Crop Straw Utilization and Coordinated Rural Ecological and Economic Development of Henan Province, China: A Comprehensive Review

Tingting Liu and Cuiping Zhao *

**Corresponding author: pingcuizhao@163.com*

DOI: 10.15376/biores.22.1.Liu

GRAPHICAL ABSTRACT



Crop Straw Utilization and Coordinated Rural Ecological and Economic Development of Henan Province, China: A Comprehensive Review

Tingting Liu and Cuiping Zhao *

Against the backdrop of China's rural revitalization strategy and its "dual carbon" goals, the utilization of crop straw resources has a significant impact on rural ecosystems and economies. This paper systematically reviews the types, output, and regional distribution of crop straw resources in Henan Province, China. It evaluates the carbon sequestration and emission reduction potential as well as the ecological and economic benefits of straw resource utilization. The comprehensive utilization of crop straw has exceeded 93%. However, the utilization has been primarily focused on fertilization (*i.e.*, direct return to fields), with a relatively low proportion allocated to high-value pathways such as fuelization, substrate, and raw-material manufacturing. Fertilization provides significant benefits in enhancing soil organic carbon and replacing chemical fertilizers. Among the pathways investigated, straw fuelization was found to have the greatest potential for carbon emission reduction; if its share increases by 20%, the carbon emission reduction could reach 10.43 million tons of carbon dioxide (CO_2) equivalent by 2033. Based on literature synthesis, this review proposes a conceptual framework in which straw resource utilization, through industrial development, income growth for farmers, and ecological improvement, may generate a virtuous cycle of "ecological improvement-economic development-feedback to ecology."

DOI: 10.15376/biores.22.1.Liu

Keywords: Crop straw utilization; Ecology and economy; Carbon emission reduction; Coordinated development

*Contact information: College of Economics and Management, Henan Agricultural University, Zhengzhou 450046, China; *Corresponding author: pingcuizhao@163.com*

INTRODUCTION

The green transformation of agriculture has become a strategic task within China's high-quality development. In 2020, China explicitly set the targets of achieving peak carbon emissions by 2030 and carbon neutrality by 2060, with emission reduction and carbon sequestration in agriculture and rural areas being key measures to realize these goals. In 2021, China's agricultural greenhouse gas emissions were approximately 9.3×10^8 t carbon dioxide equivalent (CO_2e), accounting for 7.2% of the national total (State Council of the People's Republic of China 2024). When factoring in energy consumption from both agricultural production and rural living, greenhouse gas emissions from China's agriculture and rural areas account for about 15% of the nation's total emissions. As a major component of agricultural production, crop straw yields are approximately 900 million tons annually (Shi *et al.* 2017). Rich in nutrients such as nitrogen, phosphorus, and potassium, the resource utilization of crop straw as a renewable energy source not only alleviates rural energy shortages but also promotes the green transformation and high-

quality development of agriculture. The total carbon sequestration and emission reduction achieved through comprehensive straw utilization amount to 62.6×10^6 t CO_2e per year, representing 27.7% of carbon emissions from the agricultural system and 2.1% of the national total (Zhao *et al.* 2024). In the context of the rural revitalization strategy, straw resource utilization has become a key link in sustainable agricultural development and an important lever for achieving the synergistic development of rural ecosystems and economies.

Several studies have investigated the resource utilization of crop straw, with the findings revealing significant spatiotemporal differences and thematic focuses. With the attention on sustainable development in recent years, the research focus has shifted toward the synergistic effects of the natural environment and economic development, particularly emphasizing the potential of straw utilization in greenhouse gas emission reduction, soil quality improvement, and rural economic diversification (Zhang *et al.* 2021; Krishna and Mkondiwa 2023). From a regional perspective, developed countries prioritize technological innovation and the optimization of market mechanisms, such as the commercial application of crop straw gasification for power generation and biodiesel in Europe and the United States (Scarlat *et al.* 2010). In contrast, developing countries focus predominantly on the role of straw utilization in poverty alleviation and promoting rural economic development (Qian *et al.* 2024). When evaluating carbon mitigation effects, life-cycle assessments have been widely used to analyze the carbon emissions of various straw utilization pathways, including gasification for power generation and direct combustion for heating (Lu *et al.* 2025). Regarding ecological compensation mechanisms, researchers have adopted contingent valuation methods to analyze quantitatively farmers' willingness to adopt straw-returning technologies and identify their underlying influencing factors (He *et al.* 2024). However, most previous studies have focused on a single technological pathway or a single benefit analysis, with no in-depth exploration of the intrinsic mechanisms underlying the synergistic development of ecology and economy under the integration of multiple pathways. In particular, theoretical frameworks and empirical analyses regarding the synergistic effects of simultaneous pollution reduction and carbon mitigation in comprehensive straw utilization remain insufficient (Hao *et al.* 2023). Taking Henan Province as an example, this study used quantitative and qualitative analysis methods to evaluate systematically the ecological and economic effects of straw resource utilization. Specifically, this study characterized the types, outputs, and spatial distribution of straw resources in Henan Province; assessed its carbon sequestration, emission-reduction potential, and ecological benefits; evaluated the driving role of straw utilization in rural economic growth; and ultimately clarified the intrinsic mechanisms governing the synergistic development of straw utilization and the rural ecological economy. The results provide support for the high-value utilization of crop straw in Henan Province.

As a comprehensive review, this study integrates evidence from peer-reviewed literature, official statistical yearbooks, and government reports. Following the methodological frameworks established in previous regional straw assessment studies (Wang *et al.* 2012; Su *et al.* 2020; Sanoja-López *et al.* 2024), we systematically synthesize quantitative data on straw resource availability, utilization structure, carbon emission reduction, soil carbon sequestration, and economic impacts from multiple sources. All directly cited data are labeled with their original references, and aggregated values are distinguished based on literature-derived numbers.

Following the methodological frameworks established in previous regional straw assessment and review studies (Wang *et al.* 2012; Gao *et al.* 2015; Su *et al.* 2020; Sanoja-López *et al.* 2024), we systematically synthesize quantitative data from multiple sources and distinguish literature-derived evidence from the authors' own synthetic calculations.

The quantitative carbon accounting data presented in this review are derived from studies that adopt a life-cycle assessment (LCA) framework. These studies specify system boundaries that include straw collection, transportation, pretreatment, utilization, and natural decomposition as the baseline scenario. Emission factors follow IPCC guidelines and regional inventory parameters. All specific values are cited with their original references at the point of presentation; readers are referred to the original publications for detailed parameter settings. Where data from multiple sources are synthesized, the calculation method is briefly described in the text or figure captions, and a comprehensive data-source table is provided as supplementary material.

As a comprehensive review, this study does not present new primary data from farmer surveys or economic models. Instead, it synthesizes existing evidence from peer-reviewed literature, government statistics, and case reports to construct a conceptual framework for understanding the synergistic mechanisms between straw utilization and rural ecological-economic development. This proposed framework, particularly the virtuous cycle of "ecological improvement-economic development-feedback to ecology", is derived from literature-based reasoning and is intended to guide future empirical research and policy design, rather than to claim definitive causal verification at this stage.

Current Status of Crop Straw Resources in Henan Province

Types and output of straw resources

As a major agricultural area, Henan Province is the second-largest grain-producing region in China. The main crops include wheat, corn, rice, and peanuts (Wang *et al.* 2012). Among these, wheat and corn are the two dominant grain crops, accounting for over 80% of the province's total straw production. From 2021 to 2023, the respective average annual wheat and corn straw outputs in Henan Province were 51.689 and 27.884 million tons, accounting for 53.7% and 28.9%, respectively, of the province's total. With the adjustment of agricultural planting structures and improved technology, the total straw output from major crops has maintained a steady growth trend. Wei *et al.* (2025) reported that the straw-to-grain ratios of wheat and corn have generally shown a declining trend over the past few decades. The straw-to-grain ratio of wheat decreased from 3.18 in the 1940s to 0.99 in the 2020s, with an average reduction of 0.14 every 5 years. Similarly, the straw-to-grain ratio of corn decreased from 1.27 in the 1980s to 0.83 in the 2020s, with an average reduction of 0.06 every 5 years. This decline is closely related to increases in crop yields per unit area; for example, for every 1,000-kg increase in yield per hectare, the straw-to-grain ratio of wheat has decreased by 0.36, while that of corn has decreased by an average of 0.09. In 2023, the collectable wheat straw resource in Henan Province was 34.72 million tons, and the resource utilization volume accounted for approximately 95% of the collectable resource amount. The respective shares of the five primary utilization methods—fertilizer, feed, fuel, material, or substrate—in the total resource utilization of wheat straw were 75.09%, 20.16%, 3.48%, *etc*. (Fig.1). Although the comprehensive utilization rate of wheat straw in Henan Province is relatively high, it remains heavily dominated by use as fertilizer (primarily *via* direct return to fields), whereas the proportion allocated to high-value, off-field utilization remains low.

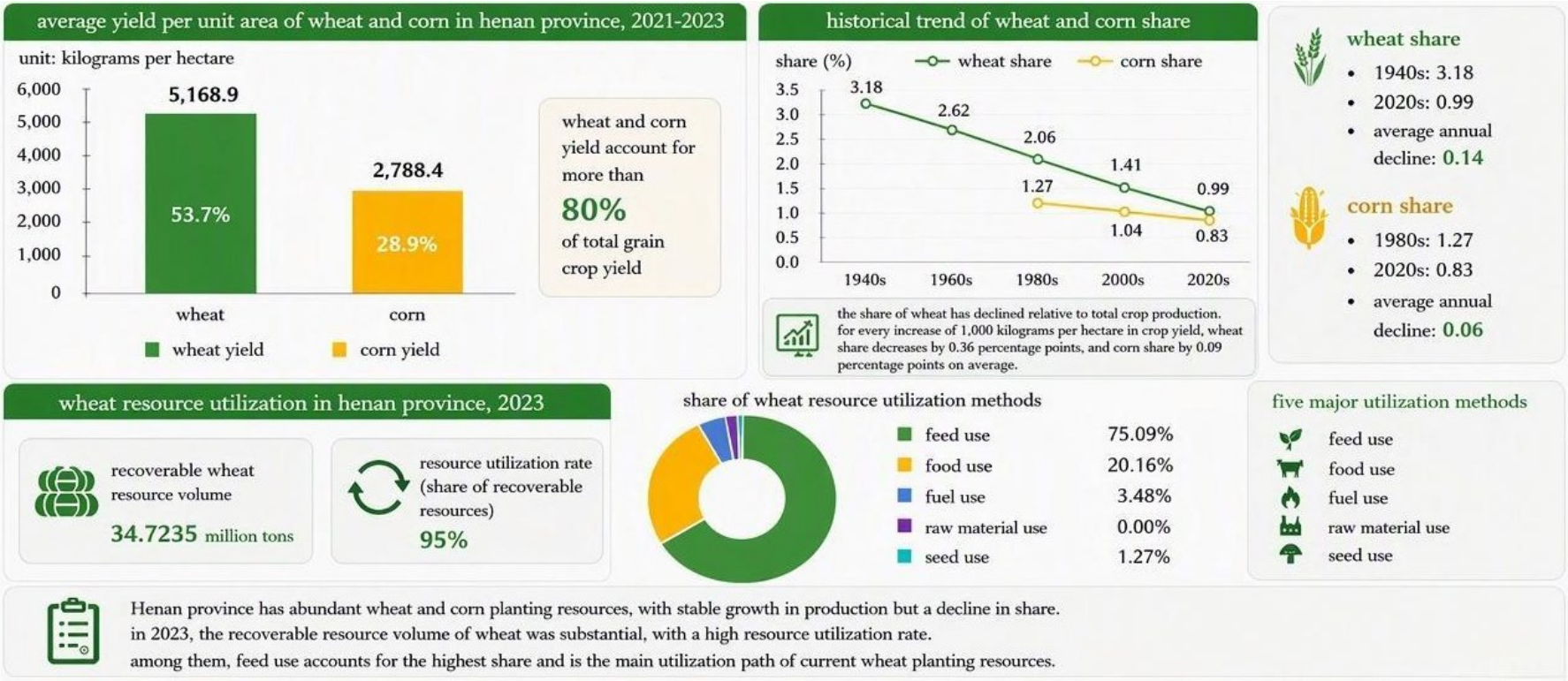


Fig. 1. The current status of crop straw resources and their utilization in Henan Province, China.
Data sources: Straw output data from Henan Statistical Yearbook (2021–2023); utilization structure data from Henan Provincial Department of Agriculture and Rural Affairs (2021–2023); straw-to-grain ratios from Wei et al. (2025). Regional distribution calculated by the authors based on these sources.

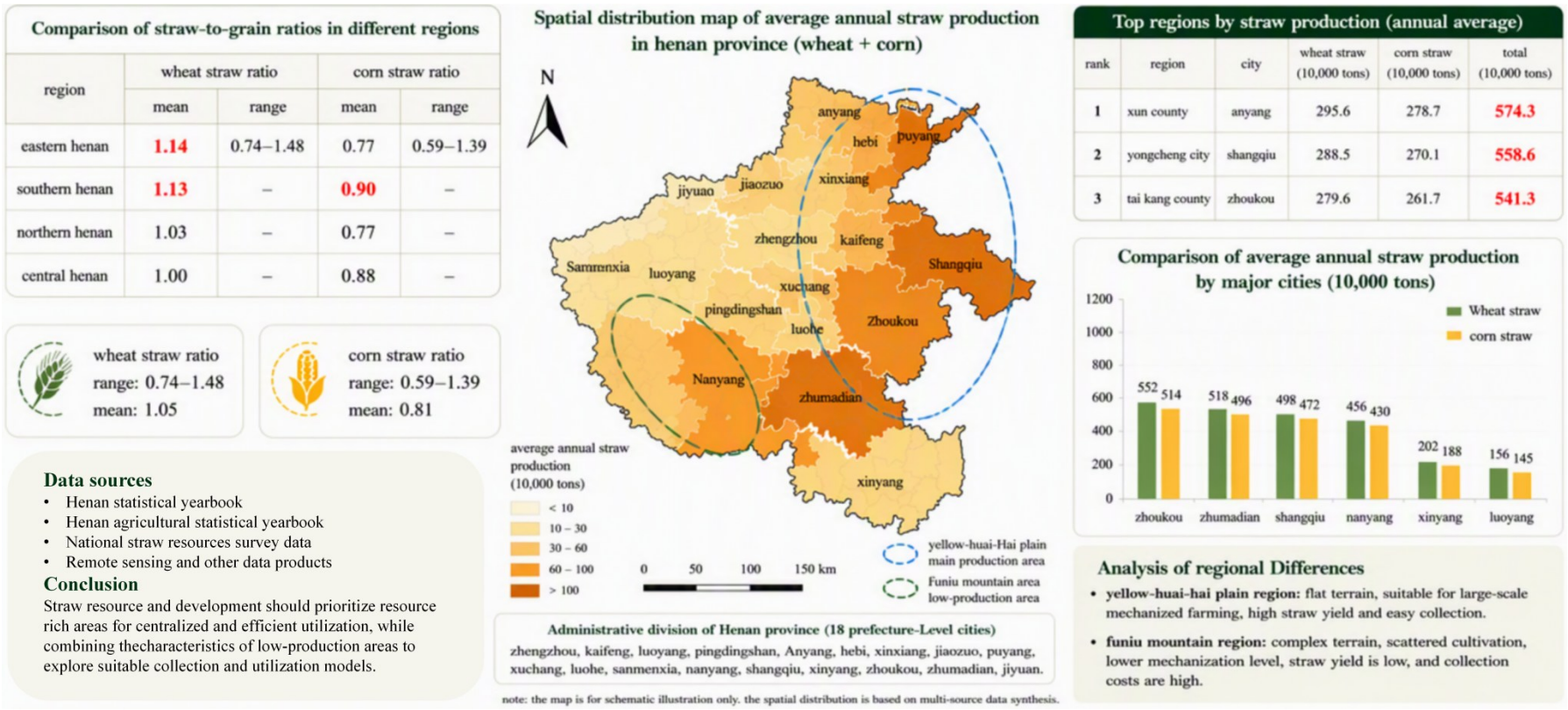


Fig. 2. Spatial distribution characteristics of crop straw resources in Henan Province, China

Regional Distribution Characteristics of Straw Resources

From a geographical perspective, the distribution of crop straw resources in Henan Province has exhibited significant spatial heterogeneity. Based on the measurement and analysis of 285 wheat samples and 173 corn samples from 14 districts and counties in Henan Province, the straw-to-grain ratios of wheat in Henan were 0.74 to 1.48 (average, 1.05), while those of corn were 0.59 to 1.39 (average, 0.81). Regional evaluations revealed that the highest wheat straw-to-grain ratio was in the eastern part of the province (1.14), followed by the southern (1.13), northern (1.03), and central-western regions (1.00). The ratios for corn were highest in the south of the province at 0.90, followed by the central-western region at 0.88, while they were lowest in eastern and northern regions, at 0.77 (Fig.2). These differences indicate that when estimating the straw resources of different regions of Henan Province, more accurate straw-to-grain ratio data are required, based on specific regional characteristics. The districts and counties with a large straw output were mainly distributed in northern Henan, eastern Henan, Nanyang, and Zhumadian. Among these, the districts and counties with the largest average annual straw outputs were Hua County, Yongcheng City, and Taikang County; their combined production of wheat and corn straw was 5.743 million tons. Straw output was relatively low in western Henan and Xinyang. Due to its vast cultivated land area and high degree of agricultural mechanization, the Huang-Huai-Hai Plain has become the main straw resource production area in Henan Province, with the straw output of Zhoukou, Zhumadian, and Shangqiu ranking among the highest in the province. In contrast, due to their complex terrain and fragmented cultivated plots, the mountainous areas of western Henan and the hilly areas of southern Henan have a relatively sparse distribution of straw resources and higher logistical and collection costs.

Current Status and Challenges of Straw Resource Utilization

Although straw is comprehensively utilized in Henan Province, the overall utilization structure requires further optimization. From 2021 to 2023, among the five primary utilization pathways for wheat and corn straw in Henan Province, use as fertilizer accounted for the highest proportion (wheat 87.7%, corn 80.9%), followed by use as feed (wheat 8.7%, corn 14.7%), and fuel (wheat 2.3%, corn 3.6%); use as substrate and material accounted for relatively low proportions. When used as fertilizer, direct return of straw to fields was found to be the principal method. However, the current amount of wheat straw utilized as fertilizer in Henan Province (24.77 million tons) vastly exceeds the recommended optimal incorporation threshold (0.1893 million tons). Furthermore, because shallow plowing is highly cost-effective, wheat straw in the province is predominantly incorporated *via* shallow tillage, resulting in an insufficient depth of rotary tillage. This practice may lead to short-term imbalances in the soil carbon-to-nitrogen ratio, an increased overwintering base of pests and diseases, and uneven seedling emergence. From a regional perspective, the comprehensive straw utilization rates in the Huang-Huai-Hai, Northwest, Southeast, and Southwest regions all exceed 80%, while that of the Northeast region is lower at only 63.13%. As a core province within the Huang–Huai–Hai region, Henan Province has achieved a high comprehensive utilization rate; however, it still faces systemic challenges, including an underdeveloped collection, storage, and transportation infrastructure, a low proportion of high-value utilization pathways, and limited willingness among farmers to participate. Consequently, the comprehensive utilization of straw in the province is currently at a critical evolutionary stage characterized by “increasing scale, optimizing structure, and awaiting breakthroughs in bottlenecks” (Zhou 2021).

Carbon-Sequestration and Emission-Reduction Effects of Straw Resource Utilization

Assessment of the carbon emission reduction effect of straw resource utilization

The emission reduction effect of straw resource utilization refers to the amount that carbon emissions can be reduced through the resource utilization of straw. Based on a life-cycle assessment, the carbon emission reduction from straw resource utilization is calculated as the substitution-driven emission reduction minus the baseline carbon emissions from natural decomposition. It should be noted that straw return to fields, particularly under flooded conditions, can stimulate CH_4 emissions due to anaerobic decomposition.

The LCA studies cited in this review (*e.g.*, Song *et al*. 2025) have incorporated CH_4 emissions using IPCC-recommended emission factors and GWP values (CH_4 = 28 CO_2e). The net emission reduction values reported in this review thus represent the balance between CO_2 sequestration and CH_4 release. Song *et al.* (2025) reported that the substitution emission reduction effect from wheat straw resource utilization in Henan Province was 2.34 million tons, while the carbon emissions from natural decomposition of wheat straw were 0.76 million tons. The emission reduction effect after full resource utilization of wheat straw in Henan Province in 2023 was 1.58 million tons of CO_2e. Among the different utilization pathways, use as fuel had the largest substitution emission reduction effect, at 1.11 million tons; use as fertilizer and as feed also produced relatively large emission reduction effects at 0.72 and 0.48 million tons, respectively, with these three pathways together constituting 98.76% of the total emission reduction effect (Fig.3).

It should be noted that the 'fuelization' pathway in this review primarily refers to direct combustion of straw or briquette fuel for rural heating and small-scale boilers, consistent with the assumptions in the cited LCA studies (*e.g.*, Song *et al.* 2025), where straw directly substitutes scattered coal in rural areas. Beyond direct combustion, biochar production *via* pyrolysis or torrefaction represents a higher-value fuelization route. Biochar has a calorific value of 23 to 29 MJ/kg, approaching that of coal, and can partially substitute for industrial coal in applications such as blast furnace injection and sintering. This pathway offers greater potential for industrial carbon mitigation but requires more advanced technology and higher initial investment. In the present review, our carbon reduction estimates are based on the direct combustion scenario; biochar production is identified as a promising direction for future research and policy development. From the perspective of the five utilization pathways in China in 2020, the respective greenhouse gas emission reductions from use as straw fertilizer, feed, fuel, substrate, and material were 7.9×10^7, 5×10^6, 3.8×10^7, 4×10^5, and 3×10^6 t CO_2e, accounting for 62.7%, 4.4%, 30.0%, 0.4%, and 2.6% of the total (Huo *et al.* 2022). Use as fertilizer and as fuel resulted in the highest emission reductions, together accounting for 92.7% of the total, contributing significantly to greenhouse gas emission reduction.

The greenhouse gas emission factors of different comprehensive straw utilization technologies vary significantly. Technologies such as pyrolysis poly-generation, briquette fuel, baling for heating, and biogas production combined with the return of digestate and residue to fields have distinct advantages in greenhouse gas emission reduction. These technologies not only directly substitute fossil energy but also increase the magnitude of soil carbon sinks through the return of by-products to fields.

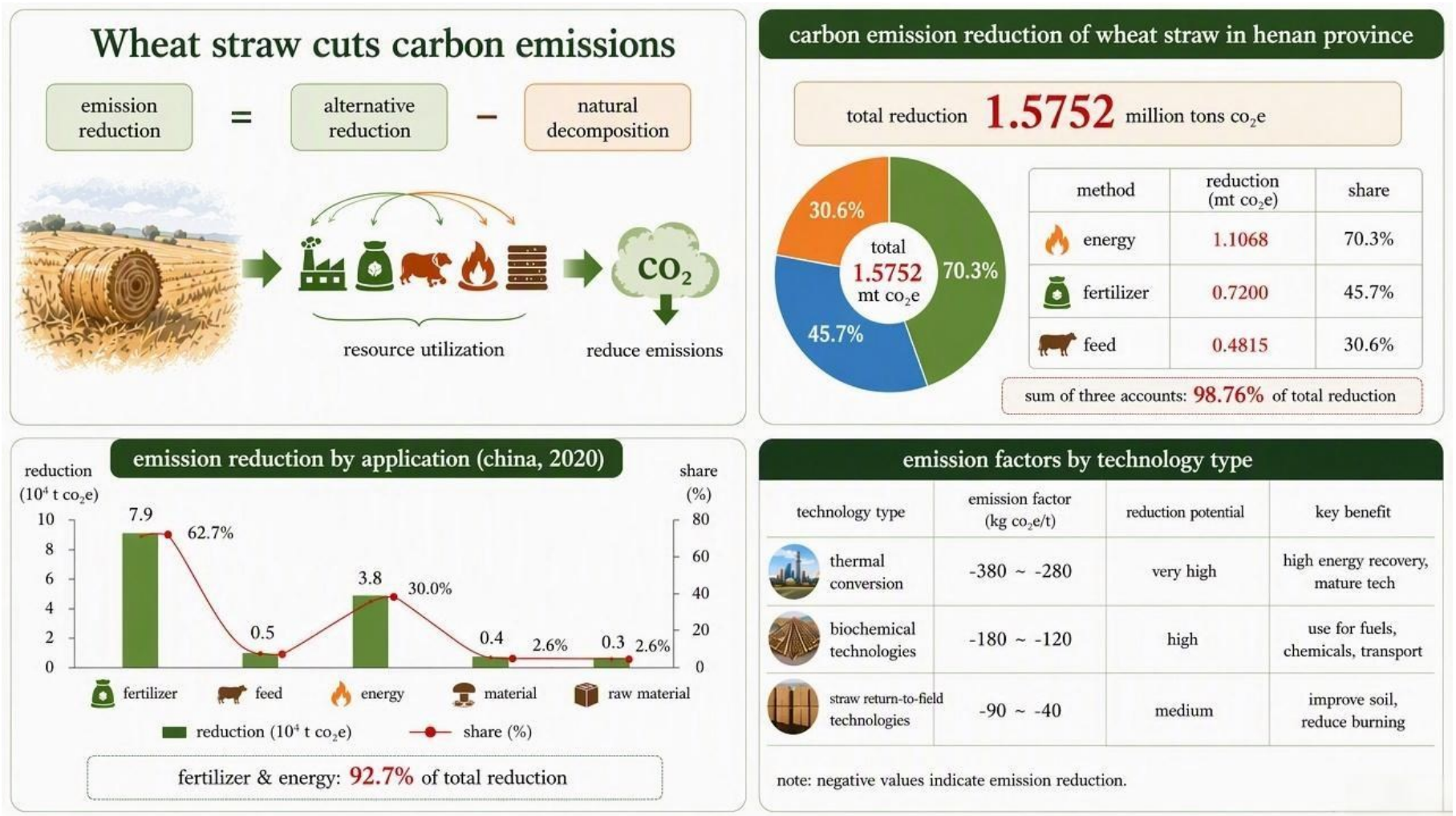


Fig. 3. Carbon emission reduction effects of straw resource utilization in Henan Province, China
Data sources: Emission factors from IPCC (2006), Song et al. (2025), and Wei et al. (2025); utilization volumes from Henan Provincial Statistical Bulletin (2021–2023). All cited LCA studies have incorporated emissions from collection, transportation, processing, and field incorporation within their system boundaries. Emission reduction values are calculated by the authors based on the LCA framework described in the cited sources.

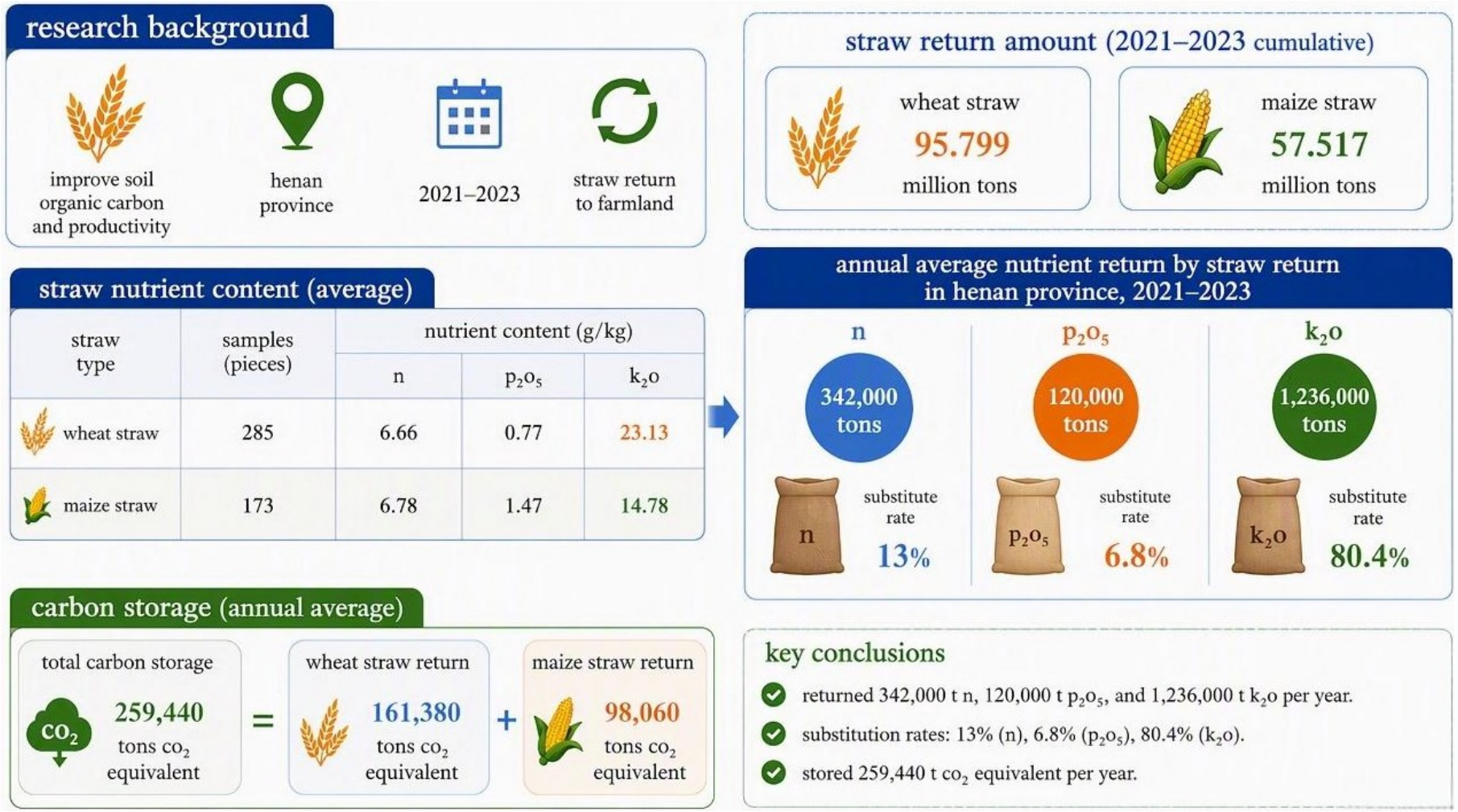


Fig. 4. Soil carbon sequestration of straw resource utilization in Henan Province, China

Soil Carbon Sequestration and Fertilizer Substitution Effects of Straw Return to Fields

Straw return to fields can increase soil organic carbon content and enhance the carbon sink function of farmlands. In the period from 2021 to 2023, Henan Province returned a cumulative total of 95.80 million tons of wheat straw and 57.52 million tons of corn straw to its farmlands (Wei *et al.* 2025). Based on an analysis of 285 wheat straw samples and 173 corn straw samples from 14 districts and counties in Henan Province, the average nitrogen, phosphorous pentoxide (P_2O_5), and potassium oxide (K_2O) contents of wheat straw were 6.66, 0.77, and 23.13 g/kg, respectively. The average nitrogen, P_2O_5, and K_2O contents of corn straw were 6.78, 1.47, and 14.78 g/kg, respectively (Fig. 4). From 2021 to 2023, the average annual amounts of nitrogen, P_2O_5, and K_2O added to farmlands through straw return in Henan Province were 342,000, 120,000, and 1.24 million tons, respectively. Straw return can substitute for 13%, 6.8%, and 80.4% of the province's agricultural consumption of nitrogen, phosphorus, and potassium fertilizers, respectively, with the substitution rate for potassium fertilizer being particularly significant. From 2021 to 2023, the average annual carbon sequestration in Henan Province was 2.59 million tons CO_2e, of which the carbon sequestration values from wheat straw and corn straw return were 1.61 and 0.98 million tons, respectively. The combined utilization of wheat and corn straw through use as fertilizer, feed, and fuel was equivalent to an average annual reduction of 2.53 million tons of CO_2e. The substitution of chemical fertilizers with nutrients returned through straw return offset 1.02 million tons of CO_2e, straw feed utilization offset 1.04 million tons CO_2e, and straw fuel utilization offset 0.47 million tons CO_2e.

Carbon Emission Reduction Potential under Different Scenarios

Song *et al.* (2025) predicted the carbon emission reduction potential of wheat straw resource utilization in Henan Province for the year 2033, a time point chosen to align with China's national 'dual carbon' strategy (post-2030 peak assessment window), under various scenarios (Table 1).

Table 1. Predictions of the Carbon Emission Reduction Potential of Wheat Straw in Henan Province under Different Scenarios in 2033

Scenario	Description of scenario	Carbon emission Reduction（× $10^4 CO_2e$）
Baseline case	Unchanged structure with only natural increase in the amount of straw	161.48
Scenario 1	All unused straw (5%) is returned to the field.	245.00
Scenario 2	20% of straw used for fertilizer is converted to use as fuel.	1043.21
Scenario 3	20% of straw used for fertilizer is converted to use as feed.	323.61

Note: All values are based on the assumptions and parameters described in Song *et al.* (2025) and the present synthesis of literature. The 20% conversion assumption in Scenarios 2 and 3 is based on technical feasibility considerations, following the common practice in scenario-analysis literature for straw utilization, where 20% represents the maximum technically achievable conversion ratio within a 10-year planning horizon under current infrastructure and farmer-acceptance conditions. The projection year 2033 is aligned with China's national 'dual carbon' strategy timeline (post-2030 peak assessment window). Actual values may vary depending on local conditions and future policy implementation.

The 20% conversion assumption in Scenario 2 is adopted based on technical feasibility considerations, following standard practice in straw utilization scenario literature where 20% represents a reasonable upper-bound conversion ratio within the projection horizon. Under the assumption that the straw-to-grain ratio and collection coefficient of wheat straw remained unchanged, the estimated collectable resource amount of wheat straw in Henan Province in 2033 was 40.3497 million tons.

The results show that the carbon emission reduction was highest under the scenario in which 20% of wheat straw is converted for use as fuel (Scenario 2), with an estimated reduction of 10.43 million tons of CO_2e, far exceeding that of both its conversion for use as feed scenario (3.24 million tons) and the full utilization scenario (2.45 million tons). The potential carbon emission reduction was greatest for Scenario 2, primarily because the traditional fossil energy that wheat straw replaces is a major source of carbon emissions.

Impact of Straw Resource Utilization on Rural Ecology

Figure 5 summarizes the impact of straw resource utilization on rural ecology, focusing primarily on the practice of returning straw to fields.

Improving Soil Quality and Enhancing Cultivated-Land Fertility

Returning straw to fields can significantly increase soil organic matter content, improve aggregate structure, and enhance water and fertilizer retention capacity. Research in Henan's main wheat-producing areas has shown that farmland utilizing straw-return technologies exhibits a 15 to 20% higher soil organic matter content than land under traditional tillage. Straw return not only improves soil structure by promoting the accumulation of particulate organic matter but also increases the soil organic carbon content. In China, straw return could increase the soil organic carbon content by 12.3%. However, straw return also introduces potential ecological risks. First, the direct return of insufficiently decomposed straw may introduce harmful substances such as heavy metals and pathogens, and excessive use may lead to imbalances in soil nutrient elements. Second, straw return can increase greenhouse gas emissions, especially nitrous oxide (N_2O). Wan *et al.* (2022) calculated that the global warming potential of soil carbon sequestration from straw return is approximately -3.56 t/(hm²·a), while the global warming potential of N_2O emissions is 1.28 to 3.22 t/(hm²·a), resulting in a total global warming potential of between -2.59 and -0.35 t/(hm²·a). Although straw return increases the absolute value of the global warming potential, it significantly reduces the net value and emission intensity of greenhouse gases by increasing organic carbon sequestration and crop yields.

Reducing Agricultural Non-Point Source Pollution and Greenhouse Gas Emissions

Straw resource utilization effectively reduces the air pollution caused by its burning. Open burning of straw releases large amounts of particulate matter, sulfur dioxide, and nitrogen oxides, severely impacting regional air quality. According to satellite remote-sensing monitoring by the Ministry of Ecology and Environment, the number of straw burning fire points nationwide in 2019 decreased by 42% compared with 2015. Through promotion of using straw for fertilizer, feed, and fuel, Henan Province has significantly curbed open burning of straw in recent years, and air quality index values in some key agricultural areas have consequently improved.

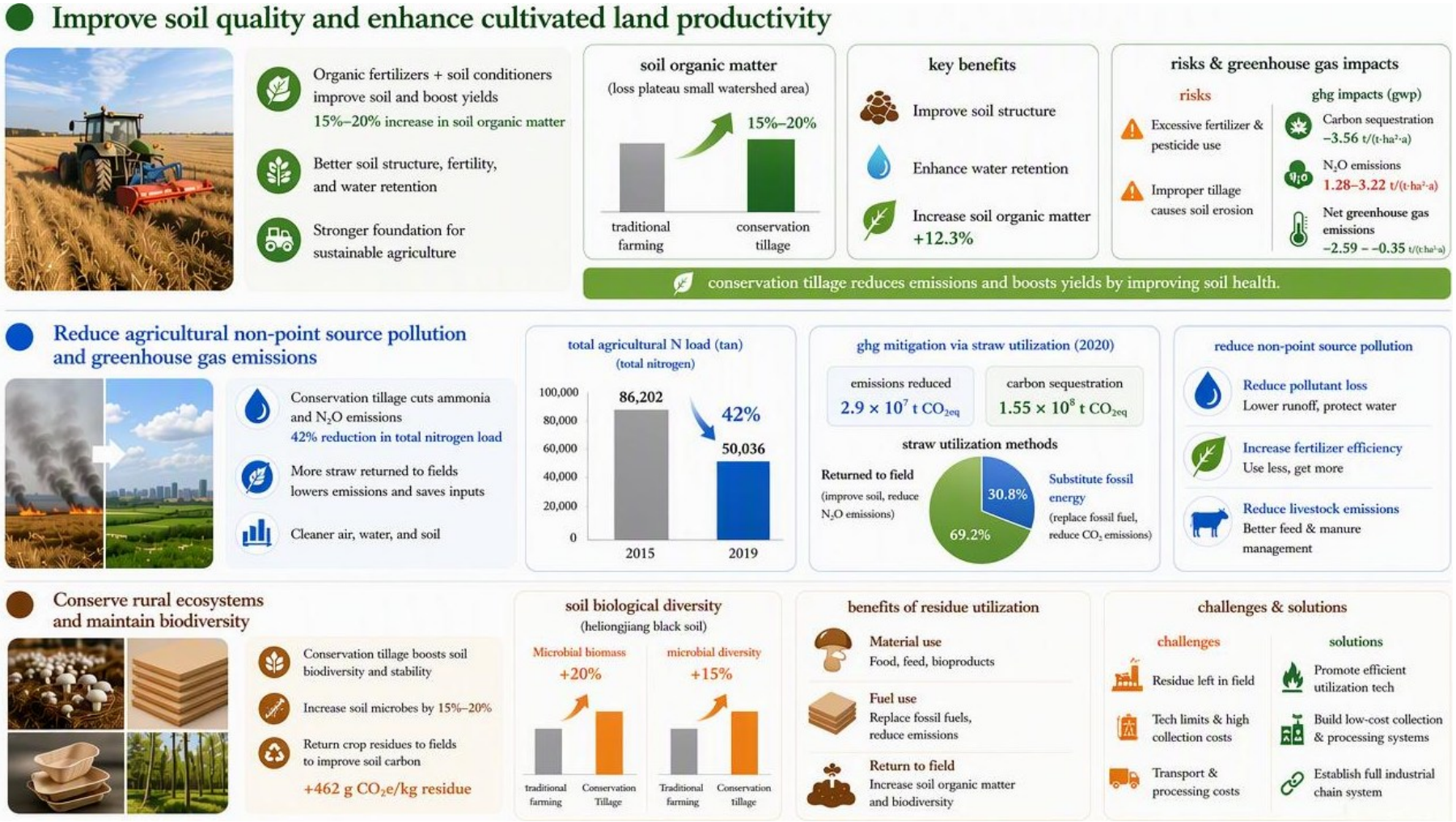


Fig. 5. Ecological and environmental effects of straw resource utilization: Pathways, benefits, and challenges



Fig. 6. Impact of straw utilization on the rural economy in Henan Province, China

From a carbon mitigation perspective, the reductions in greenhouse gas emissions achieved *via* comprehensive straw utilization are primarily derived from three mechanisms: increasing soil carbon sequestration in farmlands, reducing forest carbon loss from reduced wood harvesting, and offsetting CO_2 emissions from fossil energy displacement. In 2020, the total greenhouse gas emissions from the comprehensive straw utilization process nationwide were 2.9×10^7 t CO_2e, while the total emission reduction was 1.55×10^8 t CO_2e, of which soil and forest carbon sinks accounted for 69.2% and fossil energy displacement accounted for 30.8%.

Maintaining the Rural Ecological Balance and Biodiversity

Straw return to fields can increase the activity and diversity of soil microorganisms. Research in corn-growing areas of Henan Province has shown that soil microbial richness and evenness increases by approximately 20% and 15%, respectively, after straw return, helping to maintain the ecological balance of farmlands. Additionally, substrate utilization (such as mushroom cultivation) has established classic agricultural systems in some regions, such as cultivation of wheat straw–button and cottonseed hull–oyster mushrooms, which have developed into characteristic industries. Material utilization—such as straw-based panels, tableware, and packaging cushioning materials—substitutes for forest resources, reducing deforestation and enhancing forest carbon sinks. The forest carbon sink achieved through straw substrate utilization substituting for forest resources equates to 462 g $CO_{2,e}$/kg.

Impact of Straw Resource Utilization on the Rural Economy

Figure 6 summarizes the impact of straw resource utilization on the rural economy.

Promoting the Optimization of Rural Industrial Structure and Industrial Agglomeration

Straw resource utilization plays a significant role in promoting rural industrial development, primarily in three major areas: fertilizer processing, feed production, and biomass energy production. Through technologies such as composting, straw can be converted into high-efficiency organic fertilizer, reducing the use of chemical fertilizers and improving soil fertility. Furthermore, silage and ammoniation treatments transform straw into a vital feed source for livestock, thereby optimizing the rural industrial structure. In the energy sector, straw provides clean energy for rural areas through technologies such as gasification and power generation, promoting the development of the biomass energy industry. In Nanle County and Zhoukou City in Henan Province, the collection, processing, and sale of straw have formed a large-scale, full-chain operational model. This has driven the development of supporting industries, such as machinery manufacturing and logistics transportation, and promoted the transformation of agriculture toward diversification and ecological sustainability. For example, Nanle County has developed a circular agricultural model of "straw−feed−livestock farming−organic fertilizer−cultivation" through the development of a comprehensive straw utilization industry, with an annual straw processing capacity exceeding 500,000 tons, that employs over 2,000 local people.

Promoting Income Growth for Farmers and Job Creation

Straw sales have become an important source of revenue for farmers. According to a local government report, in Zhenping County, Henan Province, extending the agricultural industrial chains through straw utilization generates an additional income of

approximately 200 to 300 RMB per mu for local farmers (Zhenping County Government Work Report 2023). Straw utilization has also created jobs in collection, baling, transportation, and processing, alleviating the problem of idle rural labor. In Nanle County and Zhoukou City, these related industries provide substantial local employment opportunities. For example, Zhoukou City has achieved a comprehensive straw utilization percentage of 94%, with an annual processing capacity exceeding 6 million tons, employing more than 20,000 individuals. It has been estimated that industries related to comprehensive straw utilization in Henan Province have generated employment for over 100,000 people (Henan Provincial Department of Agriculture and Rural Affairs, 2023). The straw collection, storage, and transportation stages alone require large amounts of labor, providing on-site or nearby employment opportunities for the surplus rural labor force. The multiple impacts of straw resource utilization on the rural economy can be seen in Table 2.

Table 2. The Multiple Impacts of Straw Resource Utilization on the Rural Economy

Aspect of Impact	Specific Performance	Typical Example
Industrial agglomeration	Formation of a full chain comprising collection, storage, transportation, processing, and sales	Circular agriculture model in Nanle County, Henan Province
Job creation	Work created in collection, processing, and transportation	Employment of over 20,000 people in Zhoukou City, Henan Province
Income growth for farmers	Straw sales + processing income	Increased income by 200 to 300 RMB per mu (1 mu = 666.7 m^2) in Zhenping County, Henan Province
Structural optimization	Transformation from single-sector agriculture to multi-industry collaborative development	Straw + industrial models in various regions of Henan Province

Optimizing Rural Economic Structure and Enhancing Risk Resistance Capacity

Straw resource utilization promotes transformation of agriculture from a single cropping system to synergistic development of multiple industries. In Henan Province, a new economic model based on agriculture and featuring multi-industry linkages has been formed, enhancing agricultural added value and the risk-resistance capacity of the rural economy. From the perspective of economic benefits, straw feed utilization provides the livestock industry with low-cost, high-nutrient feed resources, helping to alleviate the shortage of feed grains and promoting the large-scale development of animal husbandry. Straw fuel utilization promotes the development of the biomass energy industry and drives the extension of related industrial chains such as equipment manufacturing, installation, and maintenance. Straw resource utilization also enhances the risk-resistance capacity of the rural economy. Diversified utilization methods spread the risks associated with the development of a single industry. Additionally, the straw utilization industry has localized characteristics and is relatively unaffected by external market fluctuations.

The Impact Mechanism of the Synergistic Development of Straw Resource Utilization and the Rural Ecological Economy

The impact mechanism of the synergistic development of straw resource utilization and rural ecological economy is shown in Fig. 7.

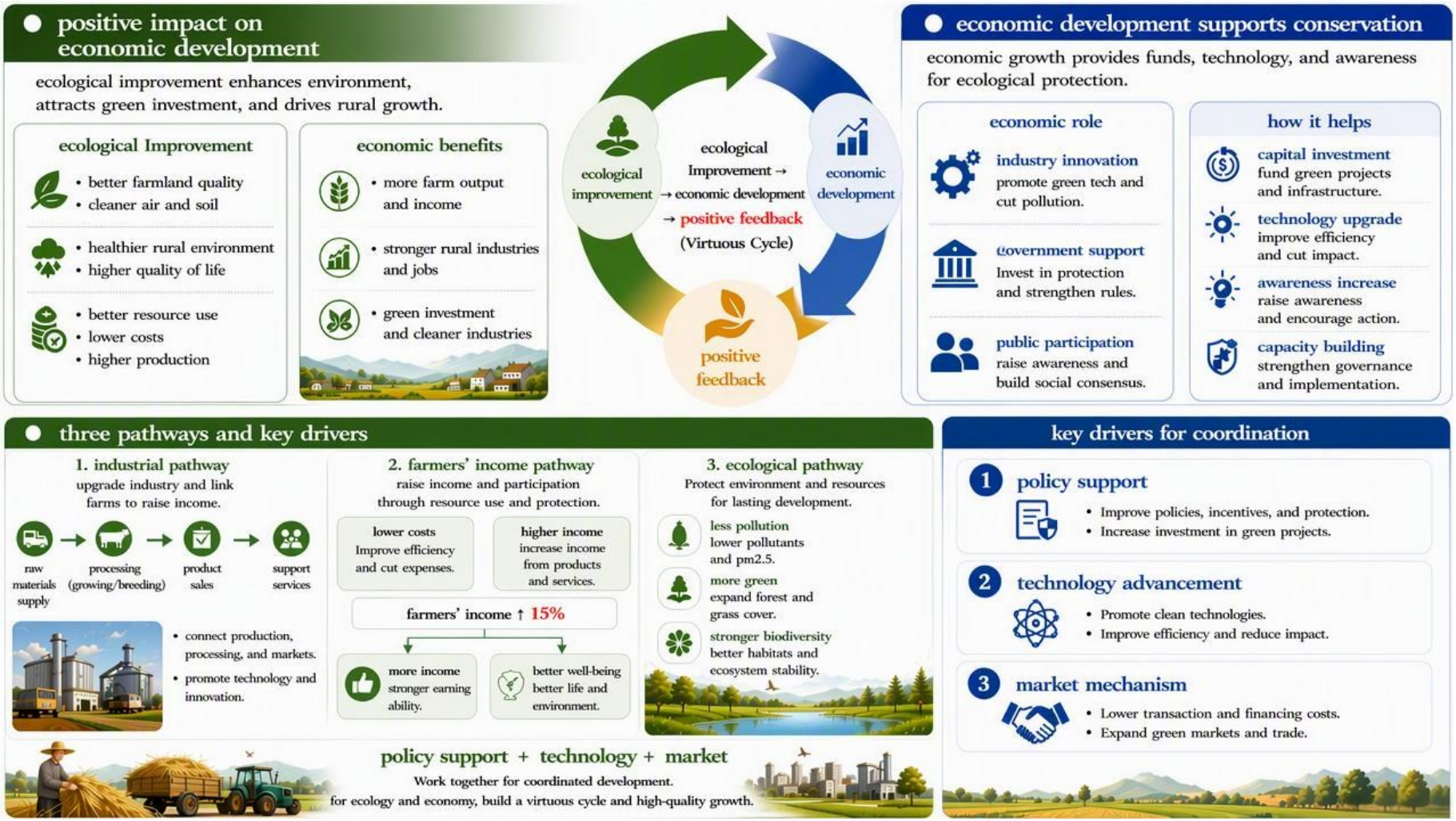


Fig. 7. The impact mechanism of the synergistic development of straw resource utilization and the rural ecological economy

Positive Feedback from Ecological Improvement to Economic Development

Straw resource utilization establishes a virtuous cycle of bidirectional interaction that drives the synergistic development of the rural ecology and economy. Ecological improvements provide the resource base and environmental capacity for economic development. Straw utilization reduces pollution from open burning and increases soil organic matter; fertile land increases agricultural output, and clean air enhances the cultural tourism value of rural areas, attracting investment in green industries. Specifically, straw return to fields improves soil fertility, reduces chemical fertilizer input, and lowers agricultural production costs. It is estimated that straw return can substitute for 13%, 6.8%, and 80.4% of the province's agricultural consumption of nitrogen, phosphorus, and potassium fertilizers, respectively, saving billions of yuan in fertilizer costs annually. At the same time, the increase in soil organic matter improves crop yields and quality, thereby increasing agricultural incomes (Guo *et al.* 2024).

The Feedback Effect of Economic Development on Ecological Protection

Economic development further reinforces ecological protection. The economic benefits generated from the straw industry can be reinvested in efficient pollution control and eco-agricultural technologies. As farmers' incomes increase, they become more willing and capable of investing in ecological protection. Technological progress and infrastructure development further strengthen the capacity for ecological protection. Specifically, the profits generated by straw-utilization enterprises can be used to develop more efficient and cleaner utilization technologies, reducing carbon emissions and pollutant emissions during the utilization process. Government tax revenues can be used to subsidize straw collection, storage, and transportation, as well as to support technology promotion and farmer training. With higher incomes, farmers are more willing to adopt scientific straw treatment methods rather than resorting to simple open burning. Based on the present synthesis of the evidence reviewed above, we propose a conceptual framework in which a virtuous cycle of 'ecological improvement−economic development−feedback to ecology' serves as the core mechanism linking straw resource utilization to the synergistic development of the rural ecological economy. This framework is derived from literature-based reasoning and supported by case examples (Ge and Fan 2026; Yu *et al.* 2025), though it remains to be empirically tested with primary data.

Analysis of Three Core Impact Pathways and Key Factors

Straw resource utilization affects the synergistic development of rural ecosystems and economies mainly through three pathways. First, the industrial development pathway, which promotes the agglomeration of industries such as fertilizers, feed, and biomass energy production, reduces transaction costs, and improves resource efficiency. Second, the income growth for farmers pathway, which provides diverse income sources through straw sales and employment in processing, enhancing farmers' willingness to protect ecosystems. Third, the ecological improvement pathway, which reduces pollution from open burning and improves soil fertility (*e.g.*, increasing soil organic matter by more than 20%), thus providing a better environmental capacity for economic development. Three key factors determine the effectiveness of this synergy. In terms of policy support, precise measures need to be implemented, such as financial incentives and subsidies, low-interest credit, and preferential land and electricity use.

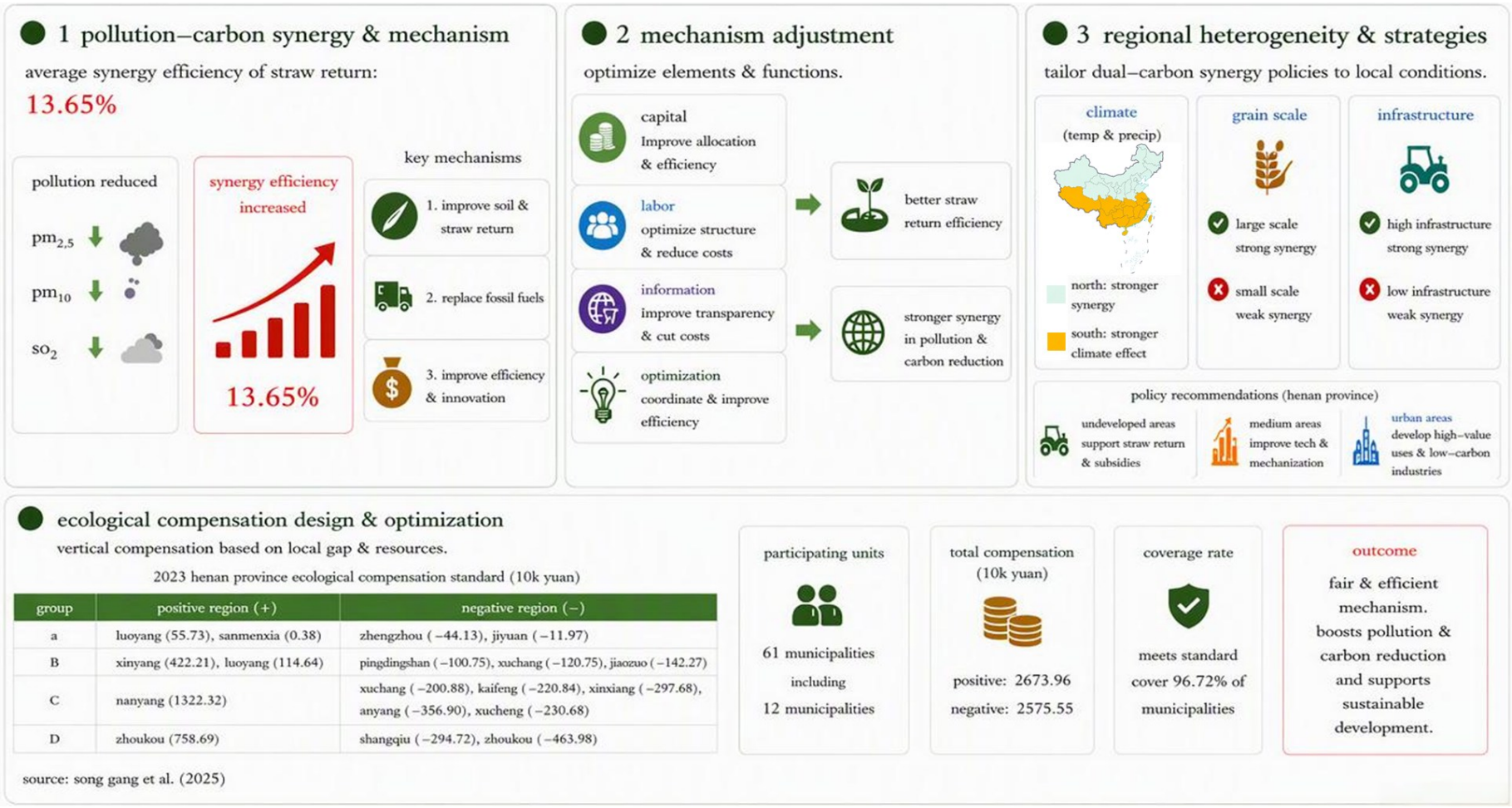


Fig. 8. Challenges and optimization pathways for achieving both pollution reduction and carbon emission mitigation through the resource utilization of straw

In terms of technological development, capital, human, and information factors can all moderate the effect of straw utilization on reducing carbon emission intensity (Yu *et al.* 2025). In terms of market mechanisms, a unified trading platform should be established, drawing on a dual-line ecological compensation mechanism of rewards and penalties to address information asymmetry and price volatility (Song *et al.* 2025).

Synergistic Dilemmas and Optimization Pathways for Pollution Reduction and Carbon Mitigation in Straw Resource Utilization

The synergistic dilemmas and optimization pathways for pollution reduction and carbon mitigation in straw resource utilization are shown in Fig. 8.

Pollution Reduction–Carbon Increase Divergence Effect and Its Causes

Although comprehensive straw utilization has tremendous theoretical potential for both pollution reduction and carbon mitigation, the synergistic effect has not yet been fully realized in practice. Using a difference-in-differences approach based on panel data from 285 prefecture-level cities in China from 2012 to 2020, Yu *et al.* (2025) found that pilot policies for comprehensive straw utilization significantly reduced the concentrations of air pollutants such as $PM_{2.5}$, PM_{10}, and SO_2, but led to an average increase in the carbon emission intensity of 13.65%, resulting in a "pollution reduction−carbon increase divergence effect." The causes of this divergence effect were: policy goals that emphasize pollution reduction while neglecting carbon mitigation; increased fossil energy consumption from off-field straw utilization; and low economic returns and inefficient technology application (Wang *et al.* 2022).

The Moderating Mechanism Enabled by Technological Factors

Technological factor endowments exert a positive marginal convergence effect on carbon emission intensity, thereby promoting the synergistic enhancement of pollution reduction and carbon mitigation. Specifically, technological factors mainly encompass capital, human, and information factors (Yu *et al.* 2025). In terms of capital factors, the volume of utility model patent applications in agriculture, forestry, animal husbandry, and fisheries can effectively suppress the increase in carbon emission intensity induced by comprehensive straw utilization pilot policies. In terms of human factors, professional farmer cooperatives are important platforms for developing and enhancing rural human resources. A high number of newly established cooperatives per 10,000 people facilitates the transfer of technologies such as straw return and biochar production to low-skilled farmers, improving the efficiency of comprehensive straw utilization and thereby negatively moderating carbon emission intensity.

Regional Heterogeneity and Differentiated Strategies

The "carbon increase" effect of pilot policies for comprehensive straw utilization exhibited regional heterogeneity, being more pronounced in northern regions, areas with smaller grain production scales, and regions with lower agricultural investment (Ge and Fan 2026). The northern climate is not conducive to rapid straw decomposition, leading to an increase in carbon emission intensity, whereas the subtropical climate in the south is more favorable for straw decomposition and soil organic carbon accumulation. High grain-producing areas enjoy significant economies of scale due to large aggregate straw volumes, rendering technology promotion more effective. In contrast, low-producing areas face fragmented utilization and small straw volumes, making economies of scale difficult to

achieve. In regions with a large investment in agriculture, forestry, and water conservancy, well-established infrastructure and economies of scale in technology application can effectively curb carbon emissions, while the opposite is true in regions with low investment (Zhang *et al.* 2024).

CONCLUSIONS

1. In this study, the impact of crop straw resource utilization on the synergistic development of rural ecosystems and economies was systematically analyzed.
2. Straw resource utilization has multiple positive effects on rural ecology and economy. Ecologically, it can improve soil quality, reduce non-point source pollution, and protect biodiversity. Economically, it can promote industrial agglomeration, income growth for farmers, and optimize economic structures.
3. Through the three pathways of industrial development, income growth for farmers, and ecological improvement, straw resource utilization has the potential to form a virtuous cycle of "ecological improvement−economic development−feedback to ecology", as conceptualized in our proposed framework. This study provides a theoretical basis and practical reference for the sustainable development of regions rich in straw resources.
4. As a comprehensive review incorporating quantitative synthesis analysis, this study has the following limitations: data heterogeneity among the cited literature, the uncertainty inherent in scenario-based assumptions (such as conversion factors and emission factors), and the absence of a thorough sensitivity analysis – all of which represent ongoing areas for further exploration in current research. Despite these limitations, the consistent findings derived from multiple independent studies provide strong support for the robustness of our primary conclusions.
5. At the same time, future research should also investigate the techno-economic feasibility of biochar production from crop straw, particularly its potential for industrial coal substitution and soil carbon sequestration.

ACKNOWLEDGMENTS

The authors are grateful for the Henan Provincial Science and Technology Tackling Program (242103810015).

DATA SOURCES

Data sources and calculation details for all quantitative values presented in the main figures and tables can be seen in Table S1 in the Appendix.

REFERENCES CITED

Gao, J., Ti, C., and Chen, N. (2015). "Environmental comparison of straw applications based on a life cycle assessment model and energy evaluation," *BioResources* 10(1),

548-565. https://doi.org/10.15376/biores.10.1.548-565

Ge, Y., and Fan, L. (2026). "Resourceful utilization of crop residue by smallholder farmers in major grain-producing areas: Pathways and countermeasures," *Scientific Reports* 16, article 5065. https://doi.org/10.1038/s41598-026-35164-7

Guo, R., Qian, R., Naseer, M. A., Han, F., Zhang, P., Jia, Z., Chen, X., and Ren, X. (2024). "Integrated straw-derived biochar utilization to increase net ecosystem carbon budget and economic benefit and reduce the environmental footprint," *Field Crops Research* 307, article 109247. https://doi.org/10.1016/j.fcr.2023.109247

Hao, X., Li, Y., Ren, S., Wu, H., and Hao, Y. (2023). "The role of digitalization on green economic growth: Does industrial structure optimization and green innovation matter?" *Journal of Environmental Management* 325, article 116504. https://doi.org/10.1016/j.jenvman.2022.116504

He, J., Zhou, W., Guo, S., Deng, X., Song, J., and Xu, D. (2024). "Environmental policy and farmers' active straw return: Administrative guidance or economic reward and punishment," *Environment, Development and Sustainability* 26(7), 17407-17430. https://doi.org/10.1007/s10668-023-03345-3

Huo, L., Yao, Z., Zhao, L., Luo, J., and Zhang, P. (2022). "Contribution and potential of comprehensive utilization of straw in GHG emission reduction and carbon sequestration," *Transactions of the Chinese Society for Agricultural Machinery (Nongye Jixie Xuebao)* 53, 349-359. https://doi.org/10.6041/j.issn.1000-1298.2022.01.038

Krishna, V. V., and Mkondiwa, M. (2023). "Economics of crop residue management," *Annual Review of Resource Economics* 15, 19-39. https://doi.org/10.1146/annurev-resource-111820-032637

Lu, M., Chen, L., Wang, S., Liu, D., Chen, J., Luo, X., Liang, T., Wang, Y., Zhao, J., and Shi, X. (2025). "Life cycle assessment of soil testing, formulated fertilization, and straw returning practices in staple and oilseed cropping systems: A multi-site analysis in Chongqing, China," *Environment, Development and Sustainability* 2025. https://doi.org/10.1007/s10668-025-06930-w

Qian, R., Guo, R., Yang, Q., Naseer, M. A., Sun, B., Wang, L., Zhang, J., Ren, X., Chen, X., and Jia, Z. (2024). "Can straw recycling achieve sustainable agriculture at the smallholder level? A case in a semi-arid region," *Journal of Cleaner Production* 439, article 140859. https://doi.org/10.1016/j.jclepro.2024.140859

Scarlat, N., Martinov, M., and Dallemand, J.-F. (2010). "Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use," *Waste Management* 30(10), 1889-1897. https://doi.org/10.1016/j.wasman.2010.04.016

Shi, Z., Jia, T., Wang, Y., Wang, J., Sun, R., Wang, F., Li, X., and Bi, Y. (2017). "Comprehensive utilization status of crop straw and estimation of carbon emission from burning in China," *Chinese Journal of Agricultural Resources and Regional Planning* 38(9), 32-37. https://doi.org/10.7621/cjarrp.1005-9121.20170905

Song, B., Xing, H., Zhang, P., and Zhang, D. (2025). "Emission reduction effects and ecological compensation mechanisms of wheat straw resource utilization in Henan Province," *Resources Science (Ziyuan Kexue)* 47(5), 1050-1062. https://doi.org/10.18402/resci.2025.05.11

State Council of the People's Republic of China (2024). *The First Biennial Transparency Report on Climate Change of the People's Republic of China*, Beijing, China.

Sanoja, L., Loor-Molina, N. S., and Luque, R. (2024). "Rice waste feedstocks: A review

of alternatives for their conversion into high-value added products," *BioResources* 19(1), 1-30. https://doi.org/10.15376/biores.19.1.Sanoja-Lopez

Su, S., Yu, Z., Zhu, W., and Chang, W. Y. (2020). "A comprehensive evaluation and optimal utilization structure of crop straw-based energy production in eastern China," *BioResources* 15(2), 2850-2868. https://doi.org/10.15376/biores.15.2.2850-2868

Wan, X., Zhao, K., Wu, X., Bai, H., Yang, X., and Gu, J. (2022). "Effects of stalk incorporation on soil carbon sequestration, nitrous oxide emissions, and global warming potential of a winter wheat-summer maize farmland," *Environmental Science* 43(1), 569-576. https://doi.org/10.13227/j.hjkx.202105185

Wang, S., Yin, C., Jiao, J., Yang, X., Shi, B., and Richel, A. (2022). "StrawFeed model: An integrated model of straw feedstock supply chain for bioenergy in China," *Resources, Conservation and Recycling* 185, article 106439. https://doi.org/10.1016/j.resconrec.2022.106439

Wang, Z., Lei, T., Yan, X., Li, Y., He, X., and Zhu, J. (2012). "Assessment and utilization of agricultural residue resources in Henan Province, China," *BioResources* 7(3), 3847-3861. https://doi.org/10.15376/biores.7.3.3847-3861

Wei, Y., Zhang, X., Song, W., Ahmad, S., Shen, Z., Liu, C., Shiyu, Z., and Xinming, M. (2025). "Spatiotemporal variations of wheat and maize grass-grain ratio and analysis of carbon sequestration and emission reduction effects of comprehensive straw utilization," *Transactions of the Chinese Society of Agricultural Engineering (Nongye Gongcheng Xuebao)* 41(17), 271-279. https://doi.org/10.11975/j.issn.1002-6819.202501039

Yu, S., Li, X., Fu, Q., and Yao, B. (2025). "Technology-empowered comprehensive utilization of crop straw: Pathways for the reduction of pollution and carbon emission," *Agricultural Technology Economics (Nongye Jishu Jingji)* 2025(12), 3-21. https://doi.org/10.13246/j.cnki.jae.2025.12.007

Zhang, Y., Li, J., Liu, H., Zhao, G., Tian, Y., and Xie, K. (2021). "Environmental, social, and economic assessment of energy utilization of crop residue in China," *Front. Energy* 15, 308-319. https://doi.org/10.1007/s11708-020-0696-x

Zhang, Y., Zhang, Y., Gao, Y., McLaughlin, N. B., Huang, D., Wang, Y., Chen, X., Zhang, S., and Liang, A. (2024). "Effects of tillage practices on environment, energy, and economy of maize production in Northeast China," *Agricultural Systems* 215, article 103872. https://doi.org/10.1016/j.agsy.2024.103872

Zhao, X., Li, R., Liu, W., Liu, W., Xue, Y., Sun, R., Wei, Y. X., Chen, Z., Lal, R., Dang, Y. P., *et al.* (2024). "Estimation of crop residue production and its contribution to carbon neutrality in China," *Resources, Conservation and Recycling* 203, 107450. https://doi.org/10.1016/j.resconrec.2024.107450

Zhou, Z. (2021). "Analysis on the present situation and predicament of high-value utilization of agricultural straw in China," *Journal of Agricultural Science and Technology (Zhongguo Nongye Keji Daobao)* 23(2), 9-16. https://doi.org/10.13304/j.nykjdb.2020.0410

Article submitted: June 25, 2026; Peer review completed: August 8, 2026; Revised version received and accepted: August 27, 2026; Published: November 18, 2026.
DOI: 10.15376/biores.22.1.Liu

APPENDIX

Table S1. Data Sources and Calculation Details for All Quantitative Values Presented in the Main Text

Figure/ Table	Quantitative Value	Value	Source Type	Original Data Source(s)	Calculation Method (if author-calculated)
Fig. 1	Wheat annual avg. output	51.689 Mt	Direct citation	Henan Statistical Yearbook 2021–2023	—
	Wheat straw-to-grain ratio (provincial avg.)	1.05	Author-calculated	Wei *et al.* (2025): 285 samples from 14 counties	Weighted average by cultivated area
	Wheat straw utilization – fertilizer share	75.09%	Author-calculated	Henan Provincial Dept. of Agriculture (2021–2023)	Calculated from raw utilization data
Fig. 3	Fuel pathway emission reduction	1.11 Mt CO_2e	Author-calculated	Utilization vol.: Henan Provincial Dept. of Agriculture; Emission factors: IPCC (2006), Song *et al.* (2025)	ER_{sub} = Straw amount × Calorific value × Coal emission factor; $ER_{net} = ER_{sub} - ER_{base}$
Fig. 3	Fertilizer pathway emission reduction	0.72 Mt CO_2e	Author-calculated	Nutrient content: Wei *et al.* (2025); Fertilizer EF: CLCD database	Based on N, P_2O_5, K_2O content × chemical fertilizer production EF
Table 1	Scenario 2 (2033) emission reduction	10.43 Mt CO_2e	Direct citation	Song *et al.* (2025)	—
Fig. 4	SOC sequestration (wheat straw)	1.61 Mt CO_2e	Author-calculated	Return amount: Wei *et al.* (2025); SOC coefficient: national meta-analysis (12.3%)	$\Delta SOC = M_{return} \times \alpha \times 3.67$
Fig. 5	Soil organic matter increase	15–20%	Direct citation	Field studies in Henan main wheat-producing areas	—