

Article

Carbon Reduction from Five Utilization Pathways of Straw in China: A Case Study of Guangdong Province

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Abstract

In the context of global climate change and the transition to a low-carbon economy, utilizing crop straw as a resource is a key strategy for green transformation. Taking Guangdong province as a case, this study investigates the carbon reduction effects of integrated straw utilization and their spatiotemporal evolution, based on crop yield data from 2019 to 2023 across various municipalities. Different from one-way straw utilization for carbon reduction, this work analyzes the carbon reduction effects of five co-existing pathways to utilize straw as fertilizer, feed, energy, substrate, and raw material. The Theil index, *slope* value, and exploratory spatial data analysis (ESDA) method are employed to form an analytical framework for the spatiotemporal evolution of carbon reductions by straw utilization. Over this five-year period, the overall and off-field straw utilization steadily increased, and a 6.2% increase in straw utilization was achieved to realize a 19.8% rise in carbon reduction. In 2023, the carbon reduction from straw utilization was chiefly contributed by fertilization, subsequently followed by feed, energy, substrate, and raw material. Over 90% of the carbon reduction contributions came from four major crops, namely rice, peanuts, sugarcane, and potatoes. Carbon reduction across different areas in Guangdong showed positive spatial correlation, with high–high (HH) and low–low (LL) clusters being the primary local autocorrelation patterns. Model applications confirm that incentive policies and industrial development largely facilitate the integrated straw utilization in Guangdong. However, further increases in straw utilization will not necessarily ensure proportional carbon reduction. The regional heterogeneity and coordinated clustering development should be considered to strengthen carbon-reduction intensity. In particular, policies should be tailored to crop straw recovery and utilization, inter-regional straw allocation, and preferentially support straw utilization for energy and as a substrate.

Keywords: bioenergy; fertilizer; animal feed; carbon emission; spatiotemporal evolution



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1. Introduction

The valorization of agricultural residues, such as crop straw, has become a focal point in global ecological sustainability initiatives [1] and in emerging investments in green industries like clean biomass energy [2]. Since China launched its comprehensive straw utilization action in 2019, the country has implemented a county-wide promotion strategy across 2579 counties [3]. According to the “National Report on Comprehensive Utilization of Crop Straw” issued by the Ministry of Agriculture and Rural Affairs, China utilized 647 million tons of crop straw in 2021. Significant breakthroughs have been made in straw

valorization, which holds immense potential for carbon reduction through soil carbon sequestration [4,5] and the substitution of fossil fuels [6–8]. The comprehensive utilization of straw in China could achieve carbon sequestration and reductions, which is equivalent to approximately 27.7% and 2.1% of carbon emissions in the agricultural system and nation in 2021, respectively [2]. Given the persistent potential for straw utilization, advancing its comprehensive utilization and improving scientific return-to-field practices and efficient removal pathways remain urgent research priorities [9].

As China's largest economic entity and a key coastal agricultural production base, Guangdong province leads other provinces in utilization practices and industry investment of straw [10]. According to the "Comprehensive Straw Utilization Implementation Plan for Guangdong Province 2023", the province aims to maintain a straw utilization rate of over 86%. Guided by the principle of adapting to local conditions, Guangdong promotes five pathways of straw utilization as fertilizer, feed, energy, substrate, and raw materials to gradually advance its industrial development across all regions. The application of straw as fertilizer is particularly critical for addressing soil issues in Guangdong. According to the monitoring data of cultivated land quality in the year of 2022 [11], the average organic matter content of soil in Guangdong is 29.6 g/kg. However, the soil is characterized by moderate nitrogen, rich phosphorus, and deficient potassium, with widespread acidification (low pH values). As straw is rich in nitrogen, phosphorus, potassium, and organic matter, its use as fertilizer is increasingly valued for its potential to enhance soil base saturation and ameliorate soil acidity [12]. From a carbon cycle perspective, returning straw to the field not only reduces emissions indirectly by substituting chemical fertilizers but also creates a carbon sink by directly adding organic carbon to the soil. Scientific straw return can reduce the use of chemical fertilizer by 10–20% [13], effectively curbing agricultural carbon emission intensity. As a feed resource, crop straw plays a vital role in animal husbandry in Guangdong, especially for ruminant nutrition [14]. Its use as feed indirectly reduces greenhouse gas emissions by replacing other feed crops with higher carbon footprints [15]. Similarly, due to its high content of carbon, nitrogen, and minerals, straw also serves as an ideal substrate for cultivating edible fungi. For raw material utilization, straw cellulose can be mixed with binders and reinforcing agents to produce green building materials, enabling long-term carbon storage in durable products such as artificial boards and composite materials [16]. In terms of energy utilization, straw is a primary feedstock for bio-based energy like biofuels. Guangdong province has the largest installed capacity for biomass power generation in China. While studies indicate that biomass power generation in the province is a notable contributor to organic carbon (OC) and volatile organic compound (VOC) emissions [17], its role in substituting fossil fuels is crucial for helping the region achieve carbon neutrality [18]. In summary, the value of straw utilization in Guangdong, particularly its low-carbon potential, is becoming increasingly evident as its application scales. However, the extent of its direct and indirect carbon reduction contributions at the regional scale has yet to be fully quantified [2].

Currently, the studies on straw utilization in China can be categorized into two primary streams. One focuses on specific regions, such as Jiangsu [19] and Shaanxi [20], primarily involving the accounting of straw utilization quantities or the analysis of utilization mechanisms. The other concentrates on the carbon reduction contributions of straw at the national scale, with two central themes: potential assessment and carbon reduction accounting. Regarding potential assessment, Zhang et al. [21] used a geographic information system (GIS) to determine the technical and sustainable potential of agricultural residues in China, and found that approximately 20% of technically collectible residues were not effectively utilized. However, the conversion of crop straw into bioenergy is constrained by factors such as topography, the distribution of cultivated land, primary crop varieties and yields,

the suitability of conversion technologies, and the economic feasibility of fuel substitution [22], all of which necessitate spatial considerations. A spatial suitability assessment by Qian et al. [23] indicated that twelve regions, including Beijing, are suitable for promoting fertilizer utilization, eight provinces, including Inner Mongolia, are fit for feed utilization, and ten provinces, including Henan, are suited to energy utilization. Zhu et al. [24] explored the energy utilization of provincial crop straw resources in China, comprehensively considering various factors influencing available resources and investigating the spatial distribution of energy projects under different scenarios. In research related to carbon emission characteristics, scholars have conducted spatiotemporal evolution analyses of carbon emissions using methods such as the Theil index, *slope*, and exploratory spatial data (ESD) analysis [25]. These methods can effectively identify the features and patterns of the spatiotemporal evolution of carbon emissions [26,27], providing valuable support for enhanced carbon management.

In carbon reduction accounting of straw, numerous studies have concentrated on quantifying emission reductions from the energy pathway [28,29], with a primary focus on greenhouse gas (GHG) mitigation from bioenergy in China. However, China's official policy explicitly outlines five principal pathways for straw utilization: fertilizer, feed, raw material, energy, and substrate (NDRC, 2016 [30]). Consequently, recent national-scale research has begun to disaggregate carbon accounting by these different valorization pathways. For instance, Shi et al. [31] focused on the GHG emissions associated with the feed and fuel pathways. Their study, centered on straw from rice, wheat, and corn, conducted an integrated assessment to quantify GHG reductions in China from 1950 to 2021. Zhao et al. [2] accounted for carbon reductions across three primary pathways—fertilizer, feed, and energy—in various Chinese provinces from 2018 to 2020. Their research encompassed nine major crop types, including rice, wheat, corn, tubers, peanuts, rapeseed, soybean, cotton, and sugarcane. This represents the most comprehensive study to date in terms of the number of utilization pathways and crop varieties. The five pathways of straw utilization for carbon reduction have been scarcely studied, and their spatial characteristics at the municipal level have yet to be studied.

Further research is needed to more precisely characterize the regional distribution of crops, develop a carbon accounting methodology oriented toward the five resource utilization pathways, and uncover the spatiotemporal evolution patterns of straw utilization and its associated carbon reductions. This work addresses these gaps by constructing a carbon accounting framework for the five resource utilization pathways and analyzing their spatiotemporal characteristics. Different from the provincial-level studies in China, this research selects the municipal-level administrative regions of Guangdong province as a case. It provides a methodological approach that can be generalized and replicated in regional studies for the carbon reductions from the five resource utilization pathways of crop straws and their evolving characteristics. The findings are intended to provide data support and theoretical reference for evaluating carbon reduction performance, planning future utilization pathways, and promoting carbon trading for straw utilization in Guangdong province.

2. Research Methodology

2.1. Crop Production and Collectable Residue Amount

Due to differences in urban economic structures and soil conditions, crop types and yields vary significantly across regions in Guangdong province. Based on the Guangdong Provincial Key Functional Zone Plan, this work categorizes the administrative regions into the following zones: urban agricultural area (UAA) (including Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Dongguan, Zhongshan, and Huizhou), plains in-

tensive agricultural area (PIAA) (including Shantou, Chaozhou, Jieyang, and Shanwei), tropical agricultural area (TAA) (including Zhanjiang, Maoming, and Yangjiang), and mountainous ecological agricultural area (MEAA) (including Shaoguan, Heyuan, Meizhou, Qingyuan, Zhaoqing, and Yunfu). Table 1 presents the average basic information for these four agricultural areas in Guangdong province from 2019 to 2023.

Table 1. Basic information of the four agricultural areas in Guangdong province.

Region ^a	Population ($\times 10^4$ People)	GDP ($\times 10^9$ Yuan)	Arable Land Area ($\times 10^4$ mu)	Crop Sown Area ($\times 10^4$ mu)	Crop Yield ($\times 10^4$ tons)	Theoretical Straw Resource Volume ($\times 10^4$ tons)	Collectable Straw Resource Volume ($\times 10^4$ tons)
UAA	7869.76	107422.2	451.32	1404.75	287.79	227.83	171.17
PIAA	1647.86	8390.78	277.36	824.81	220.78	240.12	178.89
TAA	1595.54	9362.6	1043.68	2034.19	1598.53	594.79	444.31
MEAA	1592.84	10,497.6	1099.78	2617.16	750.20	575.86	510.64
Total	12,706.00	135,673.18	2872.04	6880.91	2857.30	1738.61	1305.01

^a UAA is short for urban agricultural area, including Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Dongguan, Zhongshan, and Huizhou. PIAA is short for the plains intensive agricultural area, including Shantou, Chaozhou, Jieyang, and Shanwei. TAA is short for tropical agricultural area, including Zhanjiang, Maoming, and Yangjiang. MEAA is short for mountainous ecological agricultural area, including Shaoguan, Heyuan, Meizhou, Qingyuan, Zhaoqing, and Yunfu.

This study selected ten major crops in Guangdong province, including grain crops (rice, wheat, corn, tuber, soybean) and cash crops (peanut, tobacco, sugarcane, cassava, hemp). These ten crops in 2023 accounted for 89.03% of the province's total crop planting area (excluding vegetables). The five grain crops contributed 99.8% of the province's grain production. Meanwhile, the output of the five cash crops accounted for 91.74% of the province's cash crop production. Due to data limitations, this study focuses solely on the straw residues of these ten major crops in Guangdong province, excluding other agricultural waste straws. Annual crop yield data for Guangdong regions from 2019 to 2023 were sourced from the Guangdong Rural Statistical Yearbook and the Guangdong Statistical Yearbook (2020–2024).

The available straw resources for each crop in every region were calculated based on the grain-to-straw ratio of different crops and the characteristics that could not be collected through manual or mechanical field operations in Guangdong. The formula for calculating the available straw resources for the i -type crop in the j -region is shown in Equation (1):

$$\text{Collectable residue amount}_{i,j} = \text{Crop}_{i,j} \times \text{Cgb ratio}_i \times \text{Col ratio}_i \quad (1)$$

$\text{Crop}_{i,j}$ denotes the yield of crop type i in region j , Cgb ratio_i , which represents the straw-to-grain ratio for crop type i , refers to the classic data in Guangdong, Col ratio_i indicates the straw collection coefficient for crop type i . Crop yield data are at the city level for 21 administrative regions in Guangdong province, which are calculated annually. The straw collection rate for the same crop across different regions in Guangdong was not differentiated. Instead, the crop-to-grain ratio and collectability coefficient for Guangdong provided in the “Notice on Establishing Crop Straw Resource Ledgers” were uniformly applied (Supplementary Table S1 for details). When the straw collection coefficient was not multiplied, the value represents the total straw amount across all regions. It means that the calculated straw yield represents the theoretical maximum.

$$\begin{aligned} \text{Utilized Crop Straw amount}_{i,j} \\ = \text{Collectable residue amount}_{i,j} \times \text{Uti ratio}_{i,j} \end{aligned} \quad (2)$$

$\text{Uti ratio}_{i,j}$, which denotes the utilization ratio of crop residues type i in region j , refers to the provincial average values. Based on this, the utilization amount for each crop can be estimated, as shown in Formula (2).

2.2. Greenhouse Gas Emission Reduction Estimation for the Five Comprehensive Uses of Crop Residue

This article refers to the five utilization pathways of crop straw proposed in the “Comprehensive Straw Utilization Implementation Plan for Guangdong Province 2023”. Specifically, crop straw can be utilized in the following ways: fertilizer (returned to fields as a substitute for chemical fertilizers), feed (used as animal feed), energy (converted into biofuels via physical, thermochemical, or biochemical methods, including direct combustion for power generation, biogas, briquettes, bioethanol, and biomass pyrolysis with charcoal-gas co-production), substrate (used as a primary medium for cultivating edible fungi, seedlings, and other cultivable products), raw material (mainly for producing engineered wood panels and paper). Due to variations in straw resources, local development capabilities, and economic factors, significant differences exist across regions in the structural composition and trends of these five primary utilization pathways. Guangdong province exhibits distinct utilization patterns compared to other provinces. For example, Fang et al. (2019) [29] quantified China’s overall practices of five straw utilization pathways from 2007 to 2016, while Huo et al. (2022) [32] analyzed five utilization patterns at the provincial level in China during 2020. By examining the ratios of five utilization pathways across Guangdong’s regions, this study calculates the amount of straw utilized and the corresponding carbon reductions for each area. The five-use ratios in this study are primarily based on data from Guangdong’s official “Guangdong Yearbook” on straw utilization. Missing data for certain years were supplemented using linear interpolation. Annual total straw utilization rates for each region in Guangdong during the study period were obtained from the “Solid Waste Pollution Prevention and Control Information” announcements issued by the ecological environment bureaus of Guangdong’s various regions. For regions with missing data, estimates were made based on the provincial average total straw utilization rate for that year. Utilization rate data is presented in Supplementary Tables S2 and S3.

The fertilization method of returning crop residues to the field is the most traditional approach. The resulting carbon reduction, which stems from a decrease in chemical fertilizer usage, can be calculated using Formula (3). This value represents the indirect carbon reduction from fertilization in Guangdong.

$$\text{CRE}_{\text{fertilizer}} = \sum \text{Collectable residue amount}_{i,j} \times \text{Fertilizer ratio}_i \times \text{Nutrition index}_{i,s} \times \text{Cec}_k \quad (3)$$

$\text{Fertilizer ratio}_i$ expresses the fertilizer replacement rate of i type of straw resources. $\text{Nutrition index}_{i,s}$ denotes the nutrient index of i type of straw resources, where s represents N , P_2O_5 , and K_2O , respectively. The nutrient indices for the ten selected crops are shown in Supplementary Table S4. Cec_k denotes the carbon equivalent coefficient for k nutrients (N , P_2O_5 , and K_2O). The carbon footprint efficiency values for N ($2.116 \text{ tCO}_2\text{e/t}$), P_2O_5 ($0.636 \text{ tCO}_2\text{e/t}$), and K_2O ($0.18 \text{ tCO}_2\text{e/t}$) fertilizers were adopted as the corresponding CRE values. The carbon-reduction accounting for straw fertilization includes greenhouse gas emissions from the fuel consumption of agricultural machinery during straw returning, but excludes N_2O emissions from straw decomposition in the field.

The emission reduction from the utilization of straw as feed in Guangdong province is calculated as Formula (4):

$$CRE_{feed} = \sum Collectable\ residue\ amount_{i,j} \times Feed\ ratio_j \times Cec_i \quad (4)$$

$Feed\ ratio_j$ denotes the feed utilization ratio of crop residues in region j . Cec_i denotes the carbon equivalence coefficient for crop type i . The corresponding emission reduction coefficients for coarse straw feed, as adopted from Huo et al. (2022) [32], are listed in Supplementary Table S5. The carbon-reduction accounting for the utilization of straw as feed includes fossil fuel emissions from straw collection, storage, transport, and feed processing, as well as from manure composting and field-returning processes, and it accounts for soil carbon sequestration from indirect field return after straw digestion. However, it does not include N_2O emissions from the decomposition of livestock and poultry manure, which are returned to the field.

The emission reduction from the application of straw as energy in Guangdong province is calculated by Formula (5).

$$CRE_{energy} = \sum Collect\ residue\ amount_{i,j} \times Energy\ ratio_j \times Bio - energy\ ratio_t \times Cec_t \quad (5)$$

$Energy\ ratio_j$ denotes the energy utilization ratio of crop residues in region j . $Bio - energy\ ratio_t$ denotes the utilization ratio of the t -type biomass energy (referencing the annual production ratios of various biomass energy types from China's Annual Reports on Biomass Energy Industry Development and the 13th Five-Year Plan for Biomass Energy Development). Cec_t represents the carbon equivalent coefficient of the t -type energy. Detailed data are provided in Supplementary Table S6 and S7. The carbon reduction in straw utilization as energy is calculated to chiefly offset fossil-fuel emissions, namely, the CO_2 -equivalent greenhouse gases (including CO_2 , CH_4 , and N_2O) avoided by substituting coal and other fossil fuels.

The emission reduction achieved by using straw as a substrate in Guangdong province is as follows:

$$CRE_{substrate} = \sum Collectable\ residue\ amount_{i,j} \times substrate\ ratio_j \times Cec_r \quad (6)$$

$Substrate\ ratio_j$ denotes the culture substrate utilization ratio of crop residues in region j . Cec_r primarily refers to the carbon reduction equivalent achieved by using straw as a substrate for fungi such as mushrooms. The greenhouse gas calculation for straw utilization as substrate primarily includes emissions from energy consumption across the entire process of straw collection, storage, processing, and utilization.

The emission reduction from the treatment of straw as a raw material in Guangdong province is calculated with Formula (7).

$$CRE_{raw\ material} = \sum Collectable\ residue\ amount_{i,j} \times Raw\ material\ ratio_{j,m} \times Cec_m \quad (7)$$

This indicates the carbon emissions reduction from the utilization of straw as a raw material, primarily representing the carbon equivalent from two major products: engineered wood panels and paper manufacturing. Due to the absence of statistical data, the straw quantities for producing these two products are calculated on a 1:1 basis. $Raw\ material\ ratio_{j,m}$ denotes the utilization ratio of straw as raw material in region j by production m . The greenhouse-gas accounting for straw utilization as raw material primarily includes emissions from energy consumption across the full lifecycle chain of straw collection, storage, processing and utilization, as well as the recovery and reuse of waste engineered wood panels and paper.

The emission reduction from the comprehensive utilization of straw in Guangdong is

$$CRE = CRE_{fertilizer} + CRE_{feed} + CRE_{energy} + CRE_{substrate} + CRE_{raw\ material} \quad (8)$$

At the same time, to evaluate the effectiveness of carbon reduction, the carbon intensity is defined as Formula (9).

$$Q_{CRE} = \frac{CRE}{Utilized\ Crop\ Straw\ amount} \quad (9)$$

This is used to analyze the carbon reduction achieved through the utilization of straw per unit.

2.3. Methods for the Analysis of the Spatial Distribution Characteristics

(1) Slope

To quantitatively characterize the trends in carbon reductions from straw utilization across districts in Guangdong province, this study calculates the *slope* values for carbon reductions based on straw utilization data from 2019 to 2023.

$$Slope = \frac{n \times \sum_{i=1}^n y_i C_i^- - \sum_{i=1}^n y_i \sum_{i=1}^n C_i^-}{n \times \sum_{i=1}^n y_i^2 - (\sum_{i=1}^n y_i)^2} \quad (10)$$

where

n represents the total number of years from 2019 to 2023, which is 5 here;

y_i denotes the year (2019 is year 1), with values ranging from 1 to 5;

C_i^- represents the carbon reduction from straw utilization in the administrative region for year i .

If $Slope > 0$, it indicates that the carbon reduction from straw utilization is increasing over time; if $Slope < 0$, it indicates a decreasing trend. The magnitude of the *slope* reflects the rate of increase or decrease in regional straw utilization for carbon reduction, i.e., the degree of tendency toward either an increase or a decrease. Standard deviation classification was used to categorize the upward trends in carbon reductions from straw utilization across Guangdong's districts into four types. The specific classification criteria are shown in Table 2.

Table 2. Classification criteria for trends in carbon reduction.

Type	Slope Value
Slow Decline Type	$-(\bar{x} - s) \sim 0$
Slow Rise Type	$0 \sim \bar{x} - 0.5s$
Moderate Rise Type	$ \bar{x} - 0.5s \sim \bar{x} + 0.5s$
Rapid Rise Type	$ \bar{x} + 0.5s \sim \bar{x} + 1.5s$
Steep Rise Type	$ \bar{x} + 1.5s \sim +\infty$

Note: $|\bar{x}|$ represents the absolute average *Slope* value for cities in Guangdong province from 2019 to 2023; s denotes its standard deviation.

(2) Theil Index Method

The Theil index method, originally developed to measure income disparity across regions, is applied here to assess disparities in carbon reductions. The Theil index decomposes disparities from a spatial perspective into inter-regional and intra-regional variations, identifying the primary sources of these disparities and their respective contribution rates.

The Theil index ranges from 0 to 1, with higher values indicating greater carbon emission disparities between regions. The formula for calculating the Theil index is as follows:

$$\begin{aligned}
 T &= \sum_{i=1}^N \left(\frac{C_i^-}{C^-} \right) \ln \left(\frac{C_i^- / C_j^-}{P_i / P} \right) \\
 T_{wj} &= \sum_{i=1}^{N_j} \left(\frac{C_{ji}^-}{C_j^-} \right) \ln \left(\frac{C_{ji}^- / C_j^-}{P_{ji} / P_j} \right) \\
 T_w &= \sum_{j=1}^M \left(\frac{C_j^-}{C^-} \right) T_{wj} = \sum_{j=1}^M \left(\frac{C_j^-}{C^-} \right) \sum_{i=1}^{N_j} \left(\frac{C_{ji}^-}{C_j^-} \right) \ln \left(\frac{C_{ji}^- / C_j^-}{P_{ji} / P_j} \right) \\
 T_b &= \sum_{j=1}^M \left(\frac{C_j^-}{C^-} \right) \ln \left(\frac{C_j^- / C^-}{P_j / P} \right)
 \end{aligned} \tag{11}$$

where

i denotes an administrative district;

j denotes a region;

N is the total number of administrative districts in Guangdong province (21);

M is the total number of subdivided regions (4);

N_j denotes the number of administrative districts within the region j ;

T, T_{wj}, T_w, T_b represent the overall Theil index, the Theil index for region j , the intra-regional Theil index, and the inter-regional Theil index, respectively;

$C, C_i^-, C_j^-, C_{ji}^-$ represent the carbon reduction from straw utilization in Guangdong province, the carbon reduction from straw utilization in the i -administrative district, the carbon reduction from straw utilization in the j -region, and the carbon reduction from straw utilization in the i -administrative district within the j -region, respectively;

$P, P_i, P_j, P_{j,i}$ represent the rural population of Guangdong province, the rural population of the i -administrative district, the rural population of the j -region, and the rural population of the i -administrative district within the j -region, respectively.

The Thiel Index can also analyze inter-regional contribution rate W_b , intra-regional contribution rate W_w , and sub-regional contribution rate W_j . The inter-regional contribution rate refers to the extent to which differences between regions contribute to the total variance. The intra-regional contribution rate refers to the extent to which differences within a region contribute to the total variance. The sub-regional contribution rate refers to the contribution rate of region j 's carbon reduction from straw utilization to the total variance. The specific calculation formulas are as follows:

$$\begin{aligned}
 W_w &= T_w / T \\
 W_b &= T_b / T \\
 W_j &= \left(C_j^- / C^- \right) \times (T_{wj} / T)
 \end{aligned} \tag{12}$$

The values for carbon reductions from straw utilization in each district are based on the accounting of straw utilization for carbon reductions from 2019 to 2023.

(3) Exploratory spatial data analysis

The exploratory spatial data analysis (ESDA) method is employed to investigate the spatial distribution characteristics of variables and their interaction mechanisms. This method primarily involves global spatial autocorrelation analysis and local spatial autocorrelation analysis. The global Moran's I index is commonly used as a spatial autocorrelation measure to assess whether the overall distribution pattern of carbon reductions from straw

utilization in Guangdong province exhibits spatial clustering. The calculation formula for Moran's I is as follows:

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n w_{ij} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (13)$$

In the equation, n represents the number of spatial units delineated in the study area ($n = 21$). x_i denotes the carbon reduction from straw utilization in region i , $\bar{x}$ is the average carbon reduction from straw utilization in Guangdong province, and w_{ij} is the inverse distance weighting matrix generated based on geographic coordinates, as adopted in this report.

The global Moran's I index can only reflect the overall spatial distribution characteristics of variables across a region, but it cannot represent spatial dependencies within local areas. Consequently, it cannot reveal the specific spatial clustering evolution of carbon reductions from straw utilization across districts in Guangdong province. However, the local Moran's I index can analyze the spatial variation and significance of carbon reductions from straw utilization in a specific region and its surrounding areas. The formula for calculating the local Moran's I index for region i is as follows:

$$I_i = \frac{(x_i - \bar{x})}{S^2} \sum_{j=1}^n w_{ij} (x_j - \bar{x}) \quad (14)$$

where S^2 is the sample variance.

3. Results and Discussion

3.1. Amount of Crop Straw Utilization in Guangdong Province

Straw yield varies significantly across different regions in Guangdong province. The average values from 2019 to 2023 indicate that, when categorized by agricultural region, MEAA and TAA maintained the top two positions in available straw utilization, with 5.1064 million tons/year and 4.4431 million tons/year, respectively (Table 1). These two regions also recorded the highest utilization amounts, accounting for 73.2% of the total. PIAA and UAA exhibited similar utilization rates, accounting for approximately 13.7% and 13.2% of the total, respectively.

Guangdong province has achieved a straw utilization rate exceeding 90% for five consecutive years, rising from 90.44% in 2019 to 93.55% in 2023 (Figure 1). In 2023, the province's total straw amount reached 13.2005 million tons, with comprehensive utilization at 12.2634 million tons—a 6.2% increase compared to 2019. Furthermore, all four major regions within Guangdong province have achieved steady increases in comprehensive utilization rates over the past five years. By 2023, each region exceeded a 92.5% utilization rate, with China having an evaluated utilization rate of 90%, fulfilling the provincial target of a stable straw utilization rate above 86%. The remaining portion represents unused straw. In 2023, unused straw amounted to only 937,100 tons, a 22.6% decrease from 2019. This indicates a dual decline in both proportion and total amount, demonstrating Guangdong's effective progress in addressing open-air straw burning and promoting straw utilization. Figure 1 also illustrates regional utilization patterns. Between 2019 and 2023, straw utilization in the UAA recorded the highest growth rate of 9.2%, contributing an incremental increase of 137,700 tons (rising from 1,496,784 tons to 1,646,000 tons). Straw utilization in the MEAA grew at 6.4%, ranking second, but contributing the largest amount increase (from 4.4967 million tons to 4.7823 million tons), with an increment of 285,700 tons—nearly double that of UAA. Both PIAA and TAA recorded growth rates around 5%. Although TAA had the lowest growth rate, its increase of 204,000 tons (from 3.9711 million tons to

4.1748 million tons) was nearly three times that of PIAA's increase of 84,000 tons (from 1.5862 million tons to 1.7702 million tons). Regional utilization is influenced by straw yield distribution. Increased straw usage in Guangdong's western and northern agricultural production areas has improved the province's overall utilization rate.

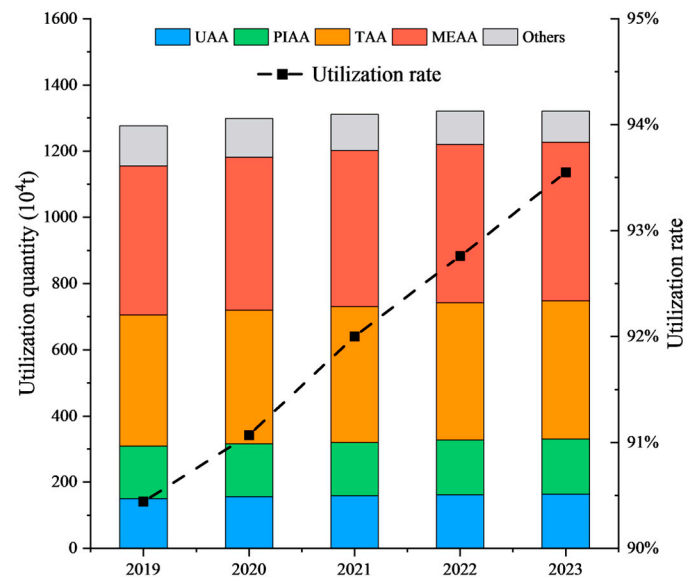


Figure 1. Utilization of agricultural straw in Guangdong province, 2019–2023.

Crop utilization structures also vary significantly across different regions in Guangdong (Figure 2). Cities such as Zhanjiang, Maoming, and Zhaoqing exhibit the highest straw utilization rates, while cities like Zhongshan, Dongguan, Zhuhai, and Shenzhen show low utilization rates, each accounting for less than 1%. The straw utilization of UAA exhibits a pronounced “two-city dominance” pattern, with Jiangmen and Huizhou occupying an absolute core position, accounting for over 84.3% of the regional total straw utilization. This stands in stark contrast to the “many cities but low amounts” characteristic of economically developed areas like Shenzhen, Dongguan, and Zhongshan. It confirms the core feature of the Pearl River Delta, where there is an inverse relationship between agricultural scale and economic level. However, the structural types of these two cities also differ significantly. Jiangmen's utilization is dominated by a single crop—rice (accounting for 82.6% of the city's total), reaching 680,900 tons in 2023 (ranking fifth among cities). Huizhou shows a greater balance: rice utilization at 339,200 tons (61.1%), while the next three crops contributed 37.3%, including potato at 53,500 tons (9.6%), maize at 85,500 tons (15.4%), and peanut at 68,300 tons (12.3%). PIAA's crop structure centers on rice straw at 1.044 million tons (62.5% of total), with tuber straw at 428,000 tons (25.6%) in second place, and peanut straw (102,400 tons) concentrated in Jieyang and Shanwei. Marginal crops like tobacco and cassava are almost entirely concentrated in Jieyang. This region maintains overall balance, primarily producing special straw products from tubers and peanuts. TAA is the region with the fewest cities among Guangdong's four major zones, but it ranks second in straw utilization. Zhanjiang city forms a unipolar core with 2.2051 million tons, including 677,500 tons of sugarcane straw (94.58% of the region's total sugarcane straw, and 81.53% of the province's total sugarcane straw), establishing itself as Guangdong's largest sugarcane production area and highlighting the tropical agricultural advantages of the Leizhou Peninsula. It also leads in peanut straw utilization at 328,500 tons and cassava straw at 17,000 tons. Maoming city's total straw amount reached 1.4215 million tons, with rice straw utilization leading the province, making it the largest grain-producing region. Yangjiang city's total straw utilization of 548,200 tons ranked last in all categories

within the region, with only corn stovers (29,900 tons, accounting for 13.64% of the region) showing relative prominence. The MEAA region leads Guangdong province in straw utilization. Among these, Zhaoqing stands out as the city with the highest utilization rate at 1.0578 million tons, accounting for 22.1% of the MEAA region's total straw utilization. Its primary crops include rice straw (770,800 tons), peanut (119,000 tons), tuber (88,100 tons), and corn (46,900 tons). Meizhou city ranked second with 925,200 tons, accounting for 24.84% of the regional utilization, with rice straw reaching 771,400 tons. Shaoguan city utilized 777,700 tons (20.88%), characterized by peanut straw (174,800 tons). Qingyuan city (746,000 tons) primarily utilized peanut straw (162,900 tons) and sugarcane straw (26,800 tons). The regional crop structure highlights mountainous agricultural characteristics, with rice straw dominating (a total of 2.6982 million tons, or 72.45%), peanut straw concentrated in Qingyuan and Shaoguan, and cassava straw primarily found in Yunfu and Meizhou.

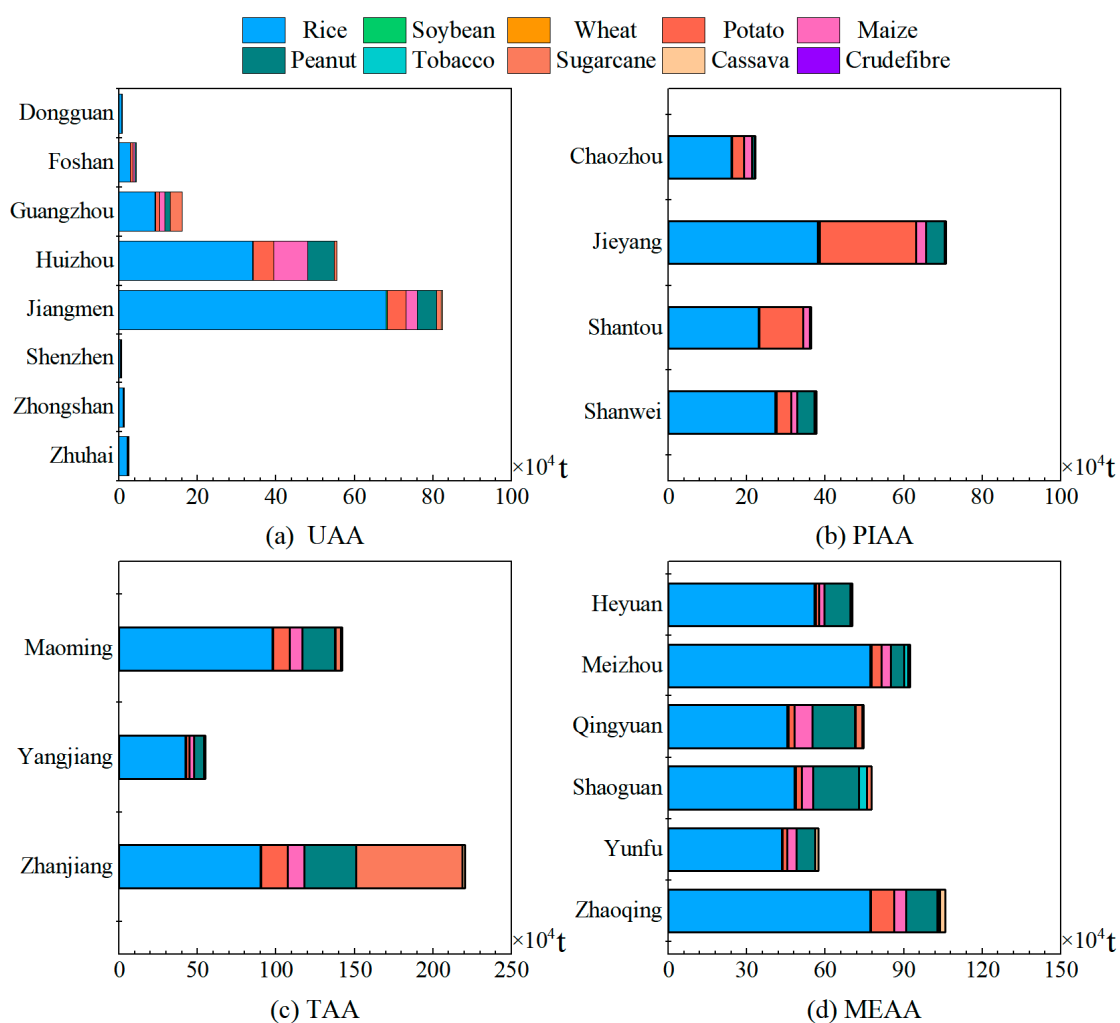


Figure 2. Straw utilization status in cities across Guangdong province in 2023.

3.2. Carbon Reduction Effects of Comprehensive Utilization of Straw in Guangdong Province

According to the “Comprehensive Straw Utilization Implementation Plan for Guangdong Province 2023”, guided by the principle of adapting to local conditions, Guangdong province is actively exploring industrialized models for straw utilization through pilot projects, model counties, and policy subsidies. This has established a framework centered on fertilizer utilization to reduce burning, complemented by diversified applications in feed, energy, substrate, and raw material (Figure 3). Fertilizer utilization remains the

predominant method, accounting for 78.7% of Guangdong's carbon reductions in 2023. However, its dominance is gradually diminishing, with the utilization amount declining from 11.007 million tons in 2019 to 9.661 million tons in 2023. Unlike fertilization, as straw utilization rates increase, there has been a corresponding rise in the off-field utilization rate of straw. Between 2019 and 2023, the proportions of straw utilized for feed, energy, substrate, and raw material reached 10.8%, 7.3%, 2.4%, and 0.8%, respectively, each achieving more than a fourfold expansion. From 2019 to 2023, the cumulative increase in off-field utilization through feed, energy, substrate, and raw materials reached 2.0574 million tons. Specifically, straw utilization as feed rose from 186,400 tons in 2019 to 275,700 tons in 2023, while energy utilization increased from 890,100 tons to 1.3185 million tons. These two utilization pathways accounted for 84.9% of the total increase. Straw utilization as substrate increased approximately threefold more than as raw material, accounting for 11.2% of the total increase. Overall, the increase in off-field utilization and the decrease in fertilization resulted in a net growth of 711,100 tons. This increase is primarily reflected in the high-value utilization of straw and the deeper processing of straw utilization. This transition indicates that the commercialization model is accelerating. Driven by policy (such as the integration of feed with the upgrading of the livestock industry and the benefits from biomass energy policies) and technological advancements (such as the use of substrate for edible fungi cultivation and raw materials for industrial use), this shift reflects the replacement of the traditional fertilization return-to-field model with more economically valuable multi-use options.

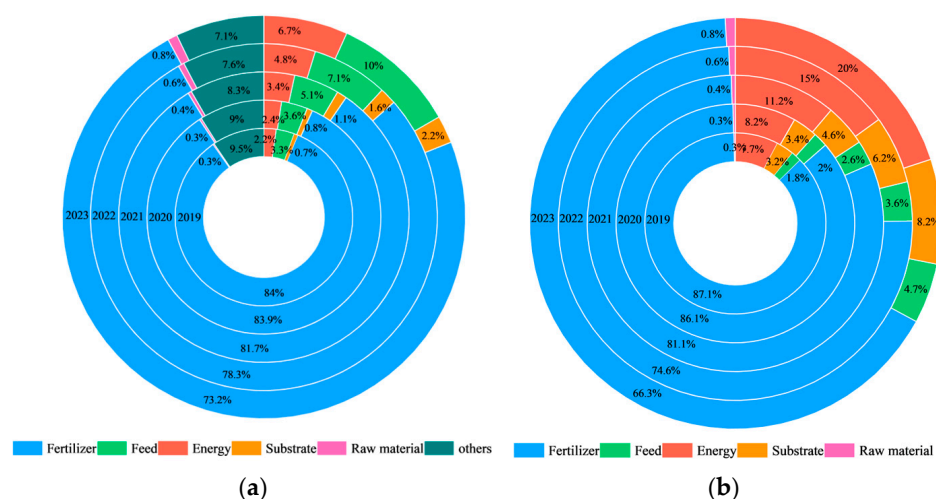


Figure 3. Straw utilization structure in Guangdong province from 2019 to 2023. (a) Comprehensive utilization structure diagram of straw. (b) Carbon reduction structure diagram of five-pathway utilization of straw.

Over the five-year period, Guangdong province achieved a 19.8% increase in carbon reduction through a 6.2% increase in straw utilization, as shown in Figure 3b and Table 3. In 2023, the province achieved a total reduction of 1.6149 million tons of CO₂ equivalent, representing an increase of 267,300 tons compared to 2019, offering a crucial direction for Guangdong's exploration of carbon neutrality pathways. In 2023, the straw utilized as fertilizer contributed the largest increment in carbon reduction, with 117.33×10^4 tons (66.3% share), followed by energy utilization at 32.22×10^4 tons of CO₂ equivalent (20.0% share). Carbon reduction from substrate and feed applications of straw amounted to 13.30×10^4 tons of CO₂ equivalent (8.2%) and 7.62×10^4 tons of CO₂ equivalent (4.7%), respectively. The smallest contribution came from the utilization of straw as raw material, with 1.28×10^4 tons of CO₂ equivalent (0.8%). Between 2019

and 2023, straw utilization as fertilizer reduced carbon emissions by 10.26 million tons (a 20.8% decrease in share) due to increased off-field straw utilization rates. Concurrently, off-field straw utilization increased carbon reduction by 36.99 million tons, a threefold growth. The conversion of straw to energy showed the largest increase in carbon reduction, rising by 21.90 million tons in 2023 compared to 2019 (a 12.3% increase in share). The carbon reduction from straw utilized as substrate increased by 9.04 million tons (a 5.0% rise in share), as feed by 5.18 million tons (a 2.9% rise in share), and as raw material by 0.87 million tons (a 0.5% rise in share). From a low-carbon perspective, Guangdong province has achieved high straw utilization rates while enhancing the low-carbon, high-value utilization of off-field straw. Carbon reduction from fertilization of straw decreased by 8.8%, while a substantial 212.2% increase was achieved through the four off-field utilization pathways—feed, energy, substrate, and raw materials. This signifies Guangdong's transition away from fertilizer-dominated straw utilization, marking a key breakthrough toward refined, off-field emission reduction. Moving forward, the five utilization pathways will continue to shift toward the four non-fertilizer approaches, superseding traditional field return methods.

Table 3. Classification criteria for trends in carbon reduction (t CO₂-eq).

Year	Fertilizer	Feed	Energy	Substrate	Raw Material	Total
2019	117.33	2.44	10.32	4.26	0.41	134.76
2020	118.99	2.70	11.41	4.71	0.45	138.25
2021	117.73	3.83	16.20	6.69	0.64	145.08
2022	114.01	5.43	22.95	9.47	0.91	152.78
2023	107.07	7.62	32.22	13.30	1.28	161.49

Figure 4 illustrates the carbon reduction effects of different straw utilization technologies in Guangdong province from 2019 to 2023. Nitrogen fertilizer substitution is the primary carbon reduction method in fertilization, achieving 882,300 tons of carbon reduction in 2023, accounting for 82.4% of the total carbon reduction. Substitutions for potassium and phosphorus fertilizers accounted for 12.0% and 5.6%, respectively. In contrast to the slight decline in carbon reduction from fertilization, biomass-based fuel pellets and power generation under energy utilization saw nearly threefold growth. In 2023, these two pathways contributed 156,200 tons and 98,600 tons of carbon reduction, respectively, together accounting for over three-quarters of total energy utilization reductions. The growth rate of energy utilization pathways significantly outpaced the decline in fertilizer utilization. This phenomenon is driven by several underlying factors: rising costs of returning straw to fields under intensive agricultural production, diminishing marginal benefits of fertilizer substitution, and the competitive diversion effect of emerging utilization methods like energy conversion on straw resources. Driven by the combined factors of the techno-economic viability of energy utilization, the gradual formation of China's carbon market, and biomass energy policy incentives, synthetic fuels continue to lead due to advantages in storage and transportation convenience, combustion efficiency, and infrastructure development. The bioethanol industry is accelerating its industrialization process. Overall, the contribution of energy utilization to emissions reductions surged from 2.51% of total straw utilization savings in 2019 to 11.44% in 2023. This reflects a paradigm shift in carbon reduction as straw resources transition from traditional agricultural recycling to industrial energy systems.

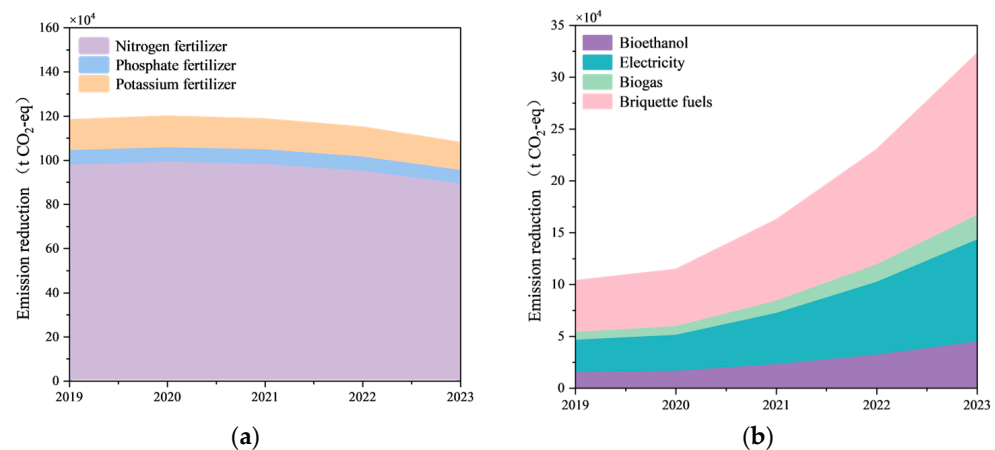


Figure 4. Characteristics of straw utilization for fertilizer and energy purposes. (a) Fertilizer utilization. (b) Energy utilization.

The regional contributions of the top four crop straws in Guangdong province—rice straw, potato straw, peanut straw, and sugarcane straw—also exhibit significant variations (Figure 5). Rice straw, peanut straw, and other crop straws follow a largely similar regional structure, with MEAA and TAA ranking first and second, accounting for approximately two-thirds of the total. The carbon reduction contribution from potato straw was primarily from PIAA (43%), with TAA and MEAA accounting for 26% and 20%, respectively. The carbon reduction contribution from sugarcane straw mainly originated from TAA, reflecting the crop cultivation patterns in the relevant regions. Additionally, Figure 5 illustrates the changes in carbon emissions reductions from the five utilization pathways of different straw types between 2019 and 2023. As the primary straw source, carbon reduction from rice straw through fertilization decreased from 629,000 tons to 559,000 tons, while its energy utilization for emissions reduction surged significantly from 68,000 tons to 210,000 tons, becoming the core driver of emission reductions for this crop and highlighting its substantial energy substitution potential. The utilization structure of tuber crop straw is more balanced. Its fertilizer utilization for emission reduction remained stable (approximately 192,000–201,000 tons), while energy (increasing from 8000 tons to 28,000 t CO₂-eq) and feed utilization for emission reduction (rising from 2000 tons to 7000 tons) achieved synergistic growth, reflecting the feasibility of multi-pathway carbon reduction. Additionally, rice straw demonstrates the most effective carbon reduction outcomes when removed from fields. Peanut and sugarcane straw exhibit similar transformation trajectories, both showing declining emission reductions from fertilization (196,000 to 188,000 tons for peanut straw, and a similar trend for sugarcane straw), while energy utilization (increased by 28,000 and 14,000 tons for peanut and sugarcane straw, respectively) and feed utilization of these two straws for emission reduction (increased by 7000 and 3000 tons for peanut and sugarcane straws, respectively) expanded exponentially, indicating effective development of high-value-added utilization directions. Other crops (including soybeans, wheat, etc.), though smaller in total volume, show a clear trend of structural transformation, with the proportion of energy utilization rapidly increasing. This comprehensive analysis demonstrates that Guangdong province, as a national leader in utilization, has successfully propelled straw utilization for major crops like rice, potato, peanut, and sugarcane from reliance on on-site plowing to a new “high-efficiency emission reduction” model led by energy utilization and supported by feed and substrate applications. Future structural transformations maximizing carbon reduction for different straw types will significantly optimize carbon reduction efficiency per unit of straw resource. While analyzing regional differences, the impacts of economic and policy factors on facilitating

the transition from fertilization to off-field utilization are considered. As shown in Table 4, market demand, straw types, the number of pilot counties, and incentive policies are the main factors to drive the off-field utilization of straw. In particular, utilization of straw as feed is a key demand for the development of the breeding industry in the relevant regional markets. Meanwhile, straw types, as well as the extension of pilot counties and the guidance of incentive policies, have largely led to differences in off-field paths of straw across various regions.

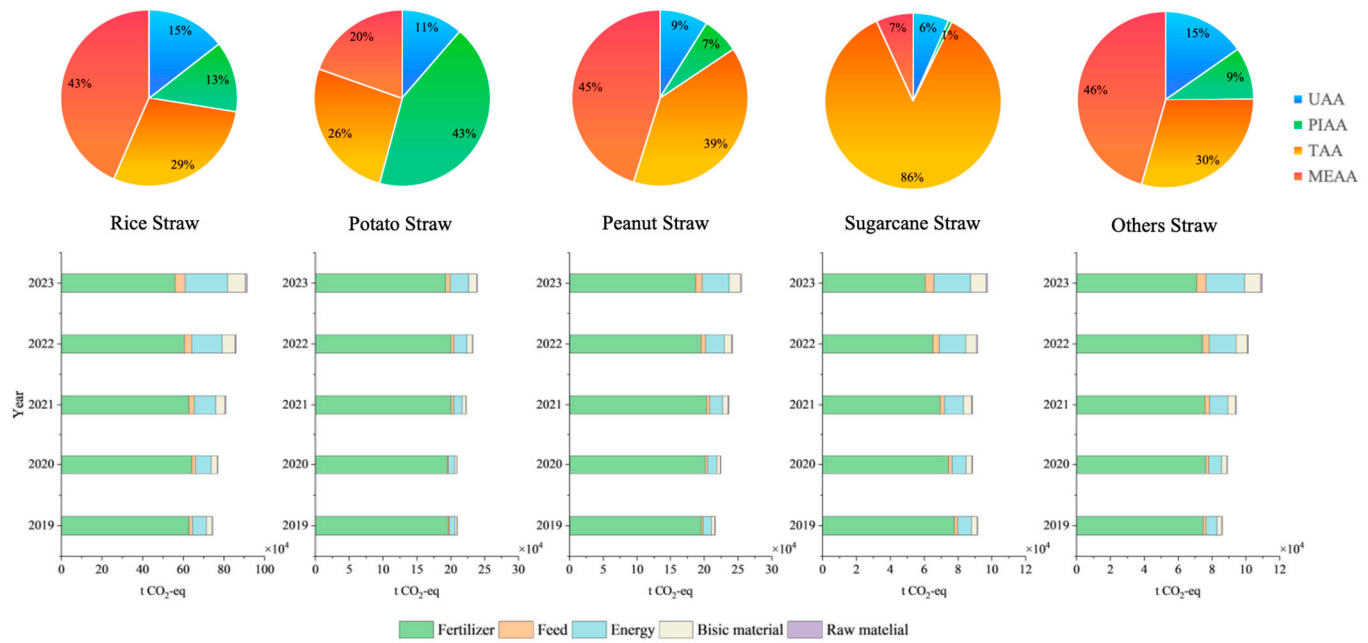


Figure 5. Carbon reduction structure and regional distribution of major crop straw in Guangdong province, 2019–2023.

Table 4. Impact of different regional conditions on the straw utilization.

Factors		Effects	Impact Degree			
			UAA	PIAA	TAA	MEAA
Industrial demand	Regional economic foundation Market demand	Carbon reduction promotion	Stronger	Strong	Strong	Strong
		Off-field promotion	Stronger	Stronger	Strong	Strong
Industrial condition	Straw availability Straw types	Carbon reduction promotion	Fair	Strong	Stronger	Stronger
		Off-field promotion	Weak	Stronger	Stronger	Stronger
Policy support	Number of pilot counties Incentive policies	Carbon reduction promotion and off-field promotion	Strong, stronger	Both fair	Both stronger	Both stronger
		Carbon reduction promotion and off-field promotion	Both strong	Both fair	Both strong	Both stronger

The incremental carbon reduction from straw utilization in Guangdong province during 2019–2023 reflects the effectiveness of increasing its comprehensive utilization rate. Based on carbon reduction intensity, Guangdong achieved a 12.9% improvement in carbon reduction efficiency, with the corresponding carbon emission intensity rising from 116.66 to 131.68 kg/t (Table 5). Simultaneously, by comparing the changes in Guangdong's per capita straw utilization and per capita carbon reduction, we observe a highly synergistic

and sustained growth trend between them. This demonstrates a positive correlation between per capita carbon reduction and per capita straw utilization, with the growth rate of the former significantly outpacing the latter's increase in straw resource utilization, ensuring continuous improvement in carbon reduction intensity. As shown in Figure 6, Guangdong's per capita straw utilization steadily increased from 0.3382 tons in 2019 to 0.3927 tons in 2023, with an average annual growth rate of 3.8%. Concurrently, per capita carbon emissions reduction rose significantly from 0.0395 tons to 0.0517 tons, achieving an average annual growth rate of 7.0%. Overall, the improvement in Guangdong's carbon reduction intensity relies on the stable and sustained expansion of straw utilization. It also profoundly reflects the province's continuous optimization and progress in the five utilization pathways (fertilizer, feed, substrate, raw material, and energy) of straw, energy substitution efficiency, and circular economy models. These advancements have enabled greater carbon reduction benefits per unit of straw resources.

Table 5. Classification criteria for trends in carbon reduction (kg CO₂-eq/t).

Year	2019	2020	2021	2022	2023	Average
Carbon Intensity	116.66	117.06	120.76	125.28	131.68	122.29

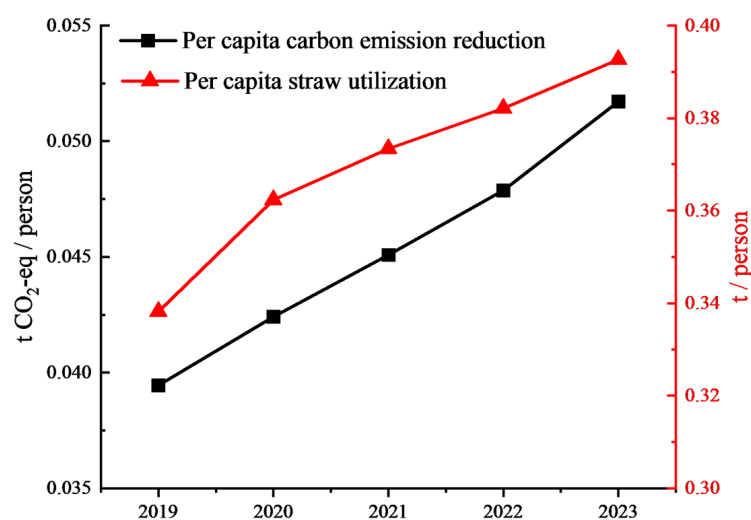


Figure 6. Carbon reduction intensity from straw utilization in Guangdong province, 2019–2023.

Additionally, significant variations exist in carbon reduction intensity across different regions and cities. Figure 7 illustrates the carbon reduction intensity of cities in various regions of Guangdong province in 2023. Zhanjiang and Maoming rank as Guangdong's top two cities in carbon reduction capacity. Both Shaoguan city (per capita utilization: 0.6744 tons/person, emissions reduction: 0.0884 tons/person) and Zhanjiang city (per capita utilization: 0.5999 tons/person, emission reduction: 0.0796 tons/capita) exceeded Guangdong's benchmark levels (0.3927 tons/capita and 0.0517 tons/capita), highlighting their dual advantages of abundant resources and efficient utilization. Furthermore, the *slope* of their center-of-gravity line reflects Guangdong's carbon intensity (1316.83 kg/t). Another TAA city, Yangjiang, also surpasses both per capita utilization and per capita carbon emission levels, though its carbon intensity falls below Guangdong's benchmark. Meanwhile, all MEAA cities exceed both per capita utilization and per capita carbon emission thresholds. Except for Zhaoqing, which aligns with the carbon intensity benchmark, all other cities slightly exceed it. Among the remaining cities exceeding both per capita resource utilization and emissions, none belong to the PIAA region, while UAA includes only Jiangmen. Conversely, among cities with below average utilization and emissions,

Jieyang and Shantou exhibit significantly higher carbon reduction intensity than average, while Shanwei, Huizhou, Chaozhou, and others show slightly elevated carbon intensity. Regionally, PIAA and UAA (excluding Jiangmen) exhibit low per capita utilization but high carbon intensity. TAA and MEAA include cities with substantial emission reductions, primarily due to per capita levels above average and relatively low carbon intensity. Currently, straw utilization for carbon reduction in Guangdong has not yet generated carbon trading cases. The carbon reduction remains a “byproduct” of straw utilization. Nearly two-thirds of cities exceed Guangdong’s carbon reduction intensity targets, indicating that the five-pronged development in the province’s major crop-producing areas is driving simultaneous improvements in both value-added utilization and carbon reduction. This is particularly evident in the TAA and MEAA regions, which possess favorable foundational conditions for future entry into carbon market transactions for straw-based carbon reduction.

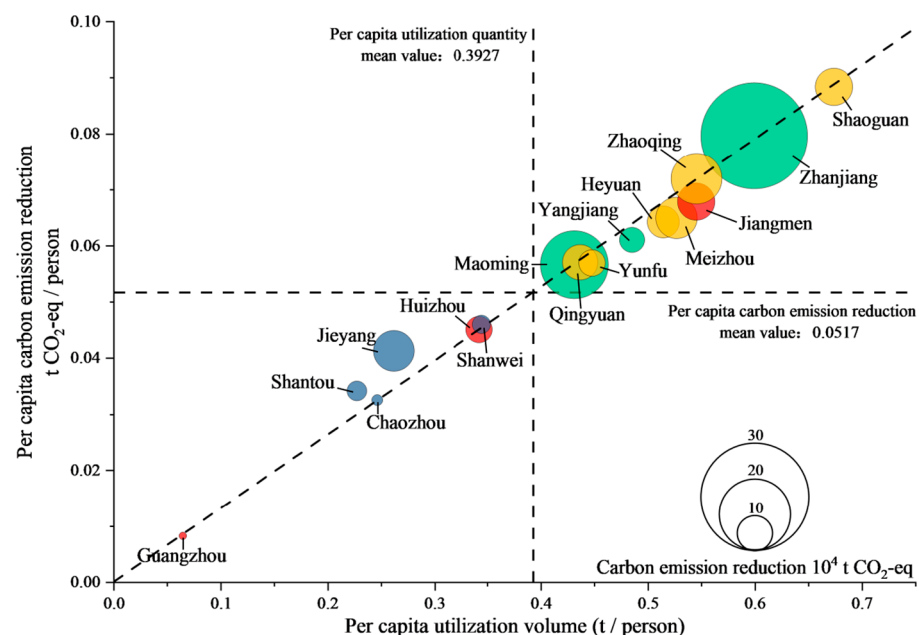


Figure 7. Per capita carbon emissions reduction from straw utilization in Guangdong cities, 2023.

To explore the robustness of the carbon reduction results, a sensitivity analysis is conducted on the annual carbon reduction intensity in Guangdong (Figure 8). Eleven key parameters are selected and set in the variation ranges of $\pm 10\%$, $\pm 20\%$, $\pm 30\%$ and $\pm 40\%$, with the relevant carbon emission factors corresponding to crop straw fertilization, feed, energy, substrate and raw material. Overall, as for carbon emission accounting methods, the carbon reduction amount is jointly determined by emission factors and straw utilization quantity. When the straw utilization quantity remains constant, the changes in carbon reduction factors exhibit a positive or negative linear correlation with carbon reduction intensity. Therefore, all four regions show similar linear variation trends, but there are still differences in influencing degree of changes in different emission factors. The emission factor of nitrogen fertilizer has the most significant impact on the carbon reduction intensity in the four regions. When the variation range of the emission factor in PIAA is $\pm 40\%$, the maximum interval of changes in carbon reduction intensity is [113 kg CO₂-eq/t, 184 kg CO₂-eq/t] (Figure 8b). The region with the smallest impact is UAA, with an interval range of [100 kg CO₂-eq/t, 155 kg CO₂-eq/t] (Figure 8a). The carbon emission factor of briquette fuels ranks second in terms of impact volatility. When the variation range of this factor is $\pm 40\%$, the difference between the maximum and minimum carbon reduction intensity in the four regions is about 10. The impact of changes in potassium fertilizer and substrate

is similar to that of briquette fuels but slightly weaker. Biogas has the smallest impact on volatility. When the variation range of the emission factor in the four regions is $\pm 40\%$, the difference in carbon reduction intensity is between 1 and 2. In addition, the emission factor of paper manufacturing is the most special. Since its value is negative, it cannot achieve carbon reduction but instead generates positive carbon emissions. However, its impact is relatively small, similar to the impact of the volatility of biogas. When the variation range of the emission factor is $\pm 40\%$, the difference in the fluctuation interval is about 2–3. In summary, although there may be certain deviations among different regions in Guangdong province and different straw utilization technologies, the carbon reduction calculation results can basically maintain relative stability when the variation range of emission factor values is within 40%.

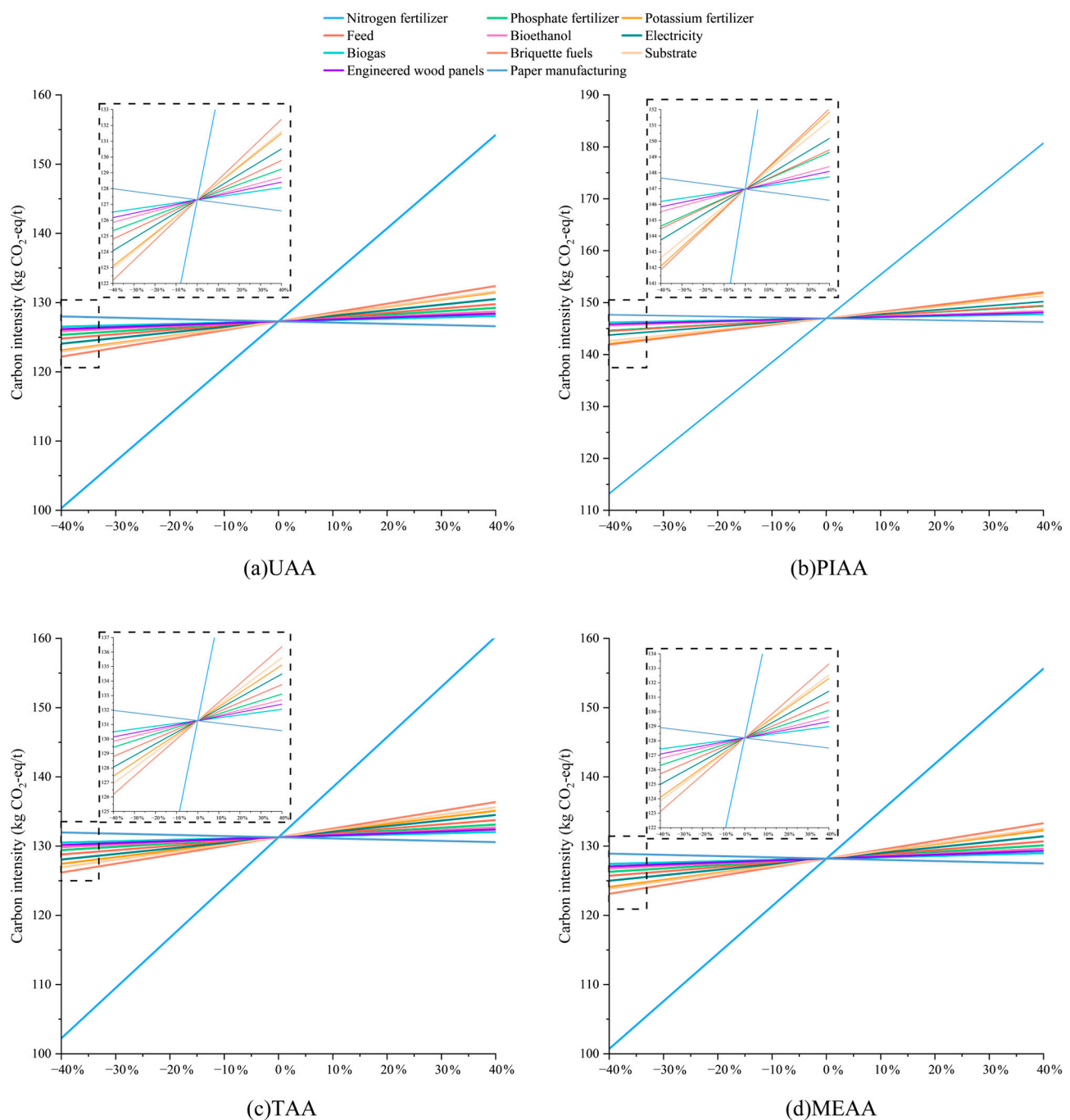


Figure 8. Sensitivity analysis of the carbon reduction in Guangdong province.

3.3. Spatiotemporal Evolution Characteristics of Carbon Reduction from Regional Straw Utilization in Guangdong Province

From 2019 to 2023, carbon reduction across all districts in Guangdong province increased to varying degrees (Figure 9). The MEAA and TAA regions experienced the most significant growth, emerging as the primary contributors to Guangdong's carbon reduction efforts. Together, these two regions consistently accounted for over 70% of the total reduction. The MEAA region maintained the largest share, rising from 37.75% in 2019 to 37.97% in 2023. As shown in Figure 9, carbon reduction from straw utilization across the six cities within MEAA steadily increased from 508,800 tons to 613,100 tons, demonstrating substantial and sustained growth with balanced development. MEAA has formed a multi-center collaborative development pattern, led by Zhaoqing city, which consistently maintained the largest reduction scale in the region, growing from 119,200 tons to 139,500 tons (with an average annual growth rate of 4.02%). Its substantial amount and stable contribution laid a solid foundation for regional emissions reduction. Meizhou city (from 92,700 tons to 114,000 tons, with an average annual growth rate of 5.3%) and Shaoguan city (from 85,000 tons to 102,000 tons, with an average annual growth rate of 4.66%) ranked second, demonstrating robust growth momentum. Together with Zhaoqing, they form the three pillars of regional emission reduction. Heyuan, Qingyuan, and Yunfu cities, though relatively smaller in scale, maintained continuous and stable positive growth, with annual growth rates of 4.1%, 6.2%, and 4.57%, respectively. Among them, Qingyuan city showed the most remarkable growth rate, indicating significant potential for future development. Driven by Zhanjiang and Maoming, the TAA region exhibits characteristics of massive scale, robust growth, and stable structure. Over the five-year period, the region's total carbon reduction surged from 454,500 tons to 548,000 tons. In 2023, the three cities in the TAA region contributed 33.94% of the region's total emission reduction, slightly lower than the six cities in the MEAA region. The three TAA cities achieved stable positive growth for five consecutive years. Zhanjiang city ranked first in Guangdong province in terms of emission reduction scale, with its reduction amount increasing from 242,000 tons to 293,000 tons. It consistently accounted for over 52% of the regional total, and its substantial scale and stable growth (average annual growth rate of 4.87%) provided a solid foundation for achieving the province's emission reduction targets. Maoming city served as a crucial pillar, ranking second in Guangdong for emission reduction scale (increasing from 154,800 tons to 186,500 tons, with an average annual growth rate of 4.77%). Together with Zhanjiang city, they form a dual-core driving pattern in western Guangdong. Although Yangjiang city has a relatively smaller scale, it has demonstrated strong growth momentum (with an average annual growth rate of 4.5%), increasing from 57,800 tons to 68,900 tons, indicating significant development potential and a strong catch-up trend.

The UAA region contributed the lowest share to Guangdong's carbon reduction efforts (12.90% in 2023), yet its overall carbon reduction volume remained stable, showing a modest 0.4% increase over the five years. Total emission reduction rose from 168,400 tons to 208,300 tons. Significant variations in carbon reduction were observed among the eight cities within the UAA region. Jiangmen and Huizhou made the most prominent contributions, achieving carbon reductions of 102,500 tons and 73,000 tons, respectively, in 2023. They accounted for 84.3% of the regional total, establishing themselves as the core drivers of straw-based carbon reduction in the Pearl River Delta. Foshan, Guangzhou, and Zhuhai maintained steady growth, with average annual rates of 6.02%, 2.82%, and 9.27%, respectively. In contrast, Zhongshan, Dongguan, and Shenzhen recorded relatively modest reductions, each below 2000 tons in 2023. Notably, Shenzhen achieved only 815.8 tons. In contrast, the PIAA region saw its contribution rate decline from 16.02% in 2019 to 15.20% in 2023, marking the only region to experience a decrease. The total

emission reduction across the four PIAA cities increased from 215,900 tons to 245,500 tons. Jieyang city dominated the regional carbon reduction effort, with its emission reduction steadily rising from 101,400 tons in 2019 to 111,300 tons in 2023, consistently accounting for over 45% of the regional total. Other cities showing growth included Shantou (with an average annual growth rate of 1.59%) and Shanwei (5.9%). Chaozhou, the smallest in scale, maintained stable carbon reduction levels.

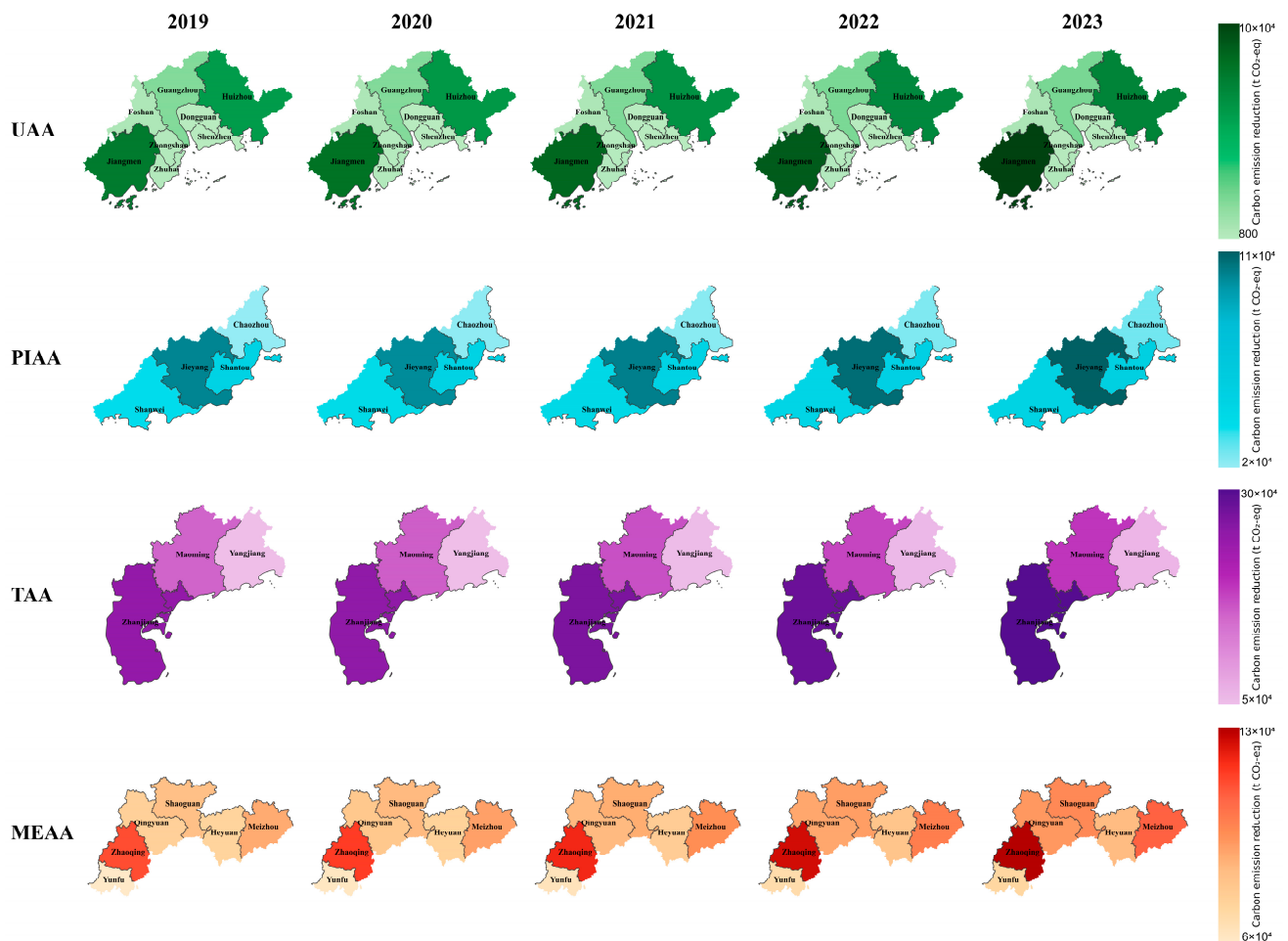


Figure 9. Distribution of carbon reduction effects from comprehensive utilization of straw in Guangdong province, 2019–2023.

To further reveal the spatiotemporal evolution patterns of carbon reduction from straw utilization in Guangdong province, this study calculated the *slope* values for carbon reduction from straw utilization in each administrative region using Equation (9). These values were categorized according to the grading criteria outlined in Table 2, with the results presented in Table 6. Overall, based on the *slope* values of comprehensive straw utilization for carbon reduction in Guangdong province, the implementation of straw utilization mitigation effects across regions shows positive progress with notable regional variations. The Urban–Agricultural–Rural Area (UAA) category exhibits a *slope* value of 9914, classified as a slow-rising trend. All its subordinate cities follow this slow-rising pattern, with Jiangmen and Huizhou exceeding this level. Shenzhen and Zhongshan are the only cities showing a negative trend. PIAA exhibits the lowest *slope* value of 7777, also classified as a slow-rising trend. Among its four cities, Shantou and Chaozhou share the slow-rising classification, while Shanwei and Jieyang fall under the medium-speed rising category. However, their total carbon reduction scale remains small, limiting

the enhancement of PIAA's overall carbon reduction effectiveness. TAA's *slope* value of 23,879 indicates a rapid increase. Zhanjiang and Maoming achieved *slope* values of 13,096 and 7969, respectively, both reaching the rapid increase level and ranking highest in Guangdong province. However, Yangjiang's moderate increase level lowered the overall regional carbon reduction effectiveness, failing to meet the rapid increase requirement. MEAA has the highest *slope* value at 26,405. Most of its subordinate cities fall into the "moderate increase" and "rapid increase" tiers. Thanks to the contributions of Meizhou, Zhaoqing, and Qingyuan, MEAA maintains a moderate increase tier. Overall, all six cities classified as rapidly rising or higher are agricultural cities, primarily distributed across the MEAA and TAA regions. The moderately rising category has the highest number of cities, with eight cities spread across four regions.

Table 6. Trends in carbon reduction from straw utilization by region in Guangdong province, 2019–2023.

Regional Division	Slope Value	Trend	Administrative Division	Slope Value	Trend
UAA	9914	Slowly Rising	Guangzhou City	584	Slowly Rising
			Shenzhen City	−49	Slowly Declining
			Zhuhai City	209	Slowly Rising
			Foshan City	280	Slowly Rising
			Huizhou City	3263	Moderately Rising
			Dongguan City	72	Slowly Rising
			Zhongshan City	−103	Slowly Declining
			Jiangmen City	5658	Rapidly Rising
PIAA	7777	Slowly rising	Shantou City	830	Slowly Rising
			Shanwei City	2650	Moderately Rising
			Chaozhou City	1501	Slowly Rising
			Jieyang City	2796	Moderately Rising
TAA	23,879	Rapidly rising	Yangjiang City	2814	Moderately Rising
			Zhanjiang City	13096	Highly Rising
			Maoming City	7969	Highly Rising
MEAA	26,405	Rapidly Rising	Shaoguan City	4183	Moderately Rising
			Heyuan City	3244	Moderately Rising
			Meizhou City	5340	Rapidly Rising
			Zhaoqing City	5146	Rapidly Rising
			Qingyuan City	5390	Rapidly Rising
			Yunfu City	3102	Moderately Rising

Figure 10 illustrates the spatial variation in carbon reduction from straw utilization across Guangdong province. Over the five-year period, the overall Theil index (T) fluctuated upward from 0.1229 to 0.1328, indicating that the absolute disparity in carbon reductions among cities within the province intensified during the study period. This further demonstrates regional differences in carbon reduction effects. Through decomposition analysis of the intra-regional Theil index (Tw) and inter-regional Theil index (Tb), it was found that intra-regional variation is the core driver of these disparities. During the study period, the intra-regional Theil index (Tw) increased from 0.0612 to 0.0701, while the inter-regional Tw remained relatively stable within the narrow range of 0.0617–0.0627. Notably, the contribution rate of intra-regional variation steadily increased from 49.78% to 52.78%, consistently exceeding 50% since 2020. This signifies that disparities among cities within the four regions have fully supplanted inter-regional differences as the primary driver of Guangdong's overall variation. To explore the specific dynamics shaping regional disparities, Table 7 compares the Theil indices and contribution rates for straw

carbon reduction effects across Guangdong's four major regions from 2019 to 2023. The Pearl River Delta region exhibits a persistently high and rising Theil index, surging from 0.4068 to 0.4667, with its contribution rate maintaining absolute dominance (increasing from 41.38% to 45.30%). This indicates that nearly half of the province's overall disparity directly stems from extreme developmental imbalances among cities within the UAA region. Its internal polarization effect—evidenced by the stark contrast between rapid growth in Jiangmen and Huizhou versus stagnation or decline in Shenzhen and Zhongshan—constitutes the primary contradiction driving provincial regional disparities. In contrast, the Theil Index for the other three major regions has remained consistently stable at extremely low levels, with their contribution to the overall disparity each below 4%. This indicates that carbon reduction development among cities within these three regions exhibits a degree of equilibrium and coordination. The inherent developmental gaps between the four regions, stemming from differences in resource endowments and functional positioning, are not the primary source of the province's overall disparity.

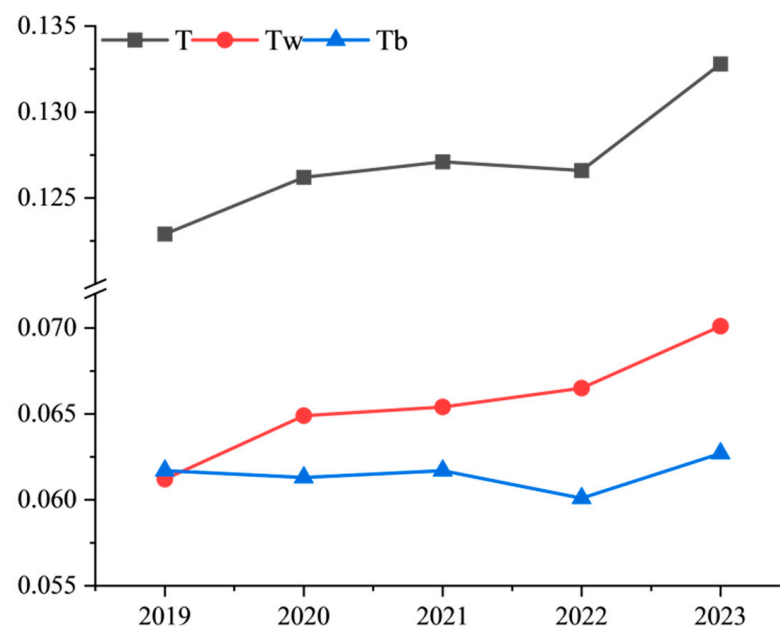


Figure 10. Trend in the Thiel index of carbon reduction intensity from comprehensive utilization of straw in Guangdong province, 2019–2023.

Table 7. Regional Theil index and contribution rates for carbon reduction from comprehensive utilization of straw in Guangdong province.

Year	Thiel Index				Contribution Rate			
	UAA	PIAA	TAA	MEAA	UAA	PIAA	TAA	MEAA
2019	0.4068	0.0077	0.0127	0.0127	41.38%	1.00%	3.49%	3.91%
2020	0.4339	0.0064	0.0127	0.0125	43.49%	0.80%	3.37%	3.76%
2021	0.4383	0.0072	0.0136	0.0114	43.50%	0.88%	3.63%	3.42%
2022	0.4446	0.0072	0.0143	0.0106	44.66%	0.87%	3.82%	3.18%
2023	0.4667	0.0061	0.0140	0.0112	45.30%	0.69%	3.57%	3.21%

Based on identifying the causes of regional differences in emission reductions, the global spatial autocorrelation coefficient was further utilized to analyze the spatial correlation of carbon reduction from straw utilization in Guangdong province. To enhance the analysis of carbon reduction effectiveness, per capita carbon emissions within a specific range were selected as the carbon emission metric. As shown in Table 8, the

Moran's I index for carbon emissions reduction from straw utilization in Guangdong province ranged between 0.276 and 0.292 during the study period, all passing the 5% significance level test. The results indicate that carbon reduction from straw utilization in Guangdong province exhibits significant positive spatial correlation in most years. Specifically, as spatial distribution locations become more clustered, regional per capita carbon reduction levels from straw utilization become more similar. Conversely, as spatial distribution locations become more dispersed, regional per capita carbon reduction levels from straw utilization become more divergent. This reveals that agricultural carbon reduction benefits exhibit persistent and stable spatial clustering and spillover characteristics in their geographic distribution. Based on the magnitude of Moran's I index, the degree of spatial clustering effects for carbon reduction from straw utilization across regions can be analyzed. Between 2019 and 2023, Moran's I first declined, then increased, falling from its peak of 0.292 in 2019 to a low of 0.276 in 2022—the period with the weakest positive spatial clustering effect and diminished spatial aggregation. Since 2022, Moran's I has risen, returning to 0.283 in 2023. This spatial pattern suggests that similar natural conditions, resource endowments, policy environments, and interregional technology diffusion and learning effects constitute the underlying mechanisms driving this spatial synergy. Notably, the high equilibrium in emission reduction effectiveness among cities within the TAA and MEAA regions stands in stark contrast to the intense polarization within the UAA regions. The significant disparities within the latter are the primary source of the province's pronounced spatial positive autocorrelation. During the study period, regions began the exploration of tailored straw utilization pathways suited to local conditions. The increased carbon reduction from these efforts enhanced agglomeration effects, indicating that the carbon reduction outcomes from straw utilization across Guangdong's regions are developing toward greater homogeneity and improvement.

Table 8. Global spatial Moran's I index for carbon emissions reduction from straw utilization in Guangdong province, 2019–2023.

Year	Moran's I	p -Value	Z
2019	0.292	0.033	2.128
2020	0.288	0.036	2.102
2021	0.278	0.041	2.042
2022	0.276	0.042	2.035
2023	0.283	0.038	2.07

Note: The global Moran's I index for the period 2019–2023 passed the 5% significance test.

Figure 11 further illustrates the spatial correlation evolution of per capita carbon emissions from comprehensive straw utilization across Guangdong province's districts during the three-year period spanning 2019, 2021, and 2023. Based on the evolution patterns revealed by the composite map, the spatial clustering patterns of carbon emissions across regions remain relatively stable, with high–high clustering (HH) and low–low clustering (LL) emerging as the predominant local spatial autocorrelation types. Administrative regions exhibiting long-term high–high clustering include Zhanjiang, Maoming, Yangjiang, Qingyuan, Yunfu, and other major agricultural production areas. These regions feature relatively developed agricultural economies, concentrated populations, extensive arable land, and substantial straw resources. Their significant carbon reduction effects from straw utilization demonstrate effective carbon reduction through urban clustering. Cities in the Pearl River Delta region, such as Guangzhou, Shenzhen, Dongguan, Zhongshan, and Zhuhai, have long been positioned in Quadrant III (“low–low clustering”), exhibiting characteristics of low-straw-carbon-reduction urban clusters. These are all highly urbanized areas in Guangdong province, serving as the economic hub of the province with relatively scarce

agricultural resources. In Quadrant IV, the cities of Zhaoqing, Jiangmen, and Shaoguan exhibit HL clustering characteristics with relatively high per capita emission reductions, surrounded by UAA-related carbon reduction cities. For example, in 2023, Zhaoqing achieved 139,500 tons of carbon emissions reduction through comprehensive straw utilization, with a per capita reduction of 0.72 tons/person. However, its neighboring city, Foshan, exhibited extremely low reduction levels, resulting in a high–low clustering pattern. Jiangmen, located in the Pearl River Delta region, demonstrated significantly higher carbon reduction than its neighboring cities, such as Foshan, Zhongshan, and Zhuhai. During the sample period, Huizhou initially belonged to the LL cluster but later moved to the HL cluster. This shift occurred because Huizhou’s carbon reduction level improved significantly, gradually approaching that of cities like Heyuan. Jieyang transitioned from HH to LH clustering. Its per capita carbon reduction growth was relatively low compared to surrounding cities with higher reduction rates (e.g., Meizhou increased by 39.9%), thus being classified as a low-reduction area alongside Chaozhou. Overall, the number of HH and LL clusters remained largely unchanged from 2019 to 2023, indicating a stable spatial agglomeration pattern. This further demonstrates the homogeneous positive evolution of carbon reduction effects from comprehensive straw utilization across Guangdong Province’s regions. For the areas with high–high patterns, it is necessary to strengthen the ecology of win–win cooperation between MEAA and TAA, promote high carbon reduction methods like straw utilization as energy and substrate, enhance inter-regional industrial coordination, and expand the large-scale utilization of straw in relevant industries. For the low–low pattern of regions in the UAA and PIAA, it is essential to strengthen support policies, accelerate infrastructure investment and construction, improve collection and transportation efficiency, reduce collection costs, and promote the marketization and commercialization of the industry.

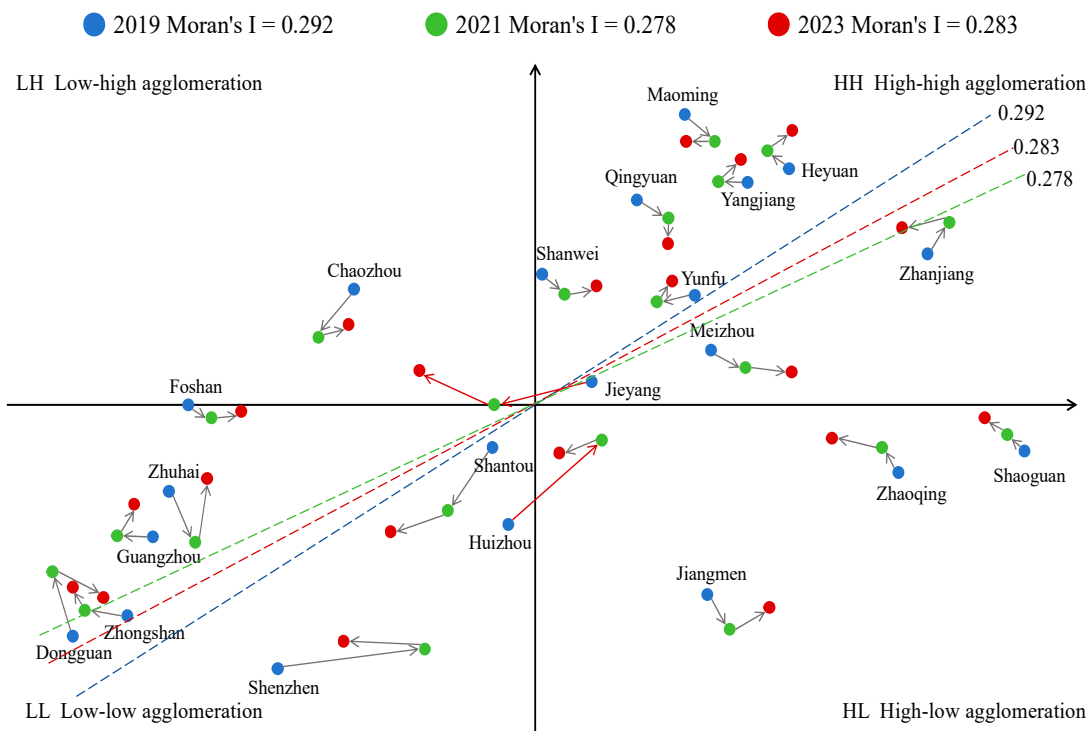


Figure 11. Spatial correlation evolution of carbon reduction effects from comprehensive utilization of straw in various cities of Guangdong province, 2019–2021–2023. Note: The arrow indicates the annual change of city.

4. Conclusions

This paper first estimates the comprehensive utilization volume of crop residues across the administrative districts of Guangdong from 2019 to 2023, based on crop yields and utilization ratios. It also presents a theoretical methodology for calculating carbon reductions resulting from crop residue utilization in the province. Subsequently, it analyzes trends in carbon reduction, utilization structures, and the characteristics of carbon reduction effects, while examining carbon reduction intensity and per capita carbon reductions. Finally, the study employs *slope* values, the Theil index, and exploratory spatial analysis methods to characterize and analyze the spatiotemporal distribution patterns and spatial clustering features of carbon emissions reductions across Guangdong's districts. The evolutionary trends of the five utilization pathways and the differential characteristics of carbon reduction can provide scientific support for formulating straw recycling and utilization plans under Guangdong province's carbon neutrality goal, rationally arranging the development, investment and construction of agricultural emission reduction projects in the regional carbon trading market, and assisting policy guidance on inter-regional straw allocation.

The research findings indicate that Guangdong province's comprehensive utilization rate of crop residues steadily increased from 2019 to 2023. The province achieved a 6.2% growth in crop residue utilization, meeting the policy target for comprehensive utilization rates. However, utilization methods for different crop residues exhibit significant variations in carbon reduction effectiveness. Therefore, attention should not be limited to overall utilization rates; it is essential to evaluate the carbon reduction quantities and intensities of different utilization methods in Guangdong. In 2023, Guangdong's total straw volume reached 13.2005 million tons, with 12.2634 million tons comprehensively utilized, resulting in a carbon reduction of 1.6149 million tons and a carbon reduction intensity of 1316.83 kg/t. Over five years, Guangdong achieved a 19.8% increase in carbon reduction despite a modest 6.2% growth in straw utilization. Notably, off-field utilization saw a significant low-carbon, high-value transformation, with the "four off-field utilization methods"—feed, energy, substrate, and raw materials—delivering a substantial 212.2% increase in carbon reduction. Overall, comprehensive straw utilization across Guangdong's regions has effectively delivered emission reductions. The MEAA and TAA zones demonstrated the most pronounced carbon reduction gains, with both exceeding the provincial per capita carbon emission level and exhibiting high-high (HH) clustering. Conversely, the UAA and PIAA zones fell below the provincial average, showing low-low (LL) clustering in the former and dispersed clustering in the latter. Regional variations in Guangdong's carbon reduction benefits show relatively minor overall differences, primarily due to varying degrees of carbon reduction across the province's four regions. Overall, enhanced clustering effects are evident among different cities.

The findings also indicate that while Guangdong Province achieved dual increases in straw utilization and carbon reduction, the latter is influenced by utilization technologies. An increase in straw utilization rates does not guarantee a proportional rise in carbon reduction, meaning that merely expanding off-field utilization cannot directly ensure greater carbon reduction effects. During the study period, the growth in carbon reduction was primarily driven by increased energy utilization. However, the volume and incremental growth of straw used for feed purposes far exceeded that for energy, and since its carbon reduction intensity was significantly lower than the Guangdong average, it contributed negatively to the overall carbon reduction effect. Furthermore, the carbon reduction intensity of fertilization was only marginally lower than Guangdong's average intensity. Therefore, reducing fertilization utilization while increasing off-field utilization, along with varying proportions of feed and energy utilization, may diminish

carbon reduction effects. The selection of utilization models is a critical issue for future industrial decision-making, influenced by multidimensional factors including industry, economy, society, and technology. Further research is needed to explore their impacts and underlying mechanisms.

Given the current status of comprehensive straw utilization in Guangdong province, only 20% of straw is currently utilized off-field. Straw utilization pathways for cities across Guangdong must be designed and decided upon through comprehensive consideration to ensure that short-term economic gains do not lead to investment wastage or regional shortages of straw inputs. It is recommended to implement differentiated straw carbon reduction strategies and formulate scientifically tailored utilization plans based on local conditions. While increasing utilization rates can enhance waste resource utilization and advance ecological conservation, it does not guarantee effective carbon reduction and sequestration solutions. Based on the national carbon neutrality strategy of China, in the short term, the industrial layout of straw utilization as feed and raw material is more in line with market laws, boasting certain economic advantages but insufficient carbon reduction benefits. In the long run, according to different types and available quantities of straw, all regions should prioritize matching industries with good carbon reduction effects, such as straw utilization as energy and substrate, and lay out the potential dividends of the future carbon economy.

Based on the above conclusions, some advice is proposed as follows.

- (1) Looking toward a future low-carbon economy, it is crucial to strategically plan for straw carbon reduction accounting and carbon trading. Guangdong province must expedite the establishment of a unified and standardized statistical system for straw utilization data and carbon reduction accounting methods. Institutions and enterprises at all levels should supplement their regular straw utilization statistical reports with missing data on the full lifecycle energy consumption during straw utilization and foundational data related to carbon reduction and sequestration accounting. Accelerating the development of carbon detection, monitoring, and digital management systems for comprehensive straw utilization is essential. Additionally, a foundational database should be established to integrate multi-level regional data across provincial, municipal, county, and village tiers. Clear regional ownership rights for straw utilization and carbon reduction efforts should also be established to lay the groundwork for future carbon trading.
- (2) Guangdong's straw utilization sector should further advance low-carbon technological innovation. Based on the province's crop types, production areas, and scale, scientifically plan and prioritize investments in greener, more efficient low-carbon straw conversion industries, particularly focusing on energy and feedstock pathways. Emphasizing the enhancement of energy conversion efficiency throughout the comprehensive utilization process, waste treatment, and by-product recycling will be crucial to achieving full-process carbon reduction in utilization technologies. Future efforts should accelerate technological breakthroughs and innovations in areas such as carbon fiber and biomass hydrogen production while proactively developing emerging high-tech industries for straw utilization.
- (3) A straw recycling and utilization plan for Guangdong province should be formulated. The carbon reduction targets, key tasks and implementation paths of straw utilization must be explicit, especially corresponding policies such as rationally arranging the development, investment and construction of carbon reduction projects, strengthening the ecological construction of the industrial chain from straw collection to utilization, formulating relevant policies for inter-regional straw allocation, industry-oriented support, and carbon trading management.

Additionally, some limitations exist for this study. The time series of the data in this work is relatively short, and the benefits of straw utilization are limited to carbon reduction contribution without considering long-term ecological effects and the economic value of carbon reduction transactions. Future work can further expand research on tracking long time series of data, establishing prediction models, and evaluating comprehensive values of carbon reduction.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su172310601/s1>, Table S1: Grass-to-grain ratio and harvestability coefficient for different crops in Guangdong Province; Table S2: Annual Comprehensive Utilization Rates of Straw in Guangdong Province; Table S3: Annual Straw Comprehensive Utilization Rates by City in Guangdong Province; Table S4: Nutrient Content Index of Crop Straws (g/kg); Table S5: Emissions Reduction Factors for Straw Utilization as Feed, Substrate, and Raw Material (g CO₂ e/ kg); Table S6: Straw Energy Utilization Ratio and Conversion Efficiency; Table S7: Carbon Emissions and Reduction Factors for Biomass Energy. References [33–59] are cited in the Supplementary Materials.

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References

1. Dai, Y.; Ding, Y.; Fu, S.; Zhang, L.; Cheng, J.; Zhu, D. Analyzing the impact of natural capital on socio-economic objectives under the framework of sustainable development goals. *Environ. Impact Assess. Rev.* **2024**, *104*, 107322. [\[CrossRef\]](#)
2. Zhao, X.; Li, R.-C.; Liu, W.-X.; Liu, W.-S.; Xue, Y.-H.; Sun, R.-H.; Wei, Y.-X.; Chen, Z.; Lal, R.; Dang, Y.P.; et al. Estimation of crop residue production and its contribution to carbon neutrality in China. *Resour. Conserv. Recycl.* **2024**, *203*, 107450. [\[CrossRef\]](#)
3. Huo, L.L.; Yao, Z.; Zhao, L.; Luo, J.; Zhang, P.; Zhang, X. Current status and construction of a standard system for greenhouse gas emission mitigation and carbon sequestration in agricultural and rural areas of China. *J. Agro-Environ. Sci.* **2023**, *42*, 242–252. (In Chinese with English Abstract). [\[CrossRef\]](#)
4. Wang, F.; Harindintwali, J.D.; Yuan, Z.; Wang, M.; Wang, F.; Li, S.; Yin, Z.; Huang, L.; Fu, Y.; Li, L.; et al. Technologies and perspectives for achieving carbon neutrality. *Innovation* **2021**, *2*, 100180. [\[CrossRef\]](#)
5. Yang, Y.; Shi, Y.; Sun, W.; Chang, J.; Zhu, J.; Chen, L.; Wang, X.; Guo, Y.; Zhang, H.T.; Yu, L.; et al. Terrestrial carbon sinks in China and around the world and their contribution to carbon neutrality. *Sci. China Life Sci.* **2022**, *65*, 861–895. [\[CrossRef\]](#)
6. Fang, Y.R.; Zhang, S.; Zhou, Z.; Shi, W.; Xie, G.H. Sustainable development in China: Valuation of bioenergy potential and CO₂ reduction from crop straw. *Appl. Energy* **2022**, *322*, 119439. [\[CrossRef\]](#)
7. DeCicco, J.M.; Liu, D.Y.; Heo, J.; Krishnan, R.; Kurthen, A.; Wang, L. Carbon balance effects of U.S. biofuel production and use. *Clim. Chang.* **2016**, *138*, 667–680. [\[CrossRef\]](#)
8. Khanna, M.; Wang, W.; Wang, M. Assessing the additional carbon savings with biofuel. *BioEnergy Res.* **2020**, *13*, 1082–1094. [\[CrossRef\]](#)
9. Liu, W.; Liu, Y.; Liu, G.; Xie, R.; Ming, B.; Yang, Y.; Guo, X.; Wang, K.; Xue, J.; Wang, Y.; et al. Estimation of maize straw production and appropriate straw return rate in China. *Agric. Ecosyst. Environ.* **2022**, *328*, 107865. [\[CrossRef\]](#)
10. Wang, S.; Li, C.J.; Hu, Y.J.; Wang, H.L.; Xu, G.T.; Zhao, G.; Wang, S.Y. Assessing the prospect of bio-methanol fuel in China from a life cycle perspective. *Fuel* **2024**, *358*, 130255. [\[CrossRef\]](#)

11. Guangdong Provincial Conditions Net. Guangdong Provincial Conditions Net. Available online: <https://dfz.gd.gov.cn/> (accessed on 28 April 2025).
12. Zhao, X.; Liu, B.; Liu, S.; Qi, J.; Wang, X.; Pu, C.; Li, S.; Zhang, X.; Yang, X.; Lal, R.; et al. Sustaining crop production in China's cropland by crop residue retention: A meta-analysis. *Land Degrad. Dev.* **2020**, *31*, 694–709. [\[CrossRef\]](#)
13. Guo, Z.; Zhang, X. Carbon reduction effect of agricultural green production technology: A new evidence from China. *Sci. Total Environ.* **2023**, *874*, 162483. [\[CrossRef\]](#)
14. Babu, S.; Singh Rathore, S.; Singh, R.; Kumar, S.; Singh, V.K.; Yadav, S.; Yadav, V.; Raj, R.; Yadav, D.; Shekhawat, K.; et al. Exploring agricultural waste biomass for energy, food and feed production and pollution mitigation: A review. *Bioresour. Technol.* **2022**, *360*, 127566. [\[CrossRef\]](#)
15. Xu, R.; Chen, J.; Yan, N.; Xu, B.; Lou, Z.; Xu, L. High-value utilization of agricultural residues based on component characteristics: Potentiality and challenges. *J. Bioresour. Bioprod.* **2025**, *10*, 271–294. [\[CrossRef\]](#)
16. China Straw Network (CSN). Straw Industry Development Report of China in 2021. Available online: <http://www.zgjgqh.com/news/show.php?itemid=7373> (accessed on 1 February 2022).
17. Zheng, Y.Q.; Liu, L.L.; Liu, R.Y. Analysis of emission inventory and characteristics of pollution emissions from elevated power and thermal production sources in Guangdong Province. *China Resour. Compr. Util.* **2025**, *43*, 187–193, (In Chinese with English Abstract). [\[CrossRef\]](#)
18. Sun, H.; Wang, E.; Li, X.; Cui, X.; Guo, J.; Dong, R. Potential biomethane production from crop residues in China: Contributions to carbon neutrality. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111360. [\[CrossRef\]](#)
19. Sun, D.; Ge, Y.; Zhou, Y. Punishing and rewarding: How do policy measures affect crop straw use by farmers? An empirical analysis of Jiangsu Province of China. *Energy Policy* **2019**, *134*, 110882. [\[CrossRef\]](#)
20. Zhu, J.C.; Li, R.H.; Zhang, Z.Q.; Meng, M.Z.; Fan, Z.M. Temporal and spatial distribution of crops straw and its comprehensive utilization mechanism in Shaanxi. *Trans. Chin. Soc. Agric. Eng.* **2013**, *29*, 1–9, (In Chinese with English Abstract).
21. Zhang, J.; Li, J.; Dong, C.; Zhang, X.; Rentizelas, A.; Shen, D. Comprehensive assessment of sustainable potential of agricultural residues for bioenergy based on geographical information system: A case study of China. *Renew. Energy* **2021**, *173*, 466–478. [\[CrossRef\]](#)
22. Wang, S.; Yin, C.B.; Li, F.D.; Richel, A. Innovative incentives can sustainably enhance the achievement of straw burning control in China. *Sci. Total Environ.* **2023**, *857*, 159498. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Qian, B.; Shao, C.; Yang, F. Spatial suitability evaluation of the conversion and utilization of crop straw resources in China. *Environ. Impact Assess. Rev.* **2024**, *105*, 107438. [\[CrossRef\]](#)
24. Zhu, K.W.; Tan, X.C.; Gu, B.H.; Lin, J.C. Evaluation of potential amounts of crop straw available for bioenergy production and bio-technology spatial distribution in China under ecological and cost constraints. *J. Clean. Prod.* **2021**, *292*, 126003. [\[CrossRef\]](#)
25. Theil, H. *Economics and Information Theory*; North Holland: Amsterdam, The Netherlands, 1967.
26. Pan, X.F.; Yuan, S.; Li, J.Q. The impact of market segmentation on carbon emissions from a spatial spillover perspective: Empirical evidence from 30 provinces in China. *Manag. Rev.* **2023**, *35*, 14–27, (In Chinese with English Abstract).
27. Pan, J.H.; Zhang, Y.N. Spatio-temporal patterns of energy carbon footprint and decoupling effect in China. *Acta Geogr. Sin.* **2021**, *76*, 206–222, (in Chinese with English abstract).
28. Sun, N.; Gao, C.; Ding, Y.; Bi, Y.; Seglah, P.A.; Wang, Y. Five-dimensional straw utilization model and its impact on carbon emission reduction in China. *Sustainability* **2022**, *14*, 16722. [\[CrossRef\]](#)
29. Fang, Y.R.; Wu, Y.; Xie, G.H. Crop residue utilizations and potential for bioethanol production in China. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109288. [\[CrossRef\]](#)
30. National Development and Reform Commission (NDRC). *The 13th Five-Year Plan for Renewable Energy Development*; NDRC: Beijing, China, 2016.
31. Shi, W.; Fang, Y.R.; Chang, Y.; Xie, G.H. Toward sustainable utilization of crop straw: Greenhouse gas emissions and their reduction potential from 1950 to 2021 in China. *Resour. Conserv. Recycl.* **2023**, *190*, 106824. [\[CrossRef\]](#)
32. Huo, L.L.; Yao, Z.L.; Zhao, L.X.; Luo, J.; Zhang, P.Z. Contribution and potential of comprehensive utilization of straw in GHG emission reduction and carbon sequestration. *Trans. Chin. Soc. Agric. Mach.* **2022**, *53*, 349–359, (In Chinese with English Abstract).
33. Wang, W.; Chen, X.Y.; Zhu, S.N.; Zhang, Y.; Wang, Q.; Liang, C.; Qi, W. Potential estimation and distribution of biomass energy resources in Guangdong Province. *Renew. Energy Resour.* **2023**, *41*, 152–159, (In Chinese with English Abstract).
34. Yin, H.J.; Zhao, W.Q.; Li, T.; Cheng, X.Y.; Liu, Q. Balancing straw returning and chemical fertilizers in China: Role of straw nutrient resources. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2695–2702. [\[CrossRef\]](#)
35. Zhang, S.Q.; Deng, M.S.; Shan, M.; Zhou, C.; Liu, W.; Xu, X.Q.; Yang, X.D. Energy and environmental impact assessment of straw return and substitution of straw briquettes for heating coal in rural China. *Energy Policy* **2019**, *128*, 654–664. [\[CrossRef\]](#)
36. Du, W.; Zhu, X.; Chen, Y.; Liu, W.; Wang, W.; Shen, G.; Tao, S.; Jetter, J.J. Field-based emission measurements of biomass burning in typical Chinese built-in-place stoves. *Environ. Pollut.* **2018**, *242*, 1587–1597. [\[CrossRef\]](#)

37. Wang, X.; Yang, L.; Steinberger, Y.; Liu, Z.; Liao, S.; Xie, G. Field crop residue estimate and availability for biofuel production in China. *Renew. Sustain. Energy Rev.* **2013**, *27*, 864–875. [\[CrossRef\]](#)
38. Huang, Y.; Zhao, Y.; Hao, Y.; Wei, G.; Feng, J.; Li, W.; Yi, Q.; Mohamed, U.; Pourkashanian, M.; Nimmo, W. A feasibility analysis of distributed power plants from agricultural residues resources gasification in rural China. *Biomass Bioenergy* **2019**, *121*, 1–12. [\[CrossRef\]](#)
39. Alengebawry, A.; Mohamed, B.A.; Ran, Y.; Yang, Y.; Pezzuolo, A.; Samer, M.; Ai, P. A comparative environmental life cycle assessment of rice straw-based bioenergy projects in China. *Environ. Res.* **2022**, *212*, 113404. [\[CrossRef\]](#)
40. Li, Y.; Zhang, R.; Liu, G.; Chen, C.; He, Y.; Liu, X. Comparison of methane production potential, biodegradability, and kinetics of different organic substrates. *Bioresour. Technol.* **2013**, *149*, 565–569. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Yang, Y.; Liang, S.; Yang, Y.; Xie, G.H.; Zhao, W. Spatial disparity of life-cycle greenhouse gas emissions from corn straw-based bioenergy production in China. *Appl. Energy* **2022**, *305*, 117854. [\[CrossRef\]](#)
42. Jittabut, P. Physical and thermal properties of briquette fuels from rice straw and sugarcane leaves by mixing molasses. *Energy Procedia* **2015**, *79*, 2–9. [\[CrossRef\]](#)
43. Ríos-Badrán, I.M.; Luzardo-Ocampo, I.; García-Trejo, J.F.; Santos-Cruz, J.; Gutiérrez-Antonio, C. Production and characterization of fuel pellets from rice husk and wheat straw. *Renew. Energy* **2020**, *145*, 500–507. [\[CrossRef\]](#)
44. Wang, Z.; Lei, T.; Yang, M.; Li, Z.; Qi, T.; Xin, X.; He, X.; Ajayebi, A.; Yan, X. Life cycle environmental impacts of cornstalk briquette fuel in China. *Appl. Energy* **2017**, *192*, 83–94. [\[CrossRef\]](#)
45. Soam, S.; Kapoor, M.; Kumar, R.; Borjesson, P.; Gupta, R.P.; Tuli, D.K. Global warming potential and energy analysis of second generation ethanol production from rice straw in India. *Appl. Energy* **2016**, *184*, 353–364. [\[CrossRef\]](#)
46. Ou, X.M.; Zhang, X.L. Fossil energy consumption and GHG emissions of final energy by LCA in China. *China Soft Sci.* **2009**, *S2*, 208–214, (In Chinese with English Abstract).
47. Yodkhum, S.; Sampattagul, S.; Gheewala, S.H. Energy and environmental impact analysis of rice cultivation and straw management in northern Thailand. *Environ. Sci. Pollut. Res.* **2018**, *25*, 17654–17664. [\[CrossRef\]](#)
48. Jiang, Z.; Dai, Y.; Du, T. Comparison of the energetic, environmental, and economic performances of three household-based modern bioenergy utilization systems in China. *J. Environ. Manag.* **2020**, *264*, 110481. [\[CrossRef\]](#)
49. Chen, H.J. Life Cycle Assessment of Biogas Production by Dry Fermentation of Rice Straw. Master's Thesis, Kunming University of Science and Technology, Kunming, China, 2013. (In Chinese with English Abstract).
50. Qin, Y.; Edwards, R.; Tong, F.; Mauzerall, D.L. Can switching from coal to shale gas bring net carbon reductions to China? *Environ. Sci. Technol.* **2017**, *51*, 2554–2562. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Dai, Y.; Zheng, H.; Jiang, Z.; Xing, B. Comparison of different crop residue-based technologies for their energy production and air pollutant emission. *Sci. Total Environ.* **2020**, *707*, 136122. [\[CrossRef\]](#)
52. Wang, C.; Chang, Y.; Zhang, L.; Pang, M.; Hao, Y. A life-cycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat in China. *Energy* **2017**, *120*, 374–384. [\[CrossRef\]](#)
53. Wang, L.; Littlewood, J.; Murphy, R.J. Environmental sustainability of bioethanol production from wheat straw in the UK. *Renew. Sustain. Energy Rev.* **2013**, *28*, 715–725. [\[CrossRef\]](#)
54. Cheng, G.; Zhao, Y.; Pan, S.; Wang, X.; Dong, C. A comparative life cycle analysis of wheat straw utilization modes in China. *Energy* **2020**, *194*, 116914. [\[CrossRef\]](#)
55. Wang, H.Y.; Wang, Y.J.; Gao, C.Y.; Wang, D.L.; Qin, C.; Bi, Y.Y. Environment impact evaluation of straw biogas project for central gas supply based on LCA. *Trans. CSAE* **2017**, *33*, 237–243, (In Chinese with English Abstract).
56. Zhao, L.; Ou, X.; Chang, S. Life-cycle greenhouse gas emission and energy use of bioethanol produced from corn stover in China: Current perspectives and future prospectives. *Energy* **2016**, *115*, 303–313. [\[CrossRef\]](#)
57. Lu, W.; Zhang, T. Life-cycle implications of using crop residues for various energy demands in China. *Environ. Sci. Technol.* **2010**, *44*, 4026–4032. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Zhao, L.; Leng, Y.W.; Ren, H.X.; Li, H. Life cycle assessment for large-scale centralized straw gas supply project. *J. Anhui Agric. Sci.* **2010**, *38*, 19462–19465, (In Chinese with English Abstract).
59. Hu, J.; Lei, T.; Wang, Z.; Yan, X.; Shi, X.; Li, Z.; He, X.; Zhang, Q. Economic, environmental and social assessment of briquette fuel from agricultural residues in China—A study on flat die briquetting using corn stalk. *Energy* **2014**, *64*, 557–566. [\[CrossRef\]](#)

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