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REVIEW

LIVESTOCK AND POULTRY MANURE MANAGEMENT FROM THE PERSPECTIVE OF CARBON NEUTRALITY IN CHINA

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KEYWORDS

valorization of animal manure, manure management, carbon emission, carbon footprint, methodology, carbon trading

HIGHLIGHTS

- Carbon reduction potential of manure treatment technologies was summarized.
- Accounting methodologies of carbon emission and footprint of manure were analyzed.
- The quote of carbon trading market at home and abroad was analyzed.
- Some points for the boost of potential of manure carbon trading were advised.

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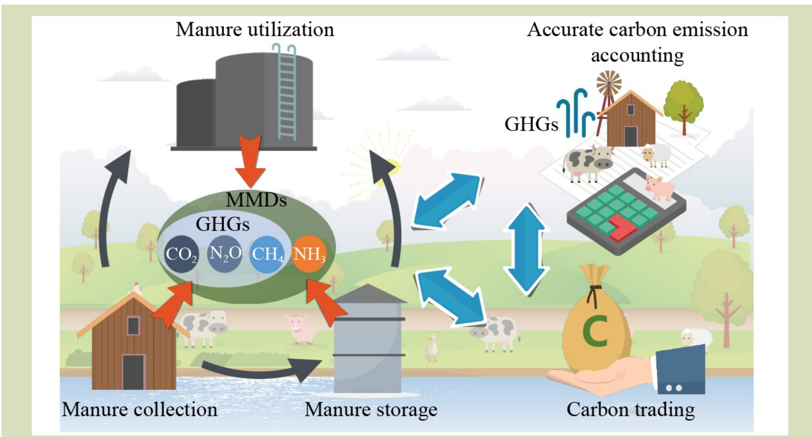
GRAPHICAL ABSTRACT



ABSTRACT

The rapid growth of the livestock and poultry production in China has led to a rise in manure generation, which contributes to the emissions of GHGs (greenhouse gases including CH_4, N_2O and CO_2) and other harmful gases (NH_3, H_2S). Reducing and managing carbon emissions has become a critical global environmental imperative due to the adverse impacts of GHGs. Unlike previous reviews that focused on resource recovery, this work provides an unique insight of transformation from resource-oriented manure treatment to integration of resource recovery with pollution reduction, carbon accounting and trading, focusing on the sustainable development of manure management system. Considering the importance of accounting methodologies for carbon emission and trading system toward carbon neutrality society, suggestions and strategies including attaching high importance to the development of more accuracy accounting methodologies and more practical GHG emission reduction methodologies are given in this paper. This work directs the establishment of carbon reduction methodologies and the formulation of governmental policies for livestock and poultry manure management system in China.

1 INTRODUCTION

Global population growth, socioeconomic development and improved living standards have led to surging demand for livestock and poultry products such as meat, eggs and milk. Consequently, livestock and poultry production has undergone rapid expansion, transitioning from small-scale family farming to large-scale operations. In particular, animal husbandry in China has had significant growth over the past 50 years, with a 13.3% increase in total output value[1]. This expansion has resulted in the production of an enormous amount of livestock and poultry manure, totaling up to 3.8 Gt annually, which is an inevitable byproduct of the livestock and poultry production[2,3]. The random discharge of livestock manure without effective treatment not only affects the construction of the ecological environment in China but also hinders the sustainable development of the ecological aquaculture industry[4–6]. The high-density livestock production and the excessive accumulation of waste on limited land has exacerbated environmental problems such as water eutrophication, heavy metal pollution and soil compaction. However, with a high organic matter content ranging from 30% to 70%, livestock and poultry manure represents a valuable carbon source that can be transformed into clean energy, such as CH_4 and H_2, through anaerobic fermentation[7]. Accordingly, livestock and poultry manure can be reduced, recycled, and treated as well as their environmental pollution can be decreased. Consequently, the potential utilization value of manure has improved greatly[8].

The resource value of manure has attracted significant attention in academic, production and utilization sectors. After decades of research and development, the technology for treating livestock and poultry manure is relatively mature. Many existing studies focused primarily on the resource properties of manure, such as the production of fertilizer, feed and bedding, while ignoring the pollution potentials attached to the manure treatment technology itself, such as the potential emissions of greenhouse gasses (GHGs) and other harmful gases. In other words, manure treatment constituted an important source of GHGs. The choice of collection technology during the manure treatment process can affect the potential emissions of harmful gases, for example, manure cleaning by water submerging produced more GHGs than dry manure collection and solid-liquid separation technology[9,10]. Also, the degradation of organic matter contained in manure under anaerobic conditions generates CH_4 and N_2O, exacerbating the emissions during manure storage. Similarly, CO_2 emission can occur during manure utilization such as the composting process for fertilizer production, while the anaerobic zone in the composting process can lead to disordered emissions of CH_4 and N_2O[11–13]. With the current emphasis on low-carbon agriculture, there is a growing interest in technologies that minimize negative environmental impacts and increase the value of agricultural byproducts. Therefore, various strategies for manure storage processes have been applied to reduce GHG emissions, such as reducing pH[14], compaction and mulching[15,16], adding appropriate regulators[17], or using storage tanks[18]. Likewise, techniques like earthworm culture (biologically transform and absorb nutrients in manure) or adding biochar to compost systems are inoculated in a compost system in the manure utilization stage, exhibiting potential in reducing emissions of NH_3, CH_4 and N_2O[19–22].

Currently, the global greenhouse effect stands as a major environmental crisis. Livestock and poultry production ranking among the three major sources of carbon emissions in Chinese agriculture[23], and its carbon emissions involve six processes, including feed grain planting, feed processing and transportation, feeding, gastrointestinal fermentation, manure management, and slaughtering and processing[24]. Livestock and poultry production accounts for 18% of global GHG emissions in 2006, higher than the emissions of the transportation industry according to the Food and Agriculture Organization of the United Nations[25–27]. The United Nations Framework Convention on climate change also predicts that by 2030, the maximum carbon emissions from livestock and poultry production could reach 4–6 Gt CO_2-eq (CO_2 equivalents)[28]. Livestock and poultry production contributes 14.5% of human-caused GHG emissions, and cattle alone are responsible for 65% of the global GHG emissions from the livestock and poultry production[29]. Hence, the significance of livestock and poultry production as a source of agricultural carbon emissions and a contributor to climate change should not be underestimated. To address these challenges, the United Nations issued the 2030 Agenda for sustainable development, which encourages countries to adopt sustainable production practices, conduct scientific research, and employ appropriate technologies as well as management methods to reduce the GHG emission potential of livestock and poultry production by 30%[3,29]. The key to achieving this goal is to encourage pollution and carbon reduction in the livestock and poultry production and develop a carbon trading market[30,31]. The theoretical basis for reducing carbon and other pollutant emissions from the livestock and poultry production include accounting for the carbon emissions and carbon footprint of production facilities, determining the influencing factors and mechanisms of carbon emission, and gradually forming the methodology of carbon emission reduction. Fossil energy consumption in livestock and poultry production could be reduced by increasing the bioenergy generated from manure[32].

Existing research has compared the carbon friendliness and technology maturity of waste recycling technologies, generally yielding positive evaluations, although some studies present contrasting results. Although some technologies are well known due to their economy and practicability, uncertainties remain regarding the potential GHG emissions during manure management at different stages because of the complex interactions between the different technologies and environmental factors. In addition, there is a notable gap in comprehensive technical guidance, systematic carbon emission accounting methods, and a complete agricultural carbon emission trading system for manure treatment processes. Resource-based, systematic technical equipment and management models are still needed during waste treatment. The standard level of livestock waste treatment and utilization is low, being restricted by policy support and investment funds. Future research should prioritize livestock waste treatment methods based on specific production models, moving beyond laboratory experiments, to realize the diversified utilization of biomass resources. All parts associated with the use of livestock and poultry waste should be rationally evaluated, including technology research and development, management mode, policy guidance, and products sale. The exploitation of the waste should be developed toward a trend of comprehensive resource utilization and product diversification. Meanwhile, byproducts with high application potential should be used to achieve a closed loop in regional agricultural nutrition, and ultimately maximize economic benefits. Here, this work delves deeper into the concept of coordinated pollution reduction and carbon reduction, moving beyond the resource-oriented treatment approach, distinguished from previous reviews focusing on resource recovery and technology on manure treatment. With the current emphasis on low-carbon agriculture, the focus has shifted toward the treatment processes and technologies for livestock and poultry manure, particularly source reduction, process control and final application. The technologies for livestock and poultry manure management are highlighted in a way that coordinates the pollution and carbon reduction objectives. In addition, the influencing factors and mechanisms of manure carbon emission are summarized. Finally, the status and potential development of the carbon trading system as well as suggestions and potential countermeasures for livestock and poultry manure pollution reduction and carbon reduction from different levels are introduced and are depicted in Fig. 1.

2 KEY TECHNOLOGIES OF MANURE MANAGEMENT IN LIVESTOCK AND POULTRY PRODUCTION

2.1 Manure collection

Collection methods of livestock and poultry manure mainly include dry collection technology (manual cleaning and mechanical cleaning), water flushing and water submerging. For example, pig and cattle producers use water submerging technology, while large-scale chicken producers employ mechanical cleaning technology using the automatic scraper or conveyor belt. The cleaning methods determine the form in

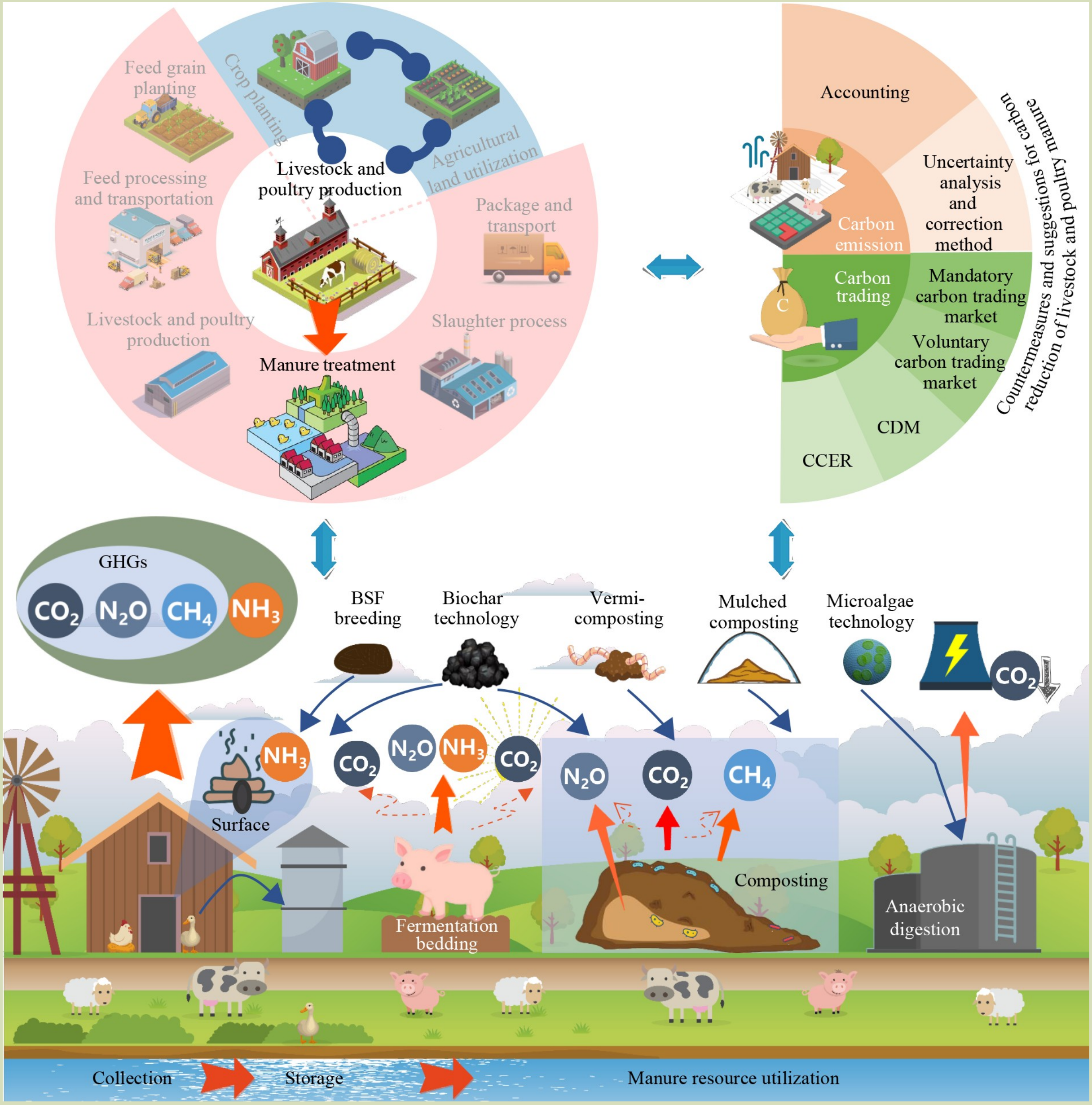


Fig. 1 Relationships between livestock and poultry manure treatment technologies, and carbon accounting and trading systems in the context of low-carbon agriculture.

which manure is stored and treated later. Manure and urine from livestock and poultry production can cause many problems for the environment if collection and processing is unduly delayed. For example, urine deposition is the main source of N_2O in pasture-based grazing systems[33].

Water submerging technology is a kind of manure-cleaning process in which a certain amount of water is injected into the manure ditch of a livestock and poultry house, the manure and urine are collected together into a tank through the leaking floor and are centralized discharged after a certain period of storage for subsequent use. In contrast to the water flushing technology, the water submerging technology does not require daily washing of the manure in livestock and poultry housing. Although having the characteristics of water-saving, few manure discharge times, and low labor cost, water submerging would produce a large amount of harmful gases, such as CH_4[9], due to anaerobic fermentation in the storage process of liquid manure waste, which degrades the air quality in the house and endangers the health of animals and workers.

To prevent the mixing of solid and liquid waste (such as manure and urine) from making subsequent storage and treatment processes more difficult, dry manure collection and solid-liquid separation technology could not only reduce the amount of waste generated and improve manure collection rate but also reduce CH_4 emission by decreasing the total amount of organic matter entering anaerobic environment[9,10]. Dry manure collection is a way to collect all or most of the solid manure from the floor of the livestock and poultry housing manually or mechanically. The residual manure and urine are washed with a small amount of water, thus avoiding the mixing of solid and liquid manure.

The solid-liquid separation process is an important step in the early stage of manure pollution reduction, linking manure waste collection and manure waste storage. It uses either mechanical or non-mechanical methods to separate and classify the solids and liquids, which could effectively reduce the uncontrolled emissions of GHGs in the process of liquid manure treatment in livestock and poultry production[34].

The potential of collection of different livestock and poultry manure, and their harmful gases emissions, has been compared above. The water flushing technology does not meet the environmental protection policy because of the high pollutant content in the wastewater and the quantity of water consumed, although it can provide a clean environment in livestock and poultry housing. Dry manure collection technology reduces the amount of water used in the waste cleaning process compared with water flushing technology, while retaining the nutrients in the solid manure and reducing the cost of subsequent waste treatment. Separating the manure and urine, dry manure collection technology can clean livestock and poultry housing efficiently, reducing the potential of harmful gases emissions. Equipment investment and maintenance costs are high for mechanical cleaning technology, although it reduces labor. Water submerging technology is more water-saving than the water flushing, and more labor-saving than the manual cleaning. However, there is higher potential for harmful gases emissions, thus it is necessary to combine it with solid-liquid separation technology, and large-capacity storage facilities are required during construction. Dry collection technology is highly recommended for low-carbon agriculture, but many other factors need to be considered in the design and construction process, such as scale of production, kinds of livestock and poultry, and construction and labor costs.

2.2 Manure storage

The utilization of livestock and poultry manure resources is restricted by temporal factors influenced by biological processes and spatial factors affected by regional conditions. Manure collected from production facilities cannot be directly returned to the field as a fertilizer but needs to be recycled through a subsequent treatment technology because the arbitrary application of manure will cause many negative effects on the environment as shown in Fig. 2. Manure storage technology can alleviate the challenges of time and space between collection and use. GHGs and NH_3 produced during improper waste storage can have many negative effects on the environment. For example, CH_4 emission during storage of slurries[35] and solid manure[36] is considered to be one of the sources of GHGs in the recycling of waste.

The factors affecting gas production during livestock and poultry waste storage include compaction and mulching, manure type and composition, storage conditions (e.g., temperature and pH) and regulators that control the mineralization of nitrogen and carbon. These factors determine the emissions of CH_4, N_2O, CO_2, and other harmful gases[18]. For example, straw cover reduced NH_3 emissions during slurry storage and a solid lid reduced CH_4 and NH_3 emissions[15]. Compaction and mulching cam reduce NH_3 and N_2O emissions when the manure contains relatively high ammonium nitrogen content[16]. Also, with a relatively short retention time, and low specific surface area and sealing performance, the option of using storage tanks reduces the likelihood of CH_4 and NH_3 emissions compared to anaerobic lagoons[18]. In addition, reducing pH during storage appears to be necessary to effectively reduce NH_3 emissions, and a combination of mulching and acidification can bring pH below 6.0 to effectively reduce CH_4 and N_2O emissions[14]. Controlling aerobic and anaerobic conditions during solid manure storage is also considered to be a source of N_2O production/consumption and emission[36]. In addition, GHG emissions can be reduced by adding appropriate regulators during waste storage. Adding biosolids in equal volume to stored cattle manure has been found to be a possible and simple way to reduce GHG emissions and global warming potential (GWP)[17].

2.3 Manure resource utilization

Resource utilization refers to the conversion of potential pollution sources in livestock and poultry manure treatment into value-added products, including biogas, fertilizer, animal feed and barn bedding, reducing their negative impacts on the environment. The principles and applications of different technologies are discussed below including their potentials for carbon emission reduction, capture, utilization and storage.

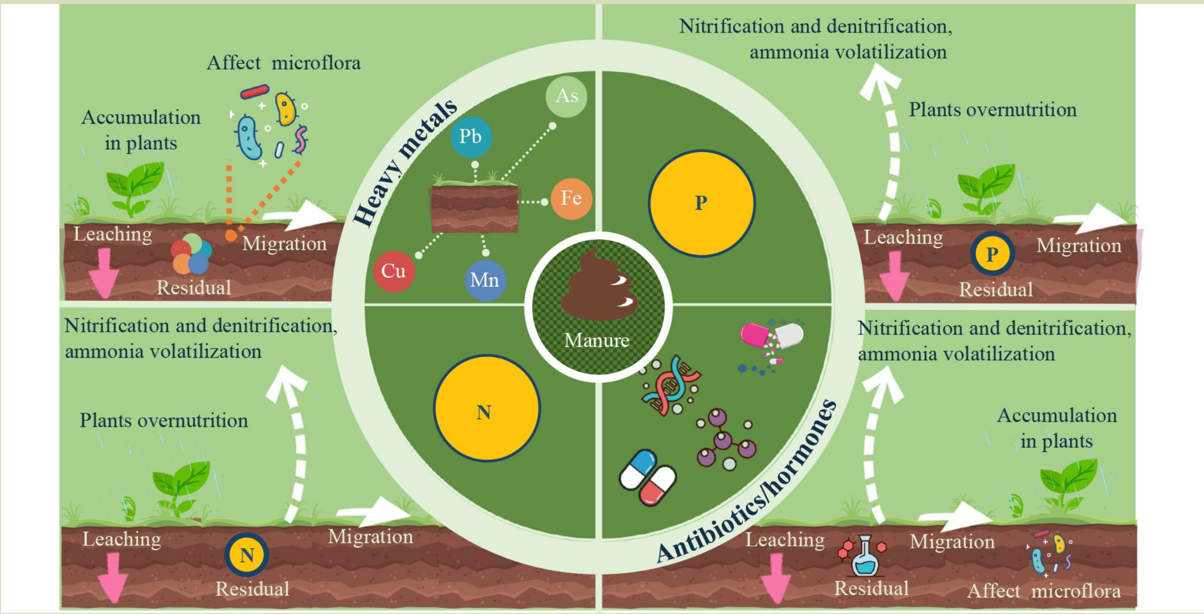


Fig. 2 Negative effects on the environment caused by the indiscriminate use of livestock and poultry manure.

2.3.1 Anaerobic digestion

Anaerobic digestion (AD) is the process of converting organic material via a combination of bacteria and archaea under anaerobic conditions into biogas which includes CH_4 and CO_2 as the main components[37,38]. AD is considered one of the most important and beneficial processes in livestock and poultry waste disposal, as well as one of the best alternatives for agricultural organic solid waste management[39]. This is because it not only reduces the negative impact of manure on the environment through reducing the GHG emissions generated during the self-decomposition but also alleviates the local energy requirements. Also, the digestate of AD is rich in nutrients and can be used as a biofertilizer in crop production. AD can be divided into liquid anaerobic digestion (L-AD) and solid-state anaerobic digestion (SS-AD). SS-AD is more suitable for cellulosic biomass feedstocks with lower water content than L-AD, which operates at a solid concentration of less than 15%. Additionally, the GWP of SS-AD is lower than that of L-AD[39].

The import of biogas fermentation systems in large-scale pig production can replace coal and thus reduce GHG emissions[40]. Some studies have also shown that the operation of livestock and poultry production using biogas power generation will result in lower GHG emissions[41]. In addition, compared with existing energy production plants, biogas power plants using CH_4 as a substitute for diesel fuel[42] and firewood for domestic cooking[43] are considered to significantly reduce GHG emission potential.

Biogas has been used in China for more than a century, and the current goal of AD technology has shifted from energy recovery to environmental protection. Currently, the application of AD technology has not only been used for home cooking but also for centralized gas supply and biogas power generation in rural areas, and comprehensive utilization of biogas residue has been carried out. There are still many obstacles to implementing AD in production facilities, although AD technology has been commercialized for many years, such as the single form of fermentation process, high cost of equipment, slow fermentation startup, low gas production efficiency, or even no gas production in winter or low-temperature conditions. Therefore, in the future, it will be necessary to conduct targeted research on the AD technology for livestock and poultry manure, including: (1) manure pretreated to improve AD efficiency, (2) suitable fermentation flora to solve the problems of low gas production efficiency and slow imitation of AD under low-temperature conditions, (3) direct return of fermentation byproducts, such as biogas slurry to the field, and development related technology to enhance combined crop and animal production, (4) mixed raw material fermentation of manure and energy crops, such as Austria and Germany, to improve the buffering capacity of the fermentation system and reduce the inhibition of salt or ammonia nitrogen in the reflux liquid on gas production, and (5) adapt biogas fermentation mode and assembly technology from Sweden, Germany, Denmark, the Netherlands and other developed countries for use in developing countries, and improve the level of design standardization of equipment, product serialization and production industrialization.

2.3.2 Composting

Composting is a biologically active aerobic process that biodegrades livestock manure into humus via the action of microorganisms. The end product of compost contains a large number of phytonutrients, mainly inorganic nitrogen and phosphorus, minimal pathogens, and almost no phytotoxins. The actual composting process will release various gases into the atmosphere in an uncontrolled manner, such as CH_4 and N_2O, produced under anaerobic conditions, as well as CO_2, under aerobic conditions, which will have varying degrees of negative impact on the environment[11]. The composting process will release, on average, 200 $kg \cdot t^{-1}$ CO_2-eq and an N_2O emission of 100 $kg \cdot t^{-1}$ CO_2-eq of wet waste[12].

To reduce harmful gas emissions (e.g., CH_4, N_2O and NH_3) and improve maturity in aerobic composting, appropriate leavening and bulking agents, such as straw and zeolite[44], are often added in the composting process. Although composting can reduce GHG emission potential in manure management to a degree, different emission factors such as season and sunlight can affect the environmental burden of the process. The experiment showed that the maximum N_2O emission in the cold season was 23 times that in the warm season, and the N_2O flux in the shaded side was higher than that in direct sunlight[45].

The anoxic zone inside the manure is also a cause of harmful gases emissions during composting, such as the uncontrolled discharge of NH_3[13]. Although intermittent aeration during composting can reduce anoxic conditions during composting, there will still be anaerobic areas within the compost heap that lead to the production of CH_4. Increasing C/N ratio and decreasing in water content increases the cumulative N_2O emission[46]. In addition, mulched composting technology has also been widely used, which is a technology that covers the compost pile with a layer of molecular film, creating a closed environment and forced aeration is performed by the oxygen pipeline at the bottom of the facility, to improve speed of decomposition speed and reduce harmful gases emissions. This reduction in harmful gases emissions are attributed to (1) the molecular film blocking the most harmful gases produced during composting, (2) condensation on the inner film due to the temperature difference which can dissolve CO_2, N_2O and NH_3 produced in the system, and allowing these to return to the system via the of gravity to be reused, and (3) forced aeration provides oxygen and reduces the production of harmful gases[47]. It has also been shown that using various molecular membranes can prevent the escape of harmful gases, pathogens, dust and odors[48].

Composting technology has substantially matured in China, with low investment, simple technology, that can produce manure as fertilizer. Composting technology is a complex biological process, along with the production of harmful gases, in which adding an appropriate amount of leavening and bulking agents can reduce the emissions of harmful gases. At present, the source reduction of harmful gases by combining microbial technology and process regulation are the focus of current research. Use of mulched composting technology is an alternative option for emission reduction.

2.3.3 Vermicomposting

Vermicomposting is one of the best technologies for the safe recycling of organic waste. Through the combined action of earthworms and related microorganisms, the organic waste is converted into finer, wetter substances rich in nutrients and can speed up the composting process. It has been shown that adding worms to compost led to decrease production of GHGs and other harmful gases. For example, the addition of earthworms in thermophilic composting could shorten the period required to reach compost maturity. Concurrently, vermicomposting can effectively reduce nitrogen loss and emissions of N_2O, NH_3, and CH_4[19,20]. Similarly, vermicomposting of duck manure reduced total emissions of N_2O and CH_4 but not CO_2 emission[44]. However, some studies reported the negative effects of vermicomposting on the environment during livestock and poultry waste treatment. An example of this is that the earthworms were found to significantly promote nitrogen conversion through enhanced nitrification increasing N_2O emission[49].

In recent years, vermicomposting has been widely used in waste biomass recycling because of its uniqueness and safety. Evaluation of the environmental friendliness of vermicomposting generally finds it to be positive, but some studies also raise concerns, such as GHGs emitted during the process that could cause secondary pollution to the environment. In addition, most recent studies on the emissions of harmful gases during vermicomposting are small-scale experiments, and the external conditions such as ambient temperature and humidity are strictly controlled. Therefore, the variable factors in production-scale vermicomposting such as source of manure, pile size, regional difference and seasonal factors still need to be evaluated. Similarly, the factors influencing harmful gases emissions during vermicomposting need further study. In addition, the end use of vermicomposting products should be linked closely to crop production, such as Germany.

2.3.4 Black soldier fly

Black soldier fly (BSF) has been recognized for the potential to recycle waste biomass like animal feed and human food[50]. Due to high nutritional characteristics, black soldier fly larvae (BSFL) can be used as a more competitive feed substitute[51]. In addition, larval biotransformation technology has also been shown advantages for waste treatment and recycling for organic fertilizer production[52]. Therefore, for livestock and poultry waste treatment, BSF may be an alternative as a means of biological transformation. When of BSF was used for manure recycling treatment, the larvae were found to absorb dry matter, nitrogen and phosphorus in the waste, and then convert these into useful biomass and reduce CH_4 emission[52]. Although rearing BSFL can produce value-added products, studies have shown that the potential for GHGs and harmful gases emissions were increased. Parodi et al.[53] cultured BSFL on pig manure, and showed that when BSFL was present, the levels of dry matter, carbon, nitrogen, phosphorus and potassium in pig manure were reduced, but the carbon loss was mainly in the form of CO_2 and was twice as waste treated without BSFL. Also, the presence of BSFL increased NH_3 emission, although it reduced the total manure nitrogen content. In addition, there was no significant difference in CH_4 emission between the two treatments, and N_2O emission was quite low in both groups.

As one of the new concepts for production of value-added products in combined crop and animal production, the rearing technology of BSF has become the focus of domestic research. However, in future studies, the effects of nutrient ratio and physicochemical properties of the medium on the cultivation of BSFL and gases emissions should be further considered.

2.3.5 Fermentation bedding

There are two types of fermentation bedding technology: *in situ* and ectopic fermentation bedding. *In situ* fermentation bedding technology is laying rice husk, sawdust, crop straw and other materials in the barn. Slurry/manure/urine produced in the production process together with the bedding materials are fermented by active microorganisms to produce organic barn bedding for livestock and poultry production. The ectopic fermentation bedding technology is separating livestock and poultry feeding from manure treatment, which is usually built outside the barn and returned to the barn after fermentation. Through the fermentation bedding system, the excrement of livestock and poultry can be rapidly degraded under the action of microorganisms to reduce the pollution of animal manure, decrease the incidence of disease, reduce odor and harmful gases emissions from livestock and poultry production, which is helpful to improve animal welfare and increase the efficiency of production facilities[54]. For example, there can be little or no N_2O produced in livestock and poultry housing where bedding is used because NH_4^+ nitration of slurry/manure/urine is avoided under anaerobic conditions[36].

The factors affecting gas emissions from fermentation bedding system include bedding material type and degree of aging, fermentation microorganism, manure contamination type, and temperature humidity index. There are various impacts of bedding material on GHGs and harmful gases emissions. Fermentation bedding made of straw mixed with pig manure can decrease N_2O, CH_4 and CO_2 emissions, but increase NH_3 emission. The possible reasons for the increase are: (1) urea degradation by urease in manure, (2) scraping manure to promote aeration, and (3) adding straw[55]. Also, the aging of bedding material significantly increased the mortality and egg loss rate of breeding ducks, while adding fermentation microorganisms to fresh bedding material has been shown to not only increase the temperature and temperature humidity index of duck breeding barns but also reduce the emissions of H_2S, NH_3, and CO_2[54]. In addition, studies have shown that the application of fermentation bed technology in a piggery can increase the temperature and reduce NH_3 emission in winter compared with standard cement floor feeding systems[56].

China has learned from the experience of Japan and South Korea, and introduced the biological fermentation bedding technology. At present, there are still some problems with fermentation bedding technology, compared with the standard bedding systems, viz., (1) higher capital investment and lower stocking density, and (2) higher maintenance costs, such as the aging of bedding, that can affect fermentation efficiency and the accumulation of heavy metal elements in the bedding will inhibit the microbial activity, (3) more difficult disease control, because commercial disinfection products and antibiotics will reduce the microbial activity in the bedding, thus affecting the fermentation efficiency, and (4) changed of environmental conditions can affect the microbial activity in the bedding and reduce fermentation efficiency of the system. Therefore, the management of bedding materials (material ratio, aging degree, tossing and stirring measures), appropriate fermentation strain addition, and environmental regulation should be addressed in future research.

2.3.6 Biochar

Biochar is produced by pyrolysis, gasification, hydrothermal carbonization and other thermochemical transformations of biomass under the condition of high temperature and low/no oxygen. Owing to its particular physical and chemical properties, biochar can be used in energy, environmental remediation, soil improvement and other fields. Currently, the research on biochar to reduce harmful gases in manure treatment involves manure storage and manure (vermi-)composting, etc. The application of biochar, such as that made from corn straw or red oak, to the surface of pig manure during the waste storage process can effectively mitigate NH_3 emissions[57]. Likewise, adding biochar may be an ideal way to reduce GHGs and other harmful gases emissions during composting. In other words, biochar not only optimizes the composting process but also improves the environmental and economic benefits of composting[58]. The addition of biochar made from the cornstalk, bamboo, woody, layer manure and coir to layered manure composting system resulted in decreased cumulative emissions of NH_3 and CH_4 by 9.2% to 24.8% and 15.5% to 26.1%[21], respectively. In addition, bamboo biochar reduced CH_4 and N_2O emissions in sheep manure composting systems, with higher percentages of biochar substantively reducing GHG emissions[22]. Biochar in vermicomposting systems has also been shown to improve the maturity and quality of the resultant compost. The addition of rice husk biochar and bamboo biochar in vermicomposting, using cow manure and straw as feedstock, reduced N_2O and NH_3 emissions by 14.9% to 55.1% and 24.9% to 66.2%, respectively[59].

Biochar has been shown to reduce harmful emissions during manure storage and (vermi-)composting, providing an eco-friendly alternative to other methods. However, most research has been conducted as laboratory experiments, thus production-scale experiments should be considered for systems where biochar acts as a regulator. The energy consumption required during biochar preparation should also be assessed. In future studies, various feedstock biochars and activation methods should be explored to meet different carbon sequestration and emission reduction objective.

2.3.7 Microalgae

As an ideal renewable biological energy, microalgae have the advantages of high photosynthetic efficiency, high biomass and oil content, and the substantial effect of carbon reduction and sequestration[60]. In livestock and poultry production, microalgae culture could be used to adsorb NH_3, thus reducing emissions[61]. As a cleaner and more promising manure treatment, the biomass produced by microalgae culture can be used to produce animal feed/bioethanol/biodiesel/AD raw material[62,63]. The use of wastewater from AD of dairy manure for the cultivation of microalgae and subsequent production of biodiesel was found to have minimal GHGs intensity (GHG emissions/bioenergy generation)[64]. In the coupling of microalgae and livestock manure AD, microalgae can absorb nutrients in manure and can use CO_2 in the system as a carbon source, to realize energy recovery and nutrient supply[65]. In dairy manure treatment, studies have shown that composite systems could reduce GHG emissions[66] and were thought to have lower GWP[67].

At present, the technology development of microalgae energy mainly includes the production of microalgae biodiesel and the extraction of microalgae oil. However, it still remains unclear if microalgae culture can deliver both high oil content and high cell density. In addition, microalgae culture has been shown to have high emission reduction potential in livestock and poultry manure treatment, but using this technology to achieve value-added effects requires evaluation of algae species, temperature, light, nutrient levels and harmful substance content. In addition, harvest and separation of algae from bulk slurry is energy intensive and technically challenging. The interaction between microalgae and nutrients or harmful substances in the system, toxicity risks, and absorption kinetics[60] need to be further studied in microalgae coupled manure treatment systems. In addition, achieving production-scale applications and extracting/produce high-value products using microalgae will not be without its challenges.

Considering all these technologies, it is clear that there are many approaches for livestock and poultry waste disposal that are relatively mature. However, manure treatment technologies inevitably cause different degrees of negative impact on the environment, especially as one of the important sources of GHGs from agriculture. Based on existing research, the principles of manure recycling treatment technology have been established, and carbon friendliness and technology maturity have been preliminarily compared, as given in Fig. 3. However, there remains gaps in the carbon emission accounting and carbon neutralization methods in agriculture, as well as the carbon emission trading system, and a more suitable, as well as objective, evaluation system is urgently needed. Therefore, considerable research on the synergy of pollution reduction and carbon reduction during livestock and poultry manure treatment is needed.

Fig. 3 Schematic (a) and comparative analysis (b) of livestock and poultry manure treatment technologies. This graph is drawn by the authors with comprehensive reference to a number of literature[9–22,33–68].

3 METHODOLOGY FOR CARBON EMISSION ACCOUNTING AND REDUCTION DURING LIVESTOCK MANURE MANAGEMENT

3.1 Analysis of factors influencing carbon emission from livestock and poultry manure

The main factors influencing carbon emission from livestock and poultry manure are as follows but there are not limited to these.

3.1.1 Type and regional distribution of livestock

Type and regional distribution of livestock are the main factors influencing carbon emission from livestock and poultry manure. The key step to compare the contribution of these two factors to global warming is obtaining the carbon emission coefficient which refers to the amount of CO_2 emitted per unit of economic output. The impact of CH_4 and other GHGs on global warming is converted into CO_2 and added to the measurement. The GHG emission coefficient of each animal production region is summarized from the "Guidelines for the preparation of national greenhouse gas inventories"[69], as shown in Table 1. The GHG emission coefficient of the manure

Table 1 GHG emission coefficients* of livestock and poultry manure management system in different regions of Chinese mainland ($kg·head^{-1}·yr^{-1}$)[69]

Regions	Livestock or poultry	CH_4	N_2O	Regions	Livestock or poultry	CH_4	N_2O
Northern China	Cow	7.46	1.846	Central southern China	Cow	8.45	1.710
	Non-dairy cattle	2.82	0.794		Non-dairy cattle	4.72	0.805
	Sheep	0.15	0.093		Sheep	0.34	0.106
	Goat	0.17	0.093		Goat	0.31	0.106
	Pig	3.12	0.227		Pig	5.85	0.157
	Poultry	0.01	0.007		Poultry	0.02	0.007
Northeastern China	Cow	2.23	1.096	Southwestern China	Cow	6.51	1.884
	Non-dairy cattle	1.02	0.913		Non-dairy cattle	4.72	0.691
	Sheep	0.15	0.057		Sheep	0.34	0.064
	Goat	0.16	0.057		Goat	0.31	0.064
	Pig	1.12	0.266		Pig	5.85	0.159
	Poultry	0.01	0.007		Poultry	0.02	0.007
Eastern China	Cow	8.33	2.065	Northwestern China	Cow	5.93	1.447
	Non-dairy cattle	3.31	0.846		Non-dairy cattle	1.86	0.545
	Sheep	0.26	0.113		Sheep	0.28	0.074
	Goat	0.28	0.113		Goat	0.32	0.074
	Pig	5.08	0.175		Pig	1.38	0.195
	Poultry	0.02	0.007		Poultry	0.01	0.007

Note: *CH_4 and N_2O are calculated 27 times and 273 times according to the CO_2-eq of the 100-year-scale CO_2 warming potential in the IPCC-AR6 Assessment Report.

management system varied greatly between livestock and poultry species and production region. Likewise, the CH_4 emissions of milking and non-milking dairy cattle in Canada during 2001 varied between regions like Atlantic, Quebec, Ontario, Prairies and British Columbia[70].

3.1.2 Seasons and treatment details during manure management

GHG emission coefficients of dairy cattle manure varies with the different seasons and different treatment stages[71]. The GHG emission coefficients (ordered from highest to lowest) in different seasons is autumn-summer-spring-winter, but it differed slightly between autumn and summer, which were significantly higher than that in the winter by about eight times for CO_2 and three times for CH_4. The cited authors also reported that the CO_2 and CH_4 emission rate of cow manure during storage increased at first and then decreased. In addition, the factors of stacking heights, temperature, and methods of stacking dung significantly affected CH_4 emission[72]. Stirring cow manure during the composting process lead to an increase in carbon emission, so stirring was not recommended, rather it was suggest to mix the compost only after 4 weeks[73].

3.1.3 Types of livestock and poultry products

Different types of livestock and poultry products have different carbon footprints. The Joint Research Center of the European Commission[74] reported that the carbon footprint of per kilogram livestock and poultry products in the European Union is in the following order: eggs < poultry < pork < mutton < beef. A significant reduction in manure production can fundamentally reduce carbon emission during manure management.

3.1.4 Social factors

China’s economic growth rate, policy tendencies, population, people’s awareness of environmental protection, and other social factors directly or indirectly affect the rate of development of the livestock and poultry industries and thus affect the production of livestock and poultry manure.

3.1.5 Others

In addition to the points discussed above, there are some other influencing factors, such as the types and the amount of feed and feed supplements use in livestock and poultry production. The age, gender, health and physiological state of the livestock and poultry may also influence the carbon emission from livestock and poultry manure. The physical conditions of the facilities where the livestock and poultry are produced, for example, the temperature, humidity, ventilation, density, are also contributing factors.

3.2 Factor decomposition methods of carbon emission

Although the information given in Section 3.1 can qualitatively reflect the factors affecting carbon emission, it cannot quantitatively explain the influencing degree of each factor. It is necessary to conduct factor decomposition research to study the degree of influence of each factor. The commonly used decomposition methods of factors influencing carbon emission can be largely divided into structural decomposition and index decomposition analyses (IDA). The former can use an input-output model to comprehensively analyze various influencing factors, especially the indirect impact of changes in the demand of one sector on other sectors but has the disadvantage of higher requirements for data collection, while the IDA is simpler and has wider applications, which can trace the causes of environmental changes related to energy efficiency or energy sources with dependent variables as indices, and find out the underlying factors that indirectly affect the combined index to provide a basis for formulating practical and reliable policies and measures[75]. IDA includes both the Laspeyres and Divisia index methods. Laspeyres index method is further divided into the Paasche, Marshall-Edgeworth, Fisher, Shapley and Sun decomposition methods. These methods are widely used across different fields of investigation, especially in energy and environment decomposition research, having the advantages such as easy to calculate and ease of understand. Fisher's decomposition method has been modified and is considered to be a multiplicative expression of the Shapley/Sun decomposition method[76,77].

3.3 Accounting methods for carbon emissions and carbon footprint of livestock manure

Accurate accounting of carbon emission and footprint for livestock and poultry manure provides the basis for formulating feasible carbon emission reduction policies in livestock production to achieve emission reduction. After decades of development, carbon accounting methods have evolved from carbon emission to carbon footprint accounting methods.

Carbon emission is related to GHG emissions. Carbon emission accounting methods include the mass-balance method, actual measurement and carbon emission factor methods. The mass-balance approach calculates the contribution of new chemicals and equipment consumed each year to meet the capacity of the new equipment or to replace the removal gas, based on the new chemicals and equipment used. The actual measurement method uses basic data measured by relevant measuring instruments and equipment in the field of the emission source, and the carbon emission is obtained after data normalization. The carbon emission factor method includes the OECD method proposed in 1991 and Intergovernmental Panel on Climate Change (IPCC) method, and constructs the activity data and emission factors for each emission source according to the carbon emission list[2]. The OECD method is an estimation method only for CH_4 emission while other GHGs accounting is not considered. Consequently, this calculation method is simple and only for estimation, with the accuracy of the calculation not high.

For carbon footprint accounting, there are tens of definitions with different meanings, but they share a relatively unified core idea, which can be summarized as the carbon footprint representing the total amount of GHG emissions caused by human production and consumption behavior, which will eventually lead to climate change and can be expressed in CO_2-eq. The essence of carbon footprint measurement is to quantify the carbon emission from human activities. The general calculation method is the empirical coefficient method[78]:

$$CF = AD \times EF \tag{1}$$

where, CF is the CO_2 emission of an activity, namely the carbon footprint, AD is the specific quantity of the activity, and EF is the carbon emission coefficient of the activity.

The commonly used carbon footprint measurement methods have gradually emerged including the IPCC method[79], input-output method (IO)[80], life cycle assessment method (LCA)[28] and hybrid method combining LCA and IO (LCA-IO)[81]. The IPCC method has been used since the mid-1990s to calculate the carbon emissions produced by agricultural activities, such as livestock and poultry production, according to the carbon emission coefficient and macroeconomic data for each region. The IPCC has three levels of accounting: The results of the accuracy and precision of levels 1 and 2 are poor. In level 3 the accuracy of emissions accounting using all levels is continuously improved, but the difficulty of accounting is in turn increased[82]. The shortcoming of the IPCC approach is that it cannot fully consider the carbon emission from livestock and poultry production. Some research has questioned the comprehensiveness of the carbon emission accounting method proposed by IPCC[83,84].

The IO method mainly uses the input-output table to obtain the production inputs and energy demand through the Leontief inverse matrix transformation and then calculates the carbon emission from livestock and poultry production according to energy emission factors. This method can reflect the relationship between various sectors of an economic system. The IO method combined with the GHG emission data of various sectors can be used to calculate the GHG emissions from the whole production chain caused by the production of products or services for end users by various sectors[85]. Also, it is suitable for macroanalysis and has the following advantages: (1) takes the whole economic system as the boundary, (2) has strong comprehensiveness, and (3) requires fewer human and material resources to calculate the carbon footprint. However, its disadvantage lies in the lag of data of the input-output table resulting in the lag of carbon emission accounting results.

The LCA method defines the boundary of the system and calculates the carbon emission generated by all livestock and poultry production activities within the boundary based on carbon emission factors to obtain the carbon footprint of all substances or activities within the life cycle of livestock and poultry production. The advantage of this method is comprehensiveness, while the disadvantage is that the selected system boundary is different, and the carbon emission accounting results are different.

The evolution and characteristics of carbon accounting methods are summarized in Table 2.

3.4 Accounting methodologies for GHGs from livestock and poultry manure

CH_4 and N_2O, which have GWP of 23 and 298 times greater than CO_2, are the main GHGs from livestock and poultry manure management system. This work summarizes the accounting methodologies for CH_4 and N_2O in manure management systems based on IPCC Guidelines for National Greenhouse Gas Inventories[87].

3.4.1 Accounting methodologies for CH_4 emission

CH_4 is one of the important GHGs emitted in manure management systems. Especially in large-scale livestock or poultry production facilities with large amounts of manure, it is easy to form an anaerobic environment in liquid-based systems like manure tanks or manure pits during the manure management process. At present, IPCC has mainly recommended the following two methodologies to account for the CH_4 emission: Methodology 1 and Methodology 2, which correspond to relatively rough estimation and relatively accurate estimation, respectively.

Table 2 Summary of carbon emission accounting methods[86]

Method	Advantage	Disadvantage	Suitable for circumstance	Classification*
Mass-balance method	Reflect the actual carbon emissions Distinguish the differences between various facilities Distinguish the differences between entire and partial equipment	Difficult to avoid systematic errors	When carbon emission sources are complex When equipment is constantly updated	A
OECD	Calculation method is simple	Accuracy of the calculation is not high	Requirement for accuracy is not high CH_4 emissions from ruminants	A
IPCC	Comprehensive calculation range; more accurate (in Tier-3)	Poor ability to handle the changes in the emission system	When emission sources are not complex or the complexity is negligible	Both A and B
I-O	Account carbon footprint and environmental impact of a product or service more completely	Weak timeliness	Macroscopic levels like countries, departments, enterprises	B
LCA	The carbon footprint and environmental impact of a product or service can be assessed more accurately The accuracy of the scope can be set according to specific goals	Boundary setting is based on strong subjectivity	Micro levels of specific products or services	B

Note: *Accounting methods include carbon emission (A) and carbon footprint (B) methods.

(1) Methodology 1 (relatively rough estimate)

$$E_{\text{manure } CH_4} = EF_{\text{manure } CH_4} \times \sum N_{Ti} \quad (2)$$

$$GHGs_{\text{manure } CH_4} = E_{\text{manure } CH_4} \times 28 \quad (3)$$

where, $E_{\text{manure } CH_4}$ is the CH_4 emission from manure, $E_{\text{manure } CH_4}$ is the emission factor of CH_4, N_{Ti} is the number of livestock and poultry production, T is the livestock species, i is different subgroups of the same livestock, and $GHGs_{\text{manure } CH_4}$ is the CH_4 emission from this manure management sector.

(2) Methodology 2 (relatively accurate calculation)

$$EF_T = (VS_T \times 365) \times (B_{OT} \times 0.67 \times \sum \frac{MCF_{S,K}}{100} \times MCF_{(T,S,K)}) \times EF_{\text{manure } CH_4} \times \sum N_{Ti} \quad (4)$$

where, EF_T is the annual CH_4 emission factor of livestock class T (kg·livestock^{-1}·yr^{-1} DM), VS_T is daily volatile of solid excreta from livestock class T (kg·livestock^{-1}·d^{-1}), 365 is the days per year, B_{OT} is maximum CH_4 production capacity of manure produced by livestock class T, 0.67 is the conversion factor of solid excreta to CH_4 (kg·m^{-3}), $MCF_{S,K}$ is CH_4 conversion factor of manure management system S in climate zone K (%), and $MCF_{T,S,K}$ is the manure proportion of livestock class T in manure management system S in climate zone K, non-dimensional parameter.

The daily volatile solid excreta from livestock is calculated as:

$$VS = \left[GE \times \left(1 - \frac{DE\%}{100}\right) + (UE \times GE)\right] \times \left(\frac{1 - ASH}{18.45}\right) \quad (5)$$

where, VS is the daily volatile of DM based solids excreta (kg·d^{-1} VS), GE is total energy consumption (MJ·d^{-1}), DE% is the digestible proportion of the feed, UE represents coefficient and it is different for various animals, UE×GE is the energy contained in urine (generally considered to be 0.04 GE for ruminant livestock or 0.02 GE for pigs fed with at least 85% grain, and if is available; country-specific values are preferable), ASH is the ash in the manure (0.08 for cattle, and if available, country-specific values are preferable), 18.45 is the conversion factor of total energy converted from DM feeds (MJ·kg^{-1}).

3.4.2 Accounting methodologies for N_2O emission

N_2O emissions from the manure storage and management sector depend on manure nitrogen and carbon content, storage duration, and management method, with direct N_2O emission was calculated as:

$$N_2O_{D(mm)} = \left[\sum_S \left[\sum_T (N_{(T)} \times N_{ex(T)} \times MS_{(T,S)})\right] \times EF_{3(S)}\right] \times \frac{44}{28} \quad (6)$$

where, $N_2O_{D(mm)}$ is the direct N_2O emission from the manure management sector (kg·yr^{-1} N_2O), $N_{(T)}$ is the number of domestic livestock of class T, $N_{ex(T)}$ is the annual average N excretion of per domestic livestock class T (kg·head^{-1}·yr^{-1} N), $MS_{(T,S)}$ is the dimensionless ratio of total annual nitrogen excretion from each livestock class T in manure management system S, and 44/28 is the conversion factor of as $N_2O\text{-}N_{(mm)}$ emission converted to $N_2O_{(mm)}$ emission.

3.5 Uncertainty analysis of carbon emission accounting results in livestock manure management

Regardless of the method used for accounting for the carbon emission and carbon footprint, the results are not completely reliable with the factors affecting the accuracy of results being regional distribution, reliability of obtained data, GHGs types and others. The evaluated research work on carbon emission from livestock and poultry production in Africa, Latin America, and Europe showed the uncertainty of carbon emission which are affected by different countries, different types of livestock and poultry, different data sources and other factors[88]. The data obtained are often inaccurate due to human factors and limited technical skills. For example, the factors leading to uncertainty in the calculation of the LCA method include numerical uncertainty caused by internal changes, inaccurate measurement, or lack of data, uncertainty caused by the construction of the LCA mathematical calculation model, and uncertainty caused by different choices under different scenarios[89]. Among the GHGs types, the uncertainty of CH_4 emission is less than for CO_2 and N_2O emissions[88].

Scholars have mostly focused on the quantitative analysis of uncertainty parameters. The commonly used quantitative methods include the data quality indicator method, Bayesian statistics, fuzzy theory, analytical uncertainty propagation, and probability method[90]. The application of Monte Carlo simulation after carbon emission accounting is considered a relatively complete process of GHG emission estimation[91]. However, Monte Carlo simulation requires a large amount of computation, but this disadvantage can be reduced by Taylor series expansion[92].

4 DEVELOPMENT STATUS OF CARBON TRADING SYSTEM

4.1 Global carbon emission trading market

As a newly oriented market for energy-saving mechanisms, carbon trading cannot only achieve the purpose of saving energy and controlling pollution but also promote the promotion of low-carbon, energy-saving technology and improve social welfare. The establishment and development of a carbon trading system in livestock and poultry production will bring substantive benefits. In the 1997 Kyoto Protocol, flexible ways to eliminate carbon emissions are based on three trading mechanisms: emissions trading, joint implementation and clean development. These three carbon trading mechanisms formed the prototype of the carbon emission trading system, with the latter of particular significance to developing countries through the provision of technical and financial support from developed countries. At present, the global carbon emission trading system has two main modes, including mandatory and voluntary trading markets. Their executor, characteristic, trading mode and representative systems or standards are summarized in Table 3.

4.2 Carbon emission trading market in China

The carbon trading market in China started in 2002 (relatively late) and has developed through the stages shown in Fig. 4. Now China's carbon emission trading market adopts a double-track system dominated by a carbon quota trading market and supplemented by Chinese-certified emission reduction (CCER) trading market. The former is mandatory based on the carbon emission quota allocated to enterprises by the government, while the latter is voluntarily. The trading mechanism between the carbon quota and the CCER trading market is shown in Fig. 5. CCER brings a voluntary emission reduction idea into the carbon quota trading market. CCER focuses on encouraging projects to reduce carbon emission. The carbon emission from controlled companies can be offset by clean energy activities or carbon sink projects undertaken by non-controlled enterprises. CCER trading companies (as company

Table 3 Main differences between the two main modes of the global carbon trading market

	Mandatory carbon trading market	Voluntary carbon trading market
Executor	Upper organization	Organizations and individuals with social responsibilities
Trading mode	Cap and trade	More flexible and unrestricted by regulations or the Kyoto Protocol
Characteristics	Policy formulation defines the total amount of GHGs Structures and current situation of the enterprise determine its specific emissions	Purchase carbon credit lines to offset its emissions Apply for certification of voluntary emission reduction (VER) projects to get VER Sell excess emission quota for profits
Typical system and standards	EU ETS (European Union) K ETS (South Korea's) NZ ETS (New Zealand's)	Gold Standard (GS) Verified Carbon Standard The Standard for VER VER + and so on

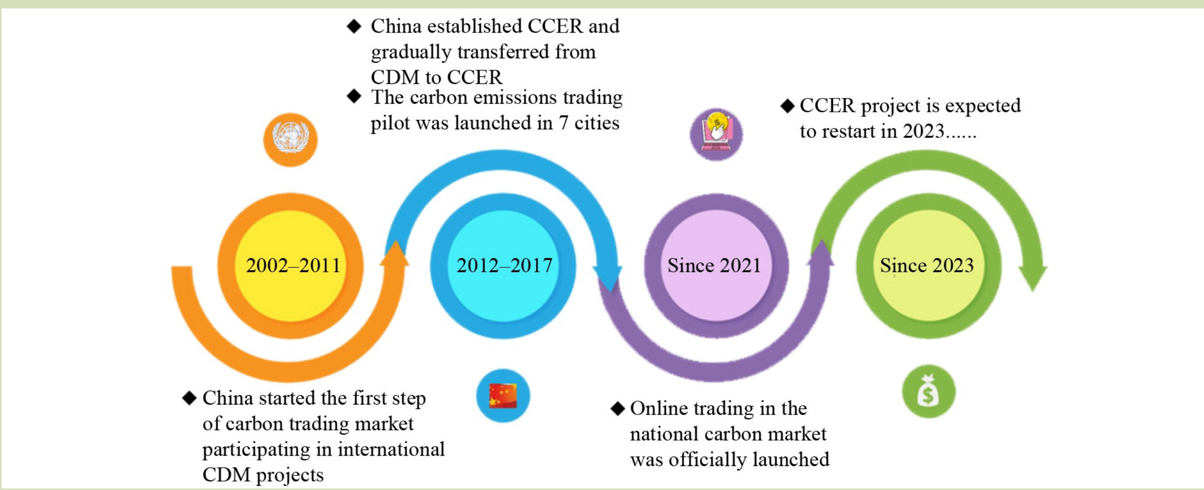


Fig. 4 Development of the carbon trading market in China.

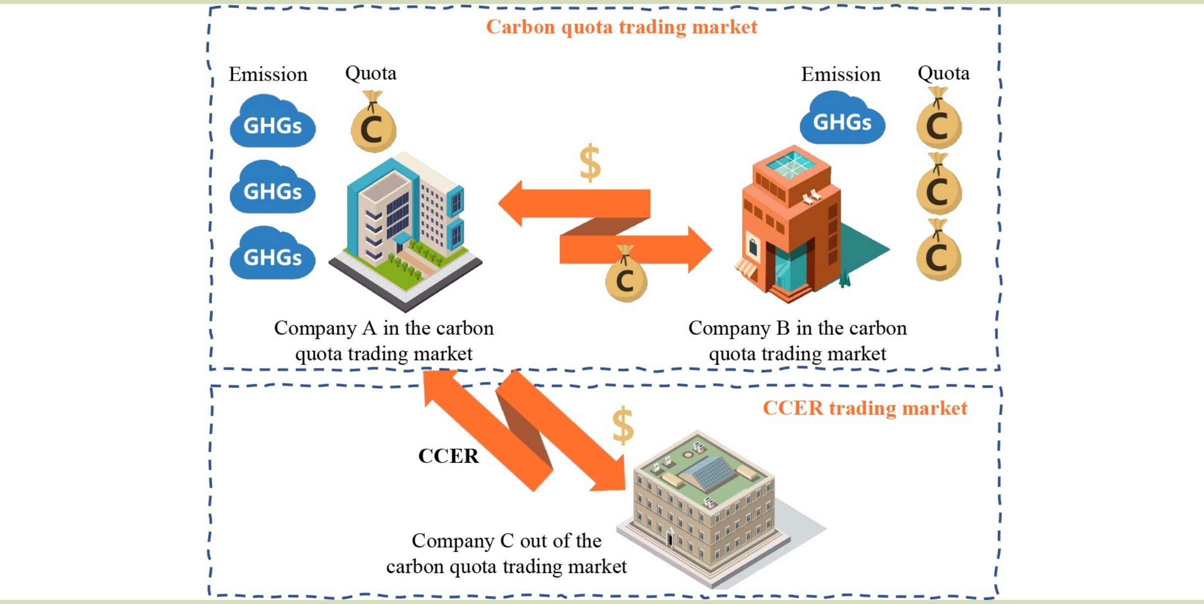


Fig. 5 Trading mechanisms of the carbon quota trading market and Chinese-certified emission reduction (CCER) trading market.

A in Fig. 5) offset their carbon emission by purchasing certificates from companies (as company C in Fig. 5) that conduct carbon offsetting activities.

The construction of the Chinese national carbon market is becoming more standardized and the overall operation is steadily progressing. The trading volume shows obvious periodicity and the average daily transaction price is relatively stable. On 31 December 2022, the cumulative trading volume of the carbon quota almost reached 10.5 billion yuan, the cumulative trading volume reached 229 Mt and the price volatility was low compared with the pilot carbon market[93].

4.3 Current status of agricultural carbon trading market in China

The carbon trading market for livestock and poultry manure management sector in China is in its initial stage but has great potential for future development. Currently, there are relative few livestock and poultry projects among the CDM projects approved by the national development and reform commission. However, the GHG emission reduction projects for livestock and poultry production, including the test and formula fertilization project, desert artificial shrub afforestation project in Xinjiang, rural household biogas project in Sichuan, rural biomass stoves project in Shanxi, are favored by buyers in the voluntary carbon market[94]. In China, the research on livestock and poultry manure management methodologies is relatively limited. Therefore, the government of China has been giving increasing importance to livestock and poultry manure management and the carbon trading market. The Climate Bureau of the National Development and Reform Commission (part the newly established Ministry of Ecology and Environment since 2018 when China carried out institutional reform) released in 2016 a list of voluntary emission reduction (VER) methodologies, including centralized treatment of dispersed manure (AM0073), integrated treatment methodology of livestock and poultry manure from different facilities (ACM0010), CH_4 recovery in manure treatment system (AMS-III.D.), and CH_4 emission reduction by composting (AMS-III.F.), which are all manure treatment methodologies. Carbon trading in the livestock and poultry industry will have great potential and significance through the gradual improvement of market conditions and the increase in social awareness. The action plan for pollution control in agriculture and rural areas (2021–2025)[95] required standards for: (1) carbon emission accounting, reporting and verification of large-scale livestock and poultry production, (2) the carbon footprint from the whole life cycle of key livestock-poultry products, and (3) maximum residue limits of livestock and poultry manure. All of the above requirements are important adjuncts to the standard of livestock and poultry manure treatment. The implementation plan for emission reduction and carbon fixation in agriculture and rural areas[96] claimed six key tasks and the enhancement of livestock and poultry manure utilization as well as the reduction of CH_4 and N_2O from livestock and poultry manure management was ordered as the second key task following the cropping industry.

5 RECOMMENDATIONS AND STRATEGIES FOR CARBON EMISSION REDUCTION DURING LIVESTOCK MANURE MANAGEMENT

According to the literature research presented above, carbon emission reduction and carbon trading for livestock and poultry manure management sector in China are at a relatively theoretical research and policy formulation stage, but have great potential for future development. Accordingly, the following recommendations are offered for consideration.

5.1 Manure treatment technologies

It is of great importance to promote safe and productive technologies for livestock and poultry manure treatment. This can be achieved through the following measures:
(1) Enhancing the technical guidance of manure treatment technology and guiding the livestock and poultry producers to promote the appropriate resources, systematic, low-carbon technology equipment and mode.
(2) Integrating carbon emission accounting methods for manure treatment and developing appropriate modes of waste treatment to reduce carbon emission and raise the standard level of waste treatment and utilization.
(3) Promoting crop-animal production integration in a way to achieve and optimal balance between them. By establishing a complete crop and animal production chain, a closed loop of regional agricultural nutrition can be realized to strengthen the management of harmful gases emissions from the whole cycle of source reduction, process control and final application. By strengthening these measures, the agroecological environment and food safety can be enhanced, carbon sinks a can be increased, and environmental pollution problems can be alleviated.

5.2 Methodologies

It is of great significance to accelerate the improvement of carbon accounting and carbon emission reduction methodologies, specifically by:
(1) Continuously promoting the research on the accounting methodology of carbon emission and carbon footprint, and to pay more attention to the accuracy of accounting results from different perspectives.
(2) Developing a large number of more general and practical GHG emission reduction methodologies are to be developed based on the existing methodologies in the field of livestock and poultry production, such as AM0073, ACM0010 and AMS-III.D.
(3) Promoting the integration of existing carbon reduction methodologies in other fields with manure treatment and recycling processes in livestock and poultry production. For example, the energy saving and carbon reduction of the livestock and poultry industry relies on photovoltaic power generation, the combination of livestock and poultry manure with the production of organic fertilizer, and the combination of livestock and poultry manure and biomass energy.

5.3 Carbon trading market

It is necessary to encourage the further development of trading market, specifically by:
(1) Guiding the development of VER projects according to local conditions of different places, and improving the operation effect and positive effect of CCER.
(2) Strengthening financial support for the operation of CCER, and further enriching the financing channels for the development of China's VER projects.
(3) Improving the construction of the carbon emission right offset market and strengthening its supporting role in the operation of VER mechanisms.
(4) Improving the top-level policy designs and encourage more enterprises to participate in VER actions.

5.4 Others

Other key endeavors include:
(1) Establishing a dynamic balance between low-carbon development and the normal supply of livestock and poultry products[97]. Neither the unilateral pursuit of carbon emission reduction can lead to the imbalance of the supply of livestock and poultry products, nor the unilateral pursuit of a short-term increase in the output of livestock and poultry products can ignore carbon emissions. Concurrently, promoting scientific and technological innovation and application should be a priority to help integrate the economic value and carbon reduction value of the livestock and poultry production.
(2) Adjusting the dietary structure[98–100]. The carbon sink function of cropping industries can alleviate carbon emissions to a certain extent. Through scientific guidance to the public, promoting the environmental friendliness of replacing animal protein with plant protein, so as to reduce consumer demand for pork, beef, mutton, poultry meat, eggs and other livestock

and poultry products, and reduce the carbon emission from livestock and poultry production.

(3) Increasing understanding of the development of livestock and poultry production in China to correctly predict the pollution trend of livestock and poultry manure. Evaluating the suitability of China's livestock and poultry production to optimize the spatial layout of intensive livestock and poultry production and guide the livestock and poultry production to transfer to areas with richer resources and greater environmental carrying capacity.

(4) Building and developing an ecological productions models combining crops and animals, and breaking through the constraints of resources and environment on industrial development. Realizing the upgrading and transformation of the livestock and poultry production from environmental pollution to ecological sustainable industry[101].

6 CONCLUSIONS

This work has discussed various technologies available for managing livestock and poultry manure with a focus on carbon emission and its reduction at collection, storage and treatment stages. The use of dry collection technology at the collection stage is highly recommended, and acidification, compaction, mulching, addition of regulators, such as biosolids and biochar, and storage tanks help reduce GHG emission during storage stage. For open systems, such as composting, achieving source reduction of harmful gases remains to be studied. Although AD technology is environmentally friendly, the problems of high investment cost and low efficiency of low-temperature CH_4 production constrain its adoption. Biochar and microalgae technologies clearly have the great potential for carbon emission reduction, but more detailed technical and economic evaluation is required. GHG emission from manure management is influenced by factors such as livestock type and distribution, and the product types, social factors, management conditions, as well as the type and amount of feed and feed supplements given to the animals. This work has provided a comparative analysis of the accounting methodologies for carbon emission and carbon footprint in livestock and poultry manure management. It has also identified uncertainty factors that can affect the accuracy of accounting results and evaluated commonly used index decomposition methods. The modified Fisher decomposition method is considered to be the most effective for explaining changes in carbon emission. China will usher in its rapid development period of agricultural carbon trading market (including for manure management) in the near future. Consequently, there is an urgent need for more general and practical carbon accounting and carbon emission reduction methodologies. More encouragement and effort from government and society would boost the development and the operation of emission reduction projects and emission reduction trading market. Centralization of animal production industries to areas of resource abundances and greater environmental carrying capacity would be beneficial. The efficient combination of crop and animal production is highlighted as key to development. Establishment of dynamic balance between development of low-carbon agriculture and animal production is recommended. Transformation of human diet structure from animal to plant protein will also facilitate reduction of carbon emission from manure. This work provides a theoretical reference informing policy formulation for livestock and poultry manure management in China.

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Compliance with ethics guidelines

Leli Zhang, Reaihan E, Mahmoud M. Ali, Hongjian Lin, Shuai Zhang, Shuqin Jin, Zhiping Zhu, Jianjun Hu, Yiqing Yao, Yong Sun, Shuiping Yan, and Zhidan Liu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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