Energy potential and environmental benefits of agricultural crop biomass resources in Henan Province, China

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Abstract: Henan Province, as one of China's largest grain production bases, produces abundant agricultural crop biomass resources every year, yet the environmental benefits from their applications remain underutilized. This study systematically investigates the theoretical and collectable outputs of major agricultural crop biomass resources in Henan from 2013 to 2023. The results show that Henan Province annually produces, on average, 1.09×10^8 t of theoretical and 8.73×10^7 t of collectable agricultural crop biomass resources, with an energy potential of about 4.44×10^7 t of standard coal equivalent (tce), accounting for about 19.7% of Henan's average annual energy consumption. Among these resources, maize stalk and wheat straw predominate, together contributing nearly four-fifths of the total agricultural crop biomass energy potential in Henan. Scenario analyses indicate that utilizing 1.485×10^7 t of agricultural crop biomass resources for energy could reduce 1.574×10^7 t of CO_2 emissions through combustion and up to 3.36×10^7 t of CO_2 emissions through pyrolysis with biochar application to soil. These findings indicate the significant role of agricultural crop biomass in supporting Henan's transition to sustainable energy and its carbon mitigation efforts.

Keywords: agricultural crop biomass, energy potential, environmental benefits, energy conversion, pyrolysis with biochar application
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1 Introduction

Energy is a key driver of economic development, but China's rapid industrialization and urbanization have led to increased energy demand, putting pressure on fossil fuels and exacerbating environmental issues like greenhouse gas (GHG) emissions and air pollution[1]. Hence, China is accelerating its transition to renewable energy, with a focus on clean solutions that reduce fossil fuel dependence and promote ecological and rural revitalization. Among renewable energy sources, biomass stands out for its dual ability to provide stable energy and manage agricultural waste. Agricultural crop biomass, such as crop straws and stalks, is one of the largest and most accessible renewable resources, particularly in China, where over 7×10^8 t of agricultural crop biomass are generated annually[2]. Henan, a major agricultural province in China, produces substantial amounts of agricultural crop biomass. Utilizing biomass energy in Henan aligns with China's carbon neutrality goals. It helps address regional agricultural waste problems, while simultaneously providing socioeconomic benefits by generating rural employment and contributing to the province's green transformation. Efficient biomass conversion can thus support both energy transformation and environmental protection, offering a win-win scenario for sustainable development. The estimation of energy potential from agricultural crop biomass resources is essential for understanding the role of agricultural crop biomass resources in regional and national energy systems. The distribution of agricultural biomass resources depends on agricultural crop production patterns. Estimating its potential enables policymakers to estimate how much agricultural crop biomass can realistically replace fossil energy in electricity generation, heating, or biofuel production[3]. Meanwhile, the utilization of agricultural crop biomass can significantly reduce carbon emissions by replacing coal, oil, or natural gas. Estimating environmental benefits, especially CO_2 emission reduction, provides strong justification for agricultural crop biomass development. Estimating the energy potential and environmental co-benefits from agricultural crop biomass ensures that policymakers can set realistic renewable energy targets, design subsidies, and implement regulations that encourage biomass utilization[4].

There are some previous studies in the literature on the estimation and analysis of energy potential from agricultural crop biomass resources around the world. For example, the energy potential derived from agricultural crop residues was estimated in Turkey[5,6], Pakistan[7], and China[8]. In their studies, some researchers converted the energy potential from agricultural crop biomass into a percentage of the total national energy consumption, or estimated its potential for biogas production. These approaches contextualize the energy potential of agricultural crop biomass. Specifically, they highlight its contribution to national energy needs. Furthermore, they emphasize its role in renewable energy generation. This can play a key part in reducing dependence on fossil fuels. While these

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studies provided valuable insights into the energy potential of agricultural crop biomass, they have not considered the corresponding environmental benefits. Additionally, the residue-to-grain ratios of agricultural crop biomass resources used for estimating their energy potential are often region-specific, yet these studies did not fully address variations in agricultural practice or environmental conditions that could affect the accuracy of the energy potential estimations. In contrast, this study aims to fill this gap by not only assessing the energy potential but also analyzing the corresponding environmental benefits from agricultural crop biomass resources.

Henan Province, located in central China, faces significant challenges regarding energy supply and demand. With rapid industrialization and urbanization, the province's energy consumption has surged, increasing reliance on energy, which has led to rising carbon emissions, contributing to environmental pollution and climate change. The demand for energy continues to grow, especially in key sectors such as manufacturing and agriculture, putting additional pressure on conventional energy sources. Biomass energy development presents a promising solution to these challenges. Henan Province is a major agricultural province in China, with abundant agricultural crop biomass resources produced annually. By tapping into agricultural crop biomass resources, Henan can diversify its energy mix, reducing dependence on fossil energy. Biomass energy not only helps meet local energy demands but also offers a sustainable alternative with a lower carbon footprint. As a renewable source of energy, biomass contributes to mitigating carbon emissions, thus supporting China's broader environmental and climate goals in Henan Province. To better utilize agricultural crop biomass resources for promoting the economic and social development of Henan, it is necessary to conduct a thorough analysis of the theoretical and collectable quantity and the availability of agricultural crop biomass resources in Henan Province, as well as to evaluate the potential energy and environmental benefits from these resources.

The primary objectives of this work are as follows: 1) to conduct a systematic assessment of the theoretical outputs, collectable quantities, and associated energy potential of agricultural crop biomass resources in Henan Province in recent years; 2) to analyze various utilizations of these agricultural crop biomass resources in Henan; and 3) to estimate the environmental benefits from the energy utilization of agricultural crop biomass resources in the province.

2 Energy production and consumption, and CO_2 emissions in Henan

2.1 General introduction of Henan

Henan Province, located in the central region of China, is a region that plays a key role in China's geography, economy, and culture. Covering an area of about 167 000 km^2, Henan is strategically positioned along the middle reaches of the Yellow River. Henan's location serves as a transportation hub connecting northern, eastern, and southern China, as shown in Figure 1. Henan's resident population in 2024 was 9.785×10^7, with an urbanization rate rising to 59.22%, indicating a clear trend of population concentration in urban areas.

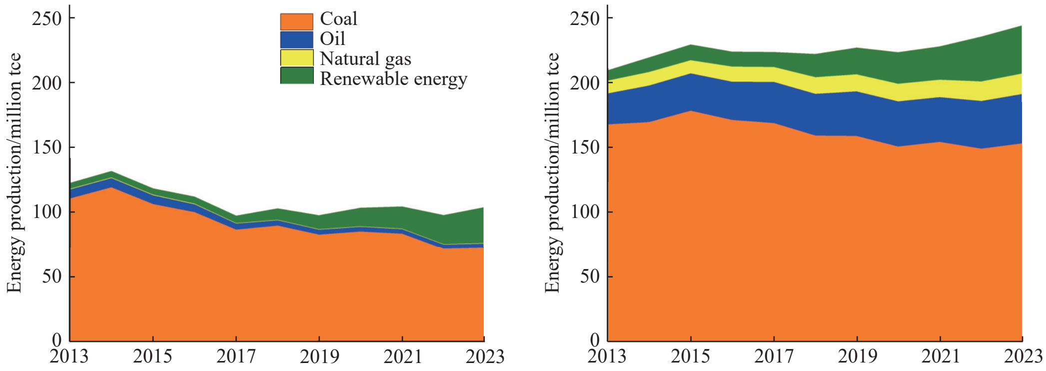
Since 2013, Henan Province has experienced continuous and rapid economic growth. Its gross domestic product (GDP) increased from CNY3.16 trillion in 2013 to CNY5.91 trillion in 2023, demonstrating a strong and steady expansion. Henan Province is one of the most important agricultural provinces in China and is often referred to as the "Granary of the Central Plains". According to the latest data, Henan's total grain output has long ranked first in China, and its wheat output accounts for more than a quarter of the total in China, making it a core region for ensuring the nation's food security[9]. Agriculture continues to be an important driver of Henan's economy, but over the years, industrialization and urbanization have significantly transformed its economic landscape. Henan Province has become a major manufacturing base, with key industries including machinery, textiles, chemicals, and electronics. Additionally, Henan has been making significant investments in areas like renewable energy, technology, and infrastructure to modernize its economy and promote innovation. Henan also faces challenges in balancing urban development with rural areas, improving environmental sustainability, and enhancing social services[10].

Figure 1 Map of Henan Province

2.2 Energy production and consumption in Henan

In this section, the energy production and consumption, and carbon emissions in Henan Province are presented to provide a comprehensive overview of Henan's energy production and consumption.

Figure 2 shows the energy production and consumption in Henan Province from 2013 to 2023 (the related data are from Henan Statistical Yearbook 2024[11]). Henan Province's energy production and consumption patterns showed a widening imbalance between supply and demand. Energy production declined from about 1.22×10^8 tce in 2013 to around 1×10^8 tce in 2023, largely due to the steady decrease in coal production, despite modest growth in renewable energy. Meanwhile, energy consumption rose from roughly 2.09×10^8 tce to 2.43×10^8 tce during the same period, driven by growing demand for oil, natural gas, and renewable energy. This divergence created a persistent and expanding energy gap from about 9.0×10^7 tce in 2013 to nearly 1.4×10^8 tce in 2023, indicating Henan's increasing reliance on external energy imports. Such dependence could raise concerns over energy safety, cost volatility, and vulnerability to supply disruptions. Additionally, this shift in energy consumption patterns signals a gradual energy transition but also underscores the change of ensuring sustainable and self-sufficient energy development in the province. Based on the energy consumption trends shown in Figure 2b, the energy consumption structure in Henan Province has been gradually changing. Although the share of coal in total energy consumption has declined over the past decade, it remained as high as 62.7% in 2023. This heavy reliance on coal posed significant challenges for the province's low-carbon transition. Consequently, the persistence of coal's high share in the energy consumption structure created mounting pressure on Henan to achieve its carbon emission reduction target, highlighting the urgent need to accelerate the shift toward renewable energy.



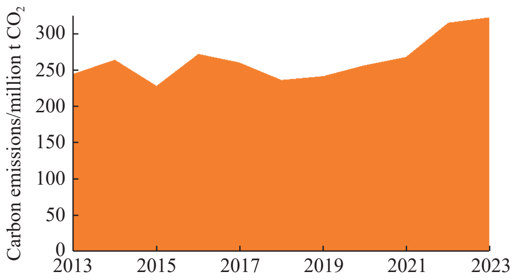
a. Energy production

b. Energy production

Figure 2 Energy production and consumption in Henan Province from 2013 to 2023

2.3 Carbon emissions in Henan

In general, energy consumption leads to some CO_2 emissions, with the combustion of fossil energy for various purposes being the primary source[12]. In the energy sector, coal-, oil-, or natural gas-fired power plants emit large amounts of CO_2; in industry, fossil fuel use for heating, machinery, and manufacturing causes many emissions; and in transportation, gasoline-, diesel-, or jet fuel-powered vehicles, ships, and airplanes release CO_2 during operation. Figure 3 shows the total carbon emissions in Henan Province from 2013 to 2023, which was made based on the data from the dataset website: https://www.heywhale.com/. The carbon emissions in Henan Province from 2013 to 2023 showed an overall upward trend, although fluctuations occurred in some years. In 2023, the carbon emissions reached the highest level of 3.2×10^8 t CO_2. This pattern indicates that Henan's economic growth and energy demand have driven long-term increases in carbon emissions, highlighting further efforts for enhanced energy transition strategies, industrial upgrading, and stricter carbon emission reduction policies to align with China's carbon peaking and neutrality targets[13].



Note: In the figure, tCO_2 represents tons of CO_2; data from the website: https://www.heywhale.com/

Figure 3 Total carbon emissions in Henan Province from 2013 to 2023

3 Data and methods

3.1 Data sources

The primary data in this study were mainly obtained from the 'Henan Statistical Yearbook 2024' and other relevant agricultural reports published by the Henan Provincial Bureau of Statistics. The data provided a reliable data foundation to estimate and analyze biomass resources from agricultural crops in Henan Province. The statistical data covered multiple years, enabling this study to analyze the changing trends of agricultural biomass resources over years.

3.2 Estimation of agricultural biomass resources

In Henan Province, the main agricultural crops include rice, wheat, maize, other grains, beans, peanuts, rapeseeds, and other oil-bearing crops. Given the relatively limited cultivation of cotton, fiber crops, and sugar crops, the biomass resources from these agricultural crops are not considered in this study. Therefore, rice straw, rice husk, wheat straw, maize stalk, maize cob, other grain crop straws, bean crop stalks, peanut vine, peanut shell, rape straw, and other oil-bearing crop straws are considered as agricultural crop biomass resources in Henan province, of which rice husk, maize cob, and peanut shell are the main agro-industrial wastes.

The theoretical quantity of agricultural crop biomass resources in Henan Province can be calculated by Equation (1):

$$T\_CR=\sum_{i=1}^{n}C_i\times r_i \tag{1}$$

where, T_CR represents the theoretical output of agricultural crop biomass resources, t; C_i represents the annual yield of the i-th agricultural crop, which can be directly obtained from the 'Henan Statistical Yearbook', t; and r_i represents the residue-to-grain ratio of the i-th agricultural crop.

The residue-to-grain is the mass of above-ground crop residue produced per unit mass of harvested grain. It is commonly employed to estimate residue availability for soil management or bioenergy from reported grain yields[14]. In general, the residue-to-grain ratio is not fixed. It depends on species, variety, crop management, climate, and final grain yield. Because of this variability, regional and crop-specific literature or datasets are usually used when converting grain production into residue production for inventory or bioenergy assessments[15]. In 2019, the Ministry of Agricultural and Rural Affairs of China released the recommended residue-to-grain ratios of major crops across various regions of China, based on extensive measured biomass data from agricultural crops (https://www.gov.cn/zhengce/zhengceku/2019-10/28/content_5445951.htm). The corresponding recommended residue-to-grain ratios of various agricultural crops in Henan Province are listed in Table 1. Generally, rice husk, maize cob, and peanut shell account for 25%, 20%, and 30% of the weight of rice, maize, and peanut respectively[2]. Therefore, their residue-to-grain ratios are 0.25, 0.20, and 0.30 respectively.

Table 1 Residue-to-grain ratios and collectable coefficients of various crops

Crop	Crop residue or agro-industrial waste	Residue-to-grain ratio ^{a}	Collectable coefficient ^{a}	Standard coal equivalent coefficient/ (tce·t^{-1}) ^{b}
Rice	Rice straw	0.93	0.74	0.43
	Rice husk	0.25	1.0	0.46
Wheat	Wheat straw	1.34	0.73	0.50
Maize	Maize stalk	1.73	0.85	0.53
	Maize cob	0.2	1.0	0.46
Other grain crops	Other grain crop straws	0.85	0.85	0.50
Bean crops	Bean crop stalks	1.57	0.56	0.54
Peanut	Peanut vine	1.22	0.83	0.53
	Peanut shell	0.3	1.0	0.54
Rapeseeds	Rape straw	2.0	0.64	0.50
Other oil-bearing crops	Other oil-bearing crop residues	1.0	0.83	0.50

Note: ^{a} Data from the Ministry of Agricultural and Rural Affairs of China (https://www.gov.cn/zhengce/zhengceku/2019-10/28/content_5445951.htm); ^{b} Data from the China Energy Statistical Yearbook.

Agricultural crop biomass resources cannot be completely collected because of stubble left in the farmland and harvest losses[16]. Stubble left in the farmland is a key farming practice for the following main reasons: 1) as the agricultural crop residues decay, they turn into organic matters, replenishing soil nutrients, improving soil structure, and boosting its ability to hold both water and nutrients; 2) the layer of stubble left on the surface shields the soil from the direct impact of rain, greatly cutting down the risk of erosion[17]. The collectable biomass resources from agricultural crops can be estimated by the following equation:

$$C\_CR=\sum_{i=1}^{n}(C_i\times r_i\times cc_i) \tag{2}$$

where, C_CR represents the collectable biomass resources from agricultural crops, t; and cc_i represents the collectable coefficient of the i-th agricultural crop biomass resource. The collectable coefficients of crop residues vary according to the type of agricultural crop biomass and the harvesting method[15]. Similarly, the Ministry of Agricultural and Rural Affairs of China provided the recommended average collectable coefficients of various agricultural crop biomass resources in Henan Province in 2019 (see Table 1). Agro-industrial wastes are centrally collected from the corresponding agro-processing factories. This ensures that almost all agro-industrial wastes can be collected; therefore, the collectable coefficients of agro-industrial wastes are all equal to 1.0.

Different agricultural crop biomass resources vary in their chemical compositions. These compositional differences directly influence their energy potentials including heating value, suitability for different conversion technologies (e.g., combustion, pyrolysis, fermentation), and overall energy conversion efficiency[18]. To estimate the energy potential of agricultural crop biomass resources, different studies employed different methods. For example, Avcıoğlu et al.[19] used the lower heating value (LHV) of each agricultural crop biomass resource to calculate the energy potential. Ozdil and Caliskan[5] provided the electricity potential produced from agricultural crop biomass resources. However, some studies usually convert the energy potential of agricultural crop biomass resources into standard coal equivalent (SCE)[2,20]. In this situation, the SCE coefficient is commonly considered, which is a conversion factor that expresses the energy potential of an agricultural crop biomass resource relative to "standard coal". The SCE coefficients of various agricultural crop biomass resources are determined by their typical heating values. Then, the energy potential of agricultural crop biomass resources can be estimated by the following formula:

$$E\_CR=\sum_{i=1}^{n}(C_i\times r_i\times cc_i\times sce_i) \tag{3}$$

where, E_CR represents the energy potential of biomass resources from agricultural crops, tce; and sce_i represents the SCE coefficient of the i-th agricultural crop biomass resource, tce/t. The SCE coefficients of various agricultural crop biomass resources are obtained from the information of 'Conversion factors from physical units to coal equivalent' in China Energy Statistical Yearbook and also listed in Table 1.

4 Agricultural crop biomass resources in Henan

Henan Province is a major agricultural province, with both its crop planting area and crop output ranking among the highest in China. Figure 4 presents the total sown area of agricultural crops in Henan Province from 2013 to 2023. Across the entire period, the sown area remained relatively stable, fluctuating slightly between 1.46×10^7 and 1.49×10^7 hm^2. There are no major upward or downward trends, indicating that Henan Province had consistently maintained a large and steady area of cultivated land over the last decade. This stability highlights the importance of Henan as a key grain-producing region in China, where farmland preservation policies may have contributed to preventing significant reductions in agricultural land.

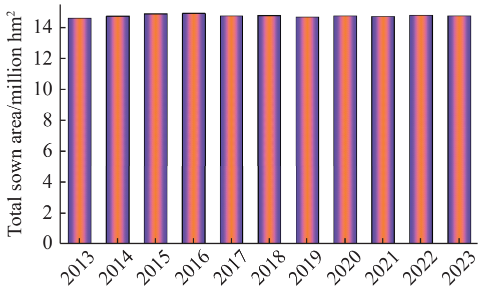


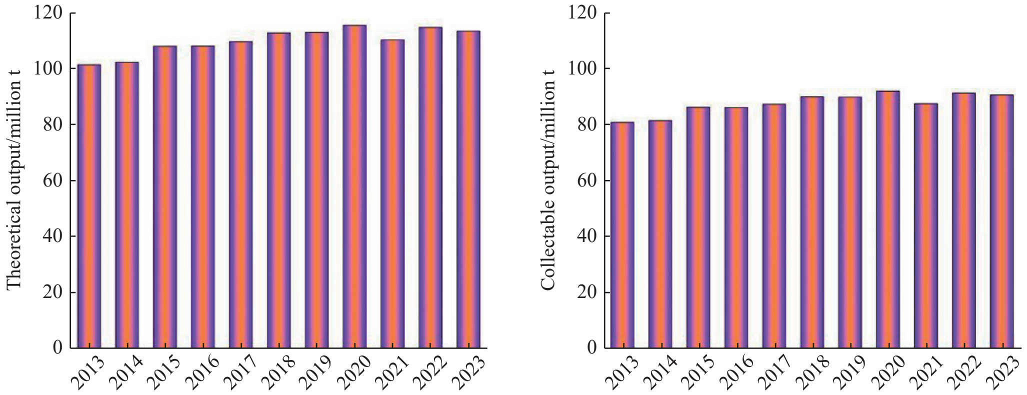
Figure 4 Total sown area of agricultural crops in Henan from 2013 to 2023

The outputs of main agricultural crop products in Henan Province from 2013 to 2023 can be obtained from Henan Statistical Yearbook and are listed in Table 2. The output of Henan Province's main crop products showed relatively small year-to-year fluctuations, maintaining an overall stable trend. Among the major crops, wheat consistently ranked first in production, followed by maize, rice, and peanut, which together contribute the largest share of total agricultural output. In contrast, the production of other grains, bean crops, rapeseeds, and other oil-bearing crops was much smaller, with limited changes over the years.

Based on the annual outputs of major agricultural crop products in Henan Province and the method for estimating agricultural crop biomass resources, the theoretical and collectable outputs of agricultural crop biomass resources in Henan from 2013 to 2023 can be obtained and are presented in Figure 5. The theoretical agricultural crop biomass output remained relatively stable over the decade, fluctuating slightly but maintaining an overall average of around 1.09×10⁸ t. The values showed only minor variation from year to year, indicating that Henan's agricultural production capacity for agricultural crop biomass resources has been consistently high throughout this period. The collectable agricultural crop biomass output followed a similar pattern of stability, averaging about 8.73×10⁸ t over the years. Due to stubble retention and collection losses of agricultural crops, the collectable output is approximately 80% of theoretical output of agricultural crop biomass resources. The overall trend of the collectable agricultural crop biomass resources over the decade indicates that Henan Province has sustained a strong potential for agricultural crop biomass utilization, with consistently high levels of theoretical production and a substantial proportion being practically collectable.

Table 2 Output of main agricultural crop products in Henan Province from 2013 to 2023

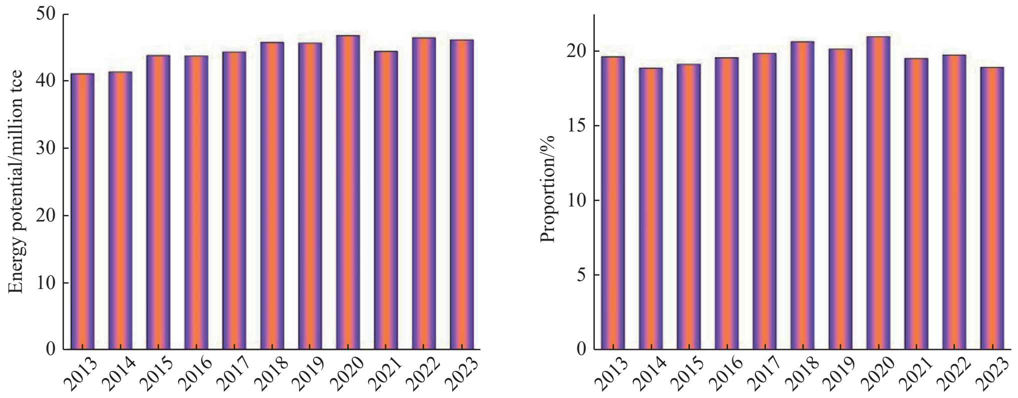
Year	Output of agricultural crop product/×10⁶ t							
	Rice	Wheat	Maize	Other grain	Bean crops	Peanut	Rapeseeds	Other oil-bearing crops
2013	4.6316	32.6633	21.1647	1.7784	0.7287	4.6919	0.5535	0.1759
2014	5.0053	33.8520	20.8889	1.5898	0.5400	4.6609	0.4969	0.1563
2015	4.9988	35.2690	22.8850	1.5494	0.4884	4.7712	0.4621	0.1566
2016	5.0829	36.1862	22.1629	1.5481	0.4900	4.9427	0.4090	0.1468
2017	4.8525	37.0521	21.7014	2.6365	0.5336	5.2981	0.4208	0.1506
2018	5.0141	36.0285	23.5138	1.9327	1.0170	5.7244	0.3897	0.1962
2019	5.1250	37.4177	22.4737	1.9372	1.0200	5.7672	0.4425	0.2448
2020	5.1371	37.5313	23.4237	2.1659	0.9787	5.9493	0.4595	0.3169
2021	4.7969	38.0286	20.3393	3.2772	0.7825	5.8812	0.4944	0.1972
2022	4.7915	38.1271	22.7505	2.2245	0.8855	6.1541	0.4901	0.1961
2023	4.7922	35.4973	23.6570	2.2962	0.9590	6.3886	0.4578	0.1840



a. Theoretical output b. Collectable output

Figure 5 Theoretical and collectable outputs of agricultural crop biomass resource in Henan Province from 2013 to 2023

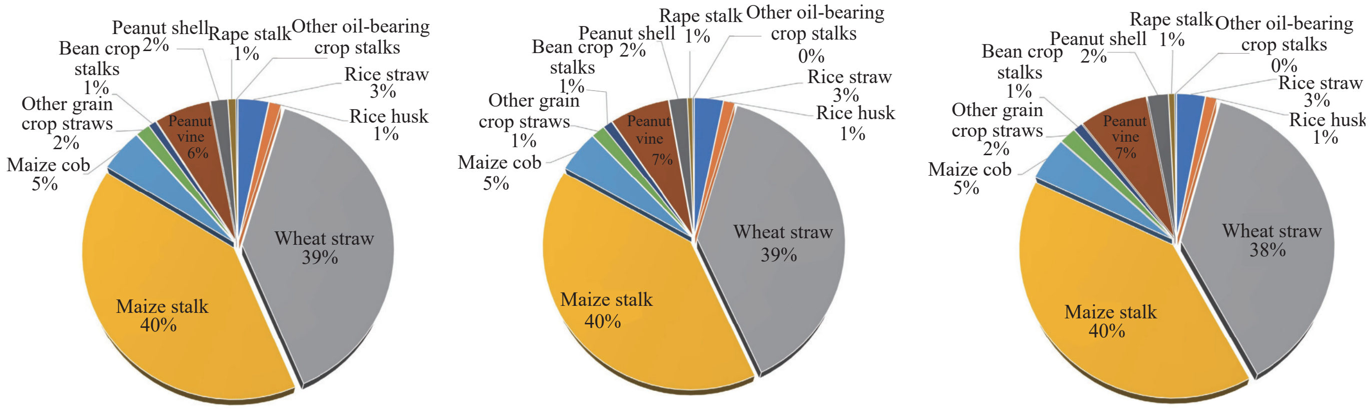
Those collectable agricultural crop biomass resources have some energy potential, which can be calculated by Equation (3) and are shown in Figure 6a. The share in the province's total energy consumption can also be calculated and is shown in Figure 6b. The energy potential of agricultural crop biomass resources in Henan Province from 2013 to 2023 showed a relatively stable upward trend, with annual values fluctuating around an average of 4.44×10⁷ tce. In the meanwhile, its share in Henan's total energy consumption averages about 19.7%, which is about one-fifth of the overall energy consumption. This indicates that agricultural crop biomass resources hold substantial energy utilization value. If effectively converted, agricultural crop biomass resources could serve as a supplementary energy source, helping to alleviate energy shortages and enhance the sustainability of the regional energy structure.



a. Energy potential b. Proportion

Figure 6 Energy potentials of agricultural crop biomass resource and their proportions in total energy consumption in Henan Province from 2013 to 2023

Figure 7 shows the share of the energy potential of various agricultural crop biomass resources in Henan Province in 2013, 2018, and 2023. Maize stalk accounted for the largest share, contributing about 40% of the total energy potential, followed closely by wheat straw at 38%. Together, these two crop residues dominated the agricultural crop biomass resource structure, providing nearly four-fifths of the total energy potential, which underscores their critical importance for agricultural crop biomass energy utilization in Henan Province. Other notable contributors included peanut vine (about 7%), maize cob (about 5%), rice straw (about 3%), peanut shell (about 2%), and other grain crop straws (about 2%). Minor contributions came from bean crop stalks, rape stalks, rice husk, and other oil-bearing crop stalks. The predominance of maize stalk and wheat straw indicates that effective collection, processing, and conversion of these two agricultural crop residues could provide a reliable and sustainable energy source, greatly reducing reliance on fossil energy and supporting rural energy transitions. Meanwhile, secondary resources such as peanut vine and maize cob also hold potential for diversification in bioenergy production, especially in regions where they are locally abundant. Even though smaller fractions like rape stalk and rice husk contributed less individually, their utilization can further enhance resource efficiency and reduce waste. Overall, prioritizing maize stalk and wheat straw is vital for maximizing agricultural crop biomass energy potential in Henan Province, while integrating smaller agricultural crop biomass resources ensures a comprehensive and sustainable approach to agricultural crop biomass management.



a. 2013 b. 2018 c. 2023

Figure 7 Proportions of various agricultural crop biomass resources in total energy potential of crop biomass resources in Henan Province in 2013, 2018, and 2023

5 Energy application of agricultural crop biomass resources in Henan

There are multiple ways to utilize agricultural crop biomass resources, including fertilization, substrate utilization, livestock feed utilization, material conversion, and energy generation[21]. In Henan Province, the predominant pathway for the comprehensive utilization of agricultural crop biomass resources is its application as fertilizer, with an estimated 5.5×10^7 t of agricultural crop biomass annually incorporated into soil[22]. According to statistics, in Henan Province, over 1.45×10^7 t of agricultural crop biomass resources are annually utilized as livestock feed. According to the Henan Statistical Yearbook[11], the annual production of edible fungi in Henan Province is about 1.85×10^6 t, implying an equivalent demand of 1.85×10^6 t of substrate-based agricultural crop biomass resources based on a 1:1 production-to-substrate mass ratio. According to Guo and Huang[23], about 1.1×10^6 t of agricultural crop biomass resources are utilized annually as industrial materials in Henan Province.

Agricultural crop biomass resources are also utilized for energy purposes through various conversion technologies, including direct combustion for heat and power generation, gasification for syngas, anaerobic digestion for biogas production, fermentation for fuel ethanol, and pyrolysis for bio-oil and biochar.

One common technology for the energy utilization of agricultural crop biomass resources is direct combustion. In this process, agricultural crop biomass is burned in boilers or furnaces to produce heat, which can be used for space heating or for generating steam to drive turbines for electricity production[24]. Combined heat and power (CHP) represents an efficient strategy for the combustion-based utilization of agricultural crop biomass resources. This approach enables the simultaneous generation of thermal energy and electricity through the combustion of biomass in CHP plants, where biomass boilers can achieve thermal efficiencies of 80%-90%[25]. In December 2019, a biomass-fired cogeneration plant in Lingbao City, Henan Province, constructed by EDF (Lingbao) Thermal Power Co., Ltd., was commissioned (https://china.edf.com/en/our-activities/renewables), which consumes about 3.0×10^5 t of agricultural and forestry residues annually, producing around 2.1×10^8 kWh of electricity, while simultaneously supplying heat sufficient to meet the heating demand of roughly 2×10^6 m^2 of building space in Lingbao City.

Gasification represents another conversion pathway for agricultural crop biomass, in which biomass is exposed to elevated temperatures (typically 700°C-1300°C) under oxygen-limited conditions. This process yields syngas (a gaseous mixture predominantly composed of CO, H_2, CO_2, and CH_4) along with biochar (a carbon-rich solid byproduct)[26]. Syngas can be directly combusted in gas turbines or internal combustion engines for power generation, thereby serving as a renewable alternative to fossil fuel-based power. It can also be further purified, compositionally adjusted, and then catalytically converted to produce methanol[27]. In June 2024, Xuchang Longji Bioenergy Co., Ltd. initiated the construction of a green methanol project in Henan Province based on the gasification of agricultural crop biomass. The facility is designed to process about 6×10^6 t of biomass resources, with an expected annual output of 1.2×10^5 t of green methanol, supplemented by about 30 000 kWh of self-generated electricity (please see the website: https://www.plas.com/news/details/1154).

Agricultural crop biomass resources can also be efficiently converted into biogas through anaerobic digestion, a sustainable process that occurs in the absence of oxygen within a sealed digester[28]. In this process, microorganisms (primarily bacteria and archaea) degrade the complex organic constituents of crop biomass, leading to the production of biogas, whose principal components are CH_4, H_2, and CO_2[29]. Biogas can be utilized for heat, electricity, or rural cooking, while the nutrient-rich digestate from anaerobic digestion serves as an organic fertilizer[30]. The Minquan Pengxiang New Energy Management Co., Ltd. biogas power plant in Shangqiu City, Henan Province employs a process integrating pretreatment of organic wastes (livestock and poultry manure, kitchen waste, and agricultural residues), anaerobic digestion, biogas purification, power generation, and utilization of digestion residues as organic fertilizers. The facility annually processes about 37 000 t of livestock and poultry manure and 5000 t of crop residues, producing around 600 000 m^3 of biogas and 400 000 kWh of electricity, alongside 3000 t of solid organic fertilizer and 34 000 t of biogas slurry for soil amendment (please see the website: http://www.minquan.gov.cn/xwzx/xzdt/content_31621).

Agricultural crop biomass can be converted into fuel ethanol through fermentation, a process that utilizes the carbohydrate fractions of biomass, primarily cellulose, hemicellulose, and starch. The conversion generally involves three major steps: pretreatment, enzymatic hydrolysis, and fermentation[31]. Pretreatment is necessary to break down the rigid lignocellulosic structure of biomass and increase the accessibility of cellulose and hemicellulose. Enzymatic hydrolysis then depolymerizes these polysaccharides into fermentable sugars, such as glucose and xylose. Subsequently, microorganisms, most commonly *Saccharomyces cerevisiae* or engineered strains of bacteria and yeast, ferment these sugars into ethanol. The resulting ethanol can be distilled and purified for use as a liquid biofuel. Compared with fossil fuels, fuel ethanol offers advantages of renewability, lower GHG emissions, and potential contributions to energy safety[32]. In October 2006, Tianguan Group launched its cellulose ethanol demonstration project in Nanyang City, Henan Province, which produced about 5000 t of fuel ethanol annually and utilized about 30 000 t of crop residues (primarily including wheat straw and maize stalk[33]).

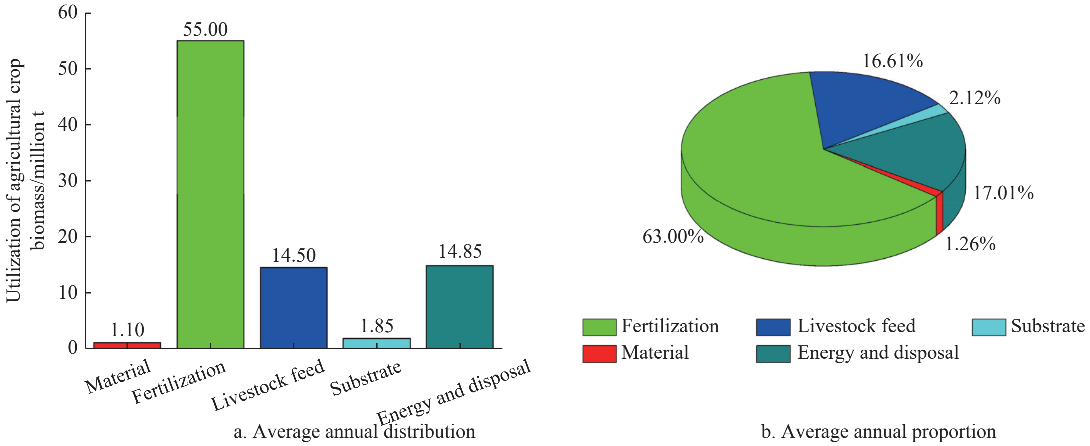
Pyrolysis of agricultural crop biomass involves thermal decomposition under oxygen-limited conditions, yielding three types of pyrolysis products: bio-oil, biochar, and syngas[34]. Bio-oil, a viscous liquid enriched with hydrocarbons and oxygenated organics, holds promise as a renewable source for transportation fuels, heating, and chemical feedstocks[35]. Biochar, the carbonaceous solid fraction, functions as a soil amendment by enhancing structure, water retention, and nutrient availability, thereby supporting crop productivity[36]. Owing to its chemical stability, biochar also contributes to long-term carbon sequestration in soil. Therefore, the pyrolysis application of agricultural crop biomass offers dual advantages, delivering energy while simultaneously providing environmental benefits. The high costs associated with the industrial application of agricultural crop biomass pyrolysis have limited its commercialization. Consequently, there have been no reported applications of agricultural crop biomass pyrolysis in Henan Province.

The available quantity of agricultural crop biomass resources for energy application is determined by subtracting their usage for fertilizer, livestock feed, mushroom substrate, and industrial material from the total annual agricultural crop biomass resources:

$$Q_E = Q_T - Q_F - Q_L - Q_S - Q_M \tag{4}$$

where, Q_T, Q_E, Q_F, Q_L, Q_S, and Q_M are the total annual quantity, and the quantities for energy application, fertilizer, livestock feed, mushroom substrate, and industrial material of agricultural crop biomass resources, respectively. Based on the estimated annual availability of agricultural crop biomass resources in Henan Province (approximately 8.73×10^7 t), and after subtracting the quantities allocated to fertilization (5.5×10^7 t), livestock feed (1.45×10^7 t), mushroom substrate (1.85×10^6 t), and industrial material (1.1×10^6 t), the remaining agricultural crop biomass resources available for energy application or left unused are limited to about 1.485×10^7 t.

Average annual distribution of agricultural crop biomass utilization in Henan Province is summarized in Figure 8. The predominant use of agricultural crop biomass resources in Henan is for fertilization, which accounts for about 63.00% of the total available agricultural crop biomass resources. This indicates that fertilization represents the primary application of such resources. In addition to this, a significant portion, amounting to 16.61%, is allocated for livestock feed. This indicates a noteworthy diversion of agricultural crop biomass towards animal husbandry. Conversely, the utilization of agricultural crop biomass as the substrate for cultivating edible fungi is relatively minor, accounting for only 2.12%. Material utilization of agricultural crop biomass is even less prevalent, at just 1.26%. The remaining 17.01% of agricultural crop biomass resources is allocated for energy production and other utilization, indicating a growing interest in renewable energy sources derived from agricultural crop residues.



a. Average annual distribution b. Average annual proportion

Figure 8 Average annual distribution and proportion of agricultural crop biomass utilization in Henan Province

6 Potential environmental benefits from energy utilization of agricultural crop biomass resources in Henan

The energy-oriented utilization of agricultural crop biomass resources not only has energy potential, but also brings environmental benefits, contributing to the sustainable development of China. Agricultural crop biomass resources, if not managed properly, often lead to open burning, causing severe air pollution and GHG emissions. Converting these resources into bioenergy or bio-based products can reduce the reliance on fossil fuels and CO_2 emissions[37].

Different conversion technologies of agricultural crop biomass result in different potentials for environmental benefits. In this study, two representative utilization scenarios of agricultural crop biomass are investigated according to their technological maturity, practical relevance, and potential contributions to both energy production and environmental sustainability. The first scenario involves the direct combustion of agricultural crop biomass for power generation, which represents the most established and widely implemented utilization pathway in large-scale biomass power plants. The second scenario considers the pyrolysis of agricultural crop biomass with biochar application to soil, a pathway that not only enables energy recovery but also enhances soil fertility and promotes long-term carbon sequestration.

To estimate the CO_2 emission reduction potential of agricultural crop biomass in Henan Province, the amount of agricultural crop biomass originally intended for energy utilization and waste disposal will be focused on. It is estimated that these resources average 1.485×10^7 t per year.

6.1 Combustion of agricultural crop biomass

In this subsection, the CO_2 emissions reduction when agricultural crop biomass is used as a substitute for coal in a CHP system is presented. The corresponding detailed explanation is outlined below.

The LHV of agricultural crop biomass is assumed to be 15 GJ/t, and the CHP system operates with an efficiency of 85%. Thus, the useful energy generated from the combustion of 1 t of agricultural crop biomass can be calculated as:

$$\mathrm{Ue} = \mathrm{LHV}_{\mathrm{biomass}} \times \varepsilon \tag{5}$$

where, Ue represents the useful energy of agricultural crop biomass per ton, $\mathrm{LHV}_{\mathrm{biomass}}$ represents the LHV of agricultural crop biomass, and ε represents the efficiency of the CHP system. Substituting the known values, the combustion of 1 ton of agricultural crop biomass can generate 12.75 GJ of useful energy.

The energy produced from 1 t of agricultural crop biomass is equivalent to the energy generated from burning a certain amount of bituminous coal, which is usually used in power generation in CHP systems. Given that the LHV of bituminous coal is about 29 GJ/t, the amount of coal required to produce 12.75 GJ of useful energy from the combustion of 1 ton of agricultural crop biomass can be calculated as:

$$\mathrm{Ec} = \frac{\mathrm{Ue}}{\mathrm{LHV}_{\mathrm{coal}}} \tag{6}$$

where, Ec represents the coal equivalent, and $\mathrm{LHV}_{\mathrm{coal}}$ represents the LHV of bituminous coal. Thus, 1 t of agricultural crop biomass is equivalent to about 0.44 t of bituminous coal.

In general, the combustion of bituminous coal releases about 2.4 t of CO_2 for 1 t of coal. Therefore, the CO_2 emissions from burning 0.44 t of bituminous coal can be calculated as:

$$\mathrm{CO}_{2,\mathrm{coal}} = \mathrm{Ec} \times \mathrm{Ef}_{\mathrm{CO_2}} \tag{7}$$

where, $CO_{2,coal}$ represents the CO_2 emissions from coal burning, and $\mathrm{Ef}_{\mathrm{CO_2}}$ represents the emission factor of bituminous coal combustion. Thus, the combustion of 0.44 t of bituminous coal releases approximately 1.06 t of CO_2. Assuming that agricultural crop biomass is carbon neutral, the CO_2 emitted during combustion is offset by the CO_2 absorbed during the growth of the crops. Therefore, no net CO_2 emissions are associated with agricultural crop biomass. Thus, the substitution of 1 t of agricultural crop biomass for bituminous coal results in a net reduction of 1.06 t in CO_2 emissions.

Thus, if the agricultural crop biomass resources originally designated for energy utilization and waste disposal in Henan Province (approximately 1.485×10^7 t) were entirely utilized for power generation through combustion, it would result in an estimated reduction of about 1.574×10^7 t of CO_2 emissions. This reduction would correspond to about 4.9% of Henan Province's total carbon emissions in 2023, estimated at 3.218×10^8 t of CO_2.

6.2 Pyrolysis of agricultural crop biomass

The whole process of agricultural crop biomass pyrolysis with biochar application to soil includes several sub-processes, including crop cultivation, biomass production, biomass pretreatment, biomass conversion via pyrolysis, and the valorization of the pyrolysis products. The production of agricultural crop biomass includes the processes of harvesting, handling, and transportation. Subsequent pretreatment of the biomass involves mechanical grinding and drying. The conversion of agricultural crop biomass is achieved via the pyrolysis process, facilitating its transformation into pyrolysis products. The valorization of pyrolysis products involves applying biochar to soil and utilizing bio-oil and pyrolysis gases as energy sources to replace fossil fuels[38].

The quantification of CO_2 absorbed by agricultural crop biomass during its growth is based on the amount of carbon fixed in its biomass through photosynthesis. Taking 1 t of dry agricultural crop biomass as an example, and assuming an average content of approximately 45% by dry mass, the crop biomass contains about 450 kg of carbon. To convert this carbon mass into its CO_2 equivalent, the molecular weight ratio of CO_2 to elemental carbon (44/12≈3.67) is applied. Accordingly, 450 kg of carbon corresponds to approximately 1.652 t of CO_2. Thus, the accumulation of 1 t of agricultural crop biomass represents the sequestration of about 1.652 t of atmospheric CO_2 during the crops' growth process.

Xu et al.[38] conducted a comprehensive life-cycle assessment to quantify the CO_2 emissions reduction potential of herbaceous biomass pyrolysis with biochar application to soil. Table 3 lists the quantities of CO_2 emissions generated from different sub-processes of the pyrolysis of agricultural crop biomass with biochar application to soil, expressed per ton of feedstock biomass. In Table 3, negative values represent the net reduction of CO_2 emissions resulting from soil carbon sequestration through biochar application, as well as from the substitution of fossil fuels by bio-oil and pyrolysis gases. From Table 3, it can be obtained that the pyrolysis system of agricultural crop biomass with biochar application to soil achieves a CO_2 emission reduction potential of about 0.612 t of CO_2 per 1 t of agricultural crop biomass.

Therefore, considering both the CO_2 uptake during crop growth and the CO_2 emission reduction from the production of agricultural crop biomass to the valorization of pyrolysis products, the overall CO_2 mitigation potential of 1 t of agricultural crop biomass via pyrolysis amounts to about 2.264 t of CO_2.

Accordingly, if those agricultural crop biomass resources in Henan Province originally designed for energy conversion and disposal (about 1.485×10^7 t) were entirely subjected to pyrolysis with subsequent biochar application to soil, the conversion process would have the potential to mitigate approximately 3.362×10^7 t of CO_2 emissions. This reduction would account for about 10.4% of Henan Province's total CO_2 emissions in 2023 (3.218×10^8 t of CO_2), which indicates that the pyrolytic utilization of agricultural crop biomass holds significant potential as a strategy for CO_2 emission reduction and climate mitigation.

Table 3 Quantities of CO_2 emissions for agricultural crop biomass pyrolysis with application to soil[a]

Item	CO_2 emissions (kgCO_{2e}· $t_{biomass}^{-1}$)
Production of agricultural crop biomass	162.85
Pretreatment of agricultural crop biomass	6.73
Pyrolysis of agricultural crop biomass	43.67
Valorization of pyrolysis products	−824.80
Total	−611.55

Note: [a] Data calculated from Xu et al.[38].

7 Practical implications

Based on the above analysis, the utilization portion of agricultural crop biomass resources for fertilization (returning to farmland) is the highest in Henan Province. However, the practical implementation of returning agricultural crop biomass to farmland is constrained by multiple practical limitations: the carbon-nitrogen disequilibrium, proliferation of soil-borne pathogens and pests, and inherently slow decomposition of agricultural crop biomass[39]. Thus, a portion of agricultural crop biomass resources currently returned to farmland could be reallocated to energy application in Henan Province from a practical application perspective. In recent years, about 5.5×10^8 t of agricultural crop biomass resources were applied annually for farmland return. If 10% of these resources were redirected for energy applications, it would provide a substantial supplementary feedstock base (5.5×10^6 t) for biomass energy application in Henan Province.

Such a reallocation would also bring some additional environmental benefits. Then, the combustion of the reallocation for power generation in the CHP system could reduce CO_2 emissions by about 5.83×10^6 t of CO_2 compared with coal-fired power generation. Furthermore, biomass pyrolysis with biochar application to soil could offer an even greater mitigation potential, sequestering approximately 1.245×10^7 t of CO_2. These pathways highlight the dual advantages of agricultural crop biomass utilization in Henan, namely supporting clean energy production while contributing to large-scale CO_2 emission reductions.

8 Conclusions

This work systematically studies the theoretical and collectable outputs, energy potential, and environmental benefits of agricultural crop biomass resources in Henan Province. The findings indicate that Henan produces a substantial and stable agricultural crop biomass resource base of approximately 8.73×10^6 t annually, with an average energy potential of 4.44×10^6 tce—equivalent to nearly one-fifth of total energy consumption in Henan. Maize stalk and wheat straw are the primary agricultural crop biomass resources, jointly accounting for about 80% of the total agricultural crop biomass energy potential in Henan. While fertilization remains the dominant utilization pathway, a significant portion of crop residues can be redirected toward energy conversion without reducing soil fertility. If 1.485×10^7 t of agricultural crop biomass currently allocated for energy and disposal would be utilized, combustion could reduce carbon emissions by about 1.574×10^7 t of CO_2 (about 4.9% of Henan's 2023 CO_2 emissions), while pyrolysis with biochar application to soil could achieve reductions of 3.36×10^7 t of CO_2 (about 10.4% of Henan's 2023 CO_2 emissions). These results highlight the dual role of biomass utilization in alleviating energy shortages and contributing to CO_2 emission reduction. Redirecting even a modest share of agricultural crop biomass from farmland return to energy application could substantially enhance renewable energy supply and environmental benefits. Overall, the study provides a scientific foundation for policymakers to optimize agricultural biomass management strategies and promote low-carbon, renewable energy development in Henan Province.

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