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Original Research

Spatial Distribution and Assessment of Biomass Energy Potential and Emission Reduction from Agricultural Waste in Zhengzhou

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Abstract

This study, based on data from the 2024 Zhengzhou Statistical Yearbook, used the ARCGIS spatial analysis methods to evaluate the biomass energy utilization potential and emission reduction benefits of major crop straws and livestock manure in Zhengzhou. The results showed that the total biomass energy utilization potential of agricultural waste in Zhengzhou in 2024 was approximately 3.58×10^5 t of standard coal, with crop straw accounting for about 3.07×10^5 t and livestock manure for about 0.51×10^5 t. Using crop straw and livestock manure as fuel, compared to standard coal, could reduce SO_2 and NO_x emissions by 4.52×10^2 t and CO_2 emissions by approximately 1.99×10^7 t. Specifically, the utilization of crop straw can reduce SO_2 and NO_x emissions by 2.69×10^2 t and CO_2 emissions by approximately 8.17×10^5 t, while the utilization of livestock manure can reduce SO_2 and NO_x emissions by 1.83×10^2 tons and CO_2 emissions by approximately 1.91×10^7 t. Through spatial analysis, the study revealed the spatial distribution characteristics of the biomass energy utilization potential and emission reduction benefits of agricultural waste, showing that agricultural waste resources in Zhengzhou were concentrated in major crop production areas and large-scale livestock farming zones, with high-value areas mainly concentrated in the eastern and southwestern regions. This study provided a quantitative analytical foundation for optimizing Zhengzhou's agricultural waste resource utilization and biomass energy development strategies, and offered scientific support for promoting local green energy development and achieving the "dual carbon" goals.

Keywords: agricultural waste, biomass energy, crop straw, livestock manure, emission reduction benefits, Zhengzhou

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Introduction

As the core city of agricultural and urban-rural integration development in the Central Plains region, Zhengzhou has a vast amount of agricultural waste resources, including crop straw and livestock manure. Improper disposal of these wastes not only leads to resource waste but also causes environmental issues such as straw burning and manure-related non-point source pollution, which in turn deteriorates the rural ecological environment and affects the quality of life for residents. Previous studies have shown that agricultural greenhouse gas emissions account for approximately 16% of the total emissions in China [1]. Therefore, promoting the proper disposal and energy utilization of agricultural waste is crucial for improving the agricultural ecological environment and plays a key role in activating the green economy of rural areas and promoting sustainable development [2].

Biomass energy, as a clean and renewable energy source, is widely stored in agricultural waste. Converting straw and livestock manure into biomass energy can effectively reduce the pollution emissions generated by traditional disposal methods such as burning and landfilling, while also addressing regional energy supply shortages without occupying additional arable land. This “waste-to-energy” model not only promotes resource recycling and improves ecological environmental quality but also provides green support for rural revitalization and the achievement of the “dual carbon” goals.

In recent years, the role of agricultural waste biomass energy utilization in supporting the “dual carbon” goals and environmental governance has become a hot topic in regional development research. Some studies have quantified the biomass energy potential of agricultural waste in different regions of China [3-5], while others have focused on the efficiency of agricultural waste utilization in rural energy substitution in the Central Plains region [6, 7]. However, most studies lack spatial analysis of the resource allocation and energy utilization potential of agricultural waste at the county scale, especially in the utilization of GIS spatial analysis methods to assess the biomass energy potential and emission reduction benefits of agricultural waste.

This study establishes a refined county-level quantitative framework to assess the biomass energy potential and associated environmental benefits of agricultural waste, specifically crop straw and livestock manure, in Zhengzhou for the year 2024. By integrating GIS-based spatial analysis, this research provides granular insights into the energy conversion potential and emission reduction impacts of these resources, establishing a scientific foundation for optimizing waste management and tailoring localized biomass energy strategies.

Two primary innovations distinguish this research from existing literature. First, by downscaling the assessment to the county level, this study addresses the limitations of previous macro-scale evaluations in the Central Plains region of China. This high-resolution analysis provides more actionable data for localized policymaking and precision resource allocation, which are often obscured in aggregate provincial-scale data. Second, the integration of GIS techniques with the Local Moran’s I index facilitates a robust examination of the spatial autocorrelation and clustering characteristics of biomass resources [8]. This methodological advancement effectively captures the spatial heterogeneity of waste distribution, overcoming the constraints of traditional statistical methods that overlook geographical connectivity.

Therefore, using Zhengzhou as a representative case study, this research leverages county-level agricultural statistics and spatial econometrics to delineate the distribution patterns of biomass potential and its corresponding carbon mitigation capacity. The findings provide critical empirical evidence to guide the strategic deployment of biomass energy facilities and promote the regional transition toward a low-carbon economy. So, this data-driven approach contributes to the achievement of China’s “dual carbon” goals and offers a replicable model for localized renewable energy solutions in rapidly urbanizing agricultural regions.

Materials and Methods

Study Area Overview

Zhengzhou is located in the heart of the Yellow River Basin in central China, with geographic coordinates ranging from 112°42′ to 114°14′E and 34°16′ to 34°58′N. It is the core city of the Central Plains urban agglomeration and also a major national transportation hub and agricultural center (Fig. 1). The city’s topography is characterized by a high southwest and low northeast, with a variety of landforms. The western part consists of the western foothills of the Taihang Mountains (such as Songshan and Mangshan), the central area is a transitional zone between the Loess Plateau and hills, while the eastern part is part of the expansive Huang-Huai-Hai Plain, with an overall elevation drop of more than 300 m. The Zhengzhou plain is particularly advantageous, benefiting from irrigation by the Yellow River and Huai River systems, with fertile soil and abundant light and heat resources. It is one of the main production areas for winter wheat in China, as well as an important base for the production of corn and vegetables, while also playing a key role in the production of commercial grain and livestock farming in the Central Plains economic zone.

The agricultural crop yield and livestock breeding data used in this study were derived from the 2024 Zhengzhou Statistical Yearbook [9]. This study is based on county-level statistical records and literature-derived coefficients rather than direct field or laboratory measurements. Therefore, the “accuracy” in this work is primarily reflected by (i) the spatial/temporal resolution of the statistical datasets (county-level annual statistics) and (ii) the uncertainty of key model parameters (e.g., straw-to-grain ratio, collectable coefficient, conversion efficiency, and emission factors). To improve transparency, an uncertainty analysis was added to quantify the influence of parameter variability on the estimated biomass energy potential and emission reduction. These data, combined with regional agricultural statistics and GIS spatial analysis methods, were used to assess the biomass energy utilization potential of agricultural waste in Zhengzhou.

Data Analysis

Estimation of Collectible Straw Resources

Due to the lack of direct data on crop straw collection, this study referred to the regional straw-to-grain ratio and collectable coefficient recommended by the Department of Agricultural Rural Science and Technology (Table 1). The collectible straw resource amount was estimated based on the yield of major crops in Zhengzhou. The specific calculation formula is as follows:

$$Q_i = C_i \rho_i K_i \tag{1}$$

Where Q_i was the collectible straw resource amount of the i crop (t), C_i was the yield of the i crop (t), ρ_i was the straw-to-grain ratio of the i crop, and K_i was the collectable coefficient of the i crop's straw.

Biomass Energy Potential of Crop Straw

Based on the China Energy Statistical Yearbook [10] and relevant studies [11, 12], combined with the primary

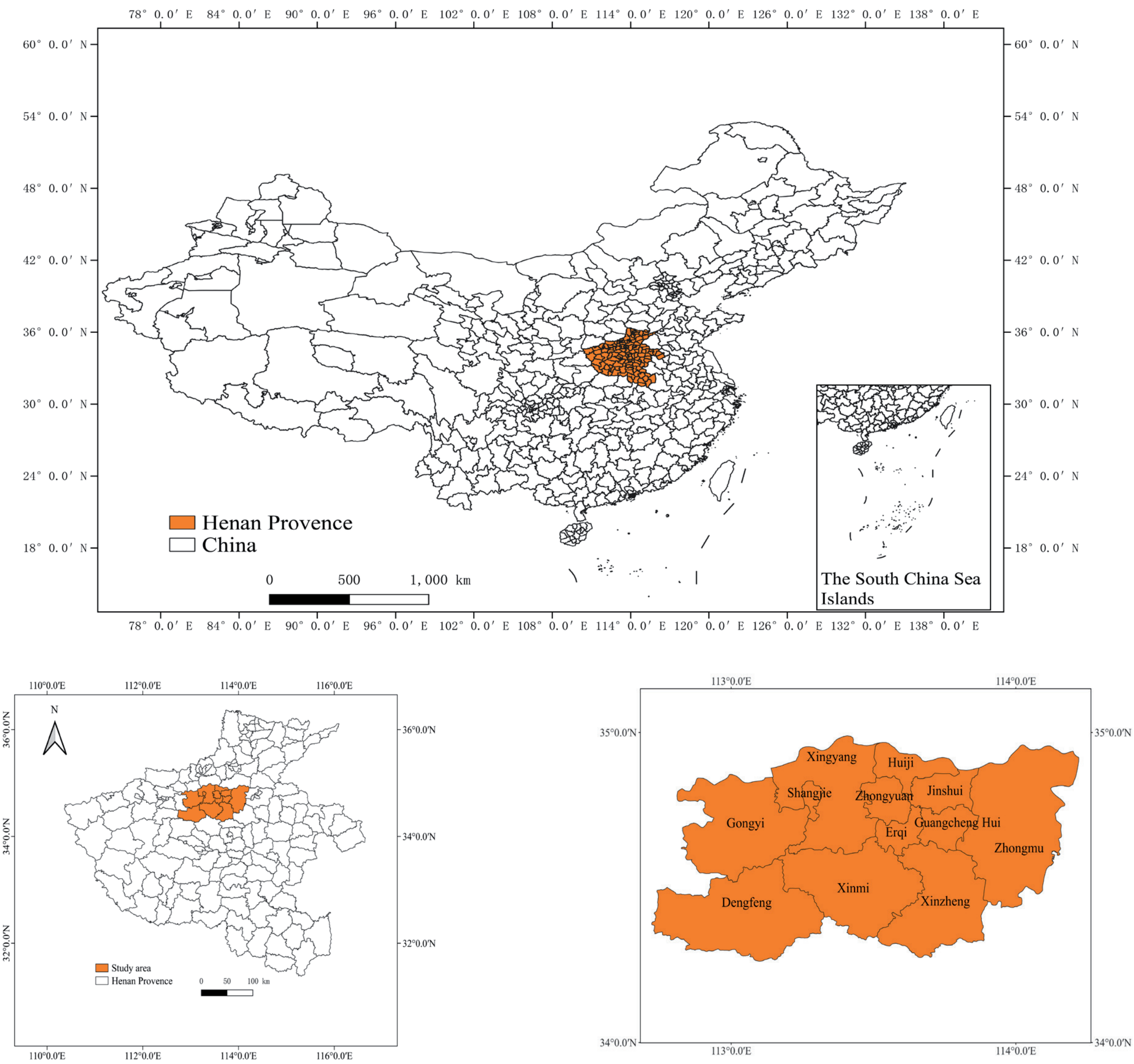

Fig. 1. The study area.

Table 1. Straw-to-grain ratio, collectable coefficient, and standard coal conversion coefficient for major crops in Zhengzhou.

Crop type	Straw-to-grain ratio	Collectable coefficient	Standard coal conversion coefficient (kg·kg^{-1})
Wheat	1.34	0.73	0.500
Corn	1.73	0.85	0.529
Legumes	1.57	0.56	0.534
Oilseed crops	1.22	0.83	0.518

utilization pathways of straw in Henan Province, the biomass energy utilization potential of crop straw in Zhengzhou was assessed. The studies showed that the main disposal routes for straw in Zhengzhou include non-energy uses such as returning to the soil as fertilizer, silage, and hay storage, as well as its use as a substrate. The proportion of straw utilized for energy purposes was 32.89% [13, 14]. The studies also indicated that the average biomass energy conversion rate for different conversion technologies was 0.48 [6, 15, 16]. This research primarily focused on the biomass energy utilization potential of crop straw, assuming a biomass energy conversion rate of 0.48, and calculated the potential for converting straw into biomass energy. The formula is as follows:

$$Q_{iE} = Q_i \eta \Phi \varepsilon \tag{2}$$

Where Q_i was the biomass energy potential of the i crop straw (in standard coal, t), η was the proportion of crop straw that could be used for energy conversion (%), Φ_i was the standard coal conversion coefficient of the i crop straw (kg·kg^{-1}), ε was the conversion efficiency of crop straw into biomass energy (%).

Assessment of Biomass Energy Utilization Potential of Livestock Manure

This study primarily calculated the biomass energy utilization potential of manure from livestock, including pigs, cattle, and sheep. Based on the livestock breeding scale and excretion coefficients in Zhengzhou, the collection amount of livestock manure was estimated, and its biomass energy utilization potential was calculated. The theoretical collection amount of livestock manure and its biomass energy utilization potential were calculated using the following formulas:

$$X_i = N_i T_i EC_i \tag{3}$$

$$FE_i = X_i S_i \beta_i \lambda_i \tag{4}$$

Where X_i was the theoretical collection amount of manure from the i livestock type (kg), N_i was the annual breeding number of the i livestock type (heads), T_i was the breeding cycle of the i livestock type (days), EC_i was the excretion coefficient of the i livestock type (kg/(head·day)), FE_i was the biomass energy utilization potential of the i livestock manure (m^3), S_i was the collectable coefficient of the i livestock manure, β_i was the dry matter content of the i livestock manure (%), λ_i was the methane production per unit mass of manure from the iii-th livestock type (m^3/kg).

The daily excretion coefficients, collectable coefficients, dry matter content, and methane production rates for different livestock are shown in Table 2 [17, 18, 20].

Spatial Analysis

To reveal the spatial distribution characteristics of agricultural waste in Zhengzhou, this study overlaid the 2024 agricultural organic waste data with the administrative division map of Zhengzhou and conducted spatial analysis using ARCGIS. Specifically, the Local Moran's I index was used to calculate spatial autocorrelation, measuring the degree of spatial correlation between grid cells and their neighboring grid cells. The calculation formulas were as follows:

$$I_i = \frac{(x_i - x_m)}{S^2} \sum_{i,j=1}^{n} W_{ij}(x_j - x_m) \tag{5}$$

Table 2. Daily excretion coefficients, collectable coefficients, dry matter content, and biogas production of different livestock.

Livestock type	Breeding cycle (days)	Excretion coefficient (kg/(head·day))	Collectable coefficient	Dry matter content (%)	Biogas production (m^3/kg)
Pigs	199	2.86	0.9	20	0.30
Cattle	365	22.51	0.6	20	0.35
Sheep	365	1.24	0.6	75	0.33

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - x_m)^2 \tag{6}$$

Where x_i and x_j represented the elevation values of grid cells i and j, x_m was the mean value of all elevation values, n was the total number of grid cells, and W_{ij} was the spatial adjacency weight matrix between each grid cell i and j in the study area.

Emission Reduction Calculation of Agricultural Waste

The biomass energy utilization of crop straw is considered a carbon-neutral renewable energy source. Although CO_2 is released during pyrolysis or combustion, this carbon originates from the atmospheric carbon absorbed during the crop growth phase, forming a closed carbon cycle, with theoretical net carbon emissions approaching zero. The energy utilization of livestock manure is primarily achieved through biogas, whose main component is CH_4, with minimal emissions of NO_x and SO_2, which can therefore be ignored [15-21]. This study calculated the emission reduction potential of crop straw and livestock manure, including the pollutant emissions from open burning of straw and the reduction in pollutants due to the substitution of coal combustion by biomass energy. The emission reduction potential of livestock manure was based on the reduction of pollutants from the substitution of fossil fuel combustion by biogas. The specific calculation formulas are as follows:

$$RP_W = \sum_{i=1} SEM_i \times (P_{SO_2} + P_{NO_X}) - \sum_{i=1} SE_i (P_{SO_2} + P_{NO_X}) \tag{7}$$

$$CP_C = \sum_{i=1} SEM_i \times P_{CO_2} - \sum_{i=1} SE_i \times P_{CO_2} \tag{8}$$

Where RP_W was the atmospheric pollutant emission reduction potential of agricultural waste (t), SEM_i was the biomass energy content of the i waste converted to standard coal (t), P_{SO_2} and P_{NO_X} were the SO_2 and NO_x emission coefficients, respectively, during the combustion of biomass energy converted from standard coal (kg/t), SE_i was the amount of the i waste converted into biomass energy (t), and CP_C was the CO_2 emission reduction potential of agricultural waste (t). P_{CO_2} were the CO_2 emission coefficients during the combustion of biomass energy converted from standard coal (kg/t). The emission coefficients during biomass energy combustion and direct combustion for crop straw and livestock manure are shown in Table 3.

Data Quality and Uncertainty Analysis

The input data for crop yield and livestock breeding scale were obtained from the Zhengzhou Statistical Yearbook 2024, which reports officially compiled annual statistics at the county (district/county-level city) scale. Since no direct measurements were performed in this study, uncertainty mainly arises from (i) the spatial aggregation of statistical data (county-level totals), and (ii) the literature-derived coefficients used in Eqs. (1)-(8), including straw-to-grain ratios and collectable coefficients (Table 1), livestock manure-related coefficients (Table 2), conversion parameters (e.g., η and ε), and emission factors (Table 3).

To evaluate the robustness of the estimated biomass energy potential and emission reduction, we conducted a one-at-a-time sensitivity analysis. Each key parameter was perturbed by ±10% while other inputs were held constant, and the resulting changes in the main outputs (collectible straw amount, standard coal equivalent, and SO_2/NO_x/CO_2 reduction) were recorded. The sensitivity index was calculated as the percentage change in each output relative to the baseline scenario. This provides an uncertainty envelope for interpreting the results and identifies the dominant contributors to overall uncertainty.

Results and Discussion

Collectible Straw Amount

As shown in Fig. 2A, the spatial distribution of the collectible straw amounts for different crops in Zhengzhou varies significantly, with key high-value areas concentrated in specific regions. The collectible straw amounts of the major crops in Zhengzhou in 2024 included four main crop types: legumes, wheat, corn, and oilseed crops. Based on the spatial distribution of collectible straw amounts for different crops in Zhengzhou in 2024, the highest collectible corn straw amounts were concentrated in the eastern parts of

Table 3. Emission coefficients of biomass from crop straw and livestock manure during standard coal conversion and direct combustion.

Waste type	Utilization method	SO_2 (kg·t^{-1})	NO_X (kg·t^{-1})	CO_2 (kg·t^{-1})
Crop straw	Direct combustion	5.63×10^{-2}	1.95	0
	Standard coal combustion	28.65	7.1	2663.7
Livestock manure	Biogas combustion	0	0	0
	Standard coal combustion	28.65	7.1	2663.7

Zhengzhou, including the districts and county-level cities of Zhongmu, Xingyang, Xinzheng, Dengfeng, and Xinmi, with each of these areas having a collectible straw amount exceeding 13.0×10³ t. The highest collectible wheat straw amounts were mainly distributed in the southwestern region, with the top five areas being Xinzheng, Xinmi, Xingyang, Dengfeng, and Zhongmu, each having a collectible straw amount exceeding 10.6×10³ t. The distribution of collectible wheat and corn straw amounts showed certain similarities, with the core high-value areas primarily located in the plains regions of Zhengzhou, where agricultural production is well-developed (e.g., the southwestern and eastern regions). This distribution pattern closely aligns with the concentration of farmland resources and the large-scale cultivation of staple crops in these areas.

The highest collectible straw amounts for legume crops were concentrated in the southern counties, with most counties having a collectible amount exceeding 1.0×10³ t. The highest collectible straw amounts for oilseed crops were found in a single eastern county, with the amount exceeding 5.0×10³ t, while other areas generally had medium to low values (≤2.9×10³ t). The distribution of collectible rice straw amounts was generally limited by climatic conditions. As Zhengzhou is a northern city, the scale of rice cultivation is limited, so no significant concentrated distribution of rice straw was observed.

This study calculated that the collectible wheat straw amount in Zhengzhou was 6.7×10⁵ t, and the collectible corn straw amount was 9.5×10⁵ t. These results are highly consistent with related studies, as wheat and corn are the major crops in Henan Province, and the distribution of straw yield at the county scale is highly correlated with the area of crop cultivation. Furthermore, the wheat straw production coefficient of 1.28 provided authoritative data for this study [22].

Building on these findings, Fig. 2B further illustrates the overall spatial pattern of straw resources, revealing a ‘core high-value concentration, peripheral gradient decrease’ distribution. In addition, the distribution of collectible straw amounts for different crops was significantly correlated with the regional agricultural production pattern. In the high-value areas of the yield

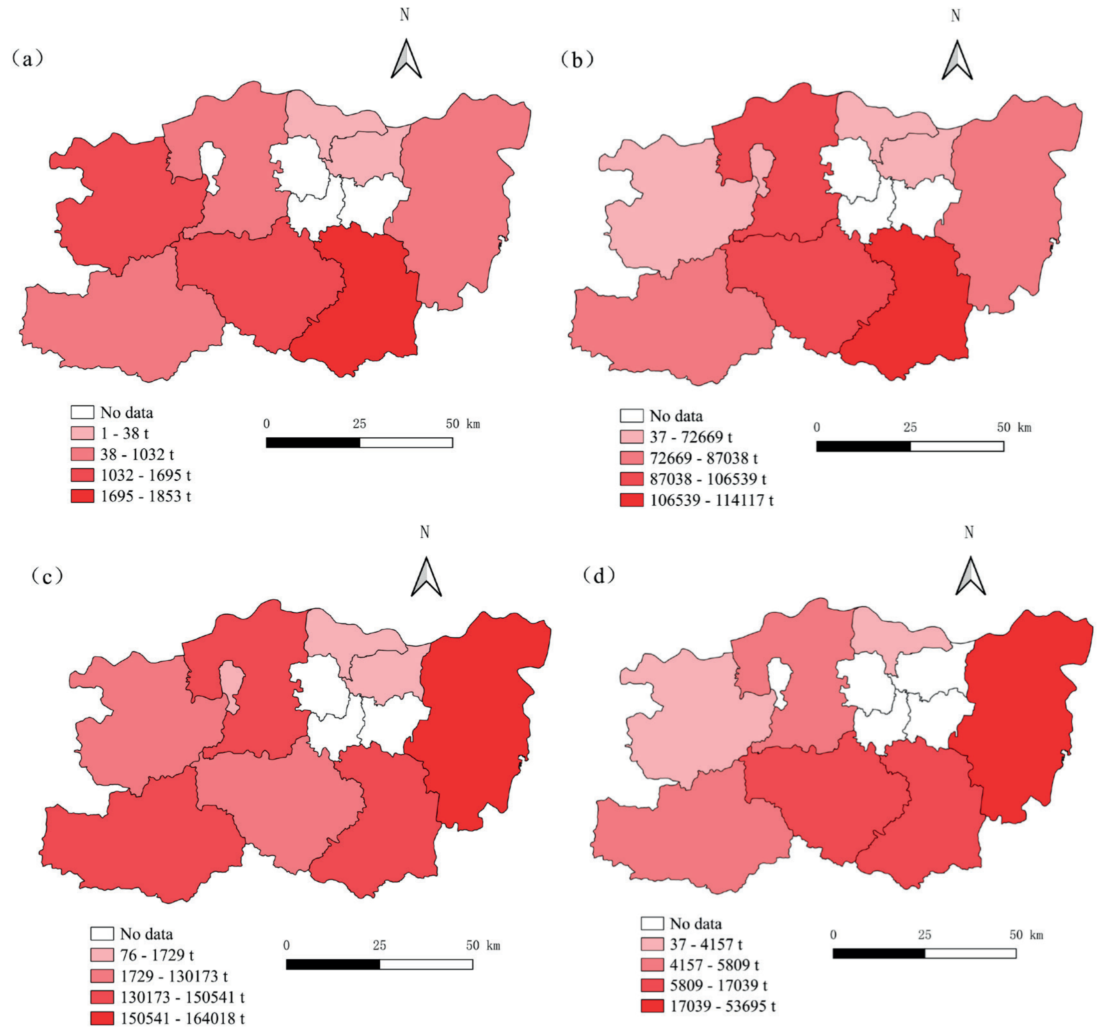

Fig. 2A. Collectible straw amounts of major crops in Zhengzhou in 2024: a) Legume crop straw, b) Wheat straw, c) Corn straw, and d) Oilseed crop straw.

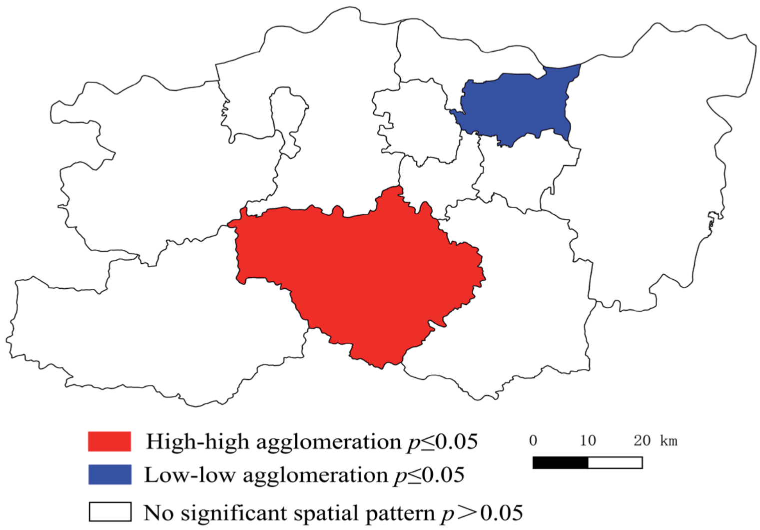

Fig. 2B. Crop straw output in Zhengzhou.

classification map, a "high-high" clustering zone was formed, where not only the local crop yield was high, but also the neighboring areas had relatively high yields. These areas typically had large cultivated land areas, high planting concentration, and were located near the Yellow River system, with abundant water resources, resulting in a strong supply capacity for straw resources. In the low-value areas, a "low-low" clustering zone was formed, where crop cultivation was diversified, but the scale of single crops was limited, leading to a lower concentration of recyclable straw amounts.

Following this, Fig. 2C focuses on the biomass energy potential of straw-based agricultural solid waste in Zhengzhou, demonstrating the contribution of different crop straw types and offering insights into the regional biomass energy potential. Each county-level unit displayed the composition of wheat, corn, cereal, and oilseed crop straw, with color proportions indicating their respective shares. Wheat and corn straw dominated, as these two types of straw have stable carbon-to-nitrogen ratios and are easier to collect on a large scale, making them high-potential, centralized biomass energy sources. Although oilseed crop straw accounted for a relatively small proportion across the region, its higher calorific value density made it suitable for distributed biomass energy utilization, thus forming an important complement to the regional biomass energy potential.

From a spatial distribution perspective, the size differences in the county-level pie charts were small, indicating that the total biomass energy potential of straw-based agricultural solid waste in Zhengzhou was relatively balanced across counties, with no significant resource gaps. This provided a stable raw material foundation for regional biomass energy utilization. However, the spatial differentiation in straw composition (e.g., the higher proportion of oilseed crop straw in the eastern regions) suggested that there were certain

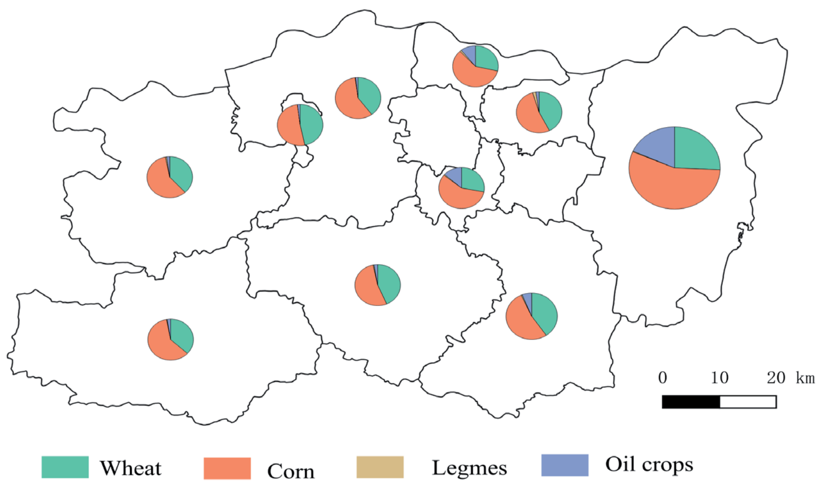

Fig. 2C. Contribution of crop straw sources in Zhengzhou in 2024.

differences in the types of biomass energy potential across counties, providing a basis for the development of regional biomass energy utilization strategies.

Biomass Energy Utilization Potential of Crop Straw

The biomass energy utilization potential and emission reduction potential of major crop straws in Zhengzhou in 2024 are shown in Table 4. Based on the calculations from Equation (2) and the data in Table 2 and Table 3, the biomass energy utilization potential of major crop straws in Zhengzhou was found to be 1.47×10^5 t of standard coal. Among them, wheat and corn straw were the primary sources of biomass energy utilization in Zhengzhou, accounting for 36% and 54% of the total potential, respectively. The biomass energy utilization potential of wheat straw was 10.98×10^4 t, while that of corn straw was 16.46×10^4 t, representing the largest shares.

Fig. 2D shows the spatial distribution of the biomass energy utilization potential of major crop straws in Zhengzhou in 2024. As shown in the figure, the high-value areas of biomass energy potential for crop straws were mainly concentrated in the eastern part of Zhengzhou. From a spatial distribution perspective, the western region of Zhengzhou, including counties like Gongyi and Dengfeng, had lower biomass energy utilization potential for crop straws, with values generally below 1800 tons, which was only 2.3% of the area with the highest potential in Zhongmu. Additionally, the top five counties for wheat straw biomass energy potential were Dengfeng, Xinmi, Xingyang, Xinzheng, and Zhongmu, with potential values exceeding 1.4×10^4 t. Similarly, the top five counties for corn straw biomass energy potential were Zhongmu, Xinmi, Xinzheng, Gongyi, and Xingyang, with potential values exceeding 1.5×10^4 t.

The spatial distribution of biomass energy potential for wheat and corn straw showed high similarity, with the core high-value areas mainly located in the southwestern Dengfeng-Xinmi region and the eastern Zhongmu-Xinzheng region. In contrast, the biomass energy potential of legume crop straws was primarily distributed in the southern part of Xinmi, the western part of Gongyi, and the central part of Xingyang. Oilseed crop straw, however, exhibited significant point concentrations, with the highest potential in Zhongmu, where the value exceeded 5×10^3 t.

Biomass Energy Utilization Potential of Livestock Manure

This study also assessed the biomass energy utilization potential of livestock manure in Zhengzhou, focusing primarily on the excreta of pigs, cattle, and sheep. Table 5 presents the biogas production potential and emission reduction potential of livestock manure in Zhengzhou.

According to the spatial distribution in Fig. 3A, the biomass energy utilization potential of livestock manure in Zhengzhou increased from west to south, differing from the east-to-west decreasing trend of livestock manure potential in Henan Province reported in previous studies. This discrepancy is attributed to Zhengzhou's geographic features: eastern Henan (e.g., Shangqiu and Zhoukou) is a major flatland agricultural area, while western Zhengzhou is mostly mountainous, and southern Zhengzhou has large-scale livestock farming [23]. The potential was concentrated in western, southern, and eastern Zhengzhou, with the southern counties having the highest potential (3.69×10^6 m^3), 1.32 times that of the western region.

The biomass energy potential of livestock manure showed some spatial correlation with that of crop straw, though differences existed. The high-value areas for livestock manure were mainly concentrated in the southern part of Zhengzhou, whereas crop straw had high-value areas more widely distributed across the southwestern and eastern counties.

Regarding the biomass energy potential of different types of livestock manure, pig manure potential was primarily concentrated in the southwestern region of Zhengzhou, particularly in Gongyi, where it reached 3.69×10^6 m^3. This was followed by Dengfeng at 3.43×10^6 m^3, and Xinmi and Xinzheng in the east and south with potential values of 2.81×10^6 m^3 and 2.79×10^6 m^3, respectively. In contrast, the northeastern county of Zhongmu showed relatively low pig manure potential, with some areas having no livestock farming.

The biomass energy utilization potential of cattle manure was mainly distributed in the eastern and central regions of Zhengzhou, especially in eastern Zhongmu, where it reached the highest at 5.25×10^6 m^3.

Table 4. Biomass energy utilization potential and emission reduction potential of major crop straws in Zhengzhou.

Crop type	Biomass energy utilization potential (10^4 t)	Energy utilization potential (10^4 t)	Atmospheric pollutant emissions (SO_2, NO_x) (10^2 t)	Emissions during energy utilization (10^2 t)	CO_2 emission reduction (10^4 t)
Wheat	10.98	5.27	39.25	1.06	29.24
Corn	16.46	7.90	58.85	1.59	43.85
Legumes	0.19	0.09	0.67	0.02	0.50
Oilseed crops	3.03	1.45	10.83	0.29	8.07

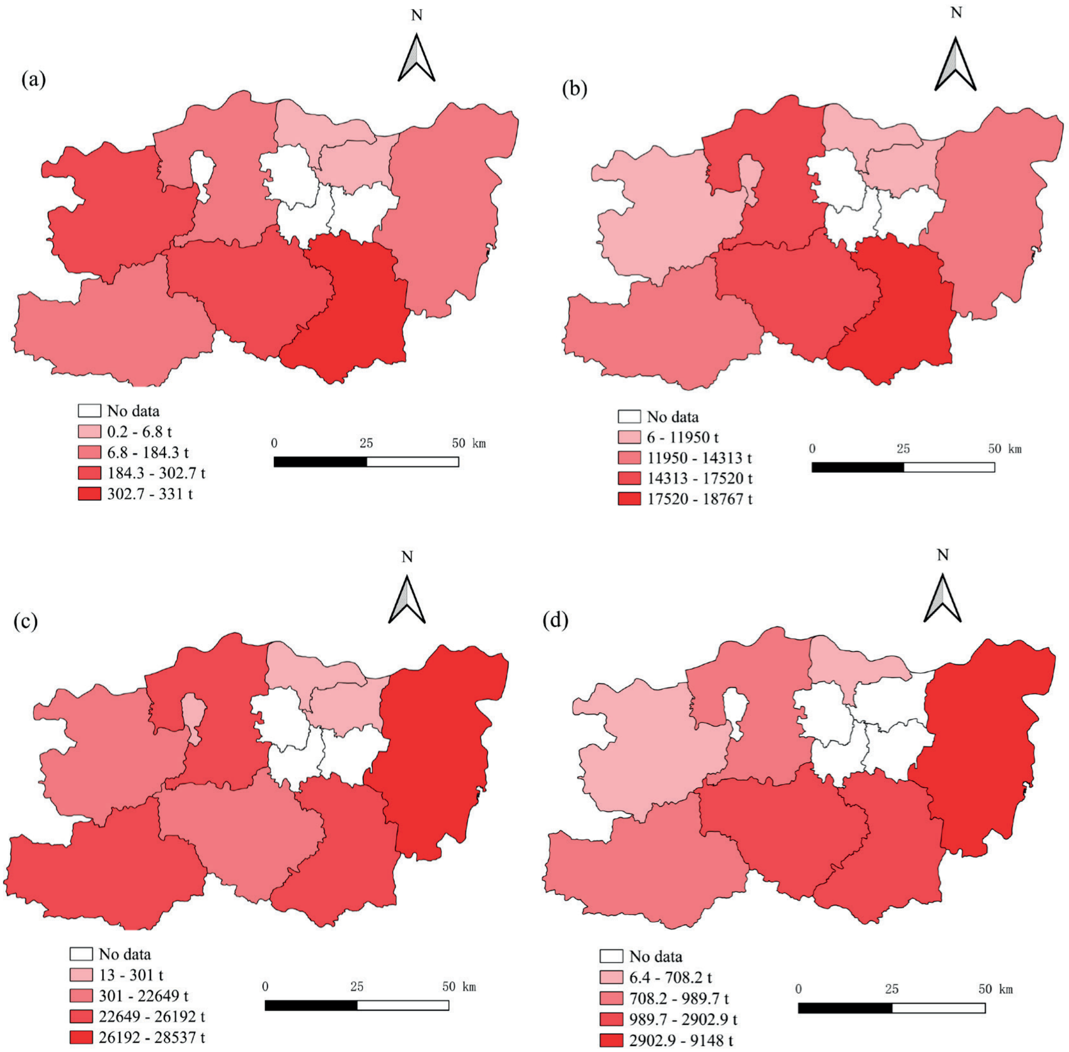

Fig. 2D. Spatial distribution of biomass energy utilization potential of major crop straws in Zhengzhou: a) legume crop straw, b) wheat straw, c) corn straw, and d) oilseed crop straw.

The next highest values were found in southwestern Dengfeng and central Xingyang, at 4.84×10^6 m³ and 4.76×10^6 m³, respectively. In the northwest, Gongyi had a relatively low cattle manure potential, with a value of only 1.49×10^6 m³.

The biomass energy potential of sheep manure showed a similar distribution pattern to cattle manure, with the highest potential concentrated in the southwestern to central regions. Southwestern Dengfeng had the highest sheep manure potential at 5.36×10^6 m³, followed by southern Xinmi and eastern Zhongmu at 3.40×10^6 m³ and 4.18×10^6 m³, respectively. Approximately 30% of counties in Zhengzhou had medium to low sheep manure biomass energy utilization potential.

From the analysis of Fig. 3B, it can be seen that the biomass energy utilization potential for cattle and sheep manure generally accounted for a higher proportion compared to pig manure in each district. This was primarily because, although pig farming in Zhengzhou had some scale, the breeding cycle for pigs is relatively short (approximately 199 days), while cattle and sheep

Table 5. Biogas production potential and emission reduction potential of livestock manure in Zhengzhou.

Livestock type	Biogas production potential (10^7 m³)	Atmospheric pollutant emission reduction (10^2 t)	CO_2 emission reduction (10^7 t)
Cattle	2.53	6.45	6.73
Sheep	2.83	7.22	7.53
Pigs	1.82	4.65	4.85

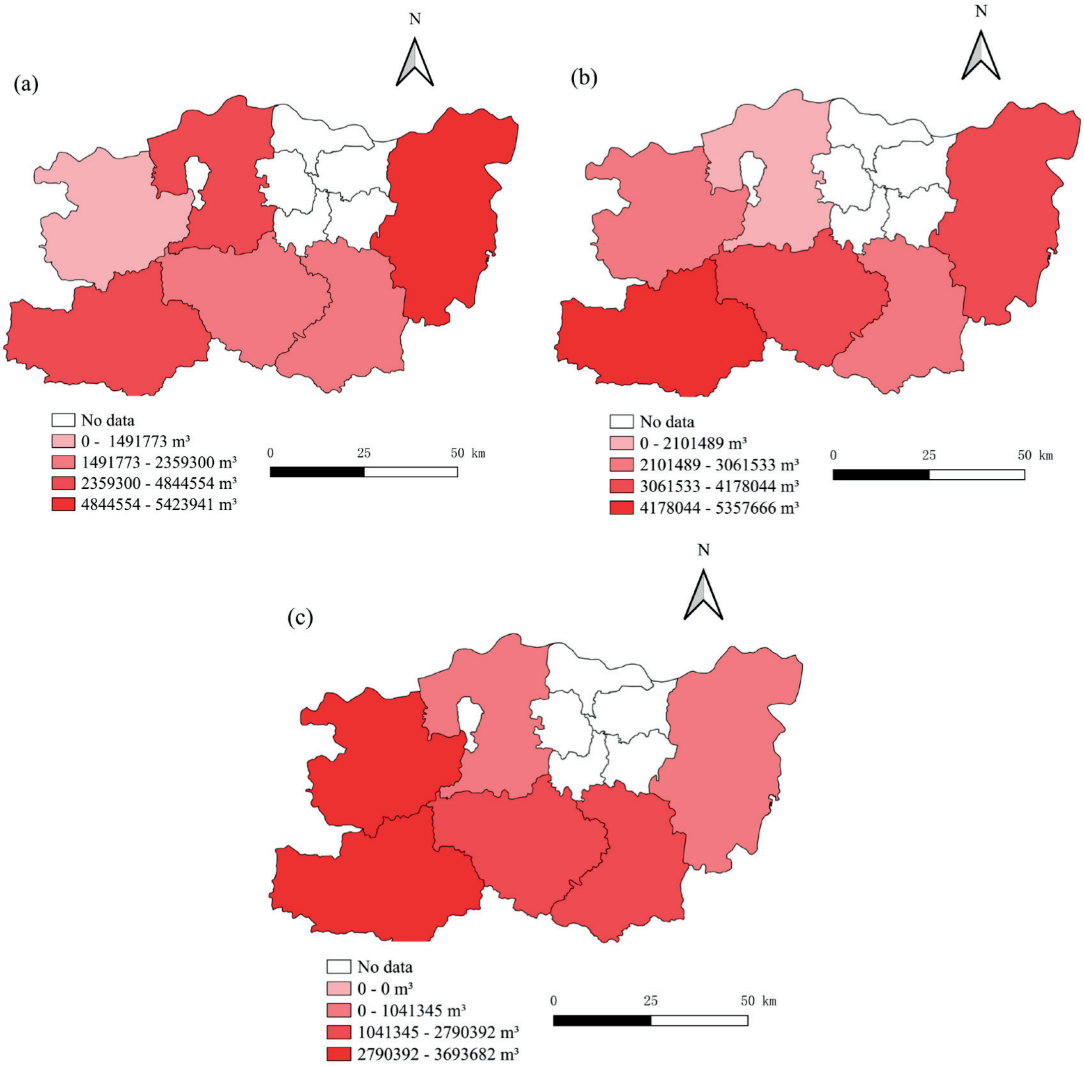

Fig. 3A. Spatial distribution of biomass energy utilization potential of livestock manure in Zhengzhou: a) cattle manure, b) sheep manure, and c) pig manure.

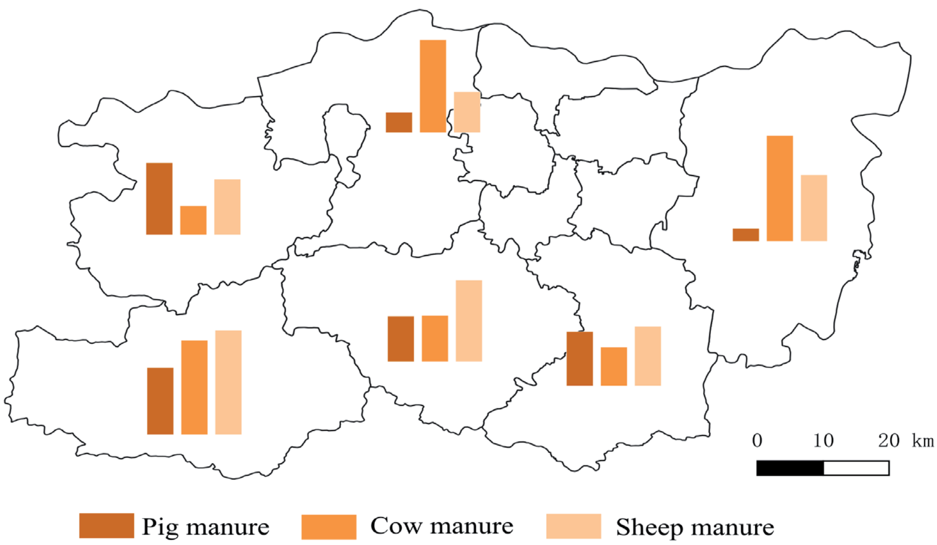

Fig. 3B. Contribution of livestock manure biomass energy potential in Zhengzhou.

have longer breeding cycles (both 365 days), resulting in a higher contribution of cattle and sheep manure at the district level. Moreover, the proportion of each type of livestock manure in biomass energy utilization did not show a "single-type dominance" in any county, reflecting the diversified sources of biomass energy from livestock manure in Zhengzhou.

Emission Reduction Analysis of Agricultural Waste

Based on the biomass energy utilization potential of agricultural waste in Zhengzhou in 2024, this study further analyzed the emission reduction potential of agricultural waste, focusing on atmospheric pollutants (SO_2, NO_x) and carbon dioxide (CO_2) emissions. The total biomass energy utilization equivalent to standard coal for agricultural waste was approximately 3.58×10^5 t. Considering that the energy conversion efficiency is less than 100%, the amount of biomass energy that can actually be converted is about 3.04×10^5 t of standard coal.

Specifically, the biomass energy utilization potential of crop straw reached approximately 3.07×10^5 t of standard coal, while that of livestock manure was 0.51×10^5 t, indicating a higher potential for crop straw than for livestock manure.

In terms of emission reduction benefits, replacing standard coal with crop straw and livestock manure could reduce SO_2 and NO_x emissions by 4.52×10^2 t and CO_2 by approximately 1.99×10^7 t. In detail, crop straw contributed to a SO_2 and NO_x reduction of 2.69×10^2 t and a CO_2 reduction of about 8.17×10^5 t, while livestock manure led to a SO_2 and NO_x reduction of 1.83×10^2 t and a CO_2 reduction of approximately 1.91×10^7 t.

Zhengzhou could achieve a carbon reduction of about 1.99×10^7 t annually through anaerobic fermentation of straw and livestock manure. This result is consistent

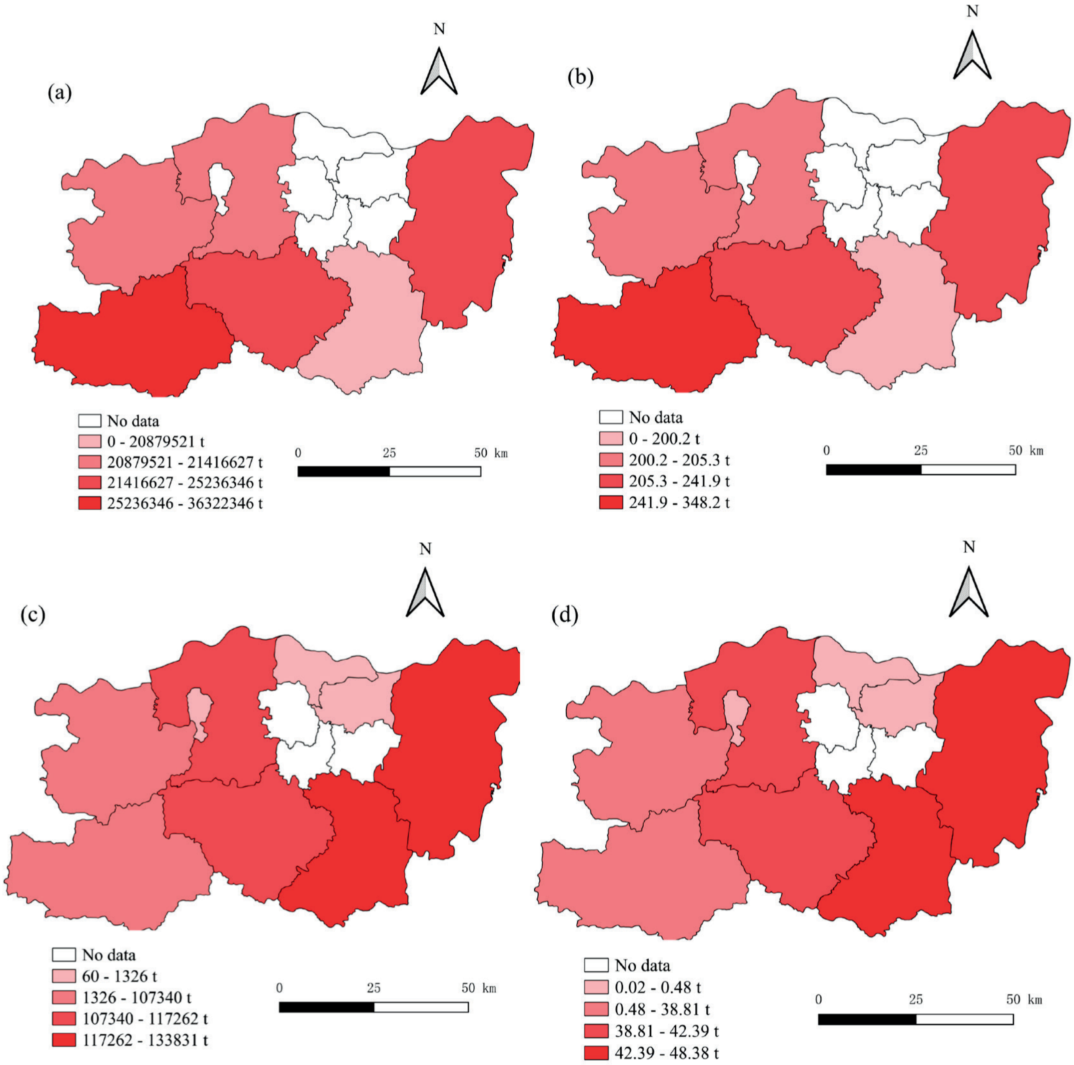

Fig. 4A. Spatial distribution of agricultural waste emission reduction potential in Zhengzhou: a) CO_2 emission reduction from livestock manure, b) atmospheric pollutant emission reduction from livestock manure, c) CO_2 emission reduction from crop straw, and d) atmospheric pollutant emission reduction from crop straw.

with the findings of Nie et al. on the carbon reduction potential of biomass energy in the Huang-Huai-Hai Plain [24]. The refined county-scale calculation results of this study fall within the reasonable range of carbon emission reduction intensity reported in existing research. Further comparison with regional studies shows this result is slightly higher than the average county-level agricultural waste carbon emission reduction capacity in Henan Province (1.8×10^7 t) [23], mainly due to the high level of large-scale agricultural waste collection and utilization in Zhengzhou as the core city of the Central Plains Urban Agglomeration. Unlike single-crop straw emission reduction studies in the Huang-Huai-Hai Plain [22], this study incorporates livestock manure contributions, which account for over 35% of total emission reduction and make up for the limitations of straw-only studies. Meanwhile, uncertainty analysis shows that the error of similar studies in the Huang-Huai-Hai Plain is typically within 15% [15], and the results of this study also fall within this credible interval, verifying the reliability of the conclusions.

Based on 1-km-resolution data, this study confirmed that the carbon reduction intensity of agricultural waste biomass energy utilization can reach 0.8~1.2 t CO_2 per ton of standard coal. Carbon reduction benefits in the Eastern and Central Plains of Henan are significantly higher in plain areas than mountainous ones due to resource concentration, which further supports the importance of promoting agricultural waste biomass energy utilization in Zhengzhou for regional "dual carbon" goals.

Fig. 4A shows the spatial distribution of the emission reduction potential of agricultural waste in Zhengzhou. The spatial distribution of atmospheric pollutants and CO_2 emission reduction potential is basically consistent, both showing a spatial pattern of "higher in the west, lower in the east, and decreasing from south to central". Crop straw emission reduction potential was mainly concentrated in the western, southern, and eastern counties, especially Zhongmu County, with SO_2 reductions of 48.38 t and CO_2 reductions of 1.34×10^5 t. Livestock manure emission reduction potential exhibited a similar distribution trend, with Dengfeng City having the highest atmospheric pollutant reduction of 348.21 t and a CO_2 reduction of 3.63×10^7 t.

Fig. 4B displays the local Moran's I spatial clustering distribution characteristics of the emission reduction potential of agricultural waste in Zhengzhou. According to the distribution shown in the figure, the high-value areas of agricultural waste emission reduction potential were primarily concentrated in the western and eastern counties, especially in Xinmi and Zhongmu, where agricultural waste resources were abundant, providing strong support for emission reduction efforts in these regions.

Further analysis showed that the "high-high clustering" zone for agricultural waste emission reduction potential in Zhengzhou was located in Xinmi, where both atmospheric pollutant reduction potential and CO_2 reduction potential were high, forming a concentrated zone for emission reduction from agricultural waste. In contrast, Jinshui had lower agricultural waste emission reduction potential, with neighboring areas also showing lower potential, forming a zone with relatively low emission reduction benefits.

The above estimates depend on county-level statistical data and literature-derived coefficients, which inevitably introduce parameter uncertainty. Although absolute estimates may vary due to parameter uncertainty, the relative spatial pattern and clustering results (Local Moran's I) are expected to be robust because the same parameter set is consistently applied

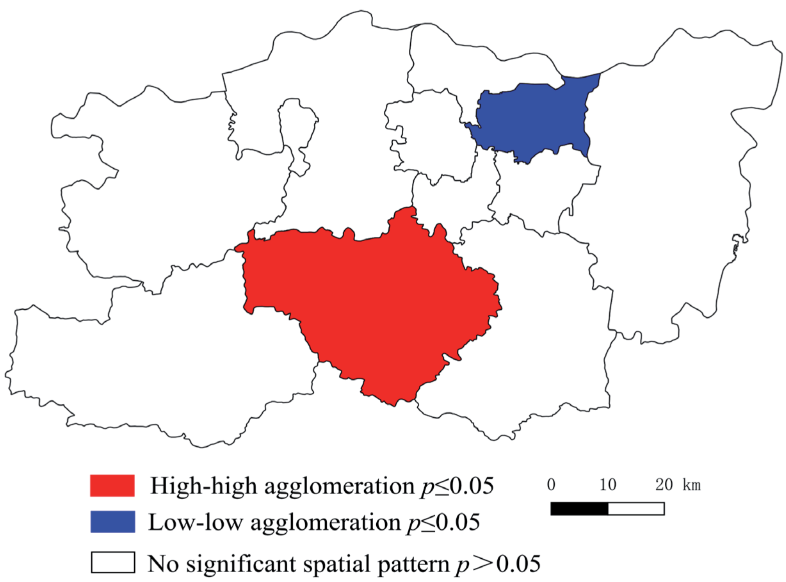

Fig. 4B. Agricultural waste emission reduction potential in Zhengzhou.

across all county units. Nevertheless, future work could further quantify uncertainty ranges (e.g., sensitivity or Monte Carlo analysis) to provide confidence intervals for the estimated energy potential and emission reduction.

Conclusions

This study quantitatively assessed the biomass energy utilization potential and emission reduction benefits of agricultural waste (including crop straw and livestock manure) in Zhengzhou, revealing their spatial distribution characteristics. The main conclusions are as follows:

(1) In 2024, the recyclable amount of major crop straws in Zhengzhou was approximately 1.8×10^6 t, with corn straw being primarily concentrated in the eastern counties and wheat straw predominantly distributed in the southwestern region. This distribution pattern reflects the characteristics of Zhengzhou's agricultural production layout and provides data support for spatial optimization of agricultural waste. The biomass energy utilization potential of crop straw was 30.66×10^6 t, with corn straw accounting for 53.68% and wheat straw for 35.81%. Additionally, the biomass energy utilization potential of the three main livestock types in Zhengzhou (cattle, sheep, and pigs) was 7.18×10^7 t, equivalent to 5.12×10^4 t of standard coal.

(2) The total biomass energy utilization equivalent to standard coal for agricultural waste in Zhengzhou was approximately 3.58×10^5 t, with crop straw utilization potential dominating, far exceeding the biomass energy potential of livestock manure. Specifically, the biomass energy utilization potential of crop straw was 3.07×10^5 t of standard coal, while the biomass energy utilization potential of livestock manure was 0.51×10^5 t of standard coal. In terms of emission reduction, the biomass energy utilization of agricultural waste can effectively reduce atmospheric pollutant emissions, particularly SO_2 and NO_x, and has a significant effect on CO_2 reduction. Specifically, the utilization of agricultural waste can reduce SO_2 and NO_x emissions by 4.52×10^2 t and CO_2 emissions by approximately 1.99×10^7 t.

(3) From a spatial distribution perspective, the biomass energy utilization potential of crop straw and livestock manure exhibited a spatial pattern of "high-value concentration and low-value sparsity", with agricultural waste resources being particularly abundant in areas such as Zhongmu, Xinzheng, and Xinmi, which have a higher emission reduction potential. The emission reduction potential of agricultural waste in Zhengzhou exhibited significant spatial autocorrelation, with high-value and low-value areas showing a "bipolar clustering" characteristic.

This study provides an important quantitative analysis foundation for the resource utilization and biomass energy development of agricultural waste in Zhengzhou. It reveals the distribution characteristics of biomass energy potential for different crop and livestock waste. In the future, Zhengzhou should formulate more refined and regionalized strategies for resource utilization and biomass energy development based on the spatial distribution of agricultural waste resources and biomass energy potential in each county. This will help promote the efficient utilization of agricultural waste and contribute to the sustainable development of the regional economy and the achievement of the "dual carbon" goals.

Author Contributions

Y.L. wrote the manuscript and acquired funding; T.G. wrote the manuscript; S.Y. analyzed the data; L.W. provided characterization support and reviewed the manuscript; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. DONG W.J., SUN S., LI T., YANG X., LI Z. Implications of the EU methane emission reduction strategy for China's carbon neutrality. Environment and Sustainable Development, **46** (2), 37, **2021** [In Chinese].
2. QI X.H., QIU B.J., FU J.Y. New implementation pathways for the resource utilization of agricultural wastes under the goal of carbon peaking and carbon neutrality. Journal of Agricultural Resources and Environment, **41** (5), 989, **2024**.
3. GUO M.X., YUAN Y., MA X.Q., ZHU L. Zoning evaluation of rural biomass energy utilization potential in Hebei Province. Energy Conservation, **39** (12), 19, **2020** [In Chinese].
4. ZHAO S.Y., YAN L.M. Analysis of spatial distribution and utilization potential of biomass energy in China. China Forestry Economics, **5**, 75, **2019**.
5. FENG X., WU G., CAO Y., ZHANG B., GUO S. Evaluation on the utilization potential of biomass energy: A case from key state-owned forest areas in Heilongjiang Province. Chinese Journal of Agricultural Resources and Regional Planning, **40** (6), 55, **2019**.
6. ZHAO Q.Y., MA R.J., ZHOU L.Y., ZHU Y.M., YAO K., LI X.Q., ZHANG X.L. Evaluation of energy potential and emission reduction of agricultural waste biomass utilization

for clean heating in rural areas of northern China. Journal of Agricultural Resources and Environment, **40** (3), 667, **2023**.
7. XU X., MOLA-YUDEGO B., SELKIMÄKI M., ZHANG X., QU M.Determinants of farmers' waste generation and disposal in rural areas of central China. Environmental Science and Pollution Research, **30** (4), 9011, **2023**.
8. QI K., ZHANG H., ZHOU Y., LIU Y., LI Q. Metaphor representation of resource nodes in cyberspace based on local Moran index and PageRank algorithm. Journal of Geo-information Science, **26** (5), 1283, **2024**.
9. Zhengzhou Municipal Bureau of Statistics, Zhengzhou Survey Team of National Bureau of Statistics. Zhengzhou Statistical Yearbook 2024. Available online: http://tjj.zhengzhou.gov.cn (accessed on October 20, 2025) [In Chinese].
10. National Bureau of Statistics of China, Energy Statistics Department. China Energy Statistical Yearbook 2023. Available online: https://www.stats.gov.cn/hd/lyzx/zxgk/nytj (accessed on October 20, 2025) [In Chinese].
11. BU R.Y., CHENG W.L., HAN S., JI G.X., TANG S., HU R., LI M., WANG H., ZHU R., WU J. Effects of combined incorporation of Chinese milk vetch and rice straw on the utilization and fate of nitrogen in a rice paddy field. Journal of Plant Nutrition and Fertilizers, **31** (3), 432, **2025**.
12. LI H., LI J., JIAO X., JIANG H., LIU Y., WANG X., MA C. The fate and challenges of the main nutrients in returned straw: A basic review. Agronomy, **14** (4), 698, **2024**.
13. CHEN L.H., SHU B.R., LI X. Evaluation of Biogas Potential of China's Livestock and Poultry Manure and Its Influencing Factors Based on Regional Differences in Excretion Coefficient. China Biogas, **37** (2), 7, **2019** [In Chinese].
14. YANG H.N., DENG L.W., WANG L., ZHENG D., LIU Y., WANG S., HUANG F.Y. Comparison of three biomass-retaining reactors of the ASBR, the UBF and the USR treating swine wastewater of biogas production, Renewable Energy. **138**, 521, **2019**.
15. HUO L.L., ZHAO L.X., YAO Z.L., LUO J., ZHANG P.Z., XIE T., JIA J.X., DENG Y., WEI X.Y. Potentiality of agricultural biomass energy for greenhouse gas emission reduction. Transactions of the Chinese Society of Agricultural Engineering, **37** (22), 179, **2021**.
16. SHU Y., LIU Y., LIU M., BI J. Energy potential and bioethanol production potential from collectable major crop residue in China. Journal of Beijing Institute of Technology (Social Sciences Edition), **25** (5), 64, **2023**.
17. WU H.W., SUN X.Q., LIAMG B.W., CHEN J.B., ZHOU X.F. Analysis of livestock and poultry manure pollution in China and its treatment and resource utilization. Journal of Agro-Environment Science, **39** (6), 1168, **2020**.
18. CHEN F., YU G., ZHANG H., LU X., HOU J. Composition and resource utilization potential of livestock manures in Guizhou province. Journal of Arid Land Resources and Environment, **34** (12), 78, **2020**.
19. HU H.Q., LI Z.H., ZHU S.Y., ZHOU C.L., ZHOU S.J., YAN S., AN L.H. Study on causes and preventive measures of methane gas poisoning in limited spaces such as livestock and poultry manure and biogas facilities. China Biogas, **42** (3), 66, **2024**.
20. CHE Q.F., CHEN X.Y., HU T.T., ZHANG J., ZHANG J., HUANG W.J., TU Q.H. Analysis of utilization potential of major crop straws and livestock manure in Jiangxi Province. Journal of Henan Agricultural Sciences, **53** (12), 86, **2024**.
21. ZHANG Z., WANG P., DAI K., QIAN W., ROY S., SHUAI R., FERRANY A. Combustion characteristics and NO production of axially staged premixed NH_3/CH_4 turbulent swirling flames. CIESC Journal, **76** (2), 835, **2025**.
22. YANG C.W., XING F., ZHU J.C., LI R.H., ZHANG Z.Q. Temporal and spatial distribution, utilization status, and carbon emission reduction potential of straw resources in China. Environmental Science, **44** (2), 1149, **2023**.
23. WU R. Potential for biomass energy utilization and emission reduction of agricultural waste in Henan Province. Renewable Energy Resources, **43** (10), 1297, **2025**.
24. NIE Y., CHANG S., CAI W., WANG C., FU J., HUI J., YU L., ZHU W., HUANG G., KUMAR A., GUO W., DING Q. Spatial distribution of usable biomass feedstock and technical bioenergy potential in China. Global Change Biology Bioenergy, **12** (1), 54, **2019**.