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EDITORIAL

VALORIZATION OF LIVESTOCK WASTE AND CARBON NEUTRALITY

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Livestock production has rapidly developed along with improvements in living standards and people’s desire for a better life. Intensive livestock production is important to guarantee supply of meat, eggs and milk, and even vegetable production, in the modern society of China. Recently, the Ministry of Agriculture and Rural Affairs jointly with the National Development and Reform Commission, the Ministry of Finance, and the Ministry of Natural Resources in China formulated and released the National Modern Facility Agriculture Construction Plan (2023–2030)[1], which proposed the construction of modern animal husbandry facilities with efficient and intensive operations, encouraging the development of three-dimensional facility farms for pigs and poultry, and promoting using multistory buildings according to local conditions. However, large-scale livestock and poultry farms have faced many challenges impacting its green and sustainable development, such as production environment, air quality, manure and sewage treatment and resource utilization.

Livestock manure contains resources and nutrients, such as N and P, at the same time, has a some of unwanted contaminants, such as heavy metals, antibiotics and resistance genes. From a development perspective, the quality of manure treatment is related to the economic benefits of livestock farms, the healthy development and even their long-term fate. In the future, large-scale livestock and poultry farming will inevitably face challenges such as water environment, and energy. The scientific treatment and resource utilization of manure are conducive to pollutant removal, reducing nutrient loss, promoting the breeding cycle, building sustainable development of resource conservation and ecological cycling pastures, and promoting sustainable development of large-scale livestock and poultry farming industry. Considering all of these points, livestock manure for agriculture has been strictly specified in Environmental Law in EU. The integrated crop-livestock mode is greatly encouraged in China via many government documents, such as National Agricultural Sustainable Development Plan (2015–2030). The integrated crop-livestock cycle has been a tradition in China for thousands of years, which recovered nutrients from manure to land is one key link. However, over the last few decades, it has caused serious non-point source pollution due to uncoupled livestock and crop supply chains. Therefore, it is necessary to recouple crop-livestock production and reestablish beneficial traditions through modern technology. One major reason is that the manure from animal production in multistory buildings is more concentrated, and the usual techniques for manure treatment and utilization cannot meet the technical requirements. It is urgent to conduct research and development for innovative technologies to realize efficient treatment and recycling of manure. These innovative technologies should focus on recycling of farm sewage after safety treatment, and methods to transform manure into bio-based recourses in order to achieve sustainable goals. Another concern is the detrimental contaminants in livestock manure, which must be reduced or removed for an integrated and sustainable crop-livestock system.

For carbon neutrality, reduction in GHGs emissions from livestock and poultry industries are needed along the entire supply chain, with upstream, midstream and downstream mitigation needed in animal production. The livestock and poultry industries constitute an important source (14%–18%) of GHGs emissions, according to UN Framework Convention on climate change and UN FAO[2,3]. Therefore, carbon neutrality should be considered during livestock production, as well as treatment and valorization of manure. By harnessing the power of modern engineering and biotechnology, it is possible to develop sustainable and eco-friendly methodologies for manure recycling. Such processes not only preserve ecosystem health and regional ecological stability, but also pave the way for a low-carbon, highly efficient model of livestock and poultry waste utilization, in line with the ethos of an ecological civilization. It is a collective obligation to recycle nutrient-rich livestock waste back into agricultural production systems, thereby converting ecological challenges into sustainable wealth generation.

Considering the global incentive for achieving carbon neutrality and growing demand for agricultural green development, we organized a special issue of *Frontiers of Agricultural Science and Engineering* focused on valorization of livestock manure and carbon neutrality as a fast-growing interdisciplinary subject. Distinct from previous issue regarding livestock manure treatment, this issue tries to address how the emerging carbon neutrality global consensus and urgent needs for sustainable livestock development impact the technologies, engineering, market and policy of modern livestock manure management.

Specifically, five broad topic areas are addressed in this special issue: including source emission reduction; biological treatment and valorization; thermal conversion and valorization; carbon capture, utilization and storage; and integrated crop-livestock mode.

In this special issue, Zhang et al. reviewed livestock and poultry manure management from the perspective of carbon neutrality in China (https://doi.org/10.15302/J-FASE-2023509). Unlike previous reviews that focused on resource recovery, this review provides an unique insight of transformation from “resource-oriented manure treatment” to “integration of resource recovery with pollution reduction, carbon accounting and trading” aiming at 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. This review provides a reference for the establishment of carbon reduction methodologies, and the formulation of governmental policies for livestock and poultry manure management system in China.

Source emission reduction. Feed production processes have been confirmed as the main sources of carbon emissions in animal production by numerous practical studies. Nowadays, nutrient strategies applied to animal production are a new perspective often mentioned to ease environmental pressures, as well as saving feed resources. The major strategies include: developing precise feed formulation by using dynamic reference nutritional values and mathematical models, improving feed use efficiency by using more digestible feed ingredients or lowering the crude protein level in diets, or supplying feed additives to enhance the nutrient utilization and reduce carbon or nitrogen emission. Ruminant meat and some dairy products have a high carbon footprint per gram of protein, whereas other meats (such as pork and poultry) and protein-rich, lightly processed dairy products (such as yogurt) have a much lower carbon footprint, since the emission of methane gas by ruminants is also a major source of greenhouse gases. The continuously increasing consumption of ruminant products and resulting large-scale breeding production are important sources of methane emissions.

Therefore, we have included the review article, “Using nutritional strategies to mitigate ruminal methane emissions from ruminants” (https://doi.org/10.15302/J-FASE-2023504), in this special issue as a representative example of source emission reduction. In this review, the methanogenesis initials in ruminants—the ruminal microbiota, and the major methanogenesis pathways in ruminants (hydrogenotrophic, acetoclastic, methyl dismutation and methyl reducing pathways) have been introduced in detail. Also, three nutritional strategies for dietary nutrient manipulation (feeding management, feed composition, forage quality and lipids supplementation), microbial manipulation (ionophore, defaunation, methanogen inhibitors and probiotics), and chemical manipulation (nitrate, organic acids, plant secondary metabolites and seaweeds supplementation) have been summarized based on the latest published studies. It is anticipate that this article will provide essential information for development of sustainable feed and livestock production system.

Precision livestock farming (PLF) is another key point for emissions control and reduction. Over the last decade, livestock industry stakeholders and researchers have developed an intense interest in PLF technologies, which monitor, model, control and manage individual animal production and the environment (microenvironment) in real-time by the application of the knowledge of animal-environment-equipment interactions and the technology of artificial intelligence, big data, smart sensing, Internet-of-Things and more. More accurate understanding of the needs, barriers and functions of PLF are being gradually developed. An earlier literature review showed the application of PLF in animal farms helps reduce the greenhouse gases and ammonia emissions in the atmosphere, and contaminants from wastes in water bodies and the soil, therefore improving environment while enhancing animal health and welfare to increase producer income[4]. An example is the real-time monitoring of live-bird weight in commercial broiler houses, where it is usually necessary to meet a target bird weight with a specific timeframe. As more non-invasive and non-stressed weight monitoring technologies are implemented, it will become possible to predict accurate weights and detect abnormal weight growth events. An accurate weight prediction in advance (e.g., 3 days) based on real-time weight data can then help predict the day when a finishing weight will be met. Also, an effective detection of abnormal weight grain events will allow the producer to intervene as soon as possible, for example by changing feeding strategy or providing medication.

Zhou et al. reported the development and evaluation of an automatic and stress-free weighing platform for monitoring the weight of floor-reared broiler chickens in commercial production (https://doi.org/10.15302/J-FASE-2023510). Regression analysis showed a strong relationship between weight estimated by the automatic weighing platform and the weight obtained by the established live-bird sales system. The platform demonstrated an average accuracy of 99.5% with the standard deviation of 2.3%. Precise and daily weight monitoring would allow the farmer to effectively optimize feeding and environmental control during broiler production. Xin et al. reported the comparison of the dispersion air pollutants (using ammonia as a representative example) emitted from multi- and single-floor pig buildings through three-dimensional simulations based on computational fluid dynamics and the validation in local pig production facilities (https://doi.org/10.15302/J-FASE-2023501). Their results showed that the ammonia dispersion distance of the multi-floor pig building was far greater than that of the single-floor building. Multi-floor buildings for pig production have recently attracted considerable attention as an emerging form of intensive livestock production in China. The results of this study should provide a basis for future development of multi-floor pig buildings.

Biological treatment and valorization. Biological treatment technologies, such as anaerobic digestion (AD) and composting, allow the conversion of livestock manure into valuable resources under mild conditions, but also reduce greenhouse gas (GHG) pollution and the dependency on fossil fuels to contribute toward a clean, safe and sustainable agriculture. AD has been shown to be an efficient and alternative technology for sustainable organic waste management due to the biogas recovery as energy sources and valuable bio-slurry rich in nutrients that can be used as fertilizer. Efficient AD has the capacity of efficiently degrade animal feces, straw and other organic matter, and other substances that are difficult to degrade under natural aerobic conditions. Co-digestion and high organism loading rate has been recognized for its benefits in providing buffering capacity, creating an appropriate nutrient ratio, enhancing system treatment capacity and methane yield. For this issue, two papers on this topic were included. The first study compared the methanogenesis potential of dry and fresh maize straw under both single substrate and co-digestion with cattle manure (https://doi.org/10.15302/J-FASE-2022471), and concluded that fresh straw provided higher CH_4 production efficiency. The main pathway in the fresh maize straw AD system was hydrogenotrophic methanogenesis, with genes encoding formylmethanofuran dehydrogenase (K00200–K00203) and tetrahydromethanopterin S-methyltransferase (K00577–K00584). The second study combined alkaline pretreatment and air mixing to further enhance the co-anaerobic co-digestion of poultry litter with wheat straw (https://doi.org/10.15302/J-FASE-2023506). Alkaline pretreatment facilitated substrate degradation and air mixing enriched the microbial activity, together enhancing methane generation. We hope these studies help advance new knowledge about and industrialization of competitive AD technologies.

Thermal conversion and valorization. Over recent years, livestock and poultry waste has emerged as a significant environmental challenge due to its adverse impacts on ecosystems and public health. However, this waste can also be viewed as a valuable resource for the production of renewable energy and value-added products. Thermal conversion technologies, such as pyrolysis, hydrothermal conversion, gasification and combustion offer promising avenues for the sustainable management and valorization of livestock and poultry waste. Thermochemical conversion can utilize waste on a large scale and with improved efficiently, and its gas, solid, and liquid products have a wide range of potential application. Nevertheless, it should be acknowledged that thermochemical conversion processes often require significant energy consumption. Additionally, due to the high moisture content of livestock manure, directly transforming it through standard thermochemical methods may not be economically viable. Consequently, hydrothermal carbonization should prove to be a more favorable option for livestock manure with high moisture content.

He et al. investigated the variation of heavy metal content during the hydrothermal carbonization of cow manure (https://doi.org/10.15302/J-FASE-2023507). Their findings indicate that the heavy metal content in hydrochar varies greatly, and the concentration of heavy metals in hydrochar can exceed that of cow manure. It proves hydrochar is feasible for use as a phosphorus-enriched organic fertilizer and/or soil amendment for agricultural applications without serious concerns about heavy metals it might contain. Also, considering the composition ratio of the raw materials, co-thermochemical conversion of waste materials represents a more economically-viable alternative. Hu et al. simulated the co-gasification process of wood chips and potato peels to produce syngas for chemical synthesis (https://doi.org/10.15302/J-FASE-2023490). The simulation reveals that low-value biomass waste, including wood chips and potato peels, can generate valuable syngas. There is a positive synergistic interaction occurs between wood chips and potato peel in co-gasification process in terms of an increase in carbon conversion efficiency. The authors concluded that co-gasification for producing syngas is feasible and environmental-friendly option to recycle and valorize potato peel. It would be highly beneficial to be able to use the moisture of the raw material itself in the steam gasification process, especially for livestock and poultry manure with high moisture content. The process of steam gasification of cow manure to produce synthesis gas was simulated by Zhang et al. (https://doi.org/10.15302/J-FASE-2023500). The study reveals that the hydrogen production can be maximized by utilizing the optimal reaction conditions, and steam gasification effectively enhances hydrogen production. However, it is important to note that the utilization of high-moisture livestock manure through thermochemical conversion is still in experimental and simulation stages due to cost-related issues. There is still a long way to go before reaching the industrialization stage, and further research is needed to improve related technologies.

Carbon capture, utilization and storage. This is a process that captures carbon dioxide emissions from sources and either reuses or stores it so that it does not enter the atmosphere. For example, there is a potential to offset 930 to 1260 Mt CO_2 equivalents annually of greenhouse gas emissions by collecting and disposing of livestock production wastes like manure via AD[5]. This greenhouse gas emission reduction mainly comes from avoiding emissions from manure management and energy produced from the biogas generated in the anaerobic digester. Especially, when the biogas is upgraded by removing CO_2 and H_2S, the bio-natural gas or biomethane can be produced, which can replace standard natural gas to narrow the gap between natural gas supply and demand in China. One of big issues in biogas upgrading is cost-effective removal of CO_2. There are several technologies available for CO_2 removal including pressurized water scrubbing, physical absorption, chemical absorption and membrane separation, in which the CO_2 chemical absorption should be given more attention because of the unique advantages including mature technology, high purity of CH_4 after CO_2 removal and negligible CH_4 loss. However, this technology still struggles with the high energy input costs because of the high CO_2 regeneration energy requirement. Consequently, one of the main challenges for CO_2 chemical absorption from biogas is determining how to reduce the energy required for CO_2 regeneration. Besides the screening of new absorbents and waste heat recovery from the stripped gas, the so-called once-through process is also a promising in that only the CO_2 absorption stage is maintained while CO_2 regeneration stage is rejected. Ideally, therefore, the energy input for CO_2 chemical absorption can decrease sharply due to the ignorance of CO_2 regeneration energy consumption. It should be noted that the screening of CO_2 absorbent is a critical because the absorbent is not recycled. Previously, biogas slurry discharged from the AD digester was experimentally confirmed as a potential absorbent because of its unique advantages of renewability, low cost, alkalinity and low phytotoxicity. For substantively improving the CO_2 absorption performance of biogas slurry, renewable ammonia aqueous solution (RAA) can be recovered from the biogas slurry by vacuum membrane distillation to capture CO_2 from biogas[6].

Sun et al. performed the simultaneous CO_2 and H_2S removal from biogas by RAA in the hollow fiber membrane contactor (https://doi.org/10.15302/J-FASE-2022473). In their study, the CO_2 and H_2S removal performance of RAA was investigated by changing the RAA absorbent, impurity concentration in RAA, CO_2 loading and reaction temperature. Their paper provides the interesting and results revealing that almost all the H_2S contained in the biogas can be removed by RAA, and about 90% CO_2 can be removed at 0.5 $mol \cdot L^{-1}$ RAA. The results verified experimentally the feasibility of RAA in once-through process. Certainly, in the future, the novel renewable CO_2 absorbents should be developed for achieving the improved CO_2 removal performance in the once-through CO_2 absorption process. Also, the storage and use of CO_2 removed from biogas should be prioritized to achieve negative carbon emissions.

Integrated crop-livestock mode. The crux of green agricultural development lies in the creation of an ecologically integrated crop-livestock system. By governing the origin, committing to eco-friendly production, and enforcing comprehensive waste treatment, we can promote resourceful utilization of manure. Bridging the current gap between crop and livestock production and promoting balanced and diverse growth is critical for the advancement of modern agriculture. Eco-agriculture represents an effective strategy to realize low-carbon, sustainable and efficient agricultural production. Given the inherent interconnect between crop and livestock production, it is essential that manure is safely treated and reused as fertilizer. This will necessitate ongoing efforts to refine biogas engineering and oxidation pond technology in terms of operational costs, efficiency and mitigation of potential secondary pollution.

In this context, we have included two noteworthy papers (https://doi.org/10.15302/J-FASE-2023480; https://doi.org/10.15302/J-FASE-2023503). They embody the possibilities of an integrated crop-livestock system that utilizes cost-effective fly ash in high concentrations to give significant COD and TP removal of chemical oxygen demand and total phosphorus, ensuring process economic feasibility. In addition, photocatalytic treatment offers promise for the post-processing of anaerobic digestion effluent and other types of wastewater. These papers provide insightful contributions toward the development of unified crop and animal production systems.

With the rapid upscaling of animal production, manure management in China have also undergone major changes. Low-carbon management of manure is challenged by many factors. For example, the demand for meat, eggs and milk will also increase, especially the demand for high-quality proteins such as beef and milk is on the rise, and animal manure, methane and other emissions will increase in parallel. The rise in animal production costs and fluctuations in the price of livestock and poultry products have led to a lack of stable profit expectations for producers, and insufficient investment motivation for waste resource utilization.

We highlight several key points for the green development of livestock manure management in China:

(1) *Developing efficient and green manure treatment technologies*. Research and development toward automatic separation of solid and liquid manure in production facilities is needed, supporting facilities for scraping feces, solid and liquid manure delivery facilities, to minimize the amount of slurry production and reduce the greenhouse gas emissions from this source. As for liquid manure treatment, research on innovative processes of established technologies, such as anaerobic fermentation should be conducted to improve the efficiency of anaerobic stage, and biogas purification and power generation technology should be developed to realize the energy potential of biogas. Carbon neutral or negative technologies are needed. As for solid manure treatment, low-carbon technologies, for example, biochar and closed aerobic composting technology, should be developed to reduce greenhouse gas emissions. Light and simplified solid and liquid manure return and utilization facilities are needed according to the type of farmland in different regions of China, so as to realize convenient and fast manure return to the field, shorten manure storage time and further reduce greenhouse gas emissions. Finally, by establishing a complete crop-livestock 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 can be increased and environmental pollution problems can be alleviated.

(2) *Developing measurable carbon accounting methodologies and incubating carbon trading market*. Increased attention needs to be given to the accuracy of accounting results from different perspectives. A large number of more general and practical GHG emission reduction methodologies could to be developed based on the existing methodologies in the field of livestock and poultry production. The integration of existing carbon reduction methodologies in other fields, such as solar energy and bioenergy is encouraged with manure management. It is necessary to encourage the further development of carbon trading market in livestock farms via many strategies, such as guiding its development depending on conditions of different places, and improving the operation effect and positive effect of CCER, strengthening financial support, enriching the financing channels, expanding the construction of the carbon emission rights offset market, improving the top-level policy designs and

encouraging more enterprises to participate in carbon trading market.

(3) *Scientific understanding of livestock manure management*. Livestock manure management is relevant to agricultural economic development, public dietary structure, resources and the environment. A dynamic balance should be established between low-carbon development and the normal supply of livestock and poultry products. Livestock and poultry production should also be upgraded and transformed from environmental pollution to ecological sustainable industry.

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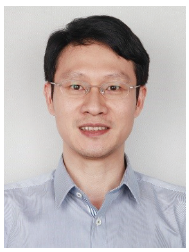

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