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Research on resource utilisation of crop residues in China: a review

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***Abstracts**: With the development of agriculture in China, the generation of agricultural waste has increased rapidly. Improper handling of agricultural waste not only causes environmental pollution, but also wastes a large amount of valuable biomass resources. It is necessary to summarize and analyse existing technologies and to continuously explore advanced technologies that are in line with China's national conditions and the current situation of rural development. The research status and development of agricultural waste resource application technology in China are summarised, and countermeasures for the application of agricultural waste resource application in China are proposed for the problems existing in the application process of agricultural waste in China. Of the comprehensive utilisation of crop straw mechanisation technology, the full life cycle assessment (LCA) is adopted as a method to reveal the impact of different utilisation methods on the life cycle.*
***Keywords**: Crop straw; Sourcing; LCA; Countermeasure*

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I. Introduction

China is a large agricultural country with abundant crop straw resources, producing about 1 billion tonnes of straw annually[1]. China produces about 20 % of the world's crop residue[2]. Crop residues are defined as crop stalks or stems left in the field after harvest. Crop residues are the most important component of China's biomass resources. At present, China's straw resources are mainly rice, maize and wheat straw, with the amount of straw from the three major crops accounting for about 83.51 % of the total, and straw from other crops, such as oilseed rape and sugar cane, accounting for a relatively small proportion as a secondary source[1]. From Figure 1, it can be seen that the theoretical resource of straw in China from 2015 to 2021 is around 800 million tonnes. The table 1 shows the grain yield and straw yield of different cereals in China. Crop residues contain large amounts of carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and other organic matter. Crop residues are used as an important source of global bioenergy due to their renewability and carbon neutrality.

Table1: Grain yield and straw yield of different cereals in China

types	grain yield(10000 tons)	Straw production(10000 tons)
Rice	20849.5	22000
wheat	13772.3	17500
corn	27720.3	34000
Beans	2351.0	3600
tubers	2977.4	2200

Fig. 1 Theoretical resource quantity of straw in china from 2015 to 2021.

Waste crop stalks cause many problems such as breeding mosquitoes and affecting sowing, which is why many farmers choose to burn them directly[3]. Straw burning is a common method of straw disposal, but straw burning can cause serious environmental pollution problems[4]. Open burning of crop residues releases large amounts of air pollutants such as soot, nitrogen oxides, sulphur dioxide and polycyclic aromatic hydrocarbons (PAHs). Open burning of crop residues contributes to global warming through the emission of greenhouse gases (ghg) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)[5]. Open burning of crop residues also releases harmful air pollutants that can seriously affect human health. These contaminants are polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) known as dioxins[6, 7]. These harmful air pollutants are potential carcinogens. Smoke from the direct burning of crop residues reduces atmospheric visibility, affects the quality of life of the local population and spreads gradually in the movement of atmospheric air currents. In addition, direct straw burning produces acid rain that enters lakes and rivers, affecting water quality[8]. Under intense pressure from various stakeholders, the government has strictly prohibited the open burning of crop residues, which has led to a significant improvement in the situation, although a small amount of open burning still exists in some areas[9].

The Ministry of Agriculture of China has proposed five main ways of straw utilisation: as fuel, fertiliser, feed, industrial raw material and substrate[10]. Crop residues can produce different biofuels such as bioethanol[11-13], biomethane[14-16], biohydrogen[17] through a number of technologies. Crop straw is a potential energy biomass resource. There are four scenarios of rice straw utilisation in India, and the results of Life Cycle Assessment (LCA) of the four straw utilisation systems show that straw power generation and biogas utilisation have better environmental performance[18].

Life Cycle Assessment is a systematic approach to quantifying the environmental burdens associated with a product, process or activity by identifying, quantifying and evaluating the impacts of utilised energy, materials and wastes that are released into the surrounding area during their life cycle. LCA consists of four interlinked steps: definition of objectives and scope, stockpile analysis, impact assessment and interpretation.

This paper maps and analyses the progress and trends of crop straw resource utilization research in China. The authors summarised and sorted out the main research hotspots of straw utilisation research in order to determine the future trends of straw utilisation research. The research hotspots, main contents, evolutionary trends of crop straw resource utilisation and their relevance to crop straw resource utilisation were discussed. The intrinsic connection of the research hotspots at different stages was analysed, and then the development direction of future research was investigated.

II. Approaches to Straw Resource Utilisation

2.1 Returning straw to the field

Population size, food demand and vegetable consumption are increasing, and some special areas may face shortages of nitrogen, phosphorus and potassium. Some studies found that carbon, nitrogen, phosphorus and potassium in 1 tonne of dry rice straw are about 383,6,1 and 19 kg, respectively[19]. Straw return to the field has a positive effect on soil fertility and crop yield, and it is considered as an environmentally friendly way of straw utilisation. Therefore, it is widely recommended by governments and scientists[20, 21]. Liu et al. used meta-analysis to explore the effects of agricultural management strategies on yield increase, soil carbon sequestration and emission reduction of different crops after straw return to the field, and concluded that the average yield increase of straw return to the field on rice, wheat and maize yields were 5.04%, 8.09% and 8.71%, respectively.

Straw is divided into direct and indirect return of straw to the field. Directly returning straw to the field is mainly direct crushing and returning straw to the field, which is crushed by machines and evenly sprinkled on the farmland, and rotary ploughing equipment is used to plough into the soil, so that the straw is fully mixed with the surface soil and decomposes and decays in the soil Straw returning straw to the field improves the structure of the soil, and improves the fertility of the soil and the yield of grain. There is also a direct return technology of straw mulching. Straw mulching refers to the technology of sowing the next crop before harvesting, crushing straw or covering the whole plant directly and evenly on the ground surface, or no-tillage direct sowing of the next crop after harvesting and mulching. Indirectly, there are straw composting and returning to the field, the straw will be chopped up and piled up or put into the pit, after the crop straw is fully rotted at high temperature, through human regulation and control, adding livestock and poultry manure and a variety of trace elements, microbial fungicide, processed into bio-organic fertilisers to return to the field.

Straw incorporation did promote the development of more reducing conditions compared to unincorporated straw , and the higher the rate of straw incorporation, the more reducing the soil was. Straw incorporation can promote the growth of soil microorganisms due to increased energy and nutrients. Straw incorporation increases soil nutrients, aggregate moisture, soil organic matter (SOM) and soil organic carbon (SOC) content.

Crop straw has been used for alternative fertiliser production, where straw is stabilised by decomposition under certain conditions and then converted to fertiliser production by various technological means[22, 23]. Organic fertilisers produced from crop residues are characterised by high organic matter and nutrient content[23]. Compared with farmyard manure, straw application has less impact on soil chemistry.

2.2 Straw forage

Straw is not efficiently absorbed directly as feed. Only 50 per cent of roughage and 10 per cent of concentrate can be used for feeding animals. Crop straw can be consumed by animals after some pretreatment. Therefore, straw pretreatment remains one of the strategies to improve the digestibility of livestock. Various physical, chemical and biological treatments have been developed to improve the quality of rice straw straw and the use of crop residues as animal feed through these specific techniques is expected to be a practical, cost effective and environmentally friendly method to improve the digestibility of straw[23, 24].

Crop residues are better converted to organic matter in the straw after simple pre-treatment such as silage, ammonification and alkalisation to obtain a nutritious feed for livestock. Silage is a microbiologically driven process used to preserve fresh feed in the form of silage for use in biorefineries and animal feed production. Straw silage is the process of inhibiting and killing a wide range of microorganisms and preserving feeds by providing an anaerobic environment for beneficial bacteria (lactobacilli, etc.) under suitable conditions so that the activities of aerobic microorganisms such as spoilage fungi diminish and to the point of cessation when oxygen is depleted. Ammoniation of straw occurs through the reaction of ammonolysis to form ammonium salts. Ammonium salt is a kind of non-protein nitrogen compound, which can be used by rumen microorganisms of ruminants to synthesise good bacterial protein and be digested and absorbed by animals, thus improving the digestibility, nutritional value and palatability of straw. Alkalisation of straw can make the cellulose, hemicellulose and lignin in straw partially decomposed, increase permeability, so that the rumen fluid in the rumen of ruminant livestock is easy to infiltrate, while a small amount of lignin is dissolved to form hydroxyessentialin, thus improving the digestibility of straw.

2.3 Energy from straw

Straw substitution for coal or natural gas reduces global warming, non-renewable energy use, human toxicity and ecotoxicity, and straw biomass conversion to energy is more effective than coal but less effective than natural gas[25]. Converting unnecessary crop residue use (e.g. cooking, open burning and other activities) to bioenergy would avoid 122 million tonnes of GHG emissions by 2021, while replacing corresponding fossil fuels with bioenergy would reduce emissions by an additional 3.4 - 88.6 billion tonnes[26].

Straw energy utilisation technologies mainly include straw direct combustion technology, straw gasification technology, straw fermentation for biogas production, straw bioethanol production technology and straw curing and moulding technology. Straw can be used to generate electricity, and most developed countries have included projects such as biomass power generation or biomass liquid fuel production in their national energy strategies[27]. Power generation technologies also include straw combustion for power generation and straw gasification for power generation. The most widely used power generation technology using biomass is direct combustion[28]. This is because direct combustion is characterised by ease of implementation and low cost. The main direct combustion technologies are fixed bed, moving bed and fluidised bed combustion[28].

Although fixed bed combustion technology is reliable and less costly than the other technologies, the variation of fuel is limited. Whereas fluidised bed combustion is more expensive, this type of boiler can handle a wide range of fuels and is becoming the preferred combustion technology for larger scale biomass combustion[28]. Large-scale straw boilers have been used in countries such as the UK and Denmark for heating, power generation and combined heat and power (CHP)[29].

Straw gasification technology is a promising green thermochemical conversion method, which is incomplete in a gasification device combustion, which carries out a variety of chemical reactions that can effectively convert crop straw into combustible gases (e.g., gaseous hydrocarbon compounds such as CO, H_2, CH_4, etc.)[30]. The energy production efficiency of this technology is 3-5 times higher than that of direct combustion. The collected combustible gases are used to generate electricity. Straw gasification improves the energy utilisation of straw to some extent and reduces air pollution caused by straw burning[23].

Crop residues can be well used for biogas production through anaerobic digestion. Anaerobic digestion (AD) is a series of reactions including hydrolysis, acid production, acetone production and methane production. It has been shown to be an effective method for producing clean biogas, liquid fertiliser, valuable digestion residues from waste biomass[10]. Fu et al. discussed different anaerobic digestion processes for treating crop residues to improve biogas production[31]. Crop residues contain high content of cellulose, hemicellulose and lignin[10]. However, due to their polymeric structure, these lignocellulosic components cannot be easily saccharified and fermented for biogas production. But pretreatment can destroy lignin in biomass and enhance the accessibility of lignocellulosic compounds. Crop residues are anaerobically fermented to produce biogas, and the by-products are digestate and digestate. The digestate can be used to feed fish and the biogas can be used as organic fertiliser and an ideal soil conditioner.

The utilisation of bioethanol as an alternative energy source is increasing. Bioethanol production from crop straw is the degradation of cellulose and hemicellulose in straw to monosaccharides by physical or chemical pre-treatment or enzymatically, followed by fermentation and distillation to produce and recover bioethanol. Straw solid moulding fuel is to soften straw at 200-300℃, crush it, add appropriate amount of binder and water to mix it, and apply certain pressure to squeeze the crop straw into pellets, blocks and rods and other moulding fuels, which has the advantages of high efficiency, cleanliness, easy to ignite, zero carbon dioxide emission, and easy to be stored and transported, and so on. The production and use of bioenergy from crop residues, in particular the blending of biofuels with conventional fuels, can prevent the overexploitation of fossil fuels, thereby reducing greenhouse gas emissions and contributing to climate change mitigation.

2.4 Use of straw as an industrial raw material

Conventional packaging materials are difficult to process for degradation, a problem that exists with catering utensils and packaging boards, which can lead to ecological pollution. Biodegradable packaging materials, such as fast food containers, cling film, inner packaging liners for fruits and vegetables and packaging boards, are produced from straw, wheat straw and corn stalks. It is safe and hygienic, degradable, non-toxic and non-polluting.

Agricultural straw is an important raw material for pulp and paper production[9]. The use of straw as a raw material for paper production can reduce the exploitation of forest resources. Paper production from straw is low-cost, clean, and widely available. With the growing demand for paper in recent years, crop residues play a vital role in the pulp and paper industry[23]. The open structure of crop straw allows for easy diffusion and penetration of chemicals during ambient cooking to form high quality pulp compared to woody materials.

At present, the application of straw in the field of building materials has been quite extensive, and the consumption of straw is large. Straw can be used as building and decorative materials. After straw is crushed and added to binders, flame retardants and other ingredients in a certain proportion, it is mechanically stirred, extruded and cured at a constant temperature, and high-quality lightweight building materials can be produced, such as lightweight wall partition boards, clay bricks and honeycomb-core composite lightweight boards, etc. These materials are low-cost, light-weight, beautifully modelled and are green and pollution-free. Beyond the initial, straw can also make building materials. China's straw building materials are mainly: straw bricks, straw man-made panels and straw cement-based composite materials. With the advantages of non-radiation, non-toxic, non-polluting, and other building materials, there is no difference in function, the structure of the building is very stable.

2.5 Straw as substrate

Crop residues can be used as a raw material for agricultural production. Straw is nutrient-rich, widely available and low-cost, and is suitable for the production of culture media for edible mushrooms. Crop straw is first crushed and then nutrients are added to make the medium. Edible fungi such as mushrooms, shiitake, black fungus and enoki mushrooms can be produced. Rice and wheat straw are potential alternative resources for mushrooms and can be used as an effective substrate for mushrooms[32]. The use of crop straw as substrate for edible mushrooms can reduce the cost of inputs as well as efficiently utilise the straw. The Fig. 2 shows that different approaches to crop straw resource utilisation.

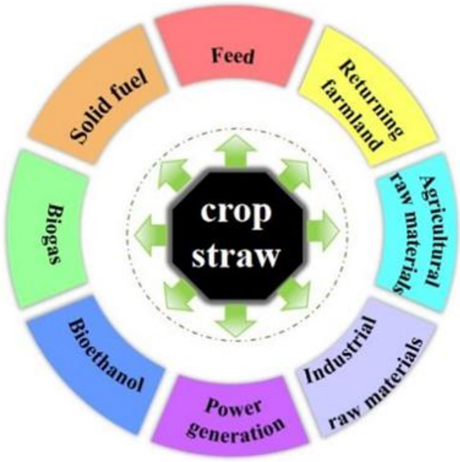

Fig. 2 Different approaches to crop straw resource utilisation.

III. Problems and countermeasures of straw utilization

At present, the comprehensive utilisation of crop straw in China is still in the primary stage, with a low level of comprehensive utilisation, small scale, decentralised and non-concentrated, low level of intensification, and a single utilisation technology, with straw returned to the field as the main focus. However, the direct return of straw to the field is likely to cause an imbalance in the soil C/N ratio, and compete with crop seedlings for nutrients, thus affecting the growth quality of seedlings. Straw for fodder requires pre-treatment. Physical treatments are not cost-effective, especially for small-scale farms, as they require expensive mechanical facilities or industrial processing[24]. Chemical treatments seem to be more practical as they do not require expensive machinery. However, chemicals can be harmful and safety measures need to be taken when using them. The amount of straw used for new energy use is very limited, and the proportion of straw used for power generation, straw gasification and straw liquefaction is still very low. The operating cost of straw power generation is high. The investment cost of generating units is higher than that of coal-fired generating units. Secondly, the calorific value of straw is low, energy density is low, and transport cost is high. Transport and storage of straw is difficult. Biogas from crop straw has been strongly promoted by the government, but the unstable operation and straw resources make the biogas usage rate low. Most crop farmers in China are small and do not engage in large-scale agricultural production, making it difficult to collect, transport and store crop straw[23, 33].

Different topographic conditions, crop types and farming systems, regional differences in the market for agricultural machinery and in the market for the supply of agricultural machinery services, and therefore constraints on mechanised crop-straw-returning technology. In some towns and villages, farmland is small, chaotic and irregularly laid out, and many mechanised ploughing roads and roads cannot be successfully docked, making it necessary for farm machinery to pay a large transfer cost. Many mountainous areas lack vast plains and are not suitable for large-scale mechanised production operations. Rice, wheat, corn straw and other different modes of field return, there is a large and medium-sized tractor input is insufficient, straw return to the field of special machinery configuration is unreasonable problem. Due to geographical and climatic conditions, there are two or even three crops planted on the same field in a year. The effect of straw return depends on scientific and reasonable return method and good quality of machinery operation. Take wheat and maize double cropping system as an example. The method of mixed burial and field return of straw has a cost advantage over other methods of field return. However, continuous and complete field return leads to excessive straw return and increased soil loading, there is not enough time for biodegradation and therefore the straw is not completely decomposed in the soil, which is not favourable for root penetration[10]. As a result, a large amount of straw accumulates in the shallow layer of the soil, which cannot be fully absorbed by the soil, soil voids increase, and soil moisture is easily lost, which affects seed germination and growth.

The rural social service system is imperfect, and the straw resource utilisation behaviour needs the help of agricultural machinery socialisation services. The cost of straw handling by farmers mainly includes machinery cost, labour cost and transportation cost. Farmers in rural areas are small and most of them are scattered, collecting straw requires a lot of manpower and material resources, which is a big investment and high collection cost, and they cannot get the economy of scale. It makes straw recycling unacceptable to both enterprises and farmers, who are the economic beneficiaries of straw recycling. If farmers are not compensated for the costs, direct burning of straw will occur. Transactions between farmers and farm machinery services must be given attention because the price of the transaction affects the realisation of the farm machinery service transaction. Many farmers are unable to make an effective judgement on the ability of straw resource utilisation to improve crop yields and increase income directly and effectively, ignoring the long-term benefits. The market mechanism of straw trading is not perfect, the trading price is not unified, and the price is lower than the farmers' expectation, which cannot fully mobilise the farmers' enthusiasm to participate.

IV. Life cycle assessment of straw utilization

LCA can be explored to quantify the environmental impacts of different utilisation and treatment of crop residues, combined with socio-economic effects, to provide decision makers with different options related to the sustainable use of crop residues[4]. The Fig. 2 shows the life cycle assessment framework. Many studies have used LCA to evaluate the environmental impacts of different crop residue treatments[1]. Silalertruksa et al. compared the LCA of direct combustion of rice straw for power generation, bioethanol fuels and fertilisers, and the bioethanol pathway was found to be the most environmentally sustainable in terms of its potential to reduce global warming and resource depletion[34]. Lansch et al. evaluated the environmental impacts of the substitution of cattle manure by a rural biogas system in Ethiopia. burning on the environment[35]. In all scenarios of this study, they controlled processes that could lead to pollution and greenhouse gas emissions to obtain better environmental advantages. Renó et al. assessed the main environmental impacts of methanol production from bagasse using the LCA approach[36]. Silalertruksa and Gheewala compared the LCA of rice straw for power generation, bioethanol fuel and fertiliser and found that the practice of bioethanol resulted in the highest environmental sustainability and reduced global warming potential[34]. Palmieri assessed the incorporation, burning and baling of straw; each mode was divided into stages of ploughing, harrowing, sowing and harvesting, and the results showed that: the decomposition stage contributed to the global warming potential as follows: 52 % for mixing and 67 % for baling[37].

The production and use of bioenergy from crop residues, in particular the blending of biofuels with conventional fuels, can prevent the overexploitation of fossil fuels, thereby reducing greenhouse gas emissions and contributing to climate change mitigation. In a study, Soam et al. noted that the use of rice straw to generate electricity reduces more greenhouse gases compared to biogas production[18].

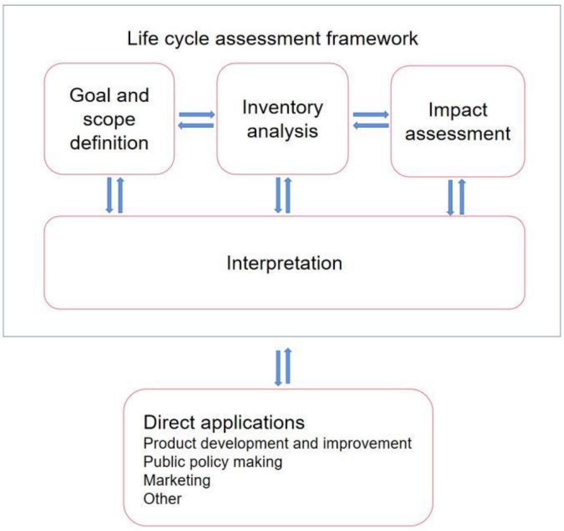

Fig. 3 Life cycle assessment framework.

V. Conclusion

This paper reviews the comprehensive utilisation of crop residues in China and raises the issue of crop residue resourcing. Adoption of full life-cycle assessment (LCA) as a methodology for the life-cycle impacts of different utilisation modes. The following suggestions are therefore given:

1) Promote the industrialisation, intensification and mechanisation of the comprehensive utilisation of crop straw.

2) The market for agricultural machinery and the market for the supply of agricultural services is rationally distributed according to regional differences.

3) Improve the rural social service system and the straw trading market mechanism, and fully mobilise the enthusiasm of farmers to participate.

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