

Comprehensive Utilization of Straw and Development of the Straw Industry (Postprint)

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Abstract

China is a major straw-producing nation. Enhancing straw utilization efficiency essentially equates to increasing agricultural resource productivity. Straw must be regarded as an agricultural product, with dedicated efforts in industrial chain segments including collection, storage, and transportation to strengthen and expand the straw industry. Full utilization of China's currently underutilized straw would be equivalent to augmenting agricultural resources by 21%-27%. Owing to China's vast territory, straw utilization models cannot be monolithic; diversification is required even within the same region. It is imperative to learn from foreign policies and measures on comprehensive straw utilization, emphasize technological integration and innovation, establish an effective straw collection-storage-transportation system, formulate and implement supporting policies for comprehensive straw utilization, conduct comprehensive surveys of straw resource availability, compile plans for comprehensive straw utilization, emphasize policy and regulation implementation, effectively utilize international carbon funds, and incorporate straw utilization into the environmental assessment and reward system for new rural construction.

Full Text

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China is the world's largest producer of straw, and improving straw utilization is substantially equivalent to increasing the productivity of agricultural

resources. Straw must be regarded as a major agricultural product, with efforts focused on collection, storage, transportation, and other industrial chain links to expand and strengthen the straw industry. If China's currently unused straw could be fully utilized, it would represent a 21%-27% increase in agricultural resources. Given China's vast territory, straw utilization patterns cannot be uniform; even within the same region, diversification is necessary. We should learn from foreign policies and measures for comprehensive straw utilization, emphasize technological integration and innovation, establish an effective straw collection-storage-transportation system, formulate and implement supportive policies, conduct comprehensive surveys of straw resources, compile straw utilization plans, ensure policy implementation, effectively utilize international carbon funds, and incorporate straw utilization into the environmental assessment and reward system for new rural construction.

Keywords: straw industry, concept of major agricultural products, value-added cycle

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China is both a major grain producer and a major straw producer. However, for a long time, we have focused only on crop grains while neglecting straw. Each year, over 300 million tons of straw rot and are burned in China, representing a tremendous waste of the arable land, freshwater, and other agricultural inputs used to produce this straw. Therefore, vigorously developing the straw industry and improving straw utilization is essentially equivalent to increasing the productivity of arable land, freshwater, and other resources. The straw industry is an emerging industry that uses straw as a link to organically integrate straw collection with ecological farming (straw as fertilizer, feed, and substrate), straw energy utilization (biogas, direct combustion for power generation), and straw material utilization (as industrial raw materials), thereby strengthening the agricultural circular economy chain, expanding agricultural development space, and increasing farmers' income and agricultural sustainability. Encouraging and guiding the development of the straw industry is of great significance for improving the comprehensive utilization level of agricultural resources, protecting the ecological environment, and accelerating the development of agricultural circular economy and low-carbon agriculture. Under modern agricultural conditions, we must adopt the concept of major agricultural products, treating crop straw as we would agricultural products, and work hard on industrial chain links such as collection-storage-transportation, circular utilization, and market services to expand and strengthen the straw industry.

Straw Production and Comprehensive Utilization in China

According to the first national straw resource survey conducted by the Ministry of Agriculture in 2009 (no new survey has been conducted since), China's theoretical straw resource quantity in 2009 was 820 million tons (air-dried, with 15% water content) (MOA, 2010). This included approximately 205 million tons of rice straw (25% of the theoretical total), 150 million tons of wheat straw

(18.3%), 265 million tons of corn stover (32.3%), 25.84 million tons of cotton stalks (3.2%), 37.37 million tons of oil crop straw (mainly rapeseed and peanut) (4.6%), 27.26 million tons of legume straw (3.3%), and 22.43 million tons of tuber crop straw (2.7%).

The Ministry of Agriculture's national survey also revealed that China's collectible straw resource quantity was 687 million tons in 2009. Of this, approximately 102 million tons were used as fertilizer (excluding root stubble returned to fields, which accounted for about 133 million tons), representing 14.78% of collectible resources; 211 million tons were used as feed (30.69%); 129 million tons were used as fuel (including new energy utilization) (18.72%); 15 million tons were used as substrate for edible mushroom cultivation (2.14%); 16 million tons were used as industrial raw materials for papermaking (2.37%); and 215 million tons were abandoned or burned (31.31%). These figures demonstrate that straw abandonment and open burning remain serious problems in China. The burned straw consists mainly of wheat, rice, and corn straw, with burning concentrated in major grain-producing areas, economically developed regions, and suburbs of large and medium-sized cities. Large-scale open burning causes significant harm: thick smoke not only increases carbon emissions but also severely pollutes the atmospheric environment, disrupts air traffic, increases traffic accidents, and causes frequent fires, resulting in serious loss of life and property. Additionally, open burning wastes biological resources, destroys soil microbial communities, and deteriorates soil nutrient cycling and physicochemical properties.

Benefit Analysis of Comprehensive Straw Utilization

Theoretical Assessment of Benefits Currently, China produces over 600 million tons of grain annually, along with approximately 800 million tons of straw, of which about 300 million tons rot and are burned, representing a waste of the arable land, freshwater, and other agricultural inputs used to produce this straw [1]. If these 300 million tons of straw could be recycled through agricultural system cycles and reused in production processes, it would be equivalent to increasing agricultural resources by 21%-27%. Generally, if a material unit can be utilized by the next production level at a rate of r after each production cycle, and one original resource unit yields resource quantity y after n cycles of recycling, then y can be calculated as:

$$y = 1 + r + r^2 + \dots + r^n = \frac{1 - r^{n+1}}{1 - r}$$

Since r is less than 1, when n is large, y can be approximated by $\frac{1}{1-r}$. Therefore, if China's currently unused 300 million tons of straw could be fully recycled through multiple cycles, one unit of agricultural resources would be transformed into $\frac{1}{1-21\%} = 1.27$ units, equivalent to a 27% increase in arable land, freshwater, and other agricultural inputs. If production structure remains unchanged, this would translate into a 27% increase in output benefits. In practice, the actual

benefit typically falls between 21% and 27%. For example, simple straw return to fields yields about a 21% resource increase, while using straw as livestock feed can achieve effects greater than 21% and approaching 27%. Such successful cases have already emerged in Zhejiang, Fujian, and Jiangsu provinces, where straw prices have risen to several hundred yuan per ton, significantly increasing farmers' income.

This demonstrates that recycling material units in straw creates value-added effects through circular utilization. The higher the recycling rate, the more pronounced the value-added effect. While a single cycle may not show significant output increases, the overall effect of multi-level cycles across multiple subsystems in a system becomes quite substantial. Moreover, beyond value-added circulation, the substitution effect generated by straw resource utilization reduces the application of chemical fertilizers and pesticides, thereby decreasing the exploitation and processing of raw resources for these agricultural inputs. Simultaneously, as waste resources are utilized, the sustainability of internal agricultural system resources increases while environmental pollution decreases, powerfully promoting sustainable agricultural development [2].

Benefit Analysis of Main Utilization Models On December 18, 2014, the Ministry of Agriculture and Zhejiang Province signed a “Memorandum of Cooperation on Jointly Building a Pilot Province for Modern Ecological Circular Agriculture,” with straw ecological circular agriculture as a key component. In 2013, our research team conducted a survey on straw resource utilization in Zhejiang Province. Based on this survey data, we conducted quantitative analyses of several major straw resource utilization models (some models were not surveyed due to time constraints).

Straw Return to Field Benefits. Full straw return through rotary tillage typically incurs additional mechanical operation costs (including labor) of about 80 yuan per ton, plus straw decomposition agent costs of about 40 yuan per ton. Thus, the total cost for full straw return is approximately 120 yuan per ton. The primary benefit comes from increased crop yields. Since chemical fertilizer application rarely changes in the short term, we temporarily exclude the benefit of fertilizer substitution from our quantitative analysis. Survey data from Zhejiang show that under full straw return, rice yields increase by about 30 kg per mu and wheat yields by about 15 kg per mu. Based on average grain-to-straw ratios and 2013 market prices, one ton of straw directly returned to fields generates approximately 110 yuan in additional crop income. In summary, under the full straw return model, costs exceed increased income by 10 yuan per ton, indicating that farmers are unwilling to adopt this practice based solely on economic benefits, not including the opportunity cost of their own straw. However, since full straw return is an effective method for improving soil quality, especially in regions with high annual accumulated temperature, the government should introduce supportive policies to incentivize farmers.

Straw Feed Benefits. This survey used ammoniated straw for cattle feeding

as a case study. Ammoniated straw feed uses ammonium hydroxide treatment, where alkali and ammonia react with straw through alkaline and ammonolysis reactions, breaking ester bonds connecting polysaccharides and lignin. This causes cellulose and hemicellulose to decompose chemically while increasing nitrogen content, promoting massive reproduction of microorganisms in ruminant rumen and improving straw digestibility.

Survey data show that one ton of straw incurs collection-storage-transportation costs (including purchase) of about 200 yuan, crushing and storage costs of about 16 yuan, labor and equipment costs of about 17 yuan, and urea costs for ammoniation of 80 yuan, totaling 313 yuan per ton. Ammoniated straw can replace concentrate feed, generating benefits of approximately 1,030 yuan per ton. Therefore, one ton of straw processed as ammoniated feed yields net benefits of about 717 yuan.

Notably, straw expanded as feed achieves even better results and should be promoted on a larger scale. Expanded straw feed involves expanding straw through equipment, then fermenting it with microbial strains to transform waste straw into high-quality biological feed rich in nutrients for cattle, sheep, deer, geese, and pigs, generating enormous economic, social, and ecological benefits. This represents a project with small investment, high returns, and benefits for both the nation and its people. Compared with traditional straw feed methods (chopping, rubbing, silage, yellow storage, ammoniation), expanded feed offers advantages including softness and tenderness, good palatability, rich nutrition, and significantly improved digestibility and intake rates. Furthermore, using a wrapping machine for sealed anaerobic fermentation ensures quality while compressing the volume (cylinders of 0.5m diameter and 0.6m height weighing about 80 kg each) and allowing storage for up to two years, making storage, use, and transportation highly convenient. Economically, processing and packaging costs total 100 yuan per ton, with straw purchase at 100 yuan per ton, giving combined costs of 200 yuan per ton. The current market price is about 400 yuan per ton, yielding profits of approximately 200 yuan per ton, or over 700 yuan per ton when sold to developed regions.

Straw Biogas Benefits. Since centralized biogas supply represents the future development direction, this survey focused on centralized straw biogas projects in Zhejiang Province. Survey data indicate that one ton of straw incurs collection-storage-transportation costs of about 200 yuan, crushing and mixing costs before fermentation of about 17 yuan, decomposition additives of about 12 yuan, and labor costs of about 16 yuan, totaling 245 yuan per ton. One ton of straw can produce 250 cubic meters of biogas, generating income of 300 yuan at 1.2 yuan per cubic meter. Additionally, biogas residue and slurry can fertilize fields, with the slurry also serving as pesticide. Survey data show that biogas residue and slurry from one ton of straw generate about 70 yuan in benefits. Thus, one ton of straw processed through biogas production yields 370 yuan in income, with net benefits of approximately 125 yuan per ton.

Straw Power Generation Benefits. Straw direct combustion power gen-

eration involves collection-storage-transportation, crushing, mixing with other materials, combustion in furnaces, and conversion of biomass energy to electricity, producing ash and other byproducts. Survey data show that one ton of straw incurs collection-storage-transportation costs of about 200 yuan, mechanical crushing and transmission costs of about 12 yuan, and labor and equipment costs of about 95 yuan, totaling 307 yuan per ton. Income includes electricity generation and byproduct (ash) sales. Due to preferential national policies, straw power generation receives 0.75 yuan per kWh, yielding about 450 yuan per ton of straw. Additionally, grass-wood ash byproducts generate 30 yuan per ton. Total income from main and byproducts reaches about 480 yuan per ton, with net benefits of approximately 173 yuan per ton.

Comprehensive Evaluation of Main Models. The survey results roughly reflect the relative benefits of straw return to fields, straw biogas, straw feed, and straw power generation. Comparison shows that straw feed through livestock digestion yields the highest benefits, making straw feed utilization an efficient model for straw resource utilization. Since this potential has not been fully realized, local governments should increase support. Some regions have already introduced relevant policies, such as subsidies of 70 yuan per cubic meter for straw silage ammoniation pools and several hundred yuan per machine for related equipment.

Between the two straw energy utilization models, although straw biogas yields slightly lower benefits than direct combustion power generation, village-level centralized straw biogas supply projects avoid the problem of excessive straw collection radius faced by direct combustion plants. Considering that biogas residue and slurry are excellent fertilizers and pesticides, straw biogas projects should be preferred from the perspectives of agricultural sustainable development and ecological environmental benefits. Straw biogas should focus on centralized supply projects for sustainable maintenance. According to surveys, a typical centralized straw biogas supply project serving 500 households produces 400,000 cubic meters of biogas annually (equivalent to 290 tons of standard coal), consuming 1,500 tons of straw. Such projects require 900 cubic meters of gas storage tanks with total investment of about 4.5 million yuan for equipment, pipelines, and management facilities, with a designed service life of 30 years, equivalent to equipment costs of about 100 yuan per ton of straw processed. As low-carbon environmental projects using renewable biomass energy to replace coal, straw biogas centralized supply projects should receive strong government support. Survey findings show these projects are basically fully supported by governments, with some localities providing subsidies of 800,000–1,000,000 yuan.

Full straw return to fields is an effective model for improving soil quality in regions with high annual accumulated temperature and should not be discouraged simply because of negative economic returns. On the contrary, governments should introduce supportive policies to incentivize farmers. Survey findings show some regions have implemented relevant policies, including subsidies of

1,500 yuan per machine for newly purchased large and medium-sized straw return machines, 500 yuan per machine for small straw return machines, 5 yuan per mu for low-stubble harvesting operations (stubble below 10 cm with straw chopped and returned to fields, achieving comprehensive utilization rates above 85%), and 1,500 yuan per unit for newly purchased straw crushing devices (used with combine harvesters).

Furthermore, it should be noted that China's vast territory encompasses diverse local conditions, so straw resource utilization models cannot be uniform. Even within the same region, models should be diversified, with multi-path network composite integration models actively promoted to achieve maximum overall benefits.

International Experience in Straw Utilization

Implementing straw return to fields to promote conservation tillage is the most common straw recycling approach internationally. In the 1930s, after the "Black Storm" event in the United States, Americans first researched and applied straw return for conservation tillage in the western regions. During the 1930s-1940s, straw mulching methods controlled wind erosion in the western prairies.

Most agricultural production in Australia uses conservation tillage techniques such as no-till and minimum tillage with straw cover. In dry farming areas, winged shovels have largely replaced moldboard plows for shallow loosening operations without soil inversion, loosening the surface 5-10 cm of soil. This cuts the root systems of previous crops and weeds while loosening soil for new crop growth and reducing production costs. Straw mulching has become an important measure for sustainable agricultural production in Australia [3].

Eighty-five percent of Canada's arable land is located in the western prairie region. To reduce wind and water erosion, Canada has adopted minimum tillage and no-till systems to promote straw return. In 1996, 23% of prairie farmland implemented minimum tillage systems and 12% implemented no-till systems. That year, Canada's conservation tillage area reached 4.955 million hectares, accounting for 12% of the country's arable land area [3].

Currently, Japan uses rice straw mainly for field return (about 76.2%), including direct incorporation into soil (about 61.5%), compost return (about 10.1%), and burning return (about 4.6%). Japan also uses rice straw as roughage for cattle (about 11.6%), with the remainder used for livestock bedding (about 6.5%), which is subsequently returned to fields as organic fertilizer.

Straw is an excellent clean and renewable energy source. Research by the International Energy Agency shows that every 2 tons of straw has calorific value equivalent to 1 ton of standard coal, with low SO₂ and CO emissions during combustion, demonstrating significant energy and environmental benefits. Straw power generation technology development has attracted attention from governments and scientists worldwide. Many countries have formulated corresponding

plans, such as Japan's "Sunshine Project," the United States' "Energy Farm," and India's "Green Energy Factory," all prioritizing biomass straw power generation technology as a key renewable energy development for the 21st century. The most internationally renowned case is Denmark's straw power generation [5].

Denmark was the world's first country to use straw for power generation. Danish company BWE pioneered straw biomass combustion power generation technology and maintains world leadership in this field. With the company's technical support, Denmark built the world's first straw biomass power plant in 1988. The Avedøre power plant south of Copenhagen, constructed in the 1990s, is acclaimed as the world's most efficient and environmentally friendly combined heat and power plant.

To encourage renewable energy development such as straw power generation, the Danish government has formulated fiscal and tax support policies. For new energy sources including straw and wind power, Denmark exempts energy taxes and carbon dioxide taxes, prioritizes the dispatch of electricity and heat from straw, and guarantees minimum grid prices. The government also sets clear requirements for power generation operators, mandating that power companies maintain a certain proportion of renewable energy capacity. In 1993, the government signed agreements with power companies requiring annual consumption of 1.4 million tons of straw and wood chips. Additionally, Denmark began taxing industrial CO₂ emissions in 1993, using the revenue to subsidize energy-saving technology and renewable energy research. Denmark has now established over 130 straw biomass power plants, with some wood chip or waste incineration plants also co-firing straw. Renewable energy accounts for over 24% of national energy consumption, transforming Denmark from a net oil importer to an oil exporter through new alternative energy sources. Danish straw power generation technology has now gone global and been listed as a key promotion project by the United Nations.

According to Denmark's latest energy plan, by 2030, even when oil and natural gas resources are depleted, Denmark will maintain energy self-sufficiency. The target energy mix will be: wind power 50%, solar 15%, and biomass and other renewable energy 35%, with biomass primarily referring to straw power generation.

Straw is an important roughage source for herbivorous livestock. Experts estimate that the nutritional value of one ton of ordinary straw is equivalent to 0.25 tons of grain on average. However, untreated straw suffers from low digestibility, low crude protein content, and poor palatability. Simple feeding results in low livestock intake that cannot meet maintenance requirements. Through scientific treatment such as silage and ammoniation, straw's nutritional value can be substantially improved, representing the main technical approach for straw feed utilization.

As early as the 1980s, the western United States widely promoted new technol-

ogy for ammoniating rice, wheat, and sorghum straw into high-nutritional-value feed. The method involves chopping crop straw and placing it in sealed drying rooms with temperatures controlled between 75–80°C, then injecting anhydrous ammonia under pressure and sealing the room for two days. When the straw fully absorbs the ammonia, it becomes ammoniated straw feed. Testing shows this ammoniated straw feed has 30% higher protein content and 50% digestible matter compared to untreated straw, significantly improving nutritional value.

Government emphasis is crucial for rapid conservation tillage development. During initial demonstration and promotion, most countries guided farmers to adopt conservation tillage techniques through project support or policy incentives, providing subsidies for purchasing conservation tillage equipment. The United States established the “National Soil Conservation Service” with dedicated funding for research, demonstration, and promotion of conservation tillage, with federal legislation mandating conservation tillage on highly erodible land. Canada includes conservation tillage in its soil conservation policies. Australia initially provided 50% subsidies for farmers purchasing no-till seeders, 70% subsidies for equipment improvement, technology demonstration, and personnel training, and preferential policies on taxes and agricultural fuel. Brazil lists conservation tillage as a national agricultural policy. Mexico provides over 20% purchase subsidies for conservation tillage equipment. Europe launched the “Life Program” to support conservation tillage technology research and demonstration. These policies have enabled large-scale promotion and application of conservation tillage in recent decades [4].

Policy Recommendations for Straw Industry Development

The benefits of the straw industry can be summarized as improving “two securities” and generating “two positive externalities.” The “two securities” are: (1) increasing the added value of grain crop straw and farmers’ income, which further stimulates farmers’ grain production enthusiasm and improves China’s food security; (2) increasing resource and energy supply, thereby improving China’s resource and energy security. The “two positive externalities” are: (1) reducing agricultural waste pollution, especially from straw burning, while increasing organic fertilizer that gradually reduces non-point source pollution from chemical fertilizers, generating positive pollution-reduction externalities; (2) increasing clean energy and resource supply to substitute fossil resources, generating positive energy-saving and emission-reduction externalities. Simultaneously, the straw industry creates new value growth points and employment opportunities for farmers, prospering agriculture and rural economies. Therefore, we recommend that the government urgently improve the policy system and increase promotion efforts.

Formulate and Implement Supportive Policies for Comprehensive Straw Utilization. Increase subsidies for straw return to fields, straw silage, biogas bacterial agents, and straw reactor technologies. Include new straw resource utilization machinery such as straw expansion feed equipment in

the agricultural machinery purchase subsidy scope, and increase subsidies for mechanized straw return operations. Subsidize straw resource utilization enterprises based on utilization volume to increase straw purchase prices and further motivate farmers. Provide credit support to relevant enterprises, adopt tax reduction or exemption policies, and implement preferential electricity pricing for straw processing (charging agricultural electricity rates, i.e., reducing one level).

Conduct Comprehensive Straw Resource Surveys. Due to insufficient attention to straw utilization, despite some surveys and analyses by relevant departments and experts, problems such as unclear straw resources and utilization status persist. Based on the Ministry of Agriculture's 2009 national straw resource survey, another comprehensive survey should be conducted to clarify straw resource potential and utilization status.

Compile Straw Utilization Plans to Improve Sustainability. Based on resource distribution surveys, reasonably determine appropriate local straw utilization methods (feed, fertilizer, energy, edible mushroom substrate, industrial raw materials), quantities, and layouts, and set development targets. Straw utilization plans should propose corresponding safeguard measures and support policies, emphasizing the need to strengthen R&D and integration of straw conversion technologies and accelerate technology transfer and promotion.

Effectively Utilize International Carbon Funds and Integrate into International Capital Flows. Straw resource utilization reduces open burning and directly decreases carbon emissions. Straw energy utilization can substitute fossil energy, and fertilizer utilization can substitute chemical fertilizers, generating indirect carbon emission reductions. Straw direct and indirect return to fields (such as through livestock digestion, edible mushroom substrate decomposition, or biogas residue/slurry) are effective means for increasing soil carbon sinks. Relevant departments should support and facilitate straw utilization projects in applying for international carbon funds, especially to accelerate subsidy feedback, increase capital flow, and improve enterprises' capacity for expanded reproduction.

Connect with Waste Treatment Policies and Incorporate Straw Resource Utilization into New Rural Construction Environmental Assessment and Reward Systems. Straw waste causes environmental pollution, while straw resource utilization significantly improves farmland and rural environments. We recommend providing additional subsidies for straw resource utilization following urban waste treatment subsidy models, and establishing environmental assessment and reward systems in new rural construction to reward villages practicing straw resource utilization [7].

Emphasize Policy Implementation and Expand Publicity and Education. Given that a certain proportion of straw open burning still occurs in China, we recommend that relevant departments strictly enforce policies and regulations. Not only should individuals burning straw be penalized, but re-

sponsible leading cadres should also be held accountable, as severe open burning generally occurs where straw utilization channels are blocked, directly related to organizational management by officials. Government guidance plays a key role, and we should raise environmental awareness among all citizens, especially provincial-level officials and entrepreneurs, through various channels, treating straw as a true resource and enhancing their capacity and investment enthusiasm for participating in the straw industry. All parties should work together to transform market development potential into real, effective markets. Meanwhile, governments at all levels should incorporate straw comprehensive utilization into government target management responsibility systems as part of efforts to promote energy conservation, emission reduction, circular economy development, and ecological civilization construction, with policy formulation and implementation [6].

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