochar to prepare it with a high added value, fertilizer-effective charcoal-based products to improve the economy.

CONCLUSIONS

1. The economics of agricultural straw charring for field return at the county scale in China was analyzed in depth using Xiangfen County as an example. The cost of biochar preparation at scale was ¥ 1107/t, which could be reduced to ¥ 507/t by removing the cost of straw, which is lower than the market trading price.
2. The higher biochar addition under the one-time field return mode was more effective in promoting wheat yield and carbon sequestration, and it provided higher economic benefits (¥ 2742/ha). Considering only the yield-increasing benefits of agricultural straw charcoal return, the economic shortfalls of batch equal-volume return and large-dose one-time return amounted to ¥ 748/ha and ¥ 63/ha, respectively.
3. Both models showed good annual profits without accounting for straw costs. It is recommended to promote the farmer-oriented model of large-dose one-time field return, and to give policy inclination and subsidies, so as to realize the double harvest of environmental and economic benefits of agricultural straw charcoal field return.

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