

Review

Regional Characteristics of Livestock and Poultry Manure Production and Sustainable Resource Utilisation Technologies in China—A Review

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Abstract

China's livestock farming scale rose from 54.4% in 2020 to 73.2% in 2023, increasing annual manure production to 3.8 billion tons and greenhouse gas emissions to 4–6 billion t carbon dioxide equivalent (CO₂-eq). Manure management has thus become a key barrier to agricultural pollution control and carbon reduction goals. This study analyses regional differences in manure generation, showing that East and Central China—comprising less than 40% of the national land area—bear over 48% of total manure and about 50% of N and P loads, whereas Northeast and Northwest China have surplus cropland absorption capacity. This reveals a clear spatial mismatch between manure production and land carrying capacity. By reviewing major treatment technologies (aerobic composting, anaerobic digestion) and utilisation pathways (fertiliser use, energy recovery) and integrating life cycle assessment (LCA) with geographic information system (GIS)-based spatial evaluation, this study highlights the advantages of technology coupling strategies. For example, anaerobic digestion combined with composting can reduce net climate impacts by 21%, and regional circular models cut full-cycle carbon footprints by 34.44%. The results underscore the need for GIS-supported spatial LCA to match technologies with regional conditions, providing a scientific basis for advancing livestock manure management and China's green agricultural transition.

Keywords: livestock and poultry manure; resource utilisation technology; life cycle assessment; regional adaptation; multi-technology coupling



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1. Introduction

Non-point-source pollution and greenhouse gas emissions from livestock manure have become major challenges in agricultural environmental management [1]. According to data from the Ministry of Agriculture and Rural Affairs, China's scale farming rate for livestock and poultry reached 73.2% in 2023, generating approximately 3.8 billion tonnes of manure annually. The Second National Pollutant Source Census Bulletin [2] reports that although the emission intensities of chemical oxygen demand (COD), total nitrogen, and total phosphorus from livestock and poultry farming have decreased by 55.5%, 67.2%, and 57.9%, respectively, when compared with those in the first national pollution census, the sector still contributes a disproportionately high share of agricultural pollution. Livestock farming accounts for 93.8% of COD and 51.3% of ammonia nitrogen emissions in agricultural water

pollution. Meanwhile, the livestock sector is also a major global source of greenhouse gases [3], with emissions (in CO₂ equivalents) reaching 4–6 billion tonnes annually [4], representing roughly 18% of total global greenhouse gas emissions.

Livestock and poultry manure resource utilisation represents a key pathway to resolving the conflict between environmental pollution and resource wastage within the livestock industry [5]. In recent years, China has introduced policies such as the 14th Five-Year Plan for Renewable Energy Development and the Guiding Opinions on Accelerating the Comprehensive Green Transformation of Agricultural Development and Promoting Ecological Revitalisation in Rural Areas. These explicitly set targets for developing biogas and promoting the substitution of chemical fertilisers with organic fertilisers. Consequently, advancing livestock manure resource utilisation is both an urgent necessity for reducing agricultural pollution and lowering greenhouse gas emissions and an indispensable pathway for achieving the green transformation of agriculture [6–8].

At present, although China has established a mainstream technological system for livestock and poultry manure treatment, including anaerobic digestion and aerobic composting [9], significant regional differences in natural conditions, agricultural production practices, and economic development still exist due to the country's vast geographical expanse. These factors exert a profound influence on the resource utilisation of livestock and poultry manure [10–15]. Optimising the efficient, site-specific utilisation of manure by integrating multiple technological pathways is key to enhancing its resource efficiency. This study examines the current production and discharge patterns of livestock manure in China, systematically reviews research progress in manure treatment and resource recovery, and focuses on exploring the regional adaptability of multi-technology integration. It aims to provide insights for optimising manure treatment models and promoting the sustainable development of the livestock industry.

This study adopts a narrative review approach to synthesise the current status of livestock manure management and technological coupling strategies. Literature was retrieved from major academic databases, including Web of Science, Scopus, and CNKI, covering the period primarily from 2010 to 2024, while also including foundational earlier works. The search keywords included combinations of “livestock manure,” “nutrient balance,” “anaerobic digestion,” “pyrolysis,” “technological coupling,” and “China.” Studies were selected based on their relevance to regional environmental characteristics, technological implementation, and policy analysis.

2. Current Status and Regional Characteristics of Livestock and Poultry Manure Production and Discharge

2.1. Current Status

With the rapid development of China's economy and society and the continuous improvement in people's living standards, the trend towards intensive and large-scale livestock farming has become increasingly pronounced [16,17]. In recent years, the rate of large-scale livestock and poultry farming in China rose from 54.4% in 2015 to 73.2% in 2023, with farming volumes also increasing annually (Figure 1). This transformation has significantly altered the production and discharge characteristics of livestock manure, leading to a sharp increase in pollutant accumulation in localised areas. If improperly managed, the associated environmental risks will be markedly higher than those of traditional free-range farming systems [18].

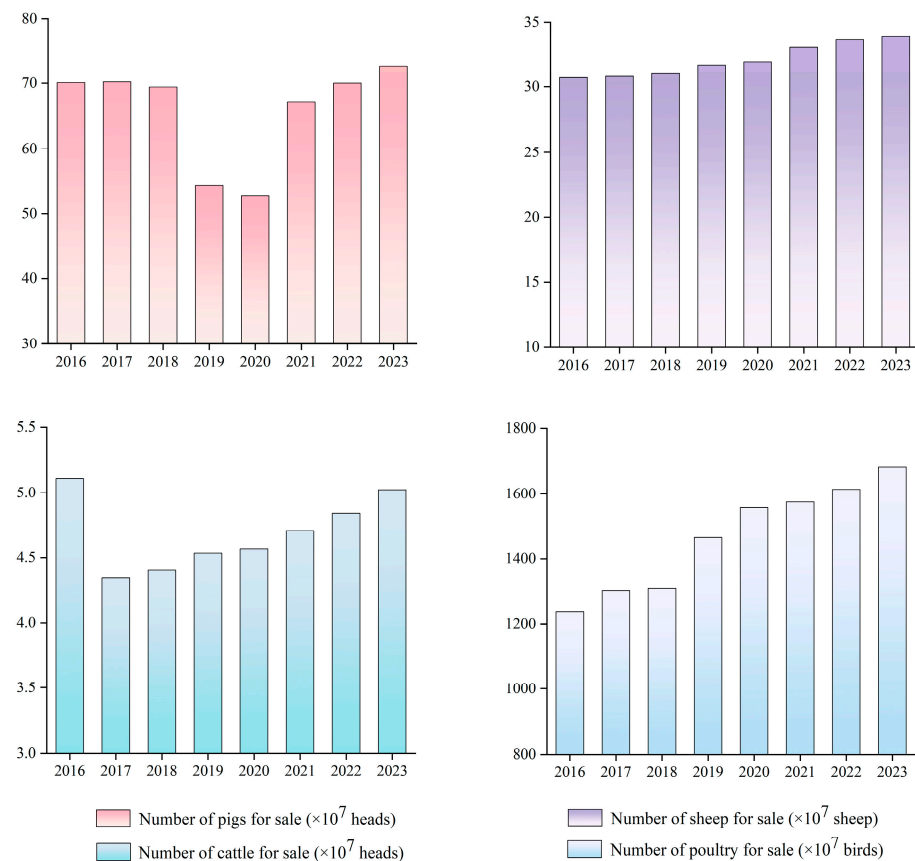


Figure 1. Numbers of livestock and poultry raised from 2016 to 2023.

The rapid expansion of large-scale livestock farming has made animal manure a significant source of agricultural non-point-source pollution. According to the Second National Pollution Census Bulletin [2], China's livestock and poultry farms discharge 596,300 tonnes of total nitrogen (TN), 119,700 tonnes of total phosphorus (TP), and 1,000,530 tonnes of chemical oxygen demand (COD) annually. These figures represent 42.1%, 56.5%, and 93.8% of total agricultural water pollutant emissions respectively. However, these aggregate figures often mask the spatial mismatch between livestock density and land carrying capacity. Furthermore, uncertainties remain in the reported loads, as traditional emission factors may underestimate the reactive nitrogen losses inherent in hyper-intensive systems. Key pollutants such as COD, TN, and TP undergo continuous migration and transformation across water–soil–air interfaces, exerting long-term pressure on the ecological environment. This not only threatens regional environmental quality and ecosystem stability, but also poses potential risks to human health and sustainable development [19–22].

2.2. Regional Characteristics

The spatial distribution of livestock and poultry manure in China is closely linked to the farming density, regional industrial structures, and resource endowments, exhibiting pronounced regional disparities and spatial misalignment [23,24]. From 2000 to 2019, the annual national production of manure and wastewater increased from 970 million tonnes to 1.21 billion tonnes, representing a 24.7% rise, with nitrogen and phosphorus pollutants rising concurrently to 20.5%. Notably, East China and South-Central China, which occupy less than 40% of the national land area, bear over 48% of the country's total manure and slurry volume and approximately 50% of the nitrogen and phosphorus load [25]. East of the Hu Huanyong Line, North China, the middle and lower reaches of the Yangtze River, and the coastal regions of South China constitute both major grain-producing areas and

zones of intensive pig and poultry farming (Figure 2). There exists a significant mismatch between manure discharge volumes and the absorption capacity of cultivated land [26]. In contrast to these intensive farming zones characterised by high stocking densities, the Northeast, Northwest, and Qinghai–Tibet Plateau regions possess vast arable land and pasture resources. However, due to low livestock densities and an insufficient scale of operations, their manure production and discharge intensity has long remained among the lowest nationwide. This suggests a ‘surplus capacity’ that remains difficult to utilise through cross-regional allocation, presenting a critical bottleneck that must be overcome for the green transformation of regional agriculture [27].

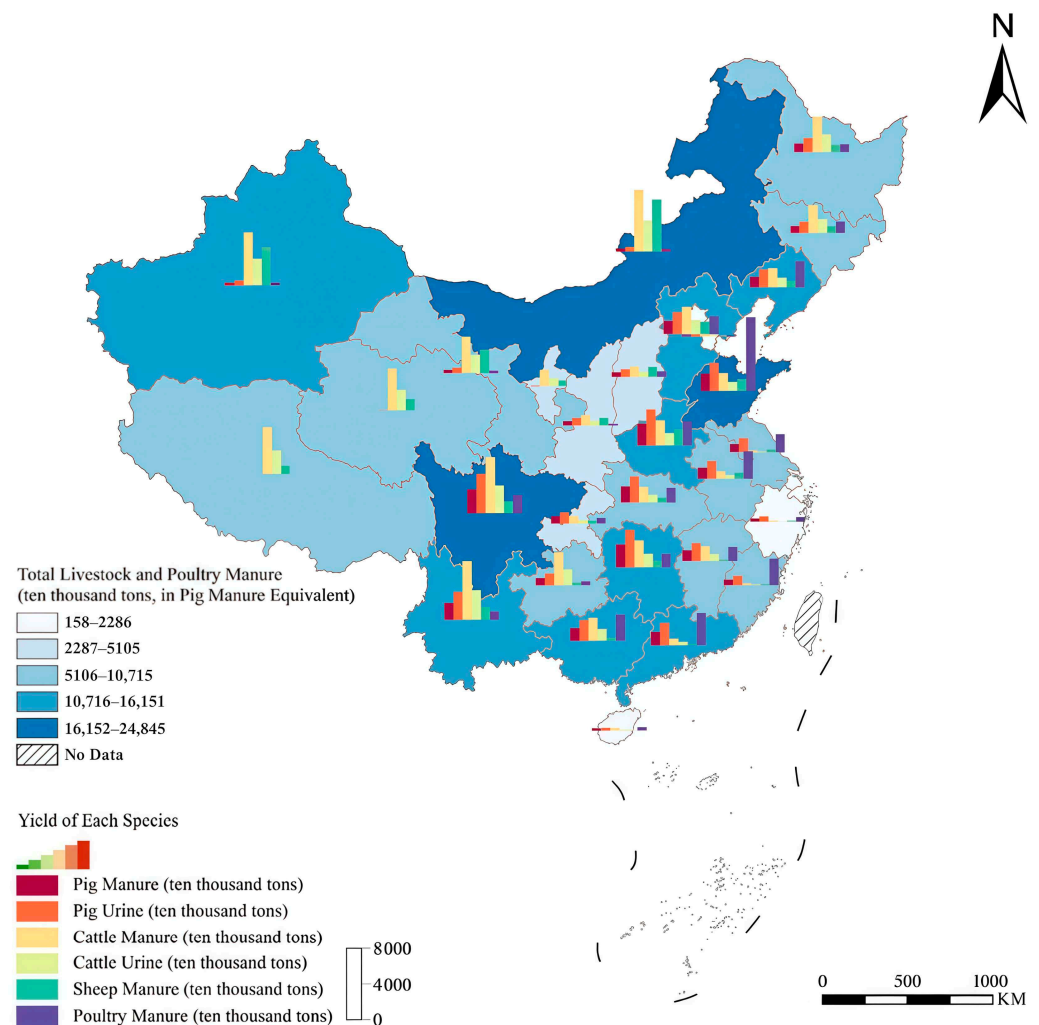


Figure 2. Livestock manure production in China’s 31 Provinces (municipalities and autonomous regions) in 2023. This map was produced based on the standard map downloaded from the National Geographic Information Public Service Platform Tianditu, bearing the review number GS(2024)0650. No modifications have been made to the map.

Based on data from the 2023 China Veterinary and Animal Husbandry Yearbook, livestock and poultry manure production volumes were estimated by province and species. Utilising daily excretion coefficients from the First National Pollutant Source Census, production volumes of pig manure, pig urine, cattle manure, cattle urine, sheep manure, and poultry manure were calculated for 31 provinces (municipalities and autonomous regions). Figure 2 indicates that in 2023, the estimated livestock manure production across 31 provinces (municipalities and autonomous regions) amounted to 1803.02 million tonnes, with estimated manure and urine totalling 860.73 million tonnes. By livestock type, the provinces with the highest pig manure production were Sichuan, Hunan, and Henan, with

a combined total of 200.93 million tonnes accounting for 26% of the national pig manure output. This highlights the manure pressure in Central and Southwestern China as core pig farming regions. Cattle manure production is highly concentrated in major pastoral provinces, with Inner Mongolia, Yunnan, and Sichuan ranking first, second, and third respectively, reflecting the geographical correlation between ruminant livestock farming and agropastoral transition zones. Sheep manure output is led by Inner Mongolia, Xinjiang, and Gansu, its distribution closely aligning with northern grasslands and agropastoral transition zones. Poultry manure production is dominated by traditional poultry-producing provinces such as Shandong, Guangdong, and Anhui, reflecting the coastal concentration of the poultry industry.

3. Livestock and Poultry Manure Treatment Technologies and Resource Utilisation Models

3.1. Resource Utilisation Model

Livestock and poultry manure resource utilisation refers to the process of converting waste products such as faeces and wastewater generated during animal husbandry into usable resources, including fertilisers, energy sources, and bedding materials, through physical, chemical, or biological methods [28]. The primary utilisation methods include fertiliser application, energy conversion, and animal feed production. According to statistics from the Ministry of Agriculture and Rural Affairs, China's comprehensive utilisation rate of livestock manure reached 79.4% in 2023.

Fertilisation represents the most traditional and direct resource utilisation method for livestock manure, centred on converting waste into organic fertiliser. By harnessing its rich nitrogen and phosphorus contents for efficient return to fields, this approach not only enhances soil structure and fertility but also holds considerable potential for reducing reliance on chemical fertilisers [29–33]. Research has indicated that as compared to conventional chemical fertilisers, the application of manure-based organic fertilisers significantly increases soil alkali-hydrolysable nitrogen and readily available phosphorus contents, by 27.8% and 21.2%, respectively [34]. It was estimated that, in 2019, the potential for livestock manure to replace nitrogen fertilisers and phosphorus fertilisers nationwide stood at 19.25% and 4.55%, respectively. Notably, the nitrogen fertiliser replacement potential in the Tibet Autonomous Region and Qinghai Province reached as high as 279.30% and 137.99%, respectively, indicating that these two provinces possess the potential for manure to fully replace, or even exceed, the required nitrogen fertiliser [25].

Energy conversion involves transforming manure waste into renewable energy through biological, chemical, or thermochemical processes, with its core objective being the recovery of energy and carbon cycling from waste materials [35]. Biogas engineering based on anaerobic digestion represents the most prevalent method for livestock manure energy conversion in intensive farming operations. This approach not only promotes resource recycling but also contributes to achieving the dual carbon goals, thereby advancing green and low-carbon development. Research indicates that, in 2017, China's potential biogas production capacity from livestock manure reached 198.3 billion cubic metres—equivalent to 142 million tonnes of standard coal—positioning the nation among the world's highest biogas producers [27].

Feed utilisation refers to the process wherein certain livestock manure is processed and conditioned to serve as roughage for ruminants or to produce protein feed, thereby achieving resource recycling within the farming system [35,36]. This model employs diverse technical approaches in practice, such as the biological treatment of livestock manure using saprophagous organisms like earthworms and black soldier flies. The proliferated earthworms and black soldier flies can serve as animal protein sources in livestock feed,

while residual matter (insect castings) is utilised as organic fertiliser for field application. Experiments have demonstrated that black soldier fly processing of pig manure reduces its volume by approximately 50%, while the insects themselves gain 42% protein and 35% fat [37]. Moreover, it is common practice to utilise processed chicken manure as feed. By fermenting materials such as chicken manure, soybean straw, distillers' grains, and peanut stalks, a concentrated feed suitable for beef cattle can be produced [38]. However, the utilisation of livestock manure as feed presents certain challenges, primarily due to the potential presence of harmful substances such as pathogens, parasites, heavy metals, and antibiotics within the manure. This poses significant safety concerns, potentially leading to secondary environmental pollution and the spread of livestock diseases.

3.2. Treatment Technology

Livestock manure treatment technology is key to addressing environmental pollution in animal husbandry and achieving resource recycling [39]. Current livestock manure treatment technologies primarily encompass aerobic composting, anaerobic digestion, and pyrolysis processing [40]. Owing to the differing characteristics of solid livestock manure (Figure 3a) and liquid manure (Figure 3b), there are marked variations in the proportion of various technologies applied [9].

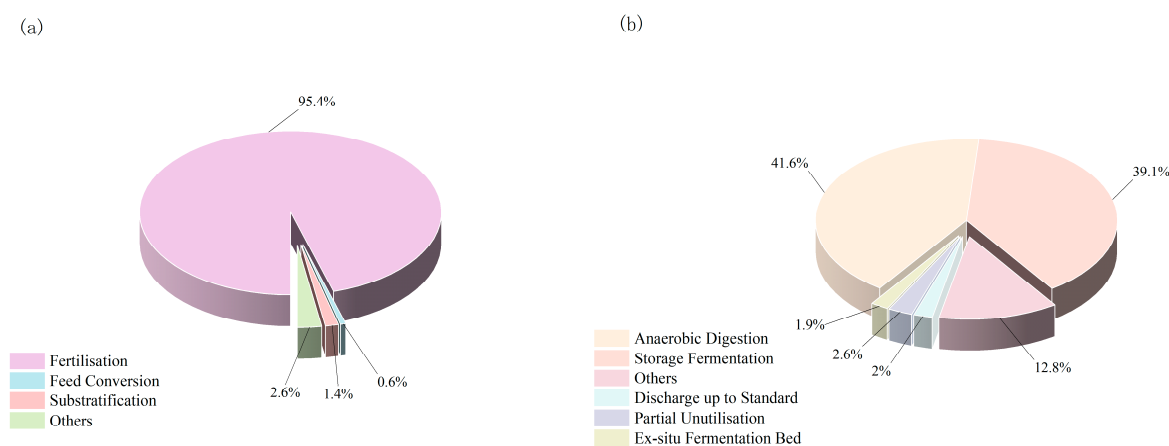


Figure 3. Proportion of various livestock and poultry manure treatment technologies ((a) solid manure, (b) liquid manure).

Aerobic composting is a biological treatment technology that utilises aerobic microorganisms to decompose organic waste under aerobic conditions. Through microbial metabolic activity, organic matter is converted into stable humus. This process is characterised by low treatment costs, a simple operation, and strong effectiveness in degrading harmful substances [41–43], ultimately producing organic fertiliser and successfully utilising livestock and poultry manure resources [44]. The most widely applied methods currently include windrow composting, static pile composting, trench composting, and fermenter composting. Their efficiency is primarily determined by the carbon-to-nitrogen ratio, moisture content, and microbial inoculants. Synergistically optimising these factors can significantly activate microbial communities, thereby enhancing organic fertiliser quality and compost production efficiency [45].

Anaerobic digestion is a process wherein anaerobic microorganisms break down organic matter in the absence of oxygen, converting livestock manure into biogas, digestate and slurry. The biogas produced contains approximately 60% methane and 40% carbon dioxide [46,47]. Its purification into biogas as a substitute for fossil fuels is emerging as a key development priority, owing to its dual potential for reducing greenhouse gas emissions and delivering long-term economic value [48–50]. This synergy between environmental

mitigation and economic gain is well-exemplified by the Beijing Deqingyuan project, the nation's first large-scale biogas initiative to utilise 100% chicken manure as its feedstock. By integrating biogas production with ecological agriculture [51], the facility processes 80,000 tonnes of poultry manure and 100,000 tonnes of wastewater annually. The operational success of this project is further evidenced by its output of 14 million kilowatt-hours of electricity and annual revenues of CNY 8 million. These results illustrate how maximising the energy conversion of livestock manure can effectively mitigate environmental pollution while ensuring economic sustainability.

Pyrolysis technology is also a highly promising method for the resource recovery and energy conversion of manure waste, currently receiving considerable attention in academic research [52]. Pyrolysis refers to the process of heating livestock manure under anaerobic or oxygen-limited conditions at medium to high temperatures, leading to its thermochemical decomposition and conversion into high-value products, including biochar rich in stable carbon and nutrients [53–55], combustible pyrolysis gas, and bio-oil with a certain calorific value [56]. This process effectively circumvents the issues associated with aerobic composting and anaerobic digestion, such as lengthy cycles, substantial land requirements, and the potential for odour and greenhouse gas emissions. It enables efficient, clean, reduced-volume and thorough resource utilisation of manure waste. However, the academic community generally recognises that pyrolysis technology involves relatively high energy consumption [57]. Therefore, the carbon emissions, energy use, and environmental and economic performance of livestock manure treatment and disposal models centred on pyrolysis require further investigation.

4. Regional Variations and Challenges in Livestock and Poultry Manure Resource Utilisation

4.1. Regional Variations

Livestock manure resource utilisation represents a pivotal measure in advancing green and sustainable agricultural development. Given China's vast expanse, regions exhibit marked disparities in natural conditions, crop–livestock structures, and levels of economic development, thereby giving rise to distinct regional characteristics in approaches to livestock manure treatment and utilisation [58,59].

In the Northeast region, the abundance of contiguous arable land and straw resources facilitates a land-centric fertilisation model. The high land carrying capacity in this area allows for localised manure treatment and direct nutrient cycling, effectively promoting the circular utilisation of livestock waste [60]. Conversely, the central and southern plains, such as Hebei, focus on a synergistic energy–fertiliser pathway centred around large-scale biogas projects. By co-fermenting crop straw with livestock manure through anaerobic digestion, these regions meet regional heating demands while returning digestate to fields, thereby simultaneously enhancing soil organic matter and achieving the dual production of energy and fertiliser [61]. Distinct strategies are also observed in the western regions. The southwestern region leverages its high proportion of cattle and sheep farming to adopt a model that prioritises both fertiliser production and energy generation, balancing nutrient supply for pastures with household heating needs [62]. Meanwhile, technological innovation in northwestern regions, such as Yinchuan in Ningxia, specifically addresses the bottleneck of low temperatures inhibiting biogas production. By integrating a two-stage fully mixed anaerobic digestion process with a solar-biogas hybrid heating system, these regions ensure stable operation in cold environments. Operational data demonstrates that this technology can process 39 m³ of manure with 6% dry solids daily, yielding 700 m³ of biogas, generating 1050 kWh of electricity, and producing 39 tonnes of biogas fertiliser, proving that climatic constraints can be mitigated through process optimisation [63].

Furthermore, the transition from fragmented treatment to regional circular systems represents a significant shift in resource efficiency. Certain regions have established integrated chains encompassing centralised manure collection, biogas power generation, and organic fertiliser production, supported by specialised service providers. Life cycle assessment studies confirm the environmental superiority of this model, indicating that such regional circular systems can reduce the full life cycle carbon footprint by 34.44% compared to traditional separate treatment methods [64,65]. These findings suggest that the green potential of livestock waste is maximised through the strategic alignment of technical processes with regional socio-ecological conditions.

4.2. Key Challenges Affecting the Resource Utilisation of Livestock Manure

4.2.1. Mismatch Between Livestock Manure and Absorption Capacity

While intensive farming scales up production efficiency, it also leads to manure and wastewater generation rates that generally exceed the immediate absorption capacity of surrounding farmland. This results in regional nutrient surpluses and triggers a series of environmental risks [66–69]. In 2016, the national application of phosphorus from livestock manure reached 2.95 million tonnes, yet its spatial distribution exhibited severe regional imbalances. The phosphorus load per unit of agricultural land in the southeast region stood at 26.33 kg/hm², with provinces such as Hunan and Beijing exceeding 42 kg/hm², significantly surpassing the annual application limit of 35 kg/hm². In intensive livestock farming regions such as North China and the middle-lower reaches of the Yangtze River, actual phosphorus return rates have approached or exceeded 50% of environmental carrying capacity. This issue is particularly acute in cash crop production areas favouring organic fertiliser application [70]. Taking Laiwu City in Shandong Province as an example, its nitrogen and phosphorus-based land carrying capacity indices stand at 2.14 and 2.36, respectively. This indicates that the volume of livestock manure generated locally has exceeded the maximum absorption capacity of surrounding farmland by more than double, presenting severe environmental overload pressures [71].

Nationally, the average livestock manure load per unit of cultivated land in 2016 stood at 0.49, placing it overall at Level II (slight environmental threat), indicating that manure waste has already constituted a potential environmental pressure. Regions such as Tibet and Qinghai reached Level V (moderately severe threat) or Level VI (very severe threat), indicating that manure production far exceeded the absorption capacity of local arable land, resulting in extremely significant environmental pressure [72]. Further analysis from the perspective of nutrient weight indicates that in 2018, the national nitrogen nutrient yield from livestock and poultry manure amounted to 1.27×10^7 tonnes. During the same period, the total theoretical nitrogen demand for crops, pasture, and plantation forests was merely 9.42×10^6 tonnes, resulting in a substantial surplus of 3.3×10^6 tonnes [73], this indicates that nitrogen nutrient production has far exceeded the actual demand of the land, resulting in both resource wastage and potential pollution risks. Furthermore, the land carrying capacity indices for livestock manure on cultivated land in Fujian, Guangdong, and Hainan Provinces reached 3.21, 2.56, and 3.67, respectively, significantly exceeding the 1.0 overload threshold.

4.2.2. Manure and Slurry Utilisation in Regional Agricultural Cultivations

The limited compatibility between manure resource utilisation technologies and regional agricultural cropping patterns constitutes another key factor constraining the resourceful utilisation of manure [74]. Different agricultural ecoregions exhibit significant variations in crop types, cropping systems, and nutrient requirements. For instance, vegetable-producing areas typically demand organic fertilisers with high readily available

nutrient content and rapid mineralisation rates, whereas grain-producing regions place greater emphasis on the persistence and stability of fertilisers [75–78]. However, current mainstream manure resource utilisation technologies, such as anaerobic digestion, produce digestate and digestate slurry that are rich in organic matter and total nutrients. Yet, their release dynamics often fail to align with the nutrient requirements of high-value crops like vegetables during specific growth stages. This mismatch results in low fertiliser utilisation rates and may even compromise crop quality and yield [79–81].

Moreover, distinct regional variations exist in China's manure management approaches: the Northeast Plain predominantly employs storage for agricultural use, while the southern hilly regions favour anaerobic digestion for agricultural application. This disparity should be addressed through differentiated technical strategies. However, the prevailing technology dissemination system generally lacks regional adaptation capabilities, failing to flexibly adjust to local crop structures, farm scales, and farmer acceptance. This further exacerbates the mismatch between technological supply and local demand [82]. Single technologies, due to their functional limitations, often struggle to simultaneously adapt to varying soil conditions, crop nutrient requirements, production scales, and farmer operational capabilities across different regions. They also find it challenging to strike a balance between treatment costs and agricultural returns. In contrast, coupled technologies achieve comprehensive coverage of the entire process—from manure treatment and nutrient conversion to safe field application—through synergistic and complementary multi-stage interactions. This enables more precise alignment with the specific requirements of regional cropping systems, effectively overcoming the limitations of single technologies in both application scenarios and functional outcomes. Consequently, coupled technologies comprehensively enhance the adaptability, operational efficiency, and sustainability of manure resource utilisation within regional agricultural systems [83,84].

5. Exploring Coupled Models for Livestock and Poultry Manure Resource Utilisation Based on Regional Variations

5.1. Life Cycle Assessment of Regional Suitability

To address challenges such as the imbalance between total livestock manure nutrient loads and regional environmental carrying capacity, alongside the inadequate compatibility between resource recovery technologies and local agricultural cropping systems, establishing a technology coupling model based on regional variations has become a critical pathway. In livestock manure resource recovery, fertiliser conversion, energy conversion, and feed conversion represent common and effective approaches. However, with escalating demands for environmental protection and resource recycling, single-use approaches struggle to simultaneously and efficiently achieve multiple objectives such as 'harmlessness', 'reduction', and 'resource recovery'. Therefore, integrating single-treatment technologies for livestock manure (Figure 4) should be considered to facilitate the efficient conversion of manure into sustainable agricultural resources, thereby maximising resource recovery efficiency and economic benefits [85].

Life cycle assessment (LCA) has become a key tool for comparing and optimising the environmental performance of different coupled technological pathways. LCA enables the quantification of environmental impacts throughout the entire process—from manure collection, transportation, and treatment to the utilisation of resource-recovered products—thereby precisely identifying environmental hotspots and avoiding potential environmental issues arising from the pursuit of 'optimal' outcomes under single-indicator assessments [86–88]. Traditional LCA studies predominantly employ national average data, which struggles to reflect regional variations. In recent years, research has increasingly integrated GIS technology, adopting spatial LCA methodologies to enhance the assess-

ment spatial resolution and improve the localisation accuracy of environmental impact evaluations [89,90]. Methodologically, spatial LCA differs from conventional LCA by incorporating site-specific characterisation factors—such as soil properties, local climate, and transport distances—rather than treating the study area as a single homogenous unit. This indicates that regional variations constitute a significant influencing factor in LCA. This indicates that regional variations constitute a significant influencing factor in LCA.

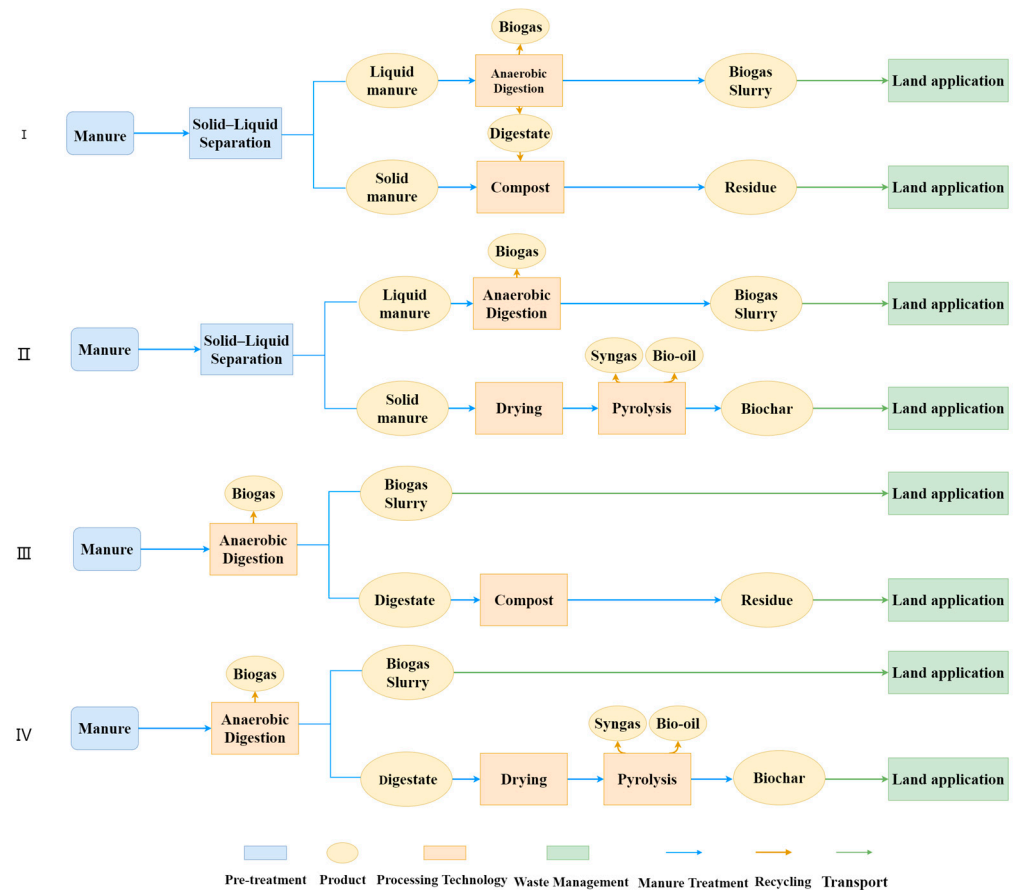


Figure 4. Technology roadmap for integrated treatment of livestock and poultry manure.

Neglecting regional characteristics will lead to distorted evaluation results, thereby compromising the applicability of technology promotion. The effectiveness of this integration in guiding decision-making is evidenced by the coupling of GIS-LCA with multi-objective programming, as applied to rainfed cropping systems in East Lorestan, Iran [91]. By processing plot-level data on land suitability and topography, this spatialized approach identifies specific crop combinations that simultaneously maximise economic profit and minimise local environmental loads. Such evidence provides a robust scientific basis for transitioning from undifferentiated, macroscopic policy frameworks to targeted technological deployment tailored to the local environmental carrying capacity and socio-economic requirements.

In livestock and poultry farming LCA studies, the regional climate significantly influences manure management practices and greenhouse gas emission pathways. Carbon emissions from pig farming exhibit marked regional variations, primarily attributable to the combined effects of local climatic conditions, feed sources, and transport distances [92]. A comparative life cycle assessment study based on the spatial distribution characteristics of manure resources further revealed that treatment models suitable for different regions exhibit distinct differentiation: in the central plains—a primary grain-producing area—the combined energy conversion and manure slurry return to fields model demonstrates the

most significant benefits in mitigating fossil fuel consumption and global warming; in the southwestern region, the off-site fermentation bed model exhibits superior overall adaptability [93]. For the ecologically fragile and arid northwestern regions, a systematic analysis was conducted that comprehensively considered the direct and indirect environmental impacts of different technologies in practical applications [94]. For instance, an LCA of dairy manure treatment revealed that employing a coupled process of hydrothermal carbonisation, algal cultivation and membrane distillation reduced the marine eutrophication potential by 16–46% and freshwater eutrophication potential by 18–99% compared to conventional treatment or anaerobic digestion alone [95]. In the context of pig manure treatment, the integration of anaerobic digestion with residue composting technology demonstrates significant potential for reducing environmental burdens. Compared to standalone incineration systems, this approach not only lowers net climate change impacts by 21% and photochemical oxidation potential by 41%, but also achieves substantial fossil fuel substitution through biogas-derived electricity generation [96].

5.2. Comparative Assessment and Implementation Status of Coupled Scenarios

In the international context, manure management strategies are fundamentally shaped by the ratio of livestock density to arable land. In regions with high land availability, such as North America and parts of Europe, the dominant model is ‘extensive land application’ governed by strict Nutrient Management Plans. The focus there is primarily on the agronomic balance of Nitrogen and Phosphorus, relying on the soil’s natural capacity to absorb waste [97]. However, China faces a unique ‘spatial mismatch’ characterised by high-density farming clusters situated in regions with limited environmental carrying capacity [98]. This constraint has necessitated a strategic shift away from simple land application toward intensive, multi-stage technological coupling. Unlike the single-mode disposal prevalent in extensive farming nations, China’s development of high-tech coupling (e.g., integrating energy recovery with fertiliser production) allows for higher volumetric processing efficiency and deeper resource recovery. This represents a distinct technological and economic advantage, as it maximises resource extraction per unit of waste, offering a replicable ‘intensive mode’ for other developing nations facing similar population-land tensions.

From an application perspective within this specific context, the deployment of coupled strategies varies by maturity. Currently, conventional biological treatment systems (Scenarios I and III), which integrate anaerobic digestion and composting, dominate the industrial landscape in China. Benefiting from established engineering standards and lower operational costs, these systems have been widely adopted in large-scale farming operations to ensure nutrient recycling. Conversely, pyrolysis-integrated systems (Scenarios II and IV) represent an emerging high-tech direction. While offering superior volume reduction and energy density (bio-oil/syngas), they remain primarily at the pilot or demonstration stage due to the higher capital requirements associated with feedstock dewatering.

Systematic assessments of livestock manure treatment technologies based on life cycle analysis (LCA) have revealed significant variations in environmental impacts and resource utilisation efficiency across different coupled processes. These variations not only provide clear guidance for technological optimisation but also expose the inherent limitations of any single technology [99–101]. Therefore, conducting regionalised analyses of livestock manure generation patterns based on LCA and assessing the suitability of resource utilisation technologies represents a crucial direction for achieving the sustainable development of livestock manure resource utilisation.

A comprehensive comparison of the four coupled scenarios highlights distinct trade-offs between energy recovery, nutrient recycling, and environmental impact. Scenarios I and III excel in nutrient recovery and technical maturity, making them the preferred choice

for major grain-producing regions. However, LCA studies indicate that they often face challenges regarding digestate volume and potential eutrophication risks if land application is not strictly managed. In contrast, Scenarios II and IV introduce thermochemical conversion to treat solid manure or digestate. While these scenarios require higher initial investment and energy input, they offer superior advantages in volume reduction and carbon sequestration. Specifically, the production of biochar in Scenarios II and IV effectively locks carbon and mitigates greenhouse gas emissions, making them particularly suitable for regions with strict carbon constraints or limited land carrying capacity. To facilitate a more direct comparison and practical application, Table 1 summarises the technical characteristics and implementation status of these scenarios.

Table 1. Comparative summary of the four coupled scenarios and their implementation status in China.

Scenario	Core Process Description	Key Advantages	Application Status	Suitable Region
I	Solid—Liquid Separation + Anaerobic Digestion (Liquid) + Composting (Solid)	Balanced nutrient recovery; Mature supply chain.	Widely Implemented (Dominant)	Southern Water Network Areas
II	Solid—Liquid Separation + Anaerobic Digestion (Liquid) + Pyrolysis (Solid)	Pathogen elimination; High-value Biochar.	Pilot/Demonstration	Arid/Water-deficient Areas
III	Direct Anaerobic Digestion + Composting (Digestate)	Max Biogas; Low operational cost.	Widely Implemented (Dominant)	Central Plains/ Grain Areas
IV	Direct Anaerobic Digestion + Pyrolysis (Digestate)	Max Energy (Biogas + Oil); Volume reduction.	Pilot/Emerging Tech	Ecologically Fragile Areas

6. Conclusions

Promoting livestock manure resource utilisation is a key pathway to achieving green and low-carbon agricultural transformation and the dual carbon goals. Nationally, the average livestock manure load per unit of cultivated land in 2016 was 0.49, placing it at Level II (slight environmental threat) and indicating that manure is a potential environmental burden. A nutrient content analysis revealed that in 2018, national nitrogen nutrient production from livestock manure reached 1.27×10^7 tonnes, while the theoretical nitrogen demand for crops, pastures, and plantation forests during the same period was only 9.42×10^6 tonnes. This indicates that nitrogen production far exceeds actual land requirements. The land carrying capacity indices for livestock manure on cultivated land in Fujian, Guangdong, and Hainan Provinces reached 3.21, 2.56, and 3.67 respectively, significantly exceeding the 1.0 overload threshold.

7. Outlook

In response to the current issues of manure production far exceeding the land carrying capacity and the difficulty of matching regional cropping patterns due to limited technological options, this study proposes the following:

- (1) Strengthen technological integration to promote synergistic pathways such as ‘anaerobic digestion + composting’ and ‘pyrolysis + biogas liquid utilisation’, enhancing the

efficiency of energy and fertiliser co-production of energy and fertilisers to achieve comprehensive and high-value manure utilisation of manure.

- (2) Optimise technological deployment according to local conditions: prioritise fertiliser return to fields in areas with concentrated arable land, while promoting biogas projects and regional circular systems in intensive livestock farming zones to improve the regional adaptability of technologies.
- (3) Establish a spatial life-cycle assessment framework integrated with GIS, combining cost–benefit analysis and social acceptability evaluations to create a multidimensional decision-support tool. This is expected to provide scientific grounds for technology selection and policy formulation across diverse regions.

Moving forward, a dual-track approach driven by policy and technology should be followed to establish a livestock manure resource utilisation system tailored to China’s regional characteristics, thereby advancing green, low-carbon, and circular agricultural development.

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