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Review

Co-processing paths of agricultural and rural solid wastes for a circular economy based on the construction concept of “zero-waste city” in China

Hongbin Cong [a,*], Haibo Meng [a], Mingsong Chen [a], Wei Song [b], Haohan Xing [a]

[a] *Institute of Energy and Environmental Protection, Chinese Academy of Agricultural Engineering Key Laboratory of Energy Resource Utilization from Agriculture Residue, Ministry of Agriculture and Rural Affairs, Beijing 100125, China*
[b] *College of Mechanical and Electrical Engineering, Qingdao Agricultural University, Qingdao 274000, China*

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A B S T R A C T

The treatment and utilisation of agricultural and rural solid wastes are important initiatives to advance high-quality agricultural development and improve rural living environment in a concerted manner. We identified the general background and need of agricultural andrural solid wastes in China, and elucidated the main sources and classified the agricultural and rural solid wastes; we grouped the wastes according to their source, value, components, and form, and described the basic characteristics of agricultural and rural solid wastes, namely, diversity, spatio-temporal fluctuations, and consistency of collection. Based on this, the technical pathways of agricultural and rural solid waste co-processing were systematically summarised for a circular economy based on the construction concept of ‘zero-waste city’ in China, including conversion to fertilisers and energy, value enhancement, and volume reduction. Three main models were developed, namely, the mixed fermentation of agricultural and rural solid wastes for fertiliser production, mixed pyrolysis/gasification/incineration for energy production, and urban-rural integrated waste treatment. Subsequently, we systematically analysed the main framework, fundamental characteristics, and applicable scenarios of the three models. We established the foundations and strategies for the co-processing and efficient utilisation of agricultural and rural solid wastes.

1. Introduction

The construction of a ‘zero-waste city’ is a powerful means to deepen the comprehensive management reform of solid waste and promote the construction of a ‘zero-waste society’ (Li, 2021). In December 2018, the General Office of the State Council issued the Pilot Work Plan for the Construction of a ‘zero-waste city’, which proposed the promotion of green agricultural production in pilot cities and the full utilisation of major agricultural solid waste, such as livestock and poultry manure, crop straw, waste agricultural film, and pesticide packaging waste, among others. Guided by the new development concepts of innovation, coordination, green development, openness, and sharing (Gao et al., 2023), the construction of a ‘zero-waste city’ will promote the reduction of solid wastes and improve resource utilisation through the practices of green production and lifestyle to minimise the environmental impact of solid waste.

The concept of a ‘circular economy’ encompasses policies and strategies for the effective utilisation of resources, while also limiting waste generation in the environment (Awasthi et al., 2022), which is similar to the construction of a ‘zero-waste city’. Circular economy, which implies waste prevention, reuse, and recycling, or the upper tiers of waste hierarchy (Luttenberger, 2020), directly contributes to the construction of a ‘zero-waste city’ owing to the reduced overall waste production from both manufacturing and raw material processing.

Agricultural and rural solid wastes, as important sources of solid wastes, mainly include straw, livestock and poultry manure, used agricultural film, discarded packaging, and domestic waste (Cong et al., 2020). The treatment and utilisation of agricultural and rural solid wastes, maintenance of a healthy agricultural ecosystem, and continuous improvement of the rural living environment are prerequisites to implementing Xi Jinping's ideas of ecological civilisation and green development. Rural areas are priority areas for improving livelihood and well-being, which concerns public health, sustainable agricultural development, and construction of beautiful

* Corresponding author.
E-mail address: conghongbin@163.com (H. Cong).

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rural areas (Cong et al., 2021). Therefore, the Chinese Government strongly emphasises the treatment and utilisation of agricultural and rural solid wastes. The construction of a 'zero-waste city' is an important measure to enhance ecological civilisation and build a beautiful country. A 'zero-waste city' also provides new opportunities for circular economy in terms of co-processing and diversified utilisation of agricultural and rural solid wastes.

Various waste-to-resource and waste-to-energy/fuel technologies have been developed and applied in recent years (He et al., 2020). Conventional waste treatment or utilisation techniques include composting, anaerobic digestion, and landfilling, whereas unconventional techniques include incineration, pyrolysis, hydrothermal processing, and enzymatic hydrolysis (Munir et al., 2021). Policies, processing methods, paths, and models for a circular economy have recently been investigated based on the above technologies, but these studies have mainly focused on municipal solid waste, industrial solid waste, and sludge. For instance, Rebehy et al. (2023) identified drivers and best practices towards circular economy for municipal solid waste management in Brazil. Awasthi et al. (2022) summarised the processing methods of municipal solid waste resources for a circular economy in China. Zhang et al. (2023) analysed the role of governments in the construction of zero-waste cities. Agricultural and rural solid wastes are characterised by large quantities and volume, diverse types, and complex properties. The treatment and utilisation of organic solid waste are limited by external factors, such as transportation, geographical conditions, and economic development level (Ke et al., 2022). It is necessary to conduct additional research on co-processing technologies and models of multiple wastes under the background of a 'zero-waste city'.

Based on the detailed understanding of waste co-processing, we aimed to: elucidate the main sources and basic characteristics of agricultural and rural solid wastes; analyse the technical routes of agricultural and rural solid waste co-processing for a circular economy based on the construction concept of a 'zero-waste city' in China; and construct co-processing models suitable for different application scenarios to provide fundamental support and decision-making reference for the treatment and efficient utilisation of agricultural and rural solid wastes.

2. Sources and classification of agricultural and rural solid wastes

2.1. Primary sources

Agricultural and rural solid wastes generally refer to solid and semi-solid wastes generated from agricultural production, rural domestic activities, and village construction activities, which cannot be reused and are thus, discarded in certain scenarios (Luo et al., 2022)). In general, they can be divided into two categories: agricultural production solid waste and rural domestic solid waste.

Agricultural solid waste refers to various solid wastes generated during agricultural production activities, including cultivation, livestock and poultry breeding, aquaculture, and on-site primary processing of agricultural products, as well as that from agricultural inputs (Li et al., 2021). Rural solid waste refers to various solid wastes generated from rural domestic and village construction activities (Hu et al., 2023), and mainly includes rural household waste, construction waste, and toilet waste.

2.2. Classification methods

In accordance with the general principles and basic methods of solid waste classification in China (Cong et al., 2020; Luo et al., 2022), agricultural and rural solid wastes were classified based on their source, value, composition, and forms (Table 1). Agricultural and rural solid wastes were combed through, inventoried, and further classified, which facilitated the systematic analysis of their basic characteristics, and technical pathways and models of their co-processing under different scenarios.

Based on their source, agricultural rural solid wastes can be divided into two primary categories: solid waste from agricultural production and rural domestic solid waste. In terms of value, they can be divided into recyclable solid waste, general solid waste, and hazardous solid waste. Recyclable solid waste refers to waste products generated during agricultural production and rural living, and can be collected for direct resale; this type of waste mainly includes end-of-life agricultural machinery, used greenhouse films, and beer bottles. With reference to the National Hazardous Waste List, hazardous solid waste mainly includes used pesticide packaging, mercury-containing waste batteries, and waste pharmaceuticals (MEE, 2021). The rest are considered as general solid wastes, which are the main components of agricultural and rural solid wastes (Cong et al., 2019a). According to their components, these solid wastes can be divided into perishable organic, difficult-to-degrade organic, and inorganic solid wastes. Agricultural and rural solid wastes primarily contain organic waste, especially perishable organic waste, which accounts for the vast majority. However, a relatively high proportion of difficult-to-degrade organic waste is present in rural household waste. Considering their forms, they can be divided into solid and semi-solid wastes, of which solid waste is predominant.

2.3. Basic characteristics

Agricultural and rural solid wastes originate from a wide range of sources and vary greatly in external form and physico-chemical properties, and their generation fluctuates geographically and seasonally, thereby exhibiting the following characteristics.

(1) Diversity. Solid wastes generated from agricultural cultivation, livestock breeding, rural life, and rural construction are diverse and complex in composition; they can be broadly categorised into more than 30 types of solid waste from agricultural production and more than 10 types of solid waste from rural life, with significant differences in their physical and chemical properties, such as calorific value and water content.
(2) Spatio-temporal fluctuations. Agricultural production, especially cultivation, is seasonal, thereby leading to the seasonal fluctuations in agricultural solid waste output. Additionally, solid waste generated from activities, such as rural tourism and agricultural carnivals, also shows seasonal characteristics. The outputs of agricultural and rural solid waste also exhibit spatial variability, influenced by factors such as the industrial structure, scale of farming, and economic status of residents in different regions.
(3) Consistency of collection. Despite the diversity and fluctuations in agricultural and rural solid wastes, they generally contain organic waste, especially perishable organic matter. From the perspective of co-processing and utilisation, agricultural production and rural domestic solid wastes can collectively be grouped according to properties, such as perishable and non-perishable, and low and high water content.

2.4. Disposal and utilisation status

In recent years, China generated approximately 870 million tons of straw and approximately 1.06 billion tons of livestock and

Table 1
Classification of agricultural and rural solid wastes.

Classification	Types		Main components	Notes
Sources	Agriculture production	Agricultural cultivation	Crop straw, fruit tree cuttings, waste mushroom spawn bags, vegetable trimmings, and rotten fruits	Agricultural rural solid waste originates from all aspects of agricultural production and rural life, and it includes various waste generated from activities such as rural tourism and agricultural carnivals. Wastes from agricultural production originate from all aspects of agricultural farming, livestock breeding, aquaculture, and on-site primary processing of agricultural products, mostly including recyclable solid wastes of plastic, metal, or glass
		Livestock farming	Livestock manure, dead livestock, and shed feathers	
		Aquaculture	Pond sludge and aquatic plant debris	
		Processing of agricultural products on site	Rice husk, peanut shells, corn cobs, fruit shells, and eggshells	
		Waste from agricultural inputs	Used agricultural films (mulch film, greenhouse film, mushroom bag film, etc.), discarded pesticide packaging and fertiliser packaging, waste nets, bedding, feed, and end-of-life agricultural equipment	
	Rural household	Rural household waste	Food waste, food packaging, used plastic shopping bags, used batteries, used home appliances, used clothing, discarded lamps, and discarded medicines	
		Rural toilet waste	Human excrement and domestic sludge	
		Rural construction waste	Slag, bricks, tiles, ceramic pieces, and scrap wood	
Values	Recyclable solid waste		End-of-life agricultural machinery, used greenhouse film, used home appliances, liquor bottles, used cartons, scrap metal, and used textiles	Recyclable solid waste is easily identified by farmers and generally recycled through the waste recycling market; hazardous solid waste in agricultural and rural solid wastes is the focus of public education and awareness campaigns. Guidance should be provided to farmers on its proper sorting and handling, followed by collective recycling and disposal established by the government
	General solid waste		Straw, livestock manure, fruit tree and wood cuttings, corn cobs, vegetable trimmings, used mulch, dead livestock, food waste, and construction debris	
	Hazardous waste		Discarded pesticide packaging, used mercury-containing batteries, discarded human drugs and animal drugs, waste lamps, and expired personal care products	
Components	Perishable organic solid waste		Straw, livestock manure, fruit tree cuttings, vegetable trimmings, peanut shells, dead livestock, food waste, toilet manure, and domestic sludge	Agricultural and rural solid wastes predominantly include organic waste, especially perishable organic solid waste, which is both a pollutant and a resource
	Recalcitrant organic solid waste		Used agricultural film, discarded pesticide packaging (plastic) and fertiliser packaging, plastic food packaging, and plastic shopping bags	
	Inorganic solid waste		Discarded pesticide packaging (quartz and metals), end-of-life agricultural machinery, end-of-life fishing machines, glass bottles, and slag	
Forms	Solid waste		Crop straw, fruit tree cuttings, waste mushroom bags, used agricultural films, discarded pesticide packaging, peanut shells, and corn cobs	Agricultural and rural solid wastes predominantly include solid waste, and semi-solid waste has a relatively concentrated distribution
	Semi-solid waste		Livestock waste, toilet waste, sludge, and food waste	

poultry manure, used approximately 2.5 million tons of agricultural film, and discarded approximately 3.5 billion pieces of pesticide packaging materials every year (MARA, 2021; XNA, 2021). In the same year, the country also produced 160 million tons of rural household waste (Liu, 2021; Shen, 2021). Through policy guidance, financial support, and market cultivation, various agricultural and rural solid waste treatment and utilisation systems have been implemented in China, wherein the utilisation rates of straw and manure exceeded 87% and 93%, respectively, and the recycling rate of agricultural film reached 80%. Approximately 97% of large-scale farms are equipped with manure treatment facilities, and more than 90% of villages have established rural domestic waste collection and treatment systems (MEE, 2022).

3. Processing technology system

The key factor to advancing the co-processing of organic agricultural and rural wastes is the development and application of practical technologies and light, simplified equipment. These mainly include technologies for the utilisation of waste as fertilisers, waste-value enhancement, energy generation, and waste reduction (Cong et al., 2019b).

3.1. Technology for the utilisation of waste as fertilisers

In addition to containing rich amounts of carbohydrate, perishable organic solid wastes, such as straw, human and animal manure, rotten fruits, weeds, and food waste, also contain nitrogen, phosphorus, potassium, and other essential or beneficial elements for plant growth; namely, calcium, magnesium, and silicon, which possess high value for utilisation as fertilisers (Dai, et al., 2021; Shi et al., 2021). Utilisation of agricultural and rural solid wastes as fertilisers primarily involves aerobic fermentation, anaerobic + aerobic fermentation, and slow pyrolysis (biochar). The utilisation of perishable organic solid waste in agricultural and rural solid wastes as fertiliser after its unified collection and classification can increase soil organic matter and effectively enhance soil mineral nutrients and carbon sequestration levels.

Aerobic composting technology refers to the biochemical process wherein organic matter is degraded with sufficient oxygen supply by aerobic and facultative bacteria. Aerobic composting temperature can generally reach 55–60 °C, which facilitates the rapid degradation of organic matter and effective killing of pathogenic bacteria and weed seeds (Wang, Liu, et al., 2021). In anaerobic and aerobic fermentation, organic waste first goes through microbial decomposition and metabolism under certain moisture, temperature, and anaerobic conditions to form a combustible gas mixture containing methane and carbon dioxide. Subsequently, further aerobic decomposition of biogas residue enhances the utilisation value of organic solid waste (Fagbohungbe et al., 2017). Slow pyrolysis refers to the process of thermal decomposition of organic solid waste under anaerobic or anoxic conditions to form stable, insoluble, highly aromatised, and carbon-rich solids (biochar). Biochar has a large specific surface area and well-developed pores, which can be used for improving and remediating soil, and its agricultural value (Cong et al., 2019c; Hamidzadeh et al., 2023). The process classification, facilities, equipment, and main features of different technical routes are shown in Fig. 1; the selection of a specific technology for a project is based on the application scenarios.

3.2. Waste-value enhancement technology

Compared with the traditional utilisation of organic solid waste as fertiliser, waste-value enhancement results in higher-value outputs; however, it generally requires higher inputs. Waste-value enhancement technology is mainly divided into two categories: raw material and substrate. Raw material utilisation refers to the manufacturing of various products or industrial raw materials using straw, fruit tree cuttings, corn cobs, fruit shells, and used agricultural films as the main input materials through physical, chemical, or biodegradation methods (Wang, Xu, et al., 2021). The products mainly include pulp, manmade panels, recycled plastics, straw sculptures, facility walls, and functional biochar-based materials (MARA, 2022). Substrate utilisation refers to the processing of straw, fruit tree cuttings, rice husk, and cow manure for the preparation of organic solid materials that provide good growth conditions and certain nutrients for animals, plants, and microorganisms, including edible mushroom substrate, plant nursery substrate, and animal bedding (Cong, et al., 2019b).

Earthworm farming is another important method for high-value utilisation of organic agricultural and rural solid wastes. Organic solid waste, such as livestock manure and straw, can be mixed in certain proportions and subjected to high-temperature fermentation for use as earthworm feed. Earthworm excrements are used to produce organic fertiliser, and the grown earthworms can be used to make earthworm active protein. Moreover, some facilities have investigated the treatment of agricultural and rural organic waste by farming black soldier flies and cockroaches (MARA, 2022). The

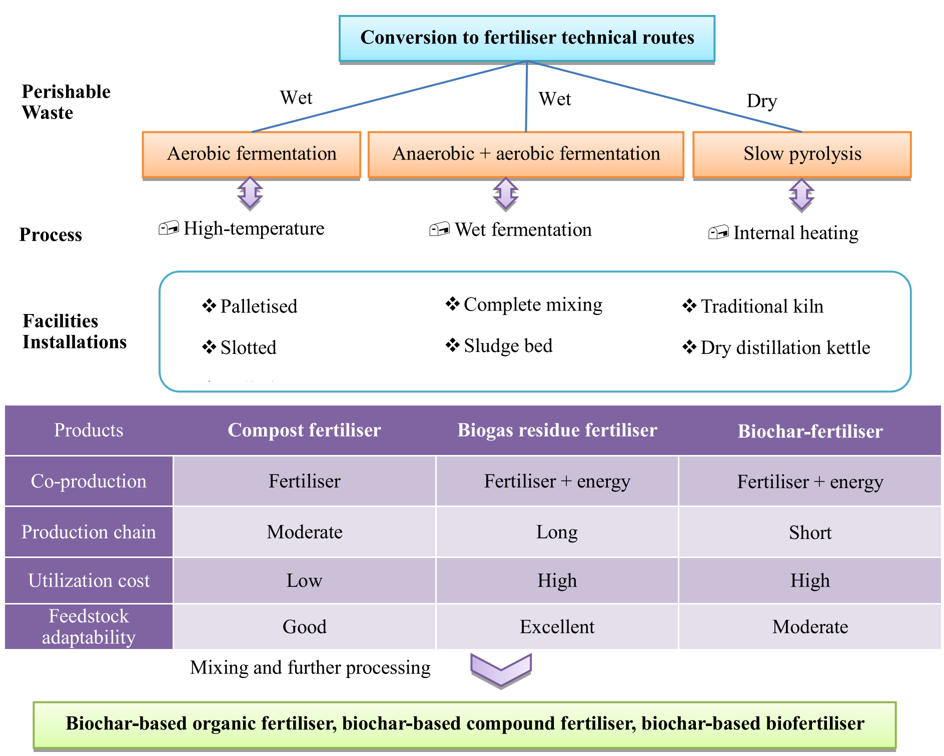

Fig. 1. Technical routes for the co-processing of agricultural and rural solid wastes as fertilisers.

co-processing routes for the high-value utilisation of agricultural and rural organic solid wastes, along with the products, are shown in Fig. 2.

3.3. Energy generation methods

Energy generation using agricultural and rural solid wastes involves physical, chemical, or biological technologies to convert the materials into energy products, such as biomass pellet, biodiesel, gas or heat, and electricity. The use of plastic-containing solid waste (Cong, et al., 2019a), which incurs high cost for sorting and is not suitable for fertiliser production or high-value use, for energy production should actively be promoted to minimise the amount of agricultural and rural solid wastes going directly to landfills.

The slow pyrolysis of biomass is a thermal decomposition process with a moderate temperature (500−600 °C), low heating rate, and long residence time in hypoxic or anaerobic conditions (Kambo et al., 2015), and is considered a promising technology for converting agroforestry residues into clean biofuels and reducing atmospheric CO_2 concentrations (Yang et al., 2021). Pyrolysis gas contains a high calorific value and is a high-quality renewable energy. Gasification technology refers to the pyrolysis and oxidative and reductive reforming reactions of organic polymers to produce combustible gases, such as carbon monoxide, hydrogen, and small hydrocarbons under certain thermodynamic conditions using air, oxygen, or water vapour as gasifying agents. Combustion technologies can generally be classified as pulverised combustion and hay bale combustion, among others. To reduce the emissions of volatile organic compounds, the furnace chamber temperature is generally required to be > 850 °C, and the flue gas residence time should be at least 2 s (Ajay et al., 2023). The technical routes and products for energy generation using organic solid waste in agriculture and rural areas are shown in Fig. 3.

3.4. Main technical routes for waste reduction

Solid waste reduction refers to the adoption of measures, such as clean generation, source reduction, and safe disposal, to reduce the quantity, volume, or harmfulness of waste and mitigate the current and future hazards of waste to human health and the environment. Agricultural and rural solid waste reduction includes both pre- and post-generation reduction. In this study, only post-generation technological measures were considered. Post-generation reduction, similar to resource reutilisation, requires a certain level of economic input and incurs environmental costs, whereas pre-generation reduction generally involves resource reutilisation measures (Liu, 2021). To promote the collective reduction of agricultural and rural solid wastes, technologies and

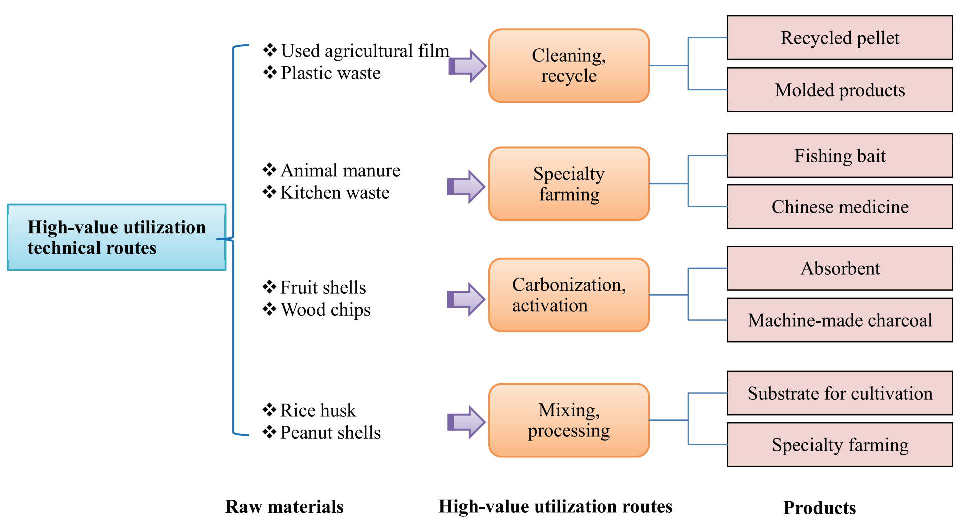

Fig. 2. Technical routes for co-processing of agricultural and rural solid wastes for high-value utilisation.

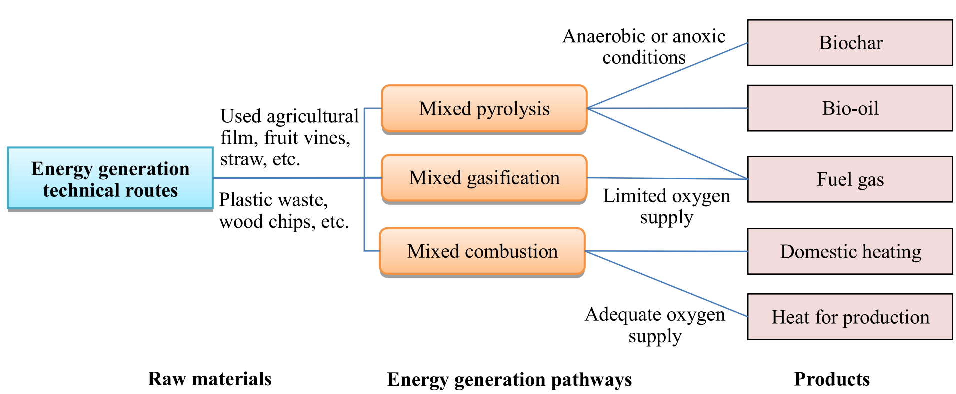

Fig. 3. Technical routes for co-processing of agricultural and rural solid wastes for energy generation.

small-scale equipment for solid waste sorting, dehydrating, and packaging need to be developed for the direct reduction of the volume or weight of solid waste. Additionally, technologies such as co-pyrolysis and co-combustion can be used for both energy generation and solid waste reduction.

4. Co-processing paths

4.1. Main model of fertiliser production through fermentation of mixed raw materials

Model framework: As shown in Fig. 4, the model is systematically constructed at three levels: waste classification, waste treatment and transformation, and product application. In the waste classification step, farmers are continuously encouraged and provided with the necessary resources to collect recyclable waste products. In general, the recycling of this type of waste is correctly conducted owing to the relatively low level of economic development in rural areas (Gross et al., 2021). Simultaneously, public awareness campaigns should focus on hazardous waste to support the establishment of an agricultural and rural hazardous waste collection and disposal system (Song et al., 2021). Additionally, farmers should be guided to classify production and domestic solid wastes into perishable and non-perishable categories regardless of the water content of the wastes. In the waste processing and transformation step, biochemical transformation technology is vital. To achieve the transformation of organic solid waste to fertilisers, aerobic and anaerobic fermentation methods are used to degrade perishable waste into organic fertilisers, and biogas can be co-produced based on actual needs. In the product application step, compost, biogas digestate fertiliser, and biogas products are directly channelled towards agricultural production or rural domestic use, thereby achieving the *in-situ* conversion of solid waste. A company in Changzhi City, Shanxi Province, has launched a 'five-in-one, one-stop' treatment model, which is a preliminary exploration of this technological model, showing good practical outcomes.

Features of the model: (1) The model focuses on biochemical transformation technologies to recycle solid waste through fertiliser production, and thus has an important role in promoting land fertilisation and increasing the soil carbon sink. (2) The model can completely use the existing facilities and equipment for fertiliser production from livestock and poultry manure to treat perishable organic waste generated by rural domestic activities, thereby improving the utilisation rate of facilities and equipment. (3) The model is flexible and can combine aerobic and anaerobic fermentation technologies in an adjustable manner, depending on the status of solid waste generation and product markets.

Application scenarios: This model can be applied to villages, towns, or farms with relatively large-scale farming or breeding activities, especially those with relatively low use of mulch film, or areas where plastic solid waste can be effectively separated from perishable organic solid waste.

4.2. Main model of energy supply through mixed feedstock pyrolysis/gasification/combustion

Model framework: As shown in Fig. 5, this model is also systematically constructed at three levels: waste classification, waste treatment and transformation, and product application. In the

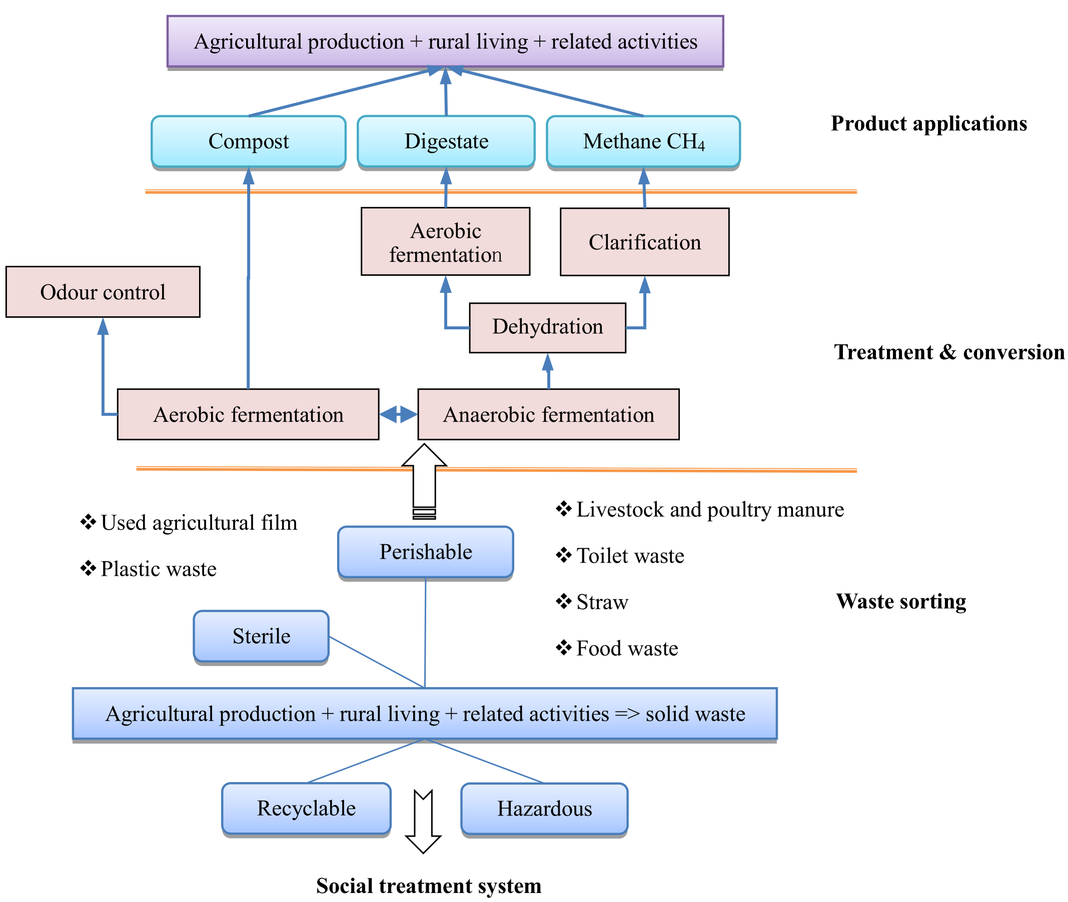

Fig. 4. Model of mixed fermentation of agricultural and rural solid wastes for fertiliser production.

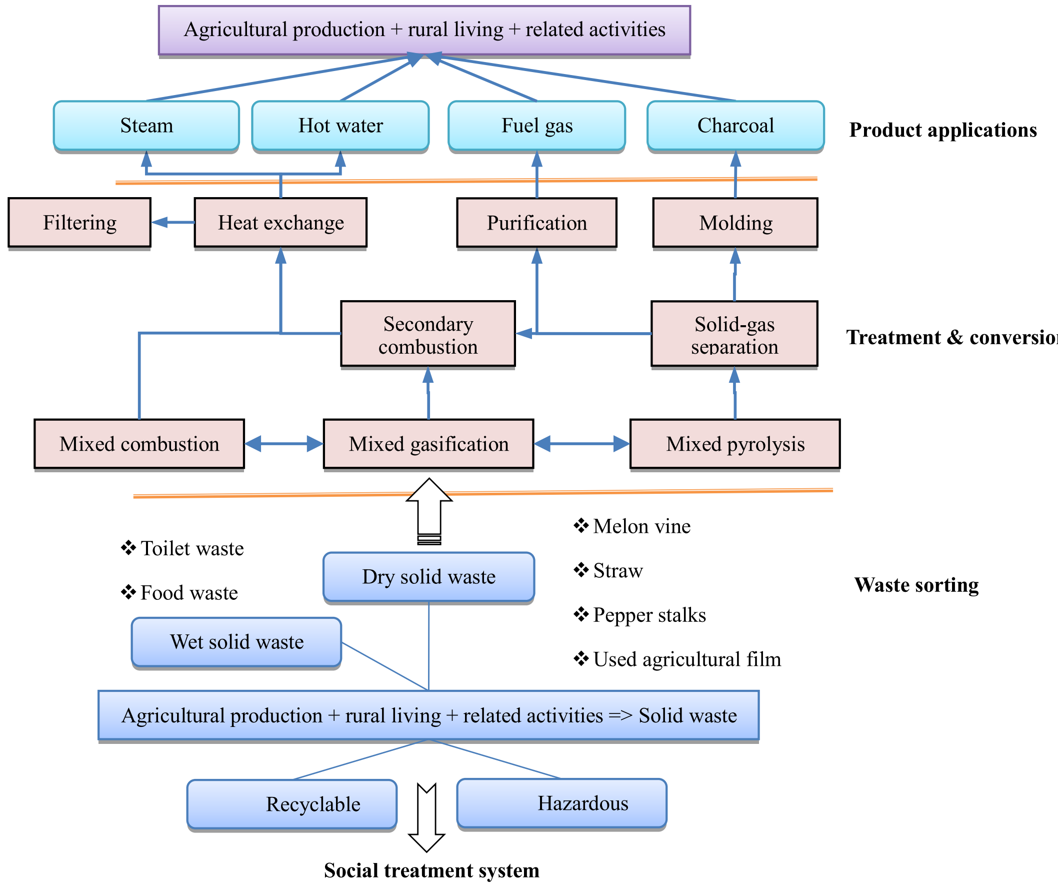

Fig. 5. Mixed pyrolysis/gasification/combustion of agricultural and rural solid wastes for the energy supply model.

waste classification step, the treatment of recyclable and hazardous wastes is similar to that in the fertiliser production model. Furthermore, farmers are guided to uniformly classify the production and domestic organic solid waste into dry and wet categories regardless of the perishability of the waste. In the waste treatment and transformation step, thermochemical transformation technology is used to convert organic solid waste with low water content into products such as gas, hot water, and steam through pyrolysis, gasification, or combustion. The co-generation of clean energy from charcoal can further realise the energy transformation of organic solid waste according to actual needs. In the product application step, all types of end-products are directly used for agricultural production or rural domestic activities to achieve the *in-situ* conversion and utilisation of solid waste. A company in Zunhua City, Hebei Province, has launched a treatment model to achieve distributed clean energy supply, and the preliminary investigation of this technological model has indicated good practical outcomes.

Model characteristics: (1) The model uses thermochemical conversion technology to achieve the local *in-situ* utilisation of solid waste through energy conversion, which has a positive impact on the structure of agricultural and rural energy and the reduction of carbon emissions. (2) The model pools solid waste together and classifies them into perishable and non-perishable wastes. These wastes can be converted into various energy products, exhibiting strong adaptability. (3) The model has flexible components, combining pyrolysis, gasification, and combustion to accommodate various generation conditions of solid waste and product markets.

Application scenarios: The model can be applied to intensive vegetable, fruit, and melon cultivation areas, grain and cotton cultivation areas, and remote mountainous areas, wherein plastic solid waste cannot easily be separated from perishable solid organic waste.

4.3. Main model of integrated urban-rural solid waste treatment

As shown in Fig. 6, various types of solid waste generated from agricultural production, rural domestic activities, and rural construction activities are collected and grouped into municipal household waste, construction waste, industrial solid waste, and hazardous solid waste, which are then collectively treated through the municipal solid waste transfer and disposal system for the integrated urban-rural treatment. This model does not require a separate agricultural and rural solid waste treatment system and is characterised by low input costs and standardised operation and management. This is suitable for suburban villages, especially where agricultural facilities are mainly used for the large-scale cultivation of fruits and vegetables, and in scenarios where perishable solid waste cannot easily be separated from used agricultural films. Moreover, as the level of agricultural economy and transportation are relatively decent in suburban areas, during the process of urban-rural integrated treatment, the value enhancement model of solid waste can be explored based on the output characteristics of solid waste and external conditions. An integrated urban-rural solid waste sanitation treatment model has been

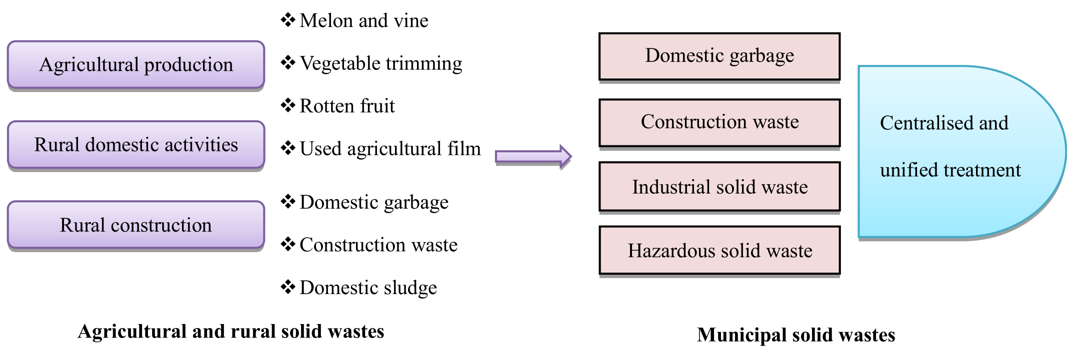

Fig. 6. Integrated urban-rural treatment model for agricultural and rural solid wastes.

introduced by a company in Panjin City, Liaoning Province, and the preliminary study of this technical model has achieved promising results.

5. Analysis of the concept and significance of co-processing

5.1. Understanding co-processing

The prefix 'co' implies 'joint' or 'together', with the connotation of collaboration or complementation. Co-processing of agricultural and rural solid wastes is based on a detailed analysis of the common characteristics of various types of agricultural and rural solid wastes and their classification methods. Through innovations in policies, technologies, models, and mechanisms, integrated planning and system design can be conducted according to local conditions to maximise the utilisation rate of facilities and equipment and reduce treatment and utilisation costs.

To understand the co-processing concept of agricultural and rural solid wastes for a circular economy under the background of the construction of a 'zero-waste city' in China, the following key points need to be noted. (1) Co-processing comprises two types of basic scenarios. The first one involves exploring complementary areas between various agricultural and rural solid wastes to overcome the drawbacks of using a single raw material and promote efficient utilisation, such as the co-pyrolysis of sludge and straw (Dai et al., 2021). The second one involves reducing the cost of separating mixed solid waste by implementing innovative mixed raw material treatment technologies and exploring low-cost treatment models, such as the co-pyrolysis of melon vines and used plastic mulch film (Wang, Burra, et al., 2021). (2) Promoting the co-processing of agricultural and rural solid wastes has more implications than just developing a new technical pathway or model. It is a systemic operation that requires systematic planning of the classification methods, treatment technologies, and product applications for agricultural and rural solid wastes by considering their inherent characteristics and external conditions. Moreover, it is essential to strengthen the coordination between responsible government divisions and public participation as well as promote innovative technology development, new policy formulation, and new exploratory mechanisms. (3) The goal of co-processing agricultural and rural solid wastes is clear, namely, to minimise the treatment cost or maximise the value of utilisation. The necessity or complementarity of different solid wastes for co-processing must be analysed, while also considering the technical feasibility and economic aspects of co-processing to evaluate its applicability.

5.2. Overview of agricultural and rural solid waste co-process in China

In recent years, approaches such as promoting the high-quality development of agriculture and rural areas, multiple routes, including government support, market operation, and public participation, have been explored and implemented to process the main solid wastes from rural production and living, such as straw, livestock and poultry manure, dead livestock and poultry, used agricultural film, discarded pesticide packaging, and rural household garbage. These routes robustly promote the treatment of agricultural surface pollution and rural living environment remediation, thereby establishing a system of policies, technologies, and markets for the treatment and utilisation of agricultural and rural solid waste. In general, the level of industrial development of straw, livestock manure, and dead livestock treatment and utilisation is relatively high, with effective results being achieved in standardised production, enterprise operation, and market-oriented operation. For the collection and treatment of used agricultural film, discarded pesticide packaging, and fertiliser packaging, several approaches have been explored, including extended producer/operator responsibility, deposits, incentives, and replacement systems. For integrated urban and rural domestic waste treatment, a model comprising collection at villages, transfer to towns, and treatment in the county has been examined. However, owing to the relatively late start of the collection and treatment of used agricultural film, discarded pesticide packaging, and rural domestic waste, the overall level of industrialised development of their treatment and utilisation is relatively low.

At present, various types of agricultural and rural solid wastes are treated by relatively independent treatment systems and relatively mature utilisation models, but some deficiencies are present in terms of co-processing. Further exploration for the co-processing routes and models is required to improve the utilisation rate of agricultural and rural solid waste treatment facilities and equipment, reduce treatment costs, and facilitate specific scenarios and actual needs. Additionally, various types of agricultural and rural solid waste treatment are under different administrative agencies. Therefore, flaws in the top-down design and departmental linkages between various agencies require changes to promote the co-processing of agricultural and rural solid wastes.

5.3. Analysis of co-processing needs

The promotion of co-processing of agricultural and rural solid wastes in a scientific, orderly, and site-specific manner under the background of a 'zero-waste city' requires the following aspects.

(1) Development of key technologies and simplified equipment. Based on the analysis of the physical and chemical properties of various types of agricultural and rural solid wastes, the mechanism of co-processing must be investigated; key technologies for co-pyrolysis, co-combustion, and co-fermentation processes must be developed for agricultural and rural solid wastes; and the development of light, simplified equipment suitable for use in rural areas must be prioritised, thereby providing technical support for the co-processing of agricultural and rural solid wastes.
(2) Exploration of co-processing pathways and models. Agricultural and rural solid wastes in rural areas need to be collectively classified and sorted based on their sources and further processed through different routes, including conversion to fertilisers, value enhancement, or energy production, according to actual needs. We need to actively explore sustainable, replicable, and generalisable models of co-processing to promote the *in-situ* use of organic solid waste in agriculture and rural areas.
(3) Construction of a long-term mechanism for operation. The farmers' sense of participation and collaboration in the sorting and related treatments of solid waste should be enhanced. This can be achieved through policy formulation, management innovation, public awareness campaigns, and market action and to strengthen coordination and communication among various government agencies to form an efficient operational framework with the participation of all stakeholders. This can help realise a long-term mechanism for the co-processing of solid waste in agriculture and rural areas.

6. Conclusions

In this study, we systematically analysed the concept and current situation of the co-processing of agricultural and rural solid wastes and summarised the basic needs in several aspects, such as the development of key technologies; creation of light, simplified equipment; exploration of co-processing routes and models; and establishment of long-term mechanisms for linked operation. Furthermore, we identified the main sources and classification methods for agricultural and rural solid wastes; classified the wastes according to their sources, value, components, and forms; and explained the basic characteristics of agricultural and rural solid wastes, namely, diversity, spatio-temporal fluctuations, and consistency of collection.

Based on the aforementioned analysis, we proposed co-processing technological routes comprising fertiliser production, value enhancement, energy production, and reduction of agricultural and rural solid wastes. Three models, namely, mixed raw material fermentation for fertiliser production, mixed raw material pyrolysis/gasification/combustion for energy production, and integrated urban-rural treatment, were further formulated for a circular economy based on the construction concept of a ‘zero-waste city’ in China. The main framework, basic characteristics, and application scenarios of the three models were systematically explained. Thus, we provide basic foundations and decision-making support for promoting and guiding the co-processing and efficient utilisation of agricultural and rural solid wastes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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