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Study on Utilization of Biochar Prepared from Crop Straw with Enhanced Carbon Sink Function in Northeast China

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Abstract: Carbon emission reduction is an important issue facing the current industrial development. With the agglomeration of old industrial bases in Northeast China and the high total carbon emission, it is difficult to achieve the goal of carbon neutrality. The objective of crop straw biochar preparation and utilization research is to achieve regional carbon neutralization and carbon sink function. The waste crop straw resources in Northeast China were huge, with an annual yield of about 7.0×10^7 tons which showed an increasing trend. The development of the biochar industry in Northeast China significantly reduced carbon emissions and the environmental pollution caused by straw burning. At the same time, it obtained a huge profit of 7.0×10^{10} RMB. Because of the special location conditions in Northeast China, the establishment of the biochar industry chain needed multi-angle research and judgment. The biochar industry in Northeast China will have a broad prospect, and the industrial demand is not only farmland soil improvement but also winter heating fuel utilization and carbon reduction. This study will further increase the carbon sink capacity in Northeast China and promote the realization of China's carbon neutrality goal, which also has important reference value for carbon reduction in other countries in the world.

Keywords: carbon peak; carbon neutralization; straw biochar; sustainable development; resource utilization

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Citation: Huang, X.; Chen, X.; Guo, Y.; Wang, H. Study on Utilization of Biochar Prepared from Crop Straw with Enhanced Carbon Sink Function in Northeast China. *Sustainability* **2023**, *15*, 6104. https://doi.org/10.3390/su15076104

Academic Editor: Farooq Sher

Received: 19 February 2023
Revised: 23 March 2023
Accepted: 28 March 2023
Published: 31 March 2023

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1. Introduction

The global production of crop straw is approximately 5×10^9 tons annually [1]. China's straw output exceeds 8.3×10^8 tons, the total yield of straw ranks the first place in the word, and the output of straw in Northeast China exceeds 10% of the China [2,3]. Northeast China faces industrial transformation and upgrading pressures [4]. The utilization of straw resources balances the increase of carbon emissions brought by the industrial transformation process [5]. This provides new ideas for regional economic development. Therefore, the utilization of straw in Northeast China is of reference value to other countries in the world. Plant straw is a biomass resource that can be used continuously [6]. The preparation of biochar from straw is an effective way to resourcefully use and solve the environmental pollution caused by straw burning [7]. Straw biochar has high utilization value as a soil conditioner and substrate material of constructed wetland [8,9]. In order to achieve global carbon emission reduction targets, the Chinese government issued the "Opinions on the complete and accurate implementation of the new development concept to do a good job of carbon attainment and carbon neutrality" in October 2021, which required the northeastern region of China to take corresponding measures against the current situation of high carbon emissions and high pollution. Straw is converted into biochar to achieve carbon sequestration, and biochar plays a good role in carbon sequestration in soil improvement [10]. According to the main data bulletin of the Third China Land Survey, the arable land area of the whole Northeast China is about 2.4×10^5 km^2, of which 1.2×10^5 km^2, 4.1×10^4 km^2, and 7.4 × 10^4 km^2 is in Heilongjiang, Jilin, and Liaoning provinces, respectively. The food crop types are mainly rice, wheat, soybean, sorghum, and other straw crops, and the total food yield accounts for the total grain yield more than 20%. The straw in Northeast China is currently mostly used for thermal combustion, which has low resource utilization and a high impact on environmental pollution. It is important to carry out research on biochar prepared from crop straw with the aim of carbon reduction and regional development.

Biochar is a Carbon-rich products with dense pore structure, large specific surface area (SSA), strong adsorption effect, and is friendly to the environment [11,12]. It has good ecological and environmental benefits. The performance of biochar is influenced by various factors, which mainly relate to the preparation of raw materials, preparation process, and preparation conditions [13]. According to the preparation process conditions, the commonly used biochar preparation techniques are mainly divided into four categories: pyrolysis, gasification, baking carbonization, and hydrothermal carbonization techniques [14]. Pyrolysis refers to the thermal decomposition of biomass at high temperatures between 300 and 1000 °C in an oxygen-free environment, and it is the more common and mature biochar preparation technology in use today [15] (Figure 1a). Temperature is the main condition affecting the preparation of biochar, and the pore volume and SSA of biochar increase at higher temperatures (700 °C) for the same pyrolysis time [16]. The use of catalysts to initiate directional pyrolysis is beneficial to enhance the yield of high-performance carbon materials in biochar [17]. The use of co-pyrolysis technology is beneficial to increase the yield and variety of biochar prepared from a variety of biomass raw materials [18]. The preparation of biochar fuel from a composite raw material of agricultural and forestry biomass mixed with coal and sludge in a certain ratio is beneficial to energy conservation [19].

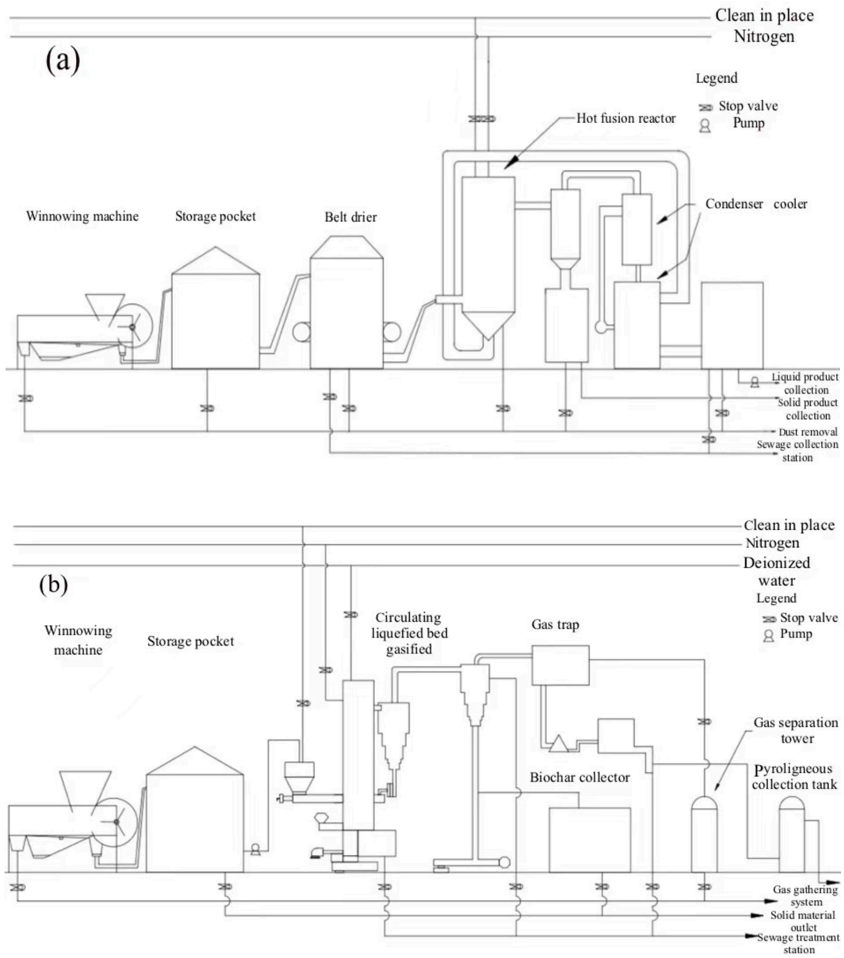


Figure 1. Preparation process of biochar ((**a**) Pyrolysis method, (**b**) Gasification method).

Biomass gasification is the process of converting and decomposing biomass feedstock through thermochemical reactions under high temperature conditions, and the products include biomass gas, heat power, liquid fertilizer, and biochar [20] (Figure 1b). The composition of biomass gas produced by gasification is mainly hydrogen, methane, and ethane. The carbon content and energy efficiency of adsorption and carbon sequestration of biochar products prepared by the gasification of different raw materials vary, and the overall biochar yield is low. About 10% of wood vinegar liquor is produced during the pyrolysis gasification of agricultural and forestry biomass [21]. Wood vinegar liquor is mostly used in agricultural yield as an organic fertilizer and antimicrobial agent, which significantly enhances plant resistance after its application on farmland [22]. Wood vinegar liquor can be mixed with biochar to further improve the soil environment, increase crop yield, and reduce soil greenhouse gas emissions by about 60% [23,24].

Baking carbonization [25] is a method of producing biochar at low temperatures in the range of 200–300 °C under anaerobic (or anoxic) conditions at atmospheric pressure. The quality of biochar prepared by baking is mainly influenced by temperature [26], which is higher than the residence time [27]. The structural properties and calorific value of biochar increase with the baking temperature. Hydrothermal carbonization [28] is the process of preparing carbon materials using water as the medium at a certain temperature range (130–250 °C) and pressure, and hydrothermal carbonization technology is not affected by the moisture of the raw material. The use of microwave-assisted hydrothermal carbonization can improve the adsorption performance of biochar [29]. The volatile fraction of the biochar product decreases, and the fixed carbon mass fraction increases during the increase in hydrothermal carbonization temperature (200–360 °C) [30]. Under the conditions of controlled reaction temperature and catalyst concentration, the combustion performance of carbon fuel products prepared by hydrothermal carbonization is improved and the ash content is significantly reduced [31], which can be an important development direction for thermal energy utilization. Combining the economic cost, biochar yield, and quality, the advantages of using pyrolysis technology for biochar in soil improvement are obvious. In addition to optimizing the preparation conditions of biochar, the modification is an important method to improve the quality of biochar [32].

Biochar, a new soil amendment, plays an important role in slowing soil acidification, fixing soil heavy metals and reducing plant heavy metal uptake [33,34]. When straw biochar was applied to a sandy ginger black soil with poor soil properties, soil organic phosphorus stability was enhanced with increasing biochar application [35]. Biochar addition to compost reduces phosphorus loss [36]. Biochar addition can reduce soil density and enhance soil water holding capacity, making the soil more suitable for crop growth [37]. Biochar can promote the interpretation of acetochlor in soil [38]. Biochar is added to constructed wetlands, and the mean removal rate of inorganic pollutants in sewage reaches 11.53% [39]. In wastewater treatment, biochar is also effective in the adsorption and fixation of organic dyes, heavy metals, nitrogen and phosphorus, antibiotics, and other organic pollutants in the water column at a cost less than activated carbon [40]. Biochar is an eco-friendly and efficient adsorbent for the removal of toxic metals from wastewater [41]. Straw biochar can also be modified to improve the application range of biochar [42,43]. Therefore, biochar should have a wide range and promising applications.

By studying the biochar utilization of crop straw in three northeastern provinces of China, the objectives of this research are to use collected data and GIS software to study the three questions: (1) What is the distribution and annual yield changes of different crop straws in Northeast China? (2) What is the potential of straw preparation of biochar to enhance carbon sink functions in Northeast China? (3) Can the industrial layout of the straw biochar industry become the base point for enhancing carbon sink functions? This study has important scientific value for China to achieve its carbon neutrality goals, and this will provide important references for other countries to enhance their carbon sink function.

2. Materials and Methods

2.1. Research Area

Northeast China refers to the region comprising the provinces of Heilongjiang, Jilin, and Liaoning and the four eastern leagues of the Inner Mongolia Autonomous Region (Hulunbeier, Xing'an, Tongliao, and Chifeng), which are home to the spring soybean subregion, the early maturing single-season rice crop area, etc. It is an important agricultural raw material yield base in China. Taking the provinces of Heilongjiang, Jilin, and Liaoning as the main subjects of the study, 19 major cities and the surrounding counties and cities were selected to analyze the changing trends of straw yield from 2017 to 2020. The objective of this study was to explore the important value of the biochar preparation from the straw industry in Northeast China for the enhancement of carbon sink functions. Based on the cultivation of straw crops in the study area, straw crops with large cultivation areas were distinguished into two categories: economic crops (e.g., soybean, sweet potato, etc.) and food crops (e.g., corn, rice, etc.), and specific analyses were conducted for each crop.

2.2. Data Collection and Processing

The data used in this paper mainly came from public data, and some data have been collected and investigated on site. The public data is from the website of the National Bureau of Statistics of China. The China Statistical Yearbook records crop yield data and makes it public on the website of the National Bureau of Statistics of China (http://www.stats.gov.cn/tjsj/ndsj/, accessed on 30 September 2021). The grass–grain ratio was calculated according to the field survey results (Table 1). The survey precision range was based on the county level. Grass-to-grain ratios were used to estimate the yield of all kinds of straw in each year. The economic benefits of straw raw materials, biochar products, and by-products were calculated according to the current mean market price in China.

Table 1. Grass to grain ratio value of crop.

Crop	Corn	Wheat	Sorghum	Soybean	Potato	Sunflower	Rice Grain
Grass Grain Ratio	1.2	1.19	1.2	1.5	0.5	1	0.9

The objective of the spatial treatment of straw yield was to analyze the change of straw yield in different regions. This study involved two types of data processing methods (GIS spatial analysis and time series analysis). ArcMap was a GIS system developed by the Environmental System Research Institute in 1978. The geographic layers of the three northeastern provinces were imported into Arcmap, and the interannual arable area data were written into the system. The spatial analysis and spatial data building functions were used to symbolically display and analyze the changes in the range of straw crops in Northeast China. At the same time, straw yield data containing linear trends and unstable seasonal components were predicted using a Winters' multiplicative model (Winters' multiplicative) with IBM SPSS Statistics software, the relevant models are shown in Equation (1).

$$\begin{aligned} l_t &= \alpha \frac{x_t}{s_{t-m}} + (1-\alpha)(l_{t-1}+b_{t-1}) \\ b_t &= \beta(l_t - l_{t-1}) + (1-\beta)b_{t-1} \\ s_t &= \gamma \frac{x_t}{l_{t-1}+b_{t-1}} + (1-\gamma)s_{t-m} \\ \hat{x}_{t+h} &= (l_t + hb_t)s_{t+h-m(k+1)},\ k = \left[\frac{h-1}{m}\right] \end{aligned} \tag{1}$$

where m is the cycle length (12 for monthly data and 4 for quarterly data), α is the horizontal smoothing parameter, β is the trend smoothing parameter, γ is the seasonal smoothing parameter, and $t + h$ is the predicted value of phase h.

Carbon emissions in the region are calculated using the carbon balance formula, as shown in Equation (2).

$$Q_{CO2} = (M_1 \times k_1 - M_2 \times k_2 - M_3 \times k_3) \times 44/12 \tag{2}$$

where Q_{CO2} is carbon dioxide emissions, t CO_{2e}; M_1 is raw material input, t; k_1 raw material carbon content, %; M_2 is product yield, t; k_2 is product carbon content, %; M_3 is waste yield, t; k_3 is waste carbon content, %; 44/12 is carbon conversion to C Conversion coefficient of O_2 (relative atomic mass of CO_2/C).

The biochar carbon sequestration capacity is the amount of carbon sequestered by biochar. The carbon sequestration capacity of biochar is maintained at around 50% without the addition of catalysts or other components for co-pyrolysis [44]. Based on the life cycle assessment method to estimate the carbon reduction capacity of biochar in China, the carbon sequestration potential of one ton of biochar reached 9.21×10^6 t CO_{2e} and the relevant calculation was carried out based on this criterion.

3. Results and Discussion

3.1. Crop Straw Yield and Distribution

3.1.1. Changes in the Cultivation Area of Crop Straw Crops

The change of yield and distribution of different straws was reflected from the change of planting area. The change of straw yield affected the supply of raw materials for biochar preparation. The change of straw distribution affected the spatial layout of straw utilization. The inter-annual distribution of the main straw crop (soybean, rice, and corn) cultivation area in the three northeastern provinces from 2017 to 2020 is shown in Figure 2. Affected by climate and topographic conditions, crops in Northeast China were mainly corn, rice, soybeans, and other crops. There was little difference between different provinces. Within the province, the largest area of crops was planted in the middle and low latitudes, and the planted area gradually decreased towards the surrounding high-density planting areas with a clear pattern of spatial distribution. The inter-annual variation in the planted area of major straw crops in Jilin Province was relatively stable. In 2020, the corn planting area had significantly decreased. The planted area of rice and corn in Liaoning Province increased significantly from 2017 to 2018, but this did not fluctuate much after 2018. The area planted with straw in Heilongjiang Province was in a stable state, but the area planted with rice decreased year by year. Therefore, the change of straw planting area did not affect the utilization of straw.

Soybean, corn, and rice were the three main straw crops grown on a large scale in Northeast China, and the cropping structure pattern was influenced by a combination of socioeconomic, natural, and national policy conditions [45]. The change of distribution in different crop planting areas had guiding significance for the use of different straw. Crop cultivation in Northeast China showed a clear distribution of spatial agglomeration within the province, which mainly concentrated in regional centers and scattered across the region. Heilongjiang Province had been the main soybean producing region in China. The area under soybean cultivation was extensive with no significant annual variation, which was the same as the area under corn cultivation. Rice acreage in Heilongjiang fluctuated with a small decline from 2017 to 2018, and this had remained stable since then. Crop cultivation was mainly located in cities with more developed economic and transportation conditions such as Harbin, Qiqihar, and Hehe city, which facilitated marketing and transportation. The area under crop cultivation in Jilin Province was generally stable, with crop cultivation mainly distributed in Changchun, Liaoyuan, and Yanbian. The area under corn cultivation decreased significantly from 2019 to 2020. The main growing areas were distributed in Liaoning Province of Shenyang, Dalian, and Fushun city; the area under rice cultivation increased significantly from 2017 to 2018 and remained stable thereafter. There are certain differences in the utilization of different straws, and the utilization of straws should be carried out under the condition of fully considering the differences in the distribution of different straws.

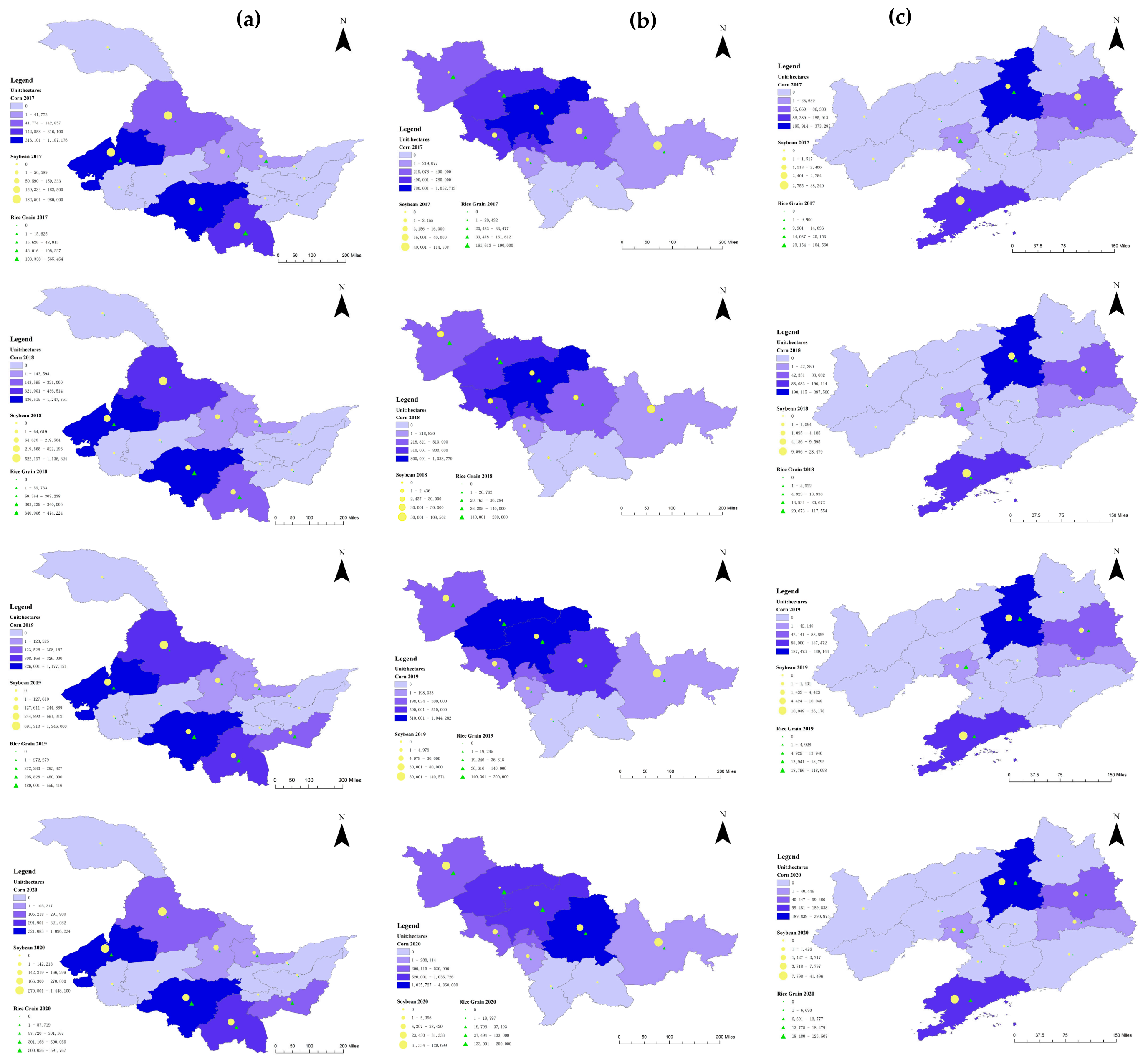
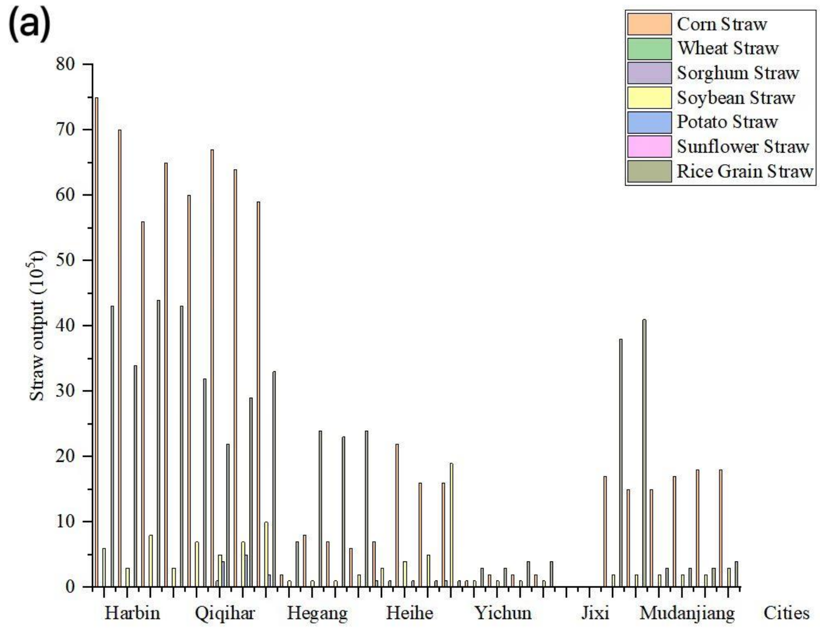


Figure 2. Inter-annual distribution of the main straw crop cultivation area in the three northeastern provinces from 2017 to 2020 ((**a**) Heilongjiang; (**b**) Jilin; (**c**) Liaoning).

Most of the eastern provinces of China had high summer temperatures, cold winters, and moderate precipitation. Crops were grown once a year; they were mainly well-adapted, sunny, and cold-tolerant crops such as corn and soybeans. The high latitude of Heilongjiang Province had also produced a relative reduction in the area under rice cultivation due to climatic conditions. The state had introduced a series of policy measures to promote agricultural development in order to stabilize the grain market [45], which had promoted an increase of the area planted with straw grain crops in the northeast including a significant increase in the area planted with rice in Shenyang, Liaoning Province. This will effectively ensure the sustainable use of straw.

3.1.2. Trends in Crop Straw Yield

Based on the acreage and annual yield data of straw crops, the straw yield in the three northeastern provinces from 2017 to 2020 was estimated (Figure 3). There was some degree of inter-annual variation in the yield of different type straws in each province, but there was overall little fluctuation, and only some cities showed relatively significant degrees of variation in some types of straw. For example, wheat straw yield in Harbin had increased year on year, and climatic conditions, precipitation, and arable land area were the main influencing factors. However, sunflower straw yield in Dalian was on a downward trend, and the main factors were the year-on-year reduction in market demand and a reduction in planted area. The yield of corn straw in Jilin decreased significantly. It was jointly affected by factors such as reduced cultivation area and reduced export demand. Therefore, changes in environmental conditions and market demand are the main reasons that affect the trend of crop straw yield changes.



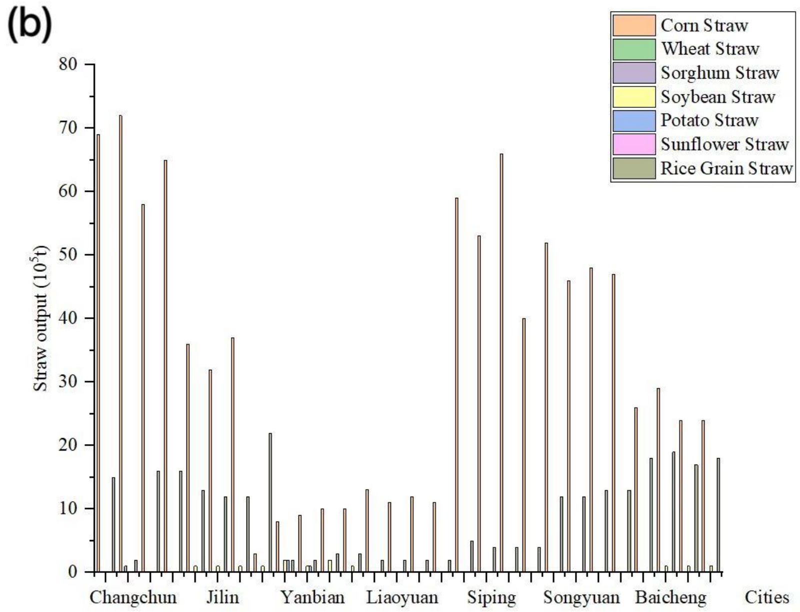


Figure 3. *Cont*.

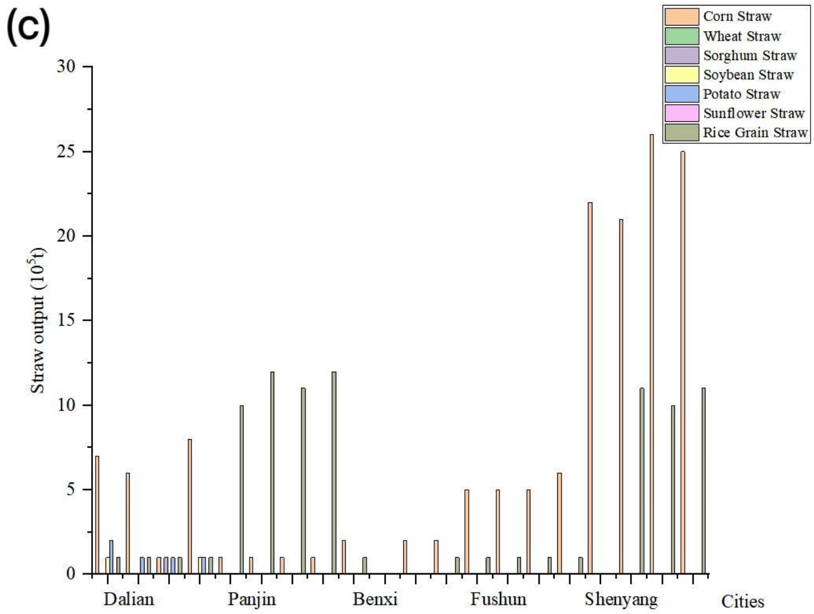


Figure 3. Crop straw yield in Northeast China from 2017 to 2020 ((**a**) Heilongjiang; (**b**) Jilin; (**c**) Liaoning).

Changes in straw crop planting patterns were a major factor affecting straw yields. Among the three major crops of soybean, corn, and rice, farmers were not very motivated to plant soybean and the planting area was small. The yield of soybean straw was relatively low compared to that of corn and rice straw, and the economic benefit advantage was not obvious. The promotion of structural reforms on the supply side of agriculture had eased the grain backlog faced by farmers, but the low purchase price of soybeans due to imported soybeans had also led to a continued decline in the area planted with soybeans and straw yield in Northeast China [46]. In contrast, corn and rice had high yields, a long-term, stable market demand, stable purchase prices, little fluctuation in planted area, and stable straw yield. Under the influence of the storage policy, there is a substitution of corn for soybean planting, which has a certain impact on soybean straw yield [47]. However, in recent years, the impact of export restrictions imposed by other countries on Chinese soybeans has also promoted the increase in the planting area of Chinese soybeans [48]. However, this has not resulted in a significant increase in planted area due to limited demand.

3.2. Forecast and Analysis of Future Crop Straw Yield

Statistics showed that from 2017 to 2020, the annual yield of straw in Northeast China was about 7.0×10^7 tons, and this showed a trend of increasing year by year. Heilongjiang province has the largest area under straw crops and the highest annual yield of straw, which will be approximately 3.7×10^7 tons in 2020. Combining the acreage and yield data of straw crops in recent years, the yield of various types of straw was processed and calculated, the exponential smoothing method was used to smooth the straw yield data of nineteen regions and seven major crops in the three northeastern provinces three times from 2017 to 2020. The forecast results of straw yield and change trends from 2020 to 2025 are shown in Figure 4. The total straw yield in the three northeastern provinces tends to be stable from 2021 to 2025. Among the major crop straw yields in Heilongjiang province, soybean straw had the largest increase, followed by rice and corn straw. Except for the decrease in corn straw production in Jilin province, straw yield in Jilin and Liaoning provinces also tended to increase. However, the overall increase was relatively small ($\leq$1%), and the change curve was like a stable horizontal linear shape. Therefore, straw can be used as a raw material of biochar in a stable and sustainable way.

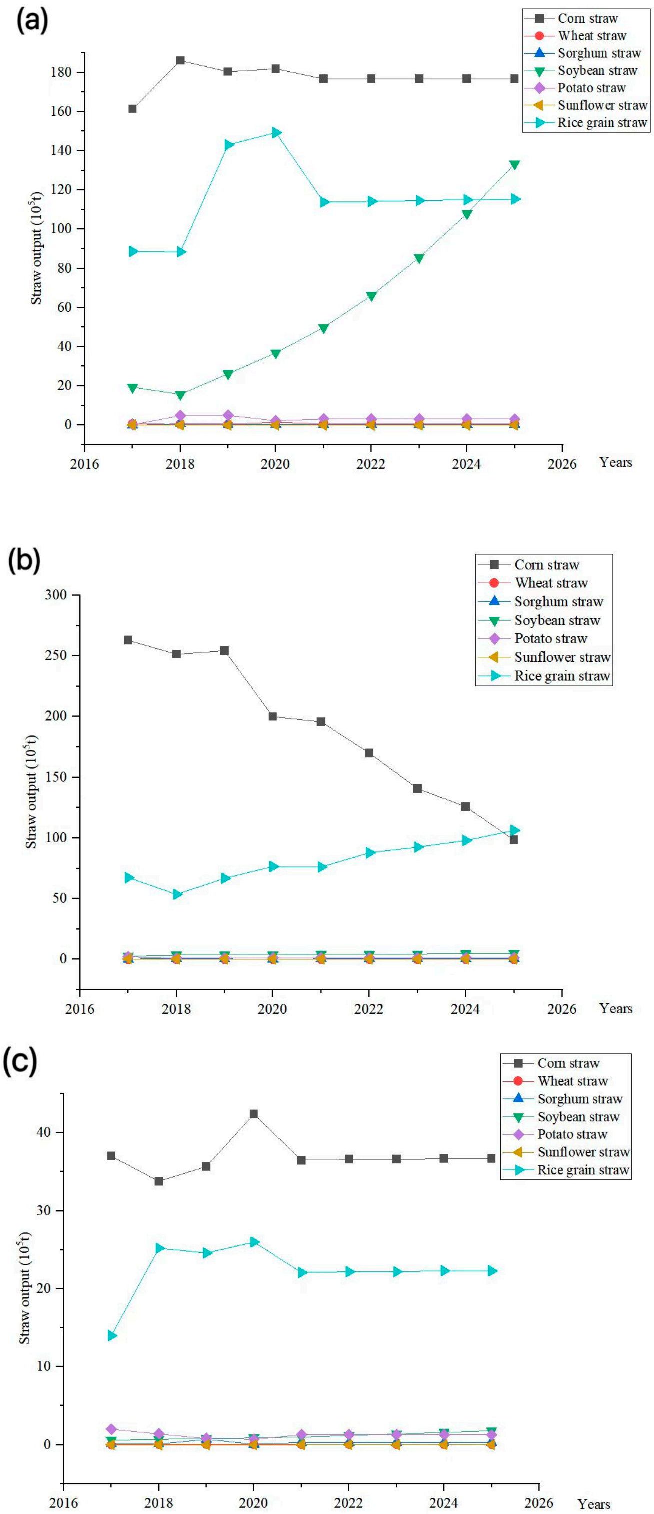


Figure 4. Changes and prediction of crop straw yield in Northeast China ((**a**) Heilongjiang; (**b**) Jilin; (**c**) Liaoning).

China's arable land area decreased by 4.9 × 10^3 km^2 from 2000 to 2015 [49], while that of the three eastern provinces decreased by 0.5 × 10^3 km^2. In the three northeastern provinces of China, the conversion of arable land to construction land accounted for 28.6% of the total land change area. Fluctuations in arable land area will lead to changes in the structure of crop cultivation and total yield. As the area of arable land decreased, the choice of crops was grown tends to be towards economically efficient and productive crops.

This had accelerated yield fluctuations in secondary crops such as sweet potatoes and sunflowers. In addition, uncertainties such as extreme weather, pests, and natural disasters also led to changes in crop yields.

In summary, the distribution of straw crops in Northeast China was extensive, and the cultivated land area was relatively stable. Various types of straw, especially straw from major crops, will remain in abundant storage and have the potential to grow in future yield, which can provide long-term and sufficient raw materials for the development of the biochar industry.

3.3. Carbon Sequestration Effect Analysis of Biochar Prepared from Straw

The change in total carbon emissions in Northeast China generally tended to be stable by 2019 [50,51]. While the growth rate of adjacent interannual data for Heilongjiang and Jilin provinces did not fluctuate much, the adjacent interannual data for Liaoning province increased year by year, which was a significant increase in the growth rate of CO_2 emissions from 2017 to 2019 (Figure 5). This may be related to the impact of the rapid development of industrial industries in Liaoning Province, which relies on its coastal geographical advantage. Therefore, how to gradually reduce carbon emissions without affecting the stable development of the regional economy is a current and future issue that needs to be addressed. Taking the total amount of biochar produced from straw feedstock from 2015 to 2019 as an example, the carbon emissions in Northeast China after the preparation of biochar based on its carbon sequestration efficiency are shown in Figure 6. The calculations showed that if all waste straw resources were used to produce biochar and sequester soil carbon, total carbon emissions could be reduced by 60%.

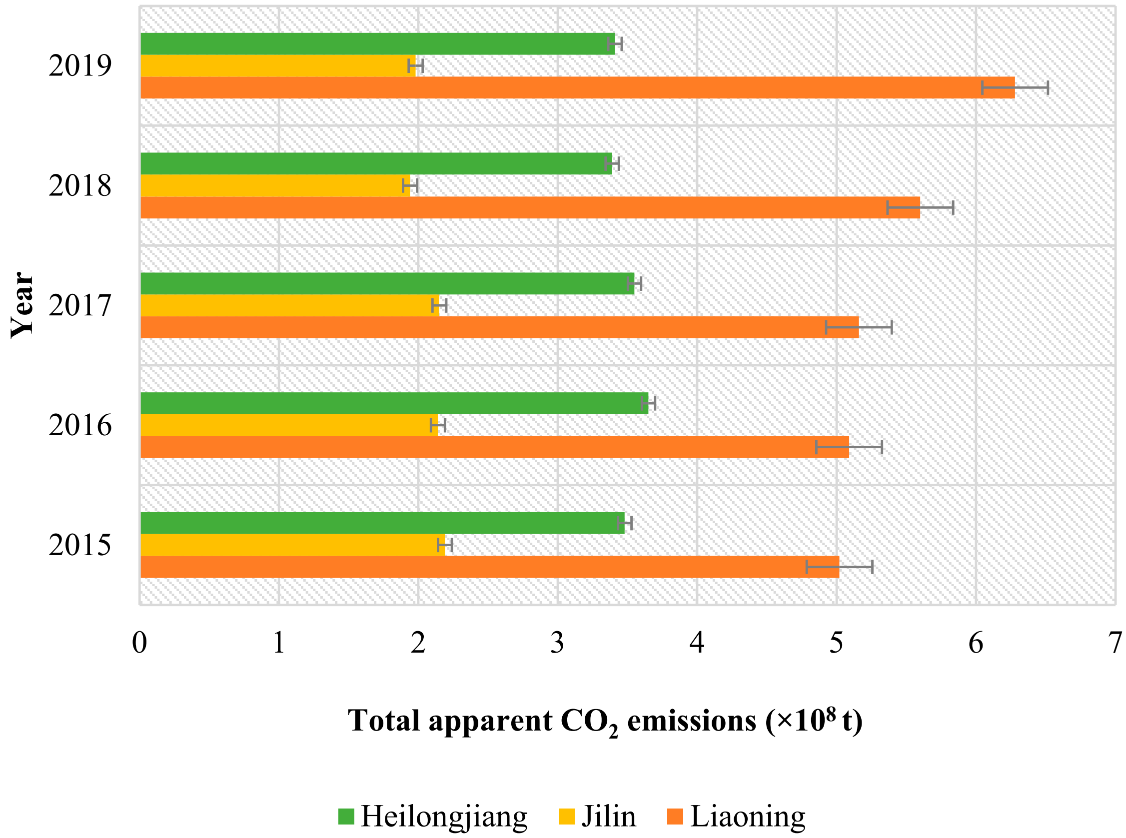


Figure 5. Total CO_2 apparent emissions in Northeast China from 2015 to 2019.

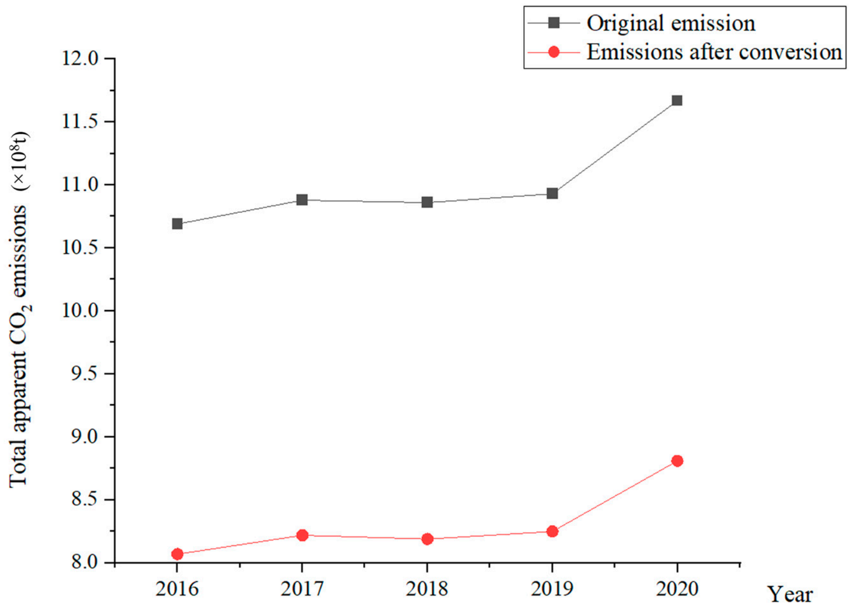


Figure 6. Comparison of total carbon emissions before and after the application of biochar in Northeast China.

Using agricultural waste biomass to produce straw biochar can reduce the environmental pollution caused by straw burning and effectively increase soil carbon sequestration capacity through soil carbon sequestration. According to calculations [52], the interannual carbon sequestration of Chinese crop straw as a raw material for biochar was as high as 5.51×10^8 t CO_{2e}, which was significantly higher than the carbon emissions from straw burning at 4.22×10^8 t CO_{2e}. The biochar yield from the pyrolysis and carbonization of straw biomass was about 31.8%, which was on a rising trend year by year with the improvement of technology. The carbon emissions of Chinese industry (mining, manufacturing, and power industry) in 2020 were 1.0×10^{10} t CO_{2e} [53]. Therefore, the use of straw to prepare biochar was of great importance to relieve the pressure on industrial carbon emissions. The net conversion of pyrolysis carbon gas cogeneration will increase by 15% by 2060 [54]. The carbon sequestration effect of straw biochar applied to soil is influenced by the properties of the biochar, the nature of the soil, and the environmental conditions, so the carbon sequestration and reduction effect were varying under different conditions. Straw biochar significantly improved soil fertility. However, due to differences in biochar raw materials and preparation techniques, different straw biochar properties had an impact on the carbon sequestration capacity of biochar [55]. Adjusting the energy mix was conducive to reducing the intensity of carbon emissions and had an important role in industrial carbon emissions. The dominant factor influencing CO_2 emissions was the proportion of coal in total energy [56]. If more biochar is used to replace coal, the impact of CO_2 emissions and air pollution will be significantly reduced.

Chen et al. [57] studied the carbon sequestration of rice straw biochar using the life cycle assessment method and found that the preparation of rice straw biochar significantly reduced the release of soil CO_2 with soil carbon sequestration of up to 9.94×10^6 t (3.65×10^7 t CO_{2e}). Corn straw biochar effectively improved soil organic matter content, soil microbial biomass nitrogen content, carbon to nitrogen ratio, and other indicators, which steadily increased the soil organic carbon fixation rate by more than 30% over a longer period [58]. After biochar was effectively treated, CO_2 emissions in soil was reduced under the conditions of appropriate additions [59]. Different soil depths, influenced by surface runoff, were also an important factor in the carbon fixation effect of straw biochar [60].

Crop yield also varied with the amount of biochar applied during biochar return. Within a certain amount of addition, crop yield increased significantly with the increase in biochar application [61]. Crop yields increased significantly after straw was returned to the field [62], so the carbon sequestration and yield increase of biochar were evident. Straw biochar return to the field not only promoted increased agricultural yields, but was also an important means of effectively increasing agricultural carbon sinks.

3.4. Economic Analysis of Straw Biochar Utilization

3.4.1. Analysis of Environmental Economic Conditions

Northeast China was the largest natural forest distribution area in China. The forest species were mainly mixed coniferous deciduous broad-leaved forests in the middle temperate zone, which were widely distributed in the Greater and Lesser Xing'an Mountains and Changbai Mountains. Forest trees cover an area of 4.5×10^5 km^2, which is a good natural ecological barrier. The large area of forest cover provided good conditions for water protection. The major rivers in the region, such as the Songhua, Neng, and Ussuri rivers, played an important role in securing water for yield and living in the surrounding areas, driving the development of coastal agriculture and fisheries and foreign trade at the border. At the same time, this also provided good environmental conditions for the development of the biochar industry. Northeast China's location in the hinterland and weak links with domestic and international markets [63] had hindered the region's rapid economic development. This was also detrimental to the development of the biochar industry. In recent years, air quality in Northeast China has been further improved as the Chinese government has raised the requirements for ecological environmental protection and pollution emission standards. However, due to the cold winter months, air quality in January-March, November, and December was affected by heating [64], so pollution emissions increased significantly compared to other seasons. This increased the pressure on environmental pollution prevention and control.

Biochar had good carbon sequestration effects and was used in agricultural yield to improve soil conditions, promote increased crop yields, enhance agricultural carbon sinks, and reduce environmental pollution. In Northeast China, there was a high demand for coal for winter heating with annual consumption exceeding 2.0×10^8 tons [65]. Based on the mean price by calorific value in the China Coal Exchange market, producers earned at least 400 RMB per ton if the same amount of biochar fuel was used to burn for heating instead of coal. According to market research data analysis [66], the production direction of straw charring products included biochar, biomass gas, and wood vinegar. When the annual yield of biochar reached 5000 tons and the market price was 3000 RMB/ton, the annual sales income reached about 1.5×10^7 RMB. The straw charring project had high profits and broad market prospects. The development of the biochar industry in the northeast can effectively alleviate problems such as the shortage of coal supply and over-exploitation, and effectively improve the environmental situation, which is of great significance to the development of the regional economy.

3.4.2. Analysis of Industrial Economic Situation

Northeast China was a base for old and heavy industries. Due to the slow transformation and upgrading of industries in Northeast China [67], the economic development level of the region had been slow to improve. Transportation in Northeast China was mainly by land, and the degree of agglomeration decreases from core urban areas to peripheral cities [68]. Railway transport was the basis of industrial development in Northeast China, and its spatial distribution extended from provincial capitals to smaller cities. Road construction in Northeast China showed a clear spatial variation of "more in the east and less in the west", but the level of construction had gradually increased, and overall construction in Liaoning Province was relatively balanced. Overall, the transportation in Northeast China was backward, which restricted the development of biochar industry. Analysis of the labor force situation showed that the high rate of population migration and the serious ageing of the population in Northeast China were not conducive to economic development [69]. Factors such as increased competition for employment, low levels of infrastructure development and slow economic growth had a significant impact on the outflow of population. County areas, constrained by unreasonable industrial structures and inadequate public service provision, had become the main areas of population loss. The loss of young and middle-aged people posed a great threat to the stable development of industries in Northeast China [70]. The loss of labor was detrimental to the development of the straw biochar industry.

The technology level was an important factor limiting the development of the biochar industry. The introduction of advanced biochar preparation technology played an important role in accelerating the technological upgrade of industries in Northeast China and promoting the re-operation of stagnant old industrial areas. Due to the relatively dispersed spatial distribution of straw raw materials, raw material storage, transportation, and product sales require wide coverage and flexible transportation, which played an important role in upgrading the transportation network in Northeast China. The increase of employments in industrial operations, raw material collection and processing, product transportation and sales also played a positive role in slowing down population loss and even attracting the inflow of foreign labor. Therefore, the development of straw biochar industry brought opportunities to local economic development. The high yield of biochar by-products, the wide application of combustible gas, bio-oil, and other products was widely used, and the high market demand had also contributed to the economic development of the biochar industry.

3.4.3. Analysis of Economic Expectations

Considering the demand for industrial land, the spatial use efficiency and economic location evaluation index of Northeast China were relatively low [71]. Economic development was closely related to local industrial policies. The old industrial areas in Northeast China accounted for a large proportion of the overall space, which were difficult to renew, which had a relatively large impact on the overall economy. These conditions restricted the development of biochar industry. Figure 7 shows that the total gross domestic product (GDP) of the three northeastern provinces in the last five years was highest in Liaoning Province, followed by Heilongjiang and Jilin Provinces. The GDP growth rate of the three provinces dropped to a five-year low in 2020 and significantly rebounded the following year. The pillar industry of economic development in the three provinces was the tertiary industry, which was the primary industry contributing more to overall GDP than the secondary industry. The analysis of industrial added value and growth rates showed that Northeast China's dependence on the secondary sector remained strong, which indicated that industry in Northeast China no longer dominated the regulation and control of the regional economy. The development of the biochar industry will be conducive to promoting the development of industry in Northeast China.

The biochar industry had a wide range of applications. Because of the low raw material costs, there were many ways to obtain economic benefits. However, the preparation of straw biochar had high requirements for industrial technology and conditions. Introducing advanced technological means and attracting outstanding talents were the guarantee for the steady development of the biochar industry. The construction of the biochar industry can promote the improvement of the backward technology and management level of the old northeast industrial zone, promote the revitalization of the old northeast industry, and also play an important role in accelerating the development of the secondary industry. Considering only the economics of preparing raw materials for biochar, the cost of recovering one ton of dry weight straw is 600 RMB, which can prepare about 350 kg of biochar under the condition of meeting the interests of farmers. Biochar can be sold in the market at 3.0–5.0 RMB/kg and a profit of approximately 2.0×10^3 RMB can be obtained from the sale of one ton of product. Based on straw yield data, a total of 7.0×10^7 tons of straw were harvested in the three eastern provinces of China in 2020 alone. If 50% of the straw is invested in biochar yield, a huge profit of 7.0×10^{10} RMB will be obtained from the sale of biochar products. If high-end biochar is prepared, its economic value will be higher. This is of great significance to promote the development of industry in the northeast.

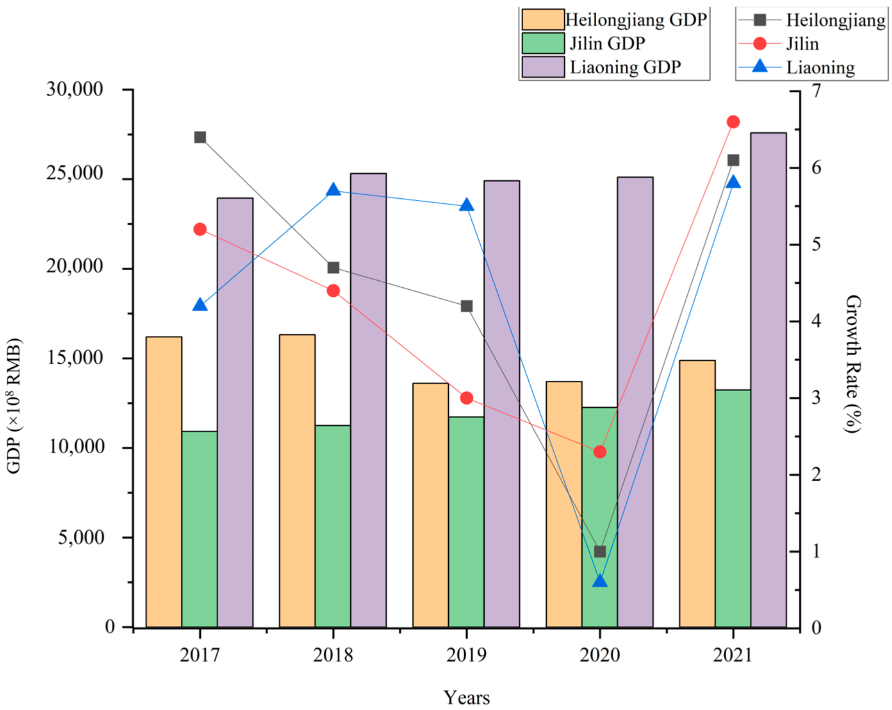


Figure 7. GDP and growth rate of the three northeastern provinces from 2017 to 2021.

3.5. Analysis on Industrialization Model of Biochar Preparation from Straw

3.5.1. Agricultural Carbon Sink Cycle Model

Against the background of high carbon prices in the global carbon trading market, the return of biochar to the field promoted agricultural efficiency [72]. Farmers were the mainstay of agricultural circular economy development. It was the main development direction of circular agriculture to recycle agricultural waste, reduce carbon emissions from straw burning, and improve economic efficiency. The resource utilization of waste was an important method of the agricultural carbon sink. The concept of the agricultural carbon cycle emphasized the coordinated development of ecology, environment, and economy, which played an important role in reducing resource waste, improving yield structure, and promoting agricultural modernization [73]. The development model of waste recycling promoted the conversion and substitution of energy [74], which was in line with the requirements of sustainable development strategies. The application of biochar materials can improve agricultural carbon sinks, increase yields and incomes, and realize the positive feedback effect of the agricultural carbon cycle. In the process of promoting the recycling model, the government needs to guide farmers' low-carbon ecological awareness, low participation, industrial technology barriers, and other related issues [75]; the purpose is to promote the comprehensive use of agricultural waste resources and sustainable economic development.

3.5.2. Biochar High-End Product Development and By-Product Treatment

In addition to being used as a soil conditioner, biochar was treated as a high-end product with high economic value (water treatment materials, electrode materials, etc.) [76,77]. This was of great significance to the promotion of biochar industry. However, in addition to the technical difficulties in the preparation of high-end biochar products, it was also a problem to connect biochar production enterprises with biochar utilization enterprises. Therefore, the development of high-end biochar products needed to be planned. Biomass thermal decomposition products were mainly divided into three categories: solid (biochar), liquid (bio-oil), and combustible gas [78]. In addition to the main product biochar, the by-products were also of high value for utilization. The pyrolysis of corn straw produced various products such as aldehydes, acids, and alcohols within a certain temperature range [79]. These organic compounds were widely used in food, medical, and industrial applications and had become an important direction for future industrialization. Northeast China was rich in straw resources and had a large number of by-products from concentrated pyrolysis, and there was great potential for the exploitation of these by-products. Therefore, it was important to carry out research on the in-depth utilization of different by-product components. However, like the preparation of high-end biochar products, the technical requirements for the utilization of by-products are high, which brings great challenges to local industrial enterprises. It is of great significance to introduce the cooperation model of high-tech enterprises to promote the development of the biochar industry.

3.6. Development Prospect Forecast

The global carbon trading system presented opportunities and challenges for China's development. In order to achieve a coordinated carbon trading mechanism, it was important to give full play to China's active role in the international carbon trading market. Supply and demand were the main factors influencing carbon price fluctuations. Achieving carbon capture, carbon neutrality, and mastering the discourse of carbon trading will be China's future goal in responding to changes in the international carbon trading mechanism [80]. Biochar technology is developing day by day, but the biochar industry in Northeast China is still in its infancy with backward technology and low marketability. This is incompatible with the rich straw resources. Different trades (agriculture, forestry, industry, etc.) lack unified coordination of demand for biochar, which further affects the market-oriented development of straw biochar products. In the future, the government will build a platform to promote exchanges between different trades and promote the development of biochar industrialization.

Northeast China is rich in agricultural resources and has a deep foundation and experience in industrial development. With the increasing demand for carbon emission reduction, the industrial model of preparing clean energy for the purpose of carbon sequestration in agricultural yield has a broad scope for development. China's northeast region is a high-quality grain yield base, and agricultural cultivation is dominated by straw crops with a long-term trend of steady growth. Straw resources are abundant. During the development of the biochar industry, it is necessary to make full use of the advantages of the rich raw materials, convenient transportation, and large proportion of land in the region to further reduce the initial capital investment and achieve better economic and ecological and environmental benefits. It is also necessary to make full use of the existing industrial conditions to develop the biochar industry and strengthen the integration of the biochar industry with existing industries in order to reduce carbon emissions and increase economic value. The existing statistical methods for straw yield are mainly calculated based on the planting area combined with the grass to grain ratio of field surveys, which may have certain deviations. The deviation of straw yield statistics will affect the design and decision-making of its resource utilization. It is recommended to improve the accuracy of straw yield technology based on on-site investigation and unmanned aerial vehicle technology in the future.

Crop straw has high annual yield, high economic value, and wide range of applications for preparing biochar, which brings development opportunities for enterprises. Companies can carry out research work from straw storage, biochar material preparation, and carbon-based fertilizer preparation according to the regional development needs. In particular, the preparation of high-end biochar materials has high economic value and broad market prospects. It is difficult for private companies to carry out large-scale research due to limited funds, so it is suggested to carry out the application research of biochar for soil improvement. The scale of application will be gradually increased from farmers to large farms. In addition, public companies and private companies cooperate to further improve the promotion scope and application value of straw biochar.

4. Conclusions and Recommendations

The research on the resource utilization of biochar prepared from crop straw in the three northeastern provinces of China had been carried out to explore its contribution to the improvement of carbon sink function in this area. The main research conclusions are as follows:

(1) The northeast biochar industry was rich in raw materials. From 2017 to 2020, the annual yield of straw in Northeast China was about 7.0×10^7 tons, which showed an increasing trend year by year. Among the main crop straw yield, the growth rate of soybean straw was the largest in Heilongjiang Province The overall growth rate of straw yield in Jilin and Liaoning Province was relatively small ($\leq$1%);
(2) As the largest grain yield base was in China, the straw resources were widely distributed in Northeast China. Straw was used steadily and sustainably as a raw material for biochar. The development of the biochar industry in Northeast China reduced carbon emissions and environmental pollution caused by straw incineration, and this also obtained a huge benefit of 7.0×10^{10} RMB. The future development space of the biochar industry will be huge;
(3) Northeast China's industry had a great demand for technical labor, and the development of the biochar industry required the introduction of high-end talents and advanced technology. The biochar industry in Northeast China will have a broad prospect, and a large amount of demand for the biochar industry involves farmland soil improvement and winter heating fuel utilization needs. The development of the biochar industry will slow down the pressure of industrial carbon emission reduction. The carbon emission reduction model of straw biochar production in Northeast China will provide an important reference for other regions;
(4) At present, the development of the biochar industry in Northeast China is in its early stage. As a new industry serving food security, environmental security, and sustainable development, the biochar industry promotes the sustainable development of the regional economy. Relying on the advantages of agricultural resources, carbon emission reduction requirements, economic benefits, and environmental benefits will gradually increase the emphasis on agricultural carbon sinks, and the biochar industrial chain system will be gradually improved;
(5) In the future, the purpose of improving the accuracy of straw yield calculation based on field surveys and unmanned aerial vehicle technology is to achieve improved straw resource utilization. At present, the development of the biochar industry is limited by the shortcomings of backward industrial technology, slow economic growth, aging population, etc. It is suggested to make full use of local industrial enterprises to develop the biochar industry. The cooperation model with high-tech enterprises in the preparation of high-end biochar products and the utilization of biochar by-products can promote the development of the biochar industry.

Author Contributions: Conceptualization, X.H. and H.W.; methodology, X.H., H.W. and X.C.; software, X.H., H.W. and X.C.; validation, H.W. and Y.G.; formal analysis, X.H. and Y.G.; investigation, X.H., X.C. and Y.G.; resources, X.H. and Y.G.; data curation, X.H., X.C. and Y.G.; writing—original draft preparation, X.H.; writing—review and editing, H.W. and X.H.; visualization, X.H. and X.C.; supervision, H.W; project administration, H.W.; funding acquisition, H.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the High-level Talent Foundation Project of Harbin Normal University (No. 1305122210) and the University student Innovation Program of Harbin Normal University (No. SD2022068).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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