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Comprehensive evaluation and operation mechanism of pig manure and sewage management in Hebei Province, China

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Comprehensive evaluation and operation mechanism of pig manure and sewage management in Hebei Province, China

Évaluation globale et mécanisme de fonctionnement de la gestion du lisier de porc et des eaux usées dans la province de Hebei, en Chine

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Abstract

Nowadays, scale-up intensive pig farming can increase profitability, but it also exacerbates environmental pollution such as the contamination caused by the disordered discharge of manure and sewage. China, as the largest pig-breeding country globally, dominates 48.4% of worldwide pork output. Pig rearing is shifting from free-range to specialization and mass farming, generating a large amount of manure and sewage simultaneously, with 4.37 billion tons accounting for 76.8% of total livestock waste discharge. Pollution caused by pig breeding has become the priority issue to be resolved. Manure & sewage management (MSM) is critical to mitigate environmental pressure and realize resource recycling. However, applications of MSM in pig farming are multitudinous, due to the complicated process sections, diverse methods and heterogeneity of farmers' characteristics and behaviors. In addition, this more intensive breeding structure is accompanied by the integrated generation of pig waste. The match is disrupted between the original MSM mode and the corresponding farmland. These issues cause the separation of cropping and breeding, hinder the transition from traditional breeding to an ecological and sustainable pig industry. Appropriate MSM mode with optimized system contributes to the mitigation of environmental pressure, integration and efficient use of resources, and provides additional financial success because of the circular economy, further achieving green scientific and sustainable pig breeding.

This study conducted a comprehensive perception of pig MSM application in Hebei province, China, based on a field survey. Collect 614 questionnaires involving information on pig farms, MSM practices performed, farmers' behaviors, perceptions and environmental awareness, and farmers' perceptions of government regulations and policies. It is representative of a region with a well-developed pig sector and can provide useful references for other regions and developing countries practicing breeding with cropland.

To begin with, this study conducted a systematic overall review of current pig MSM operational practices. Empirically categorize typical MSM modes in pig farming, distinguish and identify the characteristics of corresponding modes by data-driven typology, clustering analysis, from a scientific and statistical perspective. Five mainstream MSM modes were obtained to simplify the high diversity of MSM strategies, with highlighted advantages and performances. Traditional simple mode (TSM) is based on simple processing methods and convenient access. Mixed processing mode (MPM) is a labor-intensive saving mode with the lowest mechanization degree. Semi-biogas mode (SBM) is guided by anaerobic digestion with incompleted utilization. Professional processing with simple utilization mode (PPSUM) has comprehensive treatments with unified field application. Professional processing with full utilization mode

(PPFUM) is an integrated mode that well-performing in processing and resource multi-utilization. Mode classification enhances the efficiency of MSM and contributes to the ease of administrative convenience by the government.

Secondly, the heterogeneity of farmers' characteristics and behaviors towards five MSM modes was identified by multiple independent sample test and multinomial logistic model, to reveal the underlying determinants that might affect individual decision-making. Applicability of the respective mode was reflected in the synthesis deliberation, involving farming structure, land, farmers' characteristics and subjective awareness. Farmers' education level and pro-environmental perception significantly promoted the adoption of technology-intensive modes. Scale upgrading had a positive effect on mechanization and diversified strategies application. Land restricted the extension of modes based on field returning. Understanding these driving forces contributes to the design of an optimal and tailor-made MSM scheme with greater adaptability, meanwhile, providing credible experience and qualification to individual pig farms on appropriate mode selection to enhance effective MSM in pig farming.

Thirdly, considering the trend towards more intensive breeding, the possibility of a centralized MSM pattern is proposed to relieve environmental pressure, increase resource recovery efficiency and rebuild the coupling effect of cropping and breeding. A comprehensive comparative evaluation between individual and traditional mode (ITM) at the household level and centralized bio-energy mode (CBM) at the regional scale was conducted by life cycle assessment (LCA) and life cycle cost analysis (LCC), involving dual objectives of economy and environment. CBM appeared to be a better alternative in global warming, terrestrial acidification and marine eutrophication, with significant reductions of 49.49%, 6.8% and 4.67% respectively compared with ITM. Moreover, it demonstrated a substantial profit of 48.5 CNY from handling 1 ton of pig waste. Furthermore, both environmental and economic performance could be improved by scale expansion and transport optimization, with an optimal collection radius of less than 31.45 km, and a decrease in marginal cost in the range of 7.2-16.82 CNY. The applicability and feasibility were further explored for the mode implementation in the other seven regions in China.

Lastly, explore underlying determinants affecting farmers' decision-making on scientific and comprehensive MSM practices to cater to the goals of ecologically sustainable farming. Establish a synthetical stylized framework that matches a wide array of theoretical and empirical information, with land factors, resource endowments, policy rationality and individual characteristics. Use ologit regression model, the effect and intensity of several implicit factors were analyzed from the perspective of farm scales. Statistical results identified that strengthening land transfer and integration contributes to the adoption of combined MSM practices, enhancing technology, labor and economy endowments supports the diversity of technological applications. Additionally, farmers' environmental perception and policy rationality also reported positive

effects on enhancing waste resource utilization level and further forming the green sustainable pig industry.

In general, findings in this study are expected to mitigate environmental hazards from pig-intensive breeding, achieve maximum nutrient recycling of pig waste, and enhance MSM effectiveness and sustainability. It contributes to providing pig farmers with persuasive references on appropriate MSM mode selection, theoretical supports for the regional pattern replication in response to the updated breeding restructuring, implications for government policy-making to optimize overall benefits from environmental, economic and social impacts. In order to achieve the modernization, ecologicalization and sustainability of MSM and pig industry.

Keywords: pig farming; manure and sewage management; comprehensive evaluation; circular economy; sustainable pig industry.

Résumé

De nos jours, l'intensification de l'élevage porcin permet d'accroître la rentabilité grâce à des économies d'échelle, mais elle exacerbe également la pollution de l'environnement, notamment la contamination causée par le rejet désordonné de fumier et d'eaux usées. En Chine, qui représente 48.4% de la production mondiale de porc, le passage de l'élevage libre à la spécialisation et à l'élevage de masse génère simultanément une grande quantité de fumier et d'eaux usées, soit 4.37 milliards de tonnes, représentant 76.8% de l'ensemble des déchets d'élevage. La pollution causée par l'élevage porcin est devenue le problème prioritaire à résoudre. La gestion du fumier et des eaux usées (MSM) est donc essentielle pour atténuer la pression sur l'environnement et réutiliser le recyclage des ressources Cependant, les applications des MSM dans l'élevage porcin sont multiples, en raison de la complexité des processus, de la diversité des méthodes et de l'hétérogénéité des caractéristiques et des comportements des éleveurs. De plus, cette structure d'élevage plus intensive s'accompagne de la production intégrée de déchets porcins. La correspondance est interrompue entre le mode MSM d'origine et les terres agricoles correspondantes. Ces problèmes entraînent la séparation de la culture et de l'élevage, et entravent la transition de l'élevage traditionnel vers une industrie porcine écologique et durable. Un mode de MSM approprié avec un système optimisé contribue à l'atténuation de la pression environnementale, à l'intégration et à l'utilisation efficace des ressources, et offre un succès financier supplémentaire grâce à l'économie circulaire, réalisant ainsi un élevage porcin vert, scientifique et durable.

Cette étude a réalisé une perception globale de l'application du MSM dans l'élevage porcin dans la province du Hebei, en Chine, sur la base d'une enquête de terrain. Elle a recueilli 614 questionnaires comprenant des informations sur les exploitations porcines, les pratiques de MSM mises en œuvre, les comportements des agriculteurs, leurs perceptions, leur conscience environnementale, ainsi que leur perception des réglementations et politiques gouvernementales. Elle est représentative d'une région dotée d'un secteur porcin bien développé et peut fournir des références utiles pour d'autres régions et pays en développement pratiquant l'élevage associé aux cultures.

Pour commencer, cette étude a réalisé un examen systématique global des pratiques opérationnelles actuelles du MSM dans l'élevage porcin. Elle a catégorisé empiriquement les modes typiques de MSM, distinguant et identifiant les caractéristiques des modes correspondants par une typologie basée sur les données, une analyse de clustering, d'un point de vue scientifique et statistique. Cinq modes principaux de MSM ont été définis pour simplifier la grande diversité des stratégies de MSM, avec mise en évidence de leurs avantages et performances. Le mode simple traditionnel (TSM) repose sur des méthodes de

traitement simples et un accès facile. Le mode de traitement mixte (MPM) est un mode économisant la main-d'œuvre avec le plus bas degré de mécanisation. Le mode semi-biogaz (SBM) est guidé par la digestion anaérobie avec une utilisation incomplète. Le mode de traitement professionnel avec utilisation simple (PPSUM) offre des traitements complets avec une application unifiée sur le terrain. Le mode de traitement professionnel avec utilisation complète (PPFUM) est un mode intégré qui performe bien en termes de traitement et de multi-utilisation des ressources. La classification des modes améliore l'efficacité du MSM et contribue à la facilité de l'administration par le gouvernement.

Deuxièmement, l’hétérogénéité des caractéristiques et des comportements des agriculteurs vis-à-vis de cinq modes MSM a été identifiée par des tests sur échantillons indépendants multiples et un modèle logistique multinomial, afin de révéler les déterminants sous-jacents susceptibles d’affecter la prise de décision individuelle. L'applicabilité du mode respectif a été reflétée dans la délibération de synthèse, impliquant la structure agricole, les terres, les caractéristiques des agriculteurs et la conscience subjective. Le niveau d'éducation des agriculteurs et leur perception pro-environnementale ont favorisé de manière significative l'adoption de modes à forte intensité technologique. La montée en gamme a eu un effet positif sur la mécanisation et l'application de stratégies diversifiées. La terre a limité l'extension des modes basés sur le retour au champ. La compréhension de ces forces motrices contribue à la conception d'un schéma MSM optimal et sur mesure avec une plus grande adaptabilité, fournissant également une expérience crédible et une qualification aux fermes porcines individuelles pour une sélection de mode appropriée afin d'améliorer l'efficacité du MSM dans l'élevage porcin.

Troisièmement, compte tenu de la tendance vers une élevage plus intensif, la possibilité d'un modèle de MSM centralisé est proposée pour soulager la pression environnementale, augmenter l'efficacité de la récupération des ressources et reconstruire l'effet de couplage entre la culture et l'élevage. Une évaluation comparative complète entre le mode individuel et traditionnel (ITM) au niveau des ménages et le mode bio-énergétique centralisé (CBM) à l'échelle régionale a été menée par l'analyse du cycle de vie (LCA) et l'analyse des coûts du cycle de vie (LCC), impliquant les objectifs doubles de l'économie et de l'environnement. Le CBM s'est révélé être une meilleure alternative en termes de réchauffement global, d'acidification terrestre et d'eutrophisation marine, avec des réductions significatives de 49.49 %, 6.8 % et 4.67 % respectivement par rapport à l'ITM. De plus, il a démontré un profit substantiel de 48.5 CNY pour le traitement d'une tonne de déchets porcins. En outre, les performances environnementales et économiques pourraient être améliorées par l'expansion à grande échelle et l'optimisation des transports, avec un rayon de collecte optimal de moins de 31.45 km, et une diminution du coût marginal dans la fourchette de 7.2 à 16.82 CNY. L'applicabilité et la faisabilité ont été davantage explorées pour la mise en œuvre du mode dans les sept autres régions en Chine.

Enfin, explorer les déterminants sous-jacents affectant la prise de décision des agriculteurs sur les pratiques de MSM scientifiques et complètes pour répondre aux objectifs de l'agriculture durable écologiquement. Établissez un cadre stylisé synthétique qui correspond à un large éventail d'informations théoriques et empiriques, avec des facteurs fonciers, des dotations en ressources, la rationalité des politiques et des caractéristiques individuelles. En utilisant le modèle de régression ologit, l'effet et l'intensité de plusieurs facteurs implicites ont été analysés du point de vue des échelles de ferme. Les résultats statistiques ont identifié que le renforcement du transfert et de l'intégration des terres contribue à l'adoption de pratiques combinées de MSM, améliorant la technologie, les dotations en main-d'œuvre et l'économie soutient la diversité des applications technologiques. En plus, la perception environnementale des agriculteurs et la rationalité des politiques ont également rapporté des effets positifs sur l'amélioration du niveau d'utilisation des ressources des déchets et la formation ultérieure de l'industrie porcine durable verte.

En général, les résultats de cette étude devraient atténuer les risques environnementaux liés à l'élevage intensif de porcs, atteindre le recyclage maximal des nutriments des déchets porcins et améliorer l'efficacité et la durabilité du MSM. Elle contribue à fournir aux éleveurs de porcs des références convaincantes sur la sélection appropriée du mode MSM, des supports théoriques pour la réplication du modèle régional en réponse à la restructuration de l'élevage mise à jour, des implications pour la prise de décision gouvernementale pour optimiser gouvernementale pour optimiser les avantages globaux des impacts environnementaux, économiques et sociaux. Afin de parvenir à la modernisation, à l’écologisation et à la durabilité des MSM et de l’industrie porcine.

Mots-clés : l'élevage porcin; La gestion du fumier et des eaux usées; l’évaluation complète; économie circulaire; filière porcine durable.

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List of abbreviation

CapEx: Capital expenditure
CCER: Chinese Certified Emission Reduction
CH_4: Methane
CNG: Compressed natural gas
CNY: Chinese yuan
CO_2: Carbon dioxide
COD: Chemical oxygen demand
EIA: Environmental Impact Assessment
FAO: Food and Agriculture Organization of the United Nations
FPMF: Fine particulate matter formation
FRS: Fossil resource scarcity
FU: Functional unit
GHG: Greenhouse gas
GW: Global warming
H_2S: Hydrogen sulfide
IPCC: Intergovernmental Panel on Climate Change
LCA: Life cycle assessment
LCC: Life cycle cost
LCI: Life cycle inventory
ME: Marine eutrophication
MgEx: Management expense
MSM: Manure and sewage management
mu: 15 mu = 1 hectare
N_2: Nitrogen
N_2O: Dinitrogen monoxide
N_2O_{dir}: Direct N_2O emission
N_2O_{ind}: Indirect N_2O emission
NH_3: Ammonia
NH_4^+: Ammonium
NO: Nitrogen monoxide
NO_3^-: Nitrate

NO_x: Nitrogen oxides
NUE: Nitrogen-use efficiency
OM: Organic matter
OpEx: Operating expense
PM2.5: Particulate, <2.5 um
PO_4^{3-}: Phosphate
PRC: the People's Republic of China
SD: Standard deviation
SDG: Sustainable development goal
SO_2: Sulfur Dioxide
TA: Terrestrial acidification
TC: Total carbon
TK: Total potassium
TN: Total nitrogen,
TP: Total phosphorus
TS: Total solid
VS: Volatile solid

Chapter 1

General context and issues

Adapt from:

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1. Development of pig industry

1.1 Global pig consumption and production

Along with the increase in population and the improvement of living standards, the demand for livestock products is rising. According to the FAO[1], as a global average, per-capita meat consumption has increased by approximately 36.55 kg since 2000, to 42.26 kg in 2020. Pork is the highest meat commodity, with more than 110 million tons pork are required globally each year, reaching over 14.45 kg for the global average person consumed. This promotes the development of the livestock industry. The global meat production rose from 233.19 million tons in 2000 to 357.39 million tons in 2021. Among them, the share of pork production is significant, which has remained constant at approximately 40%, and has increased as a result from 89.25 million tons to 120.37 million tons, despite a brief dip in 2019 and 2020 because of the outbreak of African swine fever in China (**Figure 1-1**).

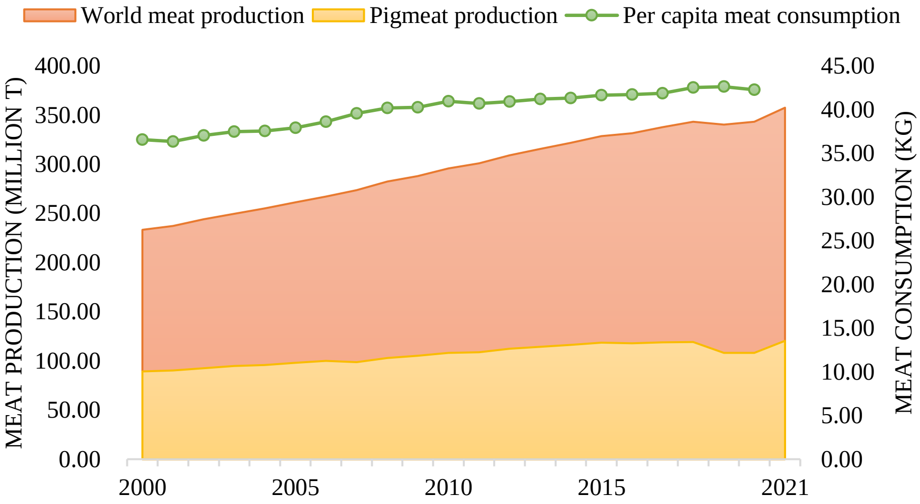

Figure 1-1. Growth in global meat and pigmeat production, and the average per-capita meat consumption from 2000 to 2021. Data source: UN Food and Agriculture Organization (FAO).

1.2 China pig industry

China has undergone a strong economic transition. According to statistics, in 2022, the value of China's livestock industry reached 4.1 trillion CNY[2], accounting for 26% of the total agricultural output value (NBSC, 2023). The national consumption is up to nearly 100 million tons, constituting 27% of the

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[1] Food and Agriculture Organization of the United Nations (FAO), https://www.fao.org/statistics/en/

[2] CNY, Chinese yuan

global edible production. Pig farming is a pillar industry. Its market scale has attained 2.15 trillion CNY. As the largest pig-breeding country globally, China dominates global pork output, producing 48.4% of worldwide pork, with 55.41 million tons of pork production and nearly 700 million pigs for slaughter (**Figure 1-2**). Consumption also trends remarkable performance, China is also the largest consumer worldwide, with 46% of the total consumption, the pork accounts for two-thirds of per capita meat consumption approximately, with 20.3 kg (NBSC 2021a).

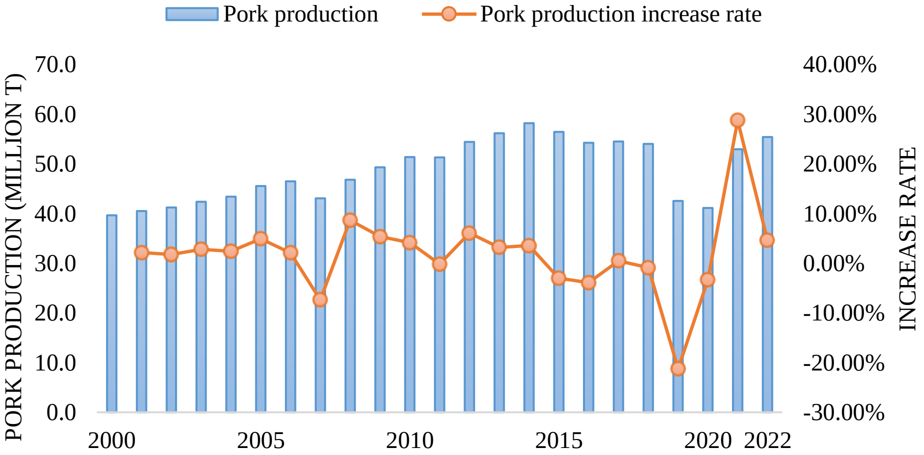

Figure 1-2. Trend of pork production in China from 2000 to 2022. Data source: National Bureau of Statistics of China.

Since the great revolution of reform and opening-up in 1978, China's level of economic development has grown dramatically (Bai et al. 2018). Pig farming is growing rapidly and gradually. The purpose of pig industry is shifting from purely pursuing pig quantitative growth to an equal emphasis integrated consideration of livestock quantitative growth, breeding structure optimization, product quality improvement and farming operational efficiency improvement (Zheng et al. 2015). Currently, China is in the stage of modernization, transformation and upgrading (from 2005 to the present) of the pig industry, focusing on the improvement and optimization of product quality, breeding structure and productive efficiency (Bai et al. 2018). Based on the dual promotion of government policies and market regulation, standardized and scaled-up pig breeding has been rapidly promoted, and the technology and management levels of production have been continuously improved. As a result, the strengthening of industry concentration has accelerated the transformation and the modernization of the pig industry.

From the perspective of breeding structure, pig rearing is shifting from free-range to specialization and mass farming, which tends to be more intensive and gradually scales up towards the direction of medium and large-scale development. The trend of concentration to the advantageous producing regions is increasingly obvious. The breeding mode of driven by leading enterprises and collaboration of scattered small-scale farms has achieved significant results on modernization of pig breeding (Xiao 2010). In terms of the number of pig households, the number of small farms with less than 500 head slaughter per year dropped by 72.5% from 82.22 to 22.58 million between 2007 and 2019. Simultaneously, there has been a steady increase in large-scale farms (>500 heads slaughtered per year), from 123.9 to 153.6 thousand.

The main pig-producing areas of southern and northern China are roughly bounded by the line of the "Qinling Mountains-Huaihe River"[3]. Since 1996, the trend of increase in the number of pigs slaughtered in the South Zone was insignificant, while the North Zone presented a yearly growth (Zhao et al., 2019a). The southern main production areas are represented by Hubei, Hunan, Sichuan and Yunnan provinces, occupying 23.81% of the national pork production. And the principal productive areas in the north are epitomized by Hebei, Liaoning, Shandong and Henan provinces, with 29.97% of the total output. Outputs in two producing regions were basically same, indicating a weakening trend in the industrial agglomeration.

2. Pollution status and resource value of manure and sewage

2.1 Pollution status in China

Rapidly developing livestock industry, while ensuring the growing meat demand, has also generated a large amount of waste and exacerbated environmental pollution caused by the disordered discharge of manure and sewage consequently. In China, over the past decade, the amount of livestock manure, urine and sewage generated rose from 3.25 billion tons to 4.24 billion tons (Hu et al. 2019). According to *China's Second National Census on the Sources of Pollution Report*[4], chemical oxygen demand (COD) emitted from the livestock farming process amounted to 10.05 million tons, accounting for 93.76% of the agricultural emissions, and 46.7% of the total national emissions. Additionally, there were 110.9 thousand tons of ammonia nitrogen, 596.3 thousand tons of total nitrogen (TN) and 119.7 thousand tons of total phosphorus (TP) emitted, accounting for 51.3%, 42.14% and 56.46% of the emissions from agricultural sources respectively. It is estimated that, in China, the loss of ammonia nitrogen and phosphorus from livestock waste has been greater than that from chemical fertilizers applied for cropping, with both direct and indirect environmental consequences.

Focusing on the pig industry as an important and fast-growing pillar of the

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[3] It is the geographic demarcation line between the northern and southern regions of China from 1908 by Xiangwen Zhang, and officially recognized by the Government of China for national statistics and planning.

[4] https://www.gov.cn/xinwen/2020-06/10/content_5518391.htm

livestock sector in China, in 2017, pig manure generation exceeded 600 million tons, or roughly one-third of the total livestock manure, however, the rate of the comprehensive resource utilization of pig manure was less desirable, being less than 50% (Li et al. 2020b). Additionally, due to the huge amount of effluent produced, pig manure, urine and sewage constituted 76.8% of the total livestock waste discharge, with 4.37 billion tons (Wu et al. 2018). The shortage of land resources has become a major constraint to the development of pig farming. According to the measurement of the land carrying capacity for manure, preliminary estimates indicate that there is still about 30% of breeding development space in Northeast China. The Southern Water Network region is limited by resource and environmental conditions. Pig industry is restricted in terms of development space.

At the early stage of the pig development in China, plantation plots were able to consume the waste from household farming, because of the relatively small rearing scale and mainly household free-range breeding, sufficient cultivable land and available labor. Pig waste can be utilized locally, which is the pattern of “integration of planting and breeding”. It is characterized by operational convenience, low-cost, and proximity to nearby fields, which is appropriate for situations with relatively small volumes of waste. This breeding pattern is economically viable and suitable for the early stages of development with small amount of pig waste (Chadwick et al. 2015; Bai et al. 2018). Meanwhile, the revenue generated by pig breeding and the savings of replacing chemical fertilizers with recycling pig waste weaken the initial emergence of environmental problems.

Because of extremely intensive farming and because of the generation of an enormous quantity of manure and sewage simultaneously on concentrated areas, the pollution generated by pig rearing has become a major issue to be tackled (Zhang et al. 2004). The uncontrolled and excessive release of pig excrement and sewage causes a slew of serious ecological problems for the soil, water and atmosphere resources. For soil degradation, manure nutrients and organic matter could enter the soil with over-fertilization, leading to soil overloading, further will destroy the soil balance, resulting in problems such as soil acidification and salinization, which affect crop growth and field sustainable use. Besides, nitrogen and phosphorus in livestock waste can be introduced into water bodies through runoff or seepage, leading to eutrophication. Furthermore, eutrophication can trigger blooms (e.g., algal outbreaks), disrupting the balance of the water ecosystem and affecting water quality and the survival of aquatic organisms. In addition, microorganisms and harmful chemicals in fecal matter may contaminate water sources, posing a threat to animal and human health. Additionally, disordered discharge of manure and sewage also significantly contributes to greenhouse gas emissions as nitrous oxide and odor emanation.

From the regional perspective, sizeable pig farms are mainly concentrated in the central and eastern regions of China, with massive waste discharge from intensive farming areas and increasing regional waste accumulation, which in turn leads to higher environmental pollution loads (Yu et al. 2011). Storage of farmland is a major constraint to pig industry development. Uneven spatial and temporal distribution of pig farming has become one of the reasons for the regional and seasonal lack of waste disposal sites. Local pig farming exceeds the environmental carrying, and some farming districts are unable to eliminate pig waste in a timely and localized manner due to the lack of farmland, resulting in dilemmas of environmental pressures, nutrient surplus and separation of farming and breeding as well as security constraints, thus affecting the sustainable development of the pig industry.

2.2 Resource value of livestock manure and sewage

Livestock waste can also be seen as a resource owing its contents in organic matter ranging from 30% to 70%, its richness in nitrogen, phosphorus and other nutrients, which can be used for organic fertilizer production. For raw pig waste, the average nitrogen and phosphorus content is around 2.2% and 4% respectively (Li et al. 2009), and timely and appropriate utilization can effectively satisfy the nutrient demand of crops. In addition, organic manure application accounts for more than 25% of total fertilizer use, which can significantly reduce ammonia volatilization (Wu et al. 2020c), because of its specialties of smooth and sustained release of nutrients, providing a comprehensive and balanced supply to plants, and non-volatile. Pig waste can enhance soil organic matter content, ensure the sustainable production capacity of farmland, while improving agricultural product quality and increasing the utilization rate of fertilizer, which is a reliable and eco-friendly option for plantation. Furthermore, pig waste can be recognized for the generation of biogas and bio-natural gas, thus supplying clean energy, reducing greenhouse gas emissions, as well as abating the environmental load and potential risk of pathogenic microorganisms from pig waste.

3. Initiatives of manure and sewage management in China

3.1 Implementation of manure and sewage management policies

Historically, a long tradition of livestock manure and sewage management (MSM) has existed in China, which can be split into three historical stages: 1) the end-of-treatment stage, 2) the aggregate control stage, and 3) the refined management stage (She et al. 2021; Zhao and Li 2021) (**Figure 1-3**).

1) End-of-treatment stage

From 2001 to 2010, the prevention and control of pollution from livestock husbandry activities was an increasingly important concern, but limited by regulatory capacity and experience. MSM targets almost exclusively involved large-scale farms, and the approaches focused on end-of-treatment. In 2001, the State Environmental Protection Administration issued *Measures for the*

Prevention and Control of Pollution from Livestock and Poultry Breeding[5], *Technical Standard of Preventing Pollution for Livestock and Poultry Breeding (HJ/T 81-2001)*[6] and *Discharge Standard of Pollutants for Livestock and Poultry Breeding (GB 18596-2001)*[7], clarifying that the control of pollution from livestock should be prioritized for a comprehensive use and be based on the principles of resourcefulness, harmlessness and minimization. In 2005, the *Animal Husbandry Law*[8] of PRC[9] was implemented, which further specified that livestock farming communities should ensure a comprehensive utilization of livestock manure and sewage or the normal operation of harmless treatment facilities, to guarantee discharge in compliance with standards, to prevent environmental pollution. In 2009, the *Technical Specifications for Pollution Treatment Projects of Livestock and Poultry Farms (HJ 497-2009)*[10], pointed out that the MSM process should be determined according to factors such as reared species, rearing scale, waste collection method, local geography environment condition, and drainage direction, the construction and operation of livestock MSM have been standardized.

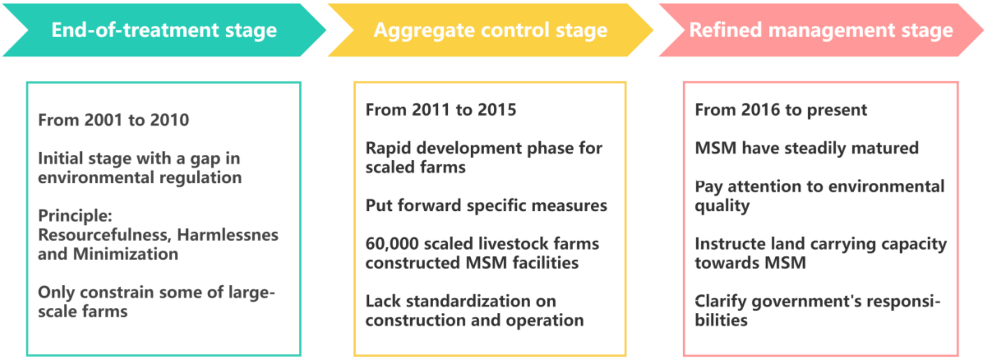

Figure 1-3. Three historical stages of the tradition of livestock manure and sewage management in China.

At this stage, livestock pollution control is still in its initial stage and there is a gap in environmental regulation basically. Only some of the large-scale farms with serious pollution of the surrounding environment have built relevant MSM facilities. However, those are generally in a spontaneous state and they lack unified planning and management. Moreover, most of the constructed facilities are not functioning properly or sometimes even not working at all, for technical and economic reasons.

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[5] https://www.gov.cn/gongbao/content/2002/content_61978.htm
[6] https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/stzl/200204/t20020401_85055.htm
[7] https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/shjbh/swrwpfbz/200301/t20030101_66550.shtml
[8] https://www.gov.cn/flfg/2005-12/29/content_141833.htm
[9] PRC, The People's Republic of China
[10] https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/other/hjbhgc/200910/t20091013_162276.htm

2) Aggregate control stage

From 2011 to 2015, which was a rapid development phase, large-scale livestock farming becomes the critical focus of agricultural pollution reduction into the national "Twelfth Five-Year Plan" binding indicators for control. In 2011, the Ministry of Environmental Protections implemented *Rules for Accounting for Total Emission Reductions of Major Pollutants in the "Twelfth Five-Year Plan"*[11], clarified the accounting methods for the reduction of COD and ammonia nitrogen emissions from livestock farming, required the implementation of cleaner rearing techniques and ecological farming practices, and further encouraged scale farms to adopt a whole-process integrated treatment approach to deal with pollutants. Based on systematically summarizing and analyzing the current situation, problems and circumstances of livestock pollution prevention and control in China, the *National "Twelfth Five-Year Plan" for Prevention and Control of Pollution from Livestock and Poultry Breeding*[12] proposed explicit requirements based on objectives, main tasks and safeguards. This was China's first special program on the prevention and control of livestock farming pollution, which was of great significance to further implement the requirements for reduction of total emission and promote the green development of livestock husbandry. Next, in 2013, the State Council published the *Regulation on the Prevention and Control of Pollution from Scale Breeding of Livestock and Poultry*[13], which was the first environment-related regulation tackling pollution in agriculture at the national level. Putting forward specific measures and encouraging the adoption of waste comprehensive utilization methods, i.e., returning land use, biogas production and organic fertilizers manufacture. Meanwhile, it has been clarified that the administrative department for environmental protection of the local governments at or above the county level has the authority to conduct on-site inspections of the environmental protection of livestock farms within its jurisdiction.

During these five years, approximately 60,000 large-scale livestock farms nationwide have initially constructed waste pollution control facilities. Local governments and farm owners have created breeding pollution prevention and control awareness. Livestock farms have also gradually emphasized waste treatment and utilization in the process of site selection, construction and production, and formed the development philosophy by means of resource utilization. However, due to the weak foundation of China's livestock breeding pollution prevention and control, the systematic breeding environmental regulatory system has not been established well, the construction and operation of pollution control facilities still lack standardization, and environmental supervision is still in a blind and passive state.

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[11] https://www.mee.gov.cn/gkml/hbb/bwj/201206/W020121012519874173523.pdf

[12] https://www.gov.cn/gzdt/2013-01/05/content_2304905.htm

[13] https://www.gov.cn/flfg/2013-11/26/content_2535095.htm

3) Refined management stage

From 2016 to the present, the efforts of China's livestock pollution prevention and control have steadily matured, and the core of MSM has shifted from aggregate control to environmental quality. In 2016, the *"Thirteenth Five-Year Plan" for Ecological and Environmental Protection*[14] proposed that more than 75% of the livestock farms should be equipped with solid waste and sewage storage and treatment facilities by 2020. In addition, *Technical Guidelines for Calculating the Land Bearing Capacity of Livestock and Poultry Manure*[15] instructed localities to reasonably measure the regional land carrying capacity of livestock waste and the area of matching land for consumption. It was emphasized that the layout of the livestock farming industry should be closely associated with regional environment quality and land carrying capacity. Thus, pig migration from the South China Water Network Area to the North Crop Producing Area with vast upland-cultivated lands is in progress, which relieves the concentration of N and P in soil (Bai et al. 2019). Establishing vital links between farms and arable land is a crucial pathway for manure recycling (Jin et al. 2021; Thornton and Herrero 2015). China has progressively promoted the establishment of scientific standards, clear authority and strict constraints on the resource utilization of livestock waste. The responsibilities of the various government departments were also gradually being clarified.

At this stage, the prevention and control of pollution from livestock farming was gradually standardized and regulated in China, livestock MSM as an indispensable and important aspect was incorporated into livestock industry development. The national livestock waste resource utilization rate reached 75% in 2019, completing the "Thirteenth Five-Year Plan" in advance. The equipment matching rate of waste treatment facilities for scale farms achieved 93%. More importantly, the emissions of COD and TN from livestock farming have been on a sustained downward trend. Nevertheless, as livestock farms are numerous and extensive, as well as the rapid development of scale farms, the deficit of pollution control facilities and the continuously prominent environmental impacts of polluting emissions were the main challenges.

3.2 Comprehensive manure and sewage treatment and utilization scheme

Though intensive pig farming poses tremendous pressure on the environment, it is possible to mitigate its impact through effective management. Since the introduction of the *National Livestock and Poultry Manure Resource Utilization County Promotion Project Programme (2018-2020)*[16], the National Animal Husbandry Station organized the collection of typical technology models for the resource utilization of livestock and poultry MSM. A total of 239 technical approaches were introduced from 29 provinces nationwide, and 9 main models

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[14] https://www.gov.cn/zhengce/content/2016-12/05/content_5143290.htm

[15] https://www.moa.gov.cn/nybgb/2018/201802/201805/t20180515_6142139.htm

[16] https://biogascn.caas.cn/zcfgbz/zcfg/676e89eb0a034a3e90f0202ab37a054e.htm

were summarized, which were refined for three aspects, including breeding and cropping combination, clean reuse and standard discharge. For pig manure and sewage treatment, the following five techniques are emphasized as follows.

1) Integrated livestock and cropping for local use

This is the most common model which is suitable for family farms, or small and medium-sized farms that involve cultivation and have arable land for waste disposal. It is an organic combination of waste collection, storage and farmland consumption, so that the waste can be effectively collected and promptly eliminated in the vicinity mainly as fertilizer sometimes after preliminary treatment. Liquid composition is processed by anaerobic digestion or aerobic treatment, or other combined technologies, and then irrigated to neighboring farmland, or it could be carried out in-depth treatment to reach pollutant emission standards and then directly discharged. Solid manure is composted and fermented for further use as fertilizer.

2) Centralized treatment with organic fertilizer processing for broader use

This model is aimed at intensive farming areas or large farms where peripheral farmland is unable to effectively absorb pig waste without the above-mentioned environmental consequences. This model features the collection, transportation, and centralized treatment of solid manure from multiple surrounding farms, to produce organic fertilizers or bio-organic fertilizers by palletizing, grooving or microbial fermentation reactors, which are then sold to farmers, resellers and shops. To achieve extensive collection, uniform treatment, and expand the radius of organic fertilizer utilization, rather than limiting it to nearby farmlands.

3) Energy conversion and recycling

The disposal of manure for energy production applies to large and medium-sized farms that can radiate a large amount of farmland, greenhouses, and fruit groves. Manure, urine and sewage produced during pig breeding are used as primary raw materials, through anaerobic fermentation, decomposing organic matter for biogas and digestate, which are subsequently used for agricultural production as fertilizers.

4) Substrate conversion and utilization

The model of substrate conversion is basically the conversion of waste solid fraction into raw substrates for other agricultural activities, which is a self-circulating model. The advantage is the scientific recycling of the tripartite combination of livestock and poultry manure, edible fungus waste slag, and crop straw. Realizing the ecological circular production of zero-waste and zero-pollution of the agricultural production chain, and improving the comprehensive utilization rate of resources. Nevertheless, there are shortcomings of such a long production chain, a high level of refined technology, and the requirement of high overall quality of producers. Therefore, it applies to large and medium-sized eco-agricultural enterprises, small rural family eco-farms, and small rural family farms in division of labor and joint business patterns.

5) "Chain Fusion"

Chain fusion means the continuous extension of the industrial chain upstream and downstream of the pig MSM and resource utilization. Promoting the mutual integration, reinforcement and co-development of multi-industry chains, forming a mutually integrated organism of six industries: planting, feed, breeding, slaughtering, energy and environmental protection, thus, realizing the internalization of the external effect of breeding waste and the effective resource utilization. However, this model has limitations and is only suitable for large-scale leading breeding enterprises with a certain industrial chain base.

Table 1-1. Introduction of pig manure and sewage processing methods[17].

Methods	Advantages	Disadvantages	Products
Sedimentation centrifugation	Low moisture content of solids	High vibration, high wear and high noise	Solid fraction of waste
Solid composting	Low investment and simple operation	Nitrogen loss and GHG emissions	Farmyard manure
Anaerobic biogas digestion	Fully sealed and environmentally friendly	High construction cost and technology requirements	Gas, digestate and sludge
Sewage oxidation pond	No labor requirement	Large construction area and GHG emissions	Slurry
Staged sedimentation oxidation pond	No labor requirement with low level of technology	Large construction area	Slurry and sludge
Industrial treatment and discharge of sewage to standard	Effortless discharge	High cost and cumbersome processing steps	Irrigation water
Off-site to Third-Party	Marketable and suitable for intensive farming region	Transport difficulties	Diversified products such as organic/compound/liquid fertilizer

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[17] According to Hu et al. 2019; Zheng et al. 2017; Qiu et al. 2012; Wu et al. 2020a; Aguirre-Villegas et al. 2019.

4. Key issues on current practices of MSM

4.1 Separation between breeding and cropping as a consequence of increase in scale of pig operations

Recently, the trend of the pig industry towards the elimination of free-ranging practices and the emergence of more intensive large-scale breeding operations was accompanied by the spatial and temporal separation between livestock and cropping (Bin et al. 2016; Zhao et al. 2019a). The rapid development of the breeding industry contributes to the improvement of the specialization of the livestock feed industry. Thus, the breeding operators are focused on scaling up, and fodder producers pay more attention to feed quality. This separation of the division of the work between different operators of the value-chain has led to the gradual withdrawal of breeding operators from participation in fodder and crop cultivation (Zhang and Wang 2021; Bin et al. 2017b; Bin et al. 2016). Well-developed professional breeding households prefer to invest in expanding the rearing scale for breeding efficiency improvement. Backyard breeding is progressively withdrawn, while large-scale and intensive breeding is developing rapidly (She et al. 2021). As the result, the amount of pig waste generated is increasing, and requiring more land for abatement. Separation between breeding and cropping leads to dilemmas involving high costs of pipeline construction and transportation during waste utilizing, and the complexity of negotiating transactions between farmers (Li 2013).

Furthermore, increases in operation scale generates a massive amount of waste during the same period and at the same place. However, cultivation is characterized by seasonality in fertilizer requirements. Because of the mismatch between the pig breeding cycle and the timing of fertilizer application, and the amount of fertilizer required, such a disconnection between breeding and cropping causes the underutilization of pig waste (Zhao et al. 2023). This structural contradiction in the farming industry is an increasingly important concern, which will not only result in the wastage of resources (Qiu et al. 2012), but also increase the chemical fertilizers use simultaneously. This lack of coordination and complementarity among agricultural industries, namely "the separation of breeding and cropping" pattern, blocks the recycling of materials between the breeding and cropping system, resulting in the massive loss of manure resources in the environment, which is the main cause of pig waste pollution.

4.2 Diseconomy of MSM by dominant small and medium-scale pig farms

At present, the cost of pig rearing in China is relatively higher than in Europe, the US, Canada, and even three times as much as in Brazil, with less upside in profits. This is mainly due to the prohibitively high cost of feed (soybeans) import (Wang and Wu 2014; Li et al. 2022). The high market volatility leads to unstable incomes for farmers. However, there is a significant expenditure on pollution control, accounting for 10%-15% of the production cost[18] (Guo et al. 2015; Li et al. 2022; Xing et al. 2019), and in addition to investments in MSM facilities, routine maintenance needs to be strengthened (Zhang 2018a). Besides, the cost of compliance with emission standards is relatively high to be practicable, with approximately 6-8 CNY per ton (Zhou et al. 2020; Tian and Liu 2023), which obviously hinders farmers' participation in pig MSM (Sui et al. 2018). Subsidy for waste resource utilization is only a driving force in the early stage, and cannot fully rely on the government to invest in the long term (Zheng et al. 2017). The "polluting" and "resourceful" nature of pig waste determine the publicity and complexity of MSM. MSM is not only the responsibility of local governments but also requires farmers' active participation.

Most of the existing MSM patterns are uneconomical, and accompanied by a severe financial burden on pig farmers, gross returns from -1.9 to -12.57 CNY/head, especially for small and medium-sized farms (Huang et al. 2016; Chen et al. 2017a). Besides, the selection of sites for farm construction of small and medium-sized farms is characterized by randomness, dispersibility and crypticity, which increase the difficulty in regulating MSM by the environmental department. Therefore, it is significant to improve farmers' intrinsic motivation, autonomy and purpose. Small-sized pig farms are the predominant pig breeding communities in China, occupying over 88.7%, and medium-sized farms account for 10.67% (MOA 2020).

Small-scale farms are mainly expected to be family-oriented, the main labor force in pig farms are family members. It is the optimal productivity when the work and labor force are matched. Thus, they are more concerned about the extra overhead associated with extra labor hiring for MSM. Additionally, because of the in-optimal breeding size, small farms generally have expensive MSM operating cost and face difficulties in financing, with relatively lower mechanization levels and risk tolerance (Chen et al. 2017a). Besides, there are around over 60% of MSM equipment construction dependent on government subsidies, demonstrating that small-scale farms are less capable of undertaking the construction of MSM facilities on their own, consequently, the pollution from pig farming by small-scale farms is likely to worsen once government subsidies are reduced (Chen et al. 2017a).

From the perspective of medium-scale farms, the average MSM cost and benefit per pig are both lower than small-scale farms. In the process of expanding the breeding scale from small to medium, the MSM facilities basically maintain the original pattern and capacity, which leads to a reduction of marginal cost (Wu et al. 2015). However, rearing expansion breaks foregone circular farming at the household level, this mismatch between waste output and cultivated field limits waste utilization.

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[18] Excluding the feed component, because feed costs account for 70%-80% of total production costs due to the imports of soybeans Bai et al. 2018.

4.3 Complex combination of approaches and indeterminate applicability

Although the National Animal Husbandry Station has officially proposed a variety of treatment approaches and utilization patterns regarding MSM, nevertheless, the comprehensive utilization rate of livestock waste is less than 60% (Wu et al. 2020a). According to Li et al. (2020a), up to 1.56 billion tons of livestock and poultry waste are not properly treated. There are still problems with confused application and difficult management, and the phenomenon of substandard non-hazardous treatment or excessive management. One of the reasons for this is the neglect of the socio-economic characteristics of different scale breeding communities and the lack of categorization of various farms for the appropriate MSM mode publicity and policy implementation (Zhu et al. 2016; Welsh and Rivers 2011; Pan and Kong 2015). Increasingly stringent environmental regulations are raising the environmental-ecological threshold for pig breeding, this one-size-fits-all approach makes local governments take excessive policy steps, and many farms have been forced to close (Hu et al. 2019).

As a matter of fact, the breeding structure is diverse, and pig MSM is complicated, which contains several phases, including collection, storage, processing and utilization. Moreover, there are various available approaches in each phase, with a variety of combinations used, such as mixed storage of pig manure and sewage with field waste lagoons and followed by field utilization, anaerobic fermentation of mixtures, solid manure composting with liquid aerobic or anaerobic processing and so on (Tang et al. 2014; Chen et al. 2017a; Li 2018). Furthermore, there are high spatial and temporal differences and variability in pig waste. Variations in waste end-use, utilization costs, soil types and crop requirements involve data from a wide variety of information systems. Moreover, it is difficult to integrate such data, resulting in complex and maybe even inappropriate design, selection and operation of MSM on a variety of farms.

Several farmers still adopt simple extensive MSM methods such as open-air composting, tank storage with natural fermentation due to the high cost, and unsystematic and unscientific knowledge of MSM technologies and modes (Gu and Du 2020). This is one of the immediate contributors to the disordered discharge of waste (Jiang et al. 2018). Although some farms are equipped with excreta treatment facilities, the prohibitive operation and maintenance costs and inadequate equipment management techniques resulted in a large number of completed facilities that were inefficient or operationally stagnant. For example, pig farms linked by biogas projects suffered from immature operating and managing techniques, inadequate waste processing and utilizing, etc. Accordingly, these not only diminished waste treatment efficiency, but also increased the burden of subsequent product handling (Tsapekos et al. 2017). For third-party governance companies, nevertheless, there is a dearth of guidelines and evidence on the appropriate scale and type of farmers (Yang 2022; Xia 2016). The ambiguity of responsibility of third-party companies and the unclear relationship between the companies and farmers cause unsound mechanisms.

4.4 Restrictive land, challenged labor, and deficient regulatory mechanisms

Field utilization has been widely regarded as a truism for effective MSM to realize resources natural ecological circulation (Shi et al. 2022; Machete and Chabo 2020). However, China faces a unique agricultural situation with huge populations and limited land. The per capita farmland area was 0.09 ha, which was significantly below the world average of 0.2 ha (Hao et al. 2023). With accelerating urbanization, there is a challenge of less available cultivable land. The competition with industrial land, residential and land roads, gradually reduced the proportion of arable land, mainly in areas within 30 km of major urban centers (Yuan et al. 2021; Li et al. 2016c). The layout of livestock and poultry farms has undergone tremendous changes, from agricultural, pastoral areas to suburbs of towns to facilitate transportation (Li et al. 2002). Furthermore, China’s agriculture is dominated by small-scale peasant economy, with more than 80% of farms operating on arable land of less than 0.56 ha (Lesiv et al. 2018), and accompanied by the issue of land fragmentation, which astricts the mechanization, scale up-grading production (Hao et al. 2023). Weindl et al. (2017) indicated that restraining land use could be a significant measure for sustainable livestock production.

Additionally, because of the improving living standards, more rural residents leave the countryside to seek work opportunities, which leads to departures from the labor force. A large amount of abandoned farmland has appeared, making the available arable land increasingly scarce. Population ageing is also intensifying, with the proportion of people over 65 in rural China tripling from 1990 to 2020, reaching about 18% in 2020 (Peng 2011; Ren et al. 2023). Ageing reduces agricultural output on cropland, but may be ameliorated by improved agricultural management (Ren et al. 2023). In addition, older farmers are associated with a relatively low level of education, which makes it difficult for them to acquire new agricultural skills and adapt to modern development patterns (Cutler et al. 2021). Furthermore, Ren et al. (2023) found that increased aging rate tends to operate less arable land. Accordingly, restrictive land and labor impede the development of modern agriculture.

Additionally, the inadequate environmental regulations and the incomplete market mechanisms of animal waste by-products are regarded as significant barriers to green and sustainable pig industry development. Currently, the coverage of regulations on breeding waste control is deficient. *Regulation on the Prevention and Control of Pollution from Scale Breeding of Livestock and Poultry* only included farms with over 500 pigs slaughtered annually in the environmental supervision system. The *Regulation on the Levying and Use of Pollutant Emission Charge*[19] stipulated only part of farms were required to levy sewage discharge charges, e.g., farms stock with >50 pigs, >50 cattle, and >5000 poultry. Thus, relatively smaller farms were left unsupervised. Additionally, the current relevant standards, norms and policy documents are mainly focused on

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[19] https://www.gov.cn/gongbao/content/2003/content_62565.htm

the principle of farm location and construction (involving away from the village, below the water source, impermeability and separation of rainwater). Furthermore, relying on regulation and supervision alone by environmental protection departments is an unsustainable initiative (Sun 2018; Hu et al. 2019). On one side, in China, departments and organizations are mainly located in urban areas, inability to fully regulate farming processes and pollution discharges in rural areas promptly. Lack of supervisory tracking of the practical implementation during MSM process (Sui et al. 2018). On the other side, some unregulated farms may not form as breeding communities, indicating a multiple and scattered distribution, which ratchets up the MSM supervision difficulty (She et al. 2021; Sui et al. 2018). The effectiveness of waste control is lagging and widespread, relying on government oversight exclusively is challenging, stimulating voluntary behavior among farmers maybe a sustainable initiative.

Profitable fertilizer market mechanisms are considered as possible mobilizers of farmers. However, market-oriented outlets for animal waste by-products have not been fully developed (Jiang and Zhou 2021). Although China has an *Organic fertilizer standard (NY/T 525-2021)*, and the *Rule of rational fertilization: Organic fertilizer (NY/T 1868-2021)*, the market price is unstable. Organic fertilizer raw material sources are varied and complex, the substances contained are difficult to identify. Furthermore, differences in processing standards result in varying by-products. Zheng et al. (2017) identified that the organic fertilizer market is initially formed but inadequate, in the absence of persuasive policy guidance and appropriate sales channels, farmers have a hesitant perception of the organic fertilizer market. Livestock waste processing-utilization scheme is a great way of killing two birds with one stone: keeping more ecological production while getting extra revenue, which contributes to voluntary-sustainable pig breeding.

4.5 Lacking a Sustainable Safeguard Mechanism of multi-actors with various endowments

Comprehensive resource utilization of pig waste under a systematic program, involving multiple endowments, is a complex and long-term challenge, but it lacks strategic planning and design (Wang 2018b; An et al. 2023). Currently, MSM models are diverse, links are cumbersome, with chaotic applications and an absence of standardized management, thus resulting in a waste of resources and funds (Ju et al. 2016). Besides, the research objective of each MSM model is unitary, considering only ecological and environmental management targets or only economic issues, without comprehensive research and feasibility analysis on the ecological and economic benefits of the MSM model, lack of formations of development mechanisms and improvement research for the efficient utilization of pig waste (Wang 2018b).

A sustainable and effective MSM mechanism requires the treatment and utilization by farmers, funding technical financial policy support by the government, mobilization and balance of markets, and transport technical assistance from third parties (Gu and Du 2020). This cannot be accomplished by a single actor but requires the collaboration of multi-actors in a vertical relationship (Wang et al. 2022a). However, the articulation and cooperation of multi-actors are fragile, and the division of responsibilities and labor is unclear. Numerous researches have focused only on the advantages and disadvantages of the MSM model or on the farmers. However, there are individual independence and economic relevance among each actor, therefore, the choice of its technological model and the distribution of its internal vertical relations require the cooperation of all subjects (Gu and Du 2020). Meanwhile, it is also necessary for the government to formulate and implement scientific and effective laws, regulations and subsidy policies, in the formation of a sustainable governance pattern, to stimulate subjects' inherent ecological self-consciousness and subjective initiative, prompting the relevant subjects to be more proactive in taking measures for pig MSM.

From the perspective of muti-actors, generally, pig farmers, cultivators, third-party companies, and government have the up-down steam relationships and interactions (**Figure 1-4**).

1) Pig farmers

Pig farmers are the direct handlers of pig waste, and they are also the most powerful and largest group engaged in waste management and utilization to achieve the green production of pig industry. Therefore, their individual behaviors are intimately related to environmental issues and resource recycling (Hu et al. 2019). An adequate acquaintance of farmers' MSM status and behavioral characteristics is necessary for more proper MSM approach promotion and policy formulation (Qiu et al. 2012).

2) Cultivators

Cultivators as waste consumers, their willingness directly affects manure outlets and resource utilization (Sang et al. 2021; Su et al. 2022). It is crucial to raise farmers' awareness of the application of organic fertilizers and promote their cooperation with pig farms, to increase returning waste rate. Cultivators also determines the amount and the form of the product consumed, thus influencing the choice of the pre-processing technologies.

3) Third-party companies

Third-party governance of environmental pollution is a mode in which the polluters entrust the environmental service companies to carry out pollution control by paying the fees according to the contract. Third-party management company is an important way to promote the professionalization of the construction and operation of environmental protection facilities, as well as an effective measure to promote the development of the environmental services industry (Yan et al. 2013). It is oriented towards marketization and specialization, in order to create a unified, standardized, competitive and well-regulated third-party governance market. The joining of third-party enterprises can attract and expand social capital investment, promote the establishment of new mechanisms for polluter-paying and third-party management, and continuously improve the level of pollution control in China (Du et al. 2022).

4) Government

Lastly, governments at various levels are generally responsible for the MSM in their respective administrative areas (Zhang et al. 2021a). In the light of local realities, clarify departmental responsibilities in accordance with the law, refine and streamline the division of tasks, improve the working mechanism, increase financial inputs, refine policies and measures, and strengthen daily supervision, to ensure that the task implementations are put in place (Zheng et al. 2017).

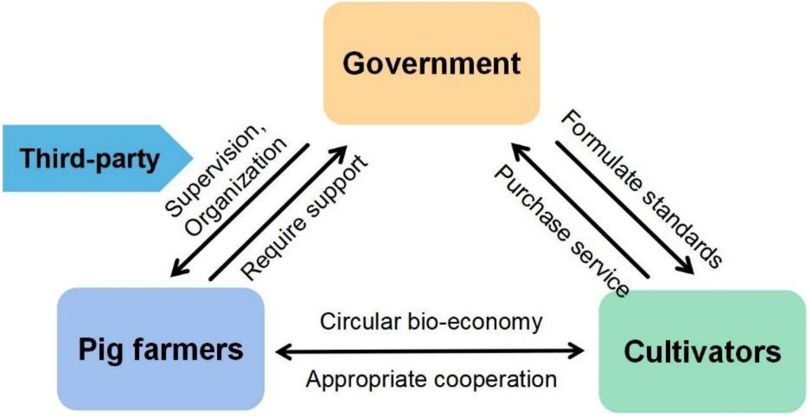

Figure 1-4. Inter-institutional coordination for pig farmers, cultivators, third-party companies and government.

In addition to the participation of muti-actors, endowments such as capital, technology, labor, land and revenue expectations all affect farmers' MSM behaviors. An institutional arrangement and sustainable safeguard mechanism are indispensable to guarantee the effectiveness and sustainability of pig MSM.

Farmers, as rational economic agents, are more profit-seeking in waste resourcing. High investment costs including facility construction, equipment operation and labor, etc., may limit MSM implementation. In addition, agricultural commodity market demand and price fluctuations affect farmers' willingness to take MSM measures. Higher agricultural prices may encourage MSM practice. Yu and Yu (2019) indicated that the perception of financial subsidies has a positive impact on farmers' willingness to participate in MSM. Feng et al. (2012) also highlighted the importance of policy support and financial incentives in the analysis of practical applications for rural biogas development in China.

MSM technologies influence nutrient use efficiency and environmental impacts on farmland. Different manure treatment methods affect the quality and suitability of pig waste. Advanced and appropriate technologies may increase fertilizing effectiveness and crop yields. Farmers need to be prepared to attempt and acquire these proper technologies to ensure the successful implementation of pig waste returning to the field. Well-established disposal facilities and convenient transportation can significantly contribute to waste recycling (Jiang et al. 2016), and technical assistance can significantly enhance farmers' willingness toward MSM (Wang et al. 2018c).

Labor, as the main performer, is directly restricted by the availability of labor within the pig farm, and alternatively by economic empowerment. Waste treatment and utilization both require additional labor, the feasibility of MSM behavior is affected by the labor availability and expense. In particular, training and education of the labor force is an important factor in improving the effectiveness of MSM (Xiaokaiti and Zhang 2023).

Land is an important factor affecting the waste returning to the arable field. Various textures and types of soil have different adaptations, especially for the soil with better absorptive capacity and water retention may be more favorable for waste utilization. The variety of crops, vegetables and fruits grown also influences the type, volume, timing and frequency of fertilizer application, as well as the practice operation, which in turn affects pre-processing steps for pig waste. More importantly, available land area determines the scale and feasibility of waste returning, and transfer price also undermines farmers' MSM behavior (Bai et al. 2018).

Revenue expectations are the perception of income received by farmers from pig waste recycling. Farmers' behavioral responses are considerably positively connected with their perception of value (Sweeney and Soutar 2001; Parasuraman and Grewal 2000). The greater the perceived benefit, the higher the likelihood of behavioral adoption (López-Nicolás et al. 2008).

5. The necessity of sustainable pig manure and sewage management for China and worldwide

In China, the shift towards scientific and efficient modern high-quality agriculture is becoming urgent. *Opinions on Promoting Quality Development of the Livestock Industry*[20] pointed out that the scale rate of livestock and poultry farming and the comprehensive utilization rate of livestock and poultry waste would reach more than 70% and 80% respectively by 2025, and over 75% and 85% separately by 2030. It is preliminarily estimated that by the same time, livestock and poultry waste disposal market size is expected to reach 220 billion CNY, there is enormous potential space for development prospects. Therefore, it is vital to investigate effective MSM technologies and solutions for environmentally friendly and economically viable agriculture.

Sustainable pig MSM and appropriate utilization create organic fertilizer placement and bio-energy generation, and offer chances for economic growth and environmental sustainability (Awasthi et al. 2019; Du et al. 2020), furthermore contribute to the circular bio-economy (García-Yuste 2020).

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[20] https://www.gov.cn/zhengce/content/2020-09/27/content_5547612.htm

Additionally, pig MSM aids in achieving the sustainable development goals (SDGs), involving SDG2 Zero Hunger, green and efficient high-quality breeding agriculture could achieve meat safety and promote sustainable agriculture, SDG7 Clean Energy, pig MSM by anaerobic digestion contributes to bio-energy utilization, and the reduction of energy carbon intensity, SDG12 Sustainable Production, appropriate waste utilization leads to organic circular agriculture, the decrease of chemical fertilizer production and the resources consumption in the corresponding production chain. Furthermore, green and sustainable MSM offers significant mitigation potential concerning climate (SDG13) and oceans (SDG14).

Chapter 2

Research objectives and thesis outline

1. Statement of the problem

The existing relevant studies in terms of pig MSM have significant reference and informational value. However, there are still deficiencies in the following areas. Firstly, lack of mode classification and judgment for the whole system of pig MSM patterns. Currently, MSM technologies have basically matured, and scholars have proposed a variety of approaches for pig MSM, such as fertilization, energy, fodder, substrate and harmlessness (Wu et al. 2018). However, most of the numerous studies focused on the physical and chemical treatment of waste, analyzing the innovations and feasibility of technological steps from a laboratory perspective. Research mainly aimed at scientific experiments for one specific method. Actually, MSM is an entire continuum of several sections, moreover, there are various available methodologies in each section, and farmers are facing diversiform choices. Consequently, the applicability and practicality of the whole MSM system in terms of macro aspects such as generation, collection, distribution, transportation, processing and reuse of products are neglected. All aspects of MSM are closely linked, therefore, a reflection on the continuity and integrality of MSM mode is meaningful. It makes sense to explore modes for the whole MSM chain.

Secondly, a majority of scholars focused on the strengths and weaknesses of the specific technologies. Furthermore, in order to clarify the performance of MSM methods, researchers have devoted to evaluating the environmental performances and economic benefits, resulting in the potential for different environmental categories (global warming potential, acidification potential, eutrophication potential, etc.) and economic values of by-products. Although the transparent and explicit evaluations of MSM methods provide a basis for information dissemination, the lack of relevant research on the adaptability of these methods impedes the promotion and popularization. Moreover, these ignore the variation in the effectiveness of mode or pattern application due to individual behavioral heterogeneity among pig farmers as implementers. The influences of farming patterns, farm scale and individual characteristics on MSM have been demonstrated (Smith et al. 2000). Most of the existing literature has studied the willingness or behavior of MSM of farmers of different scales unilaterally. Manure resource utilization, as the most critical link in the transformation of green agriculture, has become an essential part of hog farming and a practice that farmers must execute. Against this background, the study of the effects of heterogeneity in farmers' behavior on different MSM modes is of relevance. It is significant to explore the adaptability and practicability of modes towards different types of farmers.

Thirdly, the intensive development of pig farming inevitably leads to the thinking of MSM intensification. The principle of resource consolidation and reallocation not only applies to pig breeding but also has great potential for waste treatment. However, most studies aimed at individual farms, limiting the system boundary to the farm scale at the household level. Lack of in-depth exploration and analysis of regional perspectives. In third-party governance, a few have a predominantly macro-qualitative analysis. It is significant to explore the MSM sustainability by the systematic analysis from the perspective of endogenous and exogenous governance.

2. Research objectives and analytical framework

This research focuses on the question "what are the key constraints to the adoption of feasible pig MSM modes among pig farmers, to mitigate the environmental pressure and realize resource comprehensive utilization in order to achieve environmental-friendly pig specialization". The aim is to evaluate the available feasible pig MSM modes involving their advantages and limitations, environmental performances and economic potentials, and formulate practical MSM modes to cater to different pig farms. Clarify the responsibilities and contributions of all participants under the establishment of a sustainable operating mechanism. Finally, summarize the experience and lessons on pig MSM, which can enlighten other developing countries in similar predicaments. A schematic framework for creating the system of pig MSM has been produced in order to better clarify the research aims of this thesis (**Figure 2-1**). According to the aforementioned representation of the initiative and the significant problematic issues, the objectives and key hypotheses of this thesis can be split into four directions:

2.1 Summarize mainstream pig MSM modes

Regarding the problem of lack of classification and judgment for the whole system of pig's MSM patterns, as well as complicated sections, multitudinous MSM methods, and complex combination of approaches, the following research questions are proposed: 1) What is the current status of promoted pig's MSM technologies? 2) What are the typical MSM modes? 3) How to identify these MSM modes?

Systematically summarize the existing MSM information, empirically categorize available typical pig's MSM modes based on existing modes obtained, distinguish and identify the characteristics of modes. Mapping a clear current situation of MSM in pig farming from a scientific and statistical perspective, exploring empirically typical MSM pathways identified by data-driven typology. Furthermore, enhanced the efficiency of MSM and contributed to the ease of administrative convenience by government.

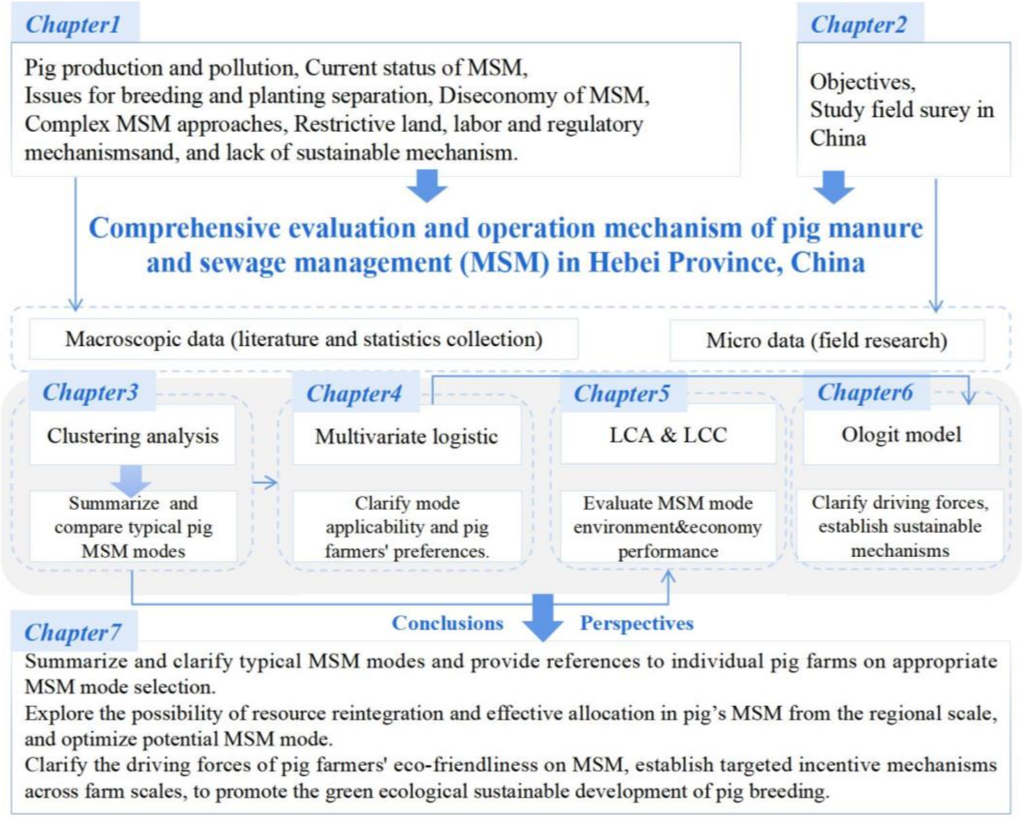

Figure 2-1. Thesis framework.

2.2 Identify farmers' heterogeneous characteristics and preferences towards various MSM modes

Concerning the issues of the heterogeneity of farmers' characteristics and their behaviors towards various MSM modes, which could affect the mode's effectiveness, the following research questions are offered: 1) What are the determinants of farmers towards various typical modes? 2) What are the characteristics and adaptability of different typical modes?

Explore the correlation between MSM modes and the pig farms, discriminate farmers' heterogeneous characteristics, inducements and preferences towards the potential MSM modes, and gather concerns and constraints when applying and popularizing. Understand the driving forces and further so as to design an optimal scheme with greater adaptability. In order to provide momentous references to individual pig farms on appropriate MSM mode selection, and support policymakers in establishing effective mechanisms to guarantee maximum acceptance by various pig farmers, therefore, promote comprehensive pig MSM across the board.

2.3 Comprehensive evaluation and optimization of centralized regional MSM for green-oriented transition

In accordance with the aforementioned concerns, and the exploration of the possibility of third-party exogenous governance. This part aims to answer the academic question of 1) what are the environmental and economic performances of a centralized mode? 2) What is the potential for resource reintegration and effective allocation in pig MSM at the regional scale?

Presented from a regional perspective, conduct a systematic analysis of the comprehensive evaluation of centralized MSM on biogas projects, and further explore its applicability and possibility in various regional contexts. Specifically, it is guided by 1) differentiating between individual MSM mode at the household level and centralized mode at the regional scale; 2) evaluating and comparing the environmental and economic performance of both modes; 3) further detecting potential trade-offs in optimizing the economic and environmental aspects of the centralized mode; 4) critically assessing the applicability and feasibility of implementing the centralized mode. In general, quantifying a specific comprehensive evaluation, contributing to a transparent understanding of the interests of relevant muti-subjects, and exploring the possibility of resource reintegration and effective allocation in pig MSM, facilitating coordinated breeding and cropping, and achieving green-oriented transition of energy at the regional level.

2.4 Recognize determinants affecting farmers' decision-making on MSM for sustainable safeguard mechanism construction

On the basis of the results obtained as described above, explore the driving forces on environmental friendliness of farmers' MSM based on breeding scale. Construct a sustainable safeguard mechanism to improve the effectiveness of pig MSM, which is accomplished in two ways from the perspective of endogenous and exogenous governance. It is guided by the academic issue of “How do farmers’ environmental MSM behaviors differ across farm scales under the constraints of arable land and environmental regulations?”

Establish a systematic and analytical framework with land factors, resource endowments, policy rationality and individual characteristics as the factors influencing farmers’ decision-making on comprehensive combined MSM approaches adoption. From the perspective of farm scales, analyze the effect and intensity of each factor respectively, and further explore the matching targeted initiatives. It will be explained by 1) What are the differences in the characteristics of various farm scales? 2) From the perspective of scales, what are the impacts of land, resource endowments and policy rationality on farmers' eco-friendly behaviors? 3) What are the effective paths to improve farmers' eco-friendly MSM behaviors by adopting more comprehensive MSM approaches?

In general, provide reference to clarify appropriate targeted recommendations to pig farms of different scales to engage in pollution prevention and control practices. More importantly, ferret out the driving forces in the pathway involved in the internalization of externalities of MSM, and establish a thorough inter-institutional coordination for sustainable MSM.

The following hypotheses are formulated,

H1: The dominant MSM modes could be classified and identified.

H2: Heterogeneous characteristics of pig farms and farmers affect the selection of MSM modes.

H3: Centralized technology mode at the regional level has better environmental and economic performance compared with traditional mode.

H4: Pig farmers' eco-friendly MSM behaviors could be improved by the modulation of land factors, resource endowments, policy rationality and individual characteristics.

This study will assist in enriching the theory and research on the resource utilization of pig waste. Based on the concept of economic and ecological environment sustainability, it summarizes different pig waste resource utilization modes, identifies the heterogeneous characteristics, and comprehensively evaluates mode economic and environmental benefits. Theoretically discuss and empirically analyze the relationship between relevant interest subjects, on this basis, explore the limiting aspects for the development of pig MSM, further discuss the countermeasures and institutional arrangements, establish sustainable incentive mechanism for the realization of the green-oriented transition of the pig industry.

3. Structure of the thesis

Thesis chapters that follow the aforementioned objectives and research questions are organized into seven chapters:

Chapter 1 (Introduction) concerns the general context of this study, describes the background of pig industry in China, pig waste pollution status, current situation of manure and sewage management, and problematic issues.

Chapter 2 describes the deficiencies of the existing research in conjunction with the issues aforementioned, provides research questions and objectives, and sketches the analytical framework and thesis structure. Furthermore, introduces field survey and data collection, the dataset will be adopted for subsequent studies.

Chapter 3 maps a clear current situation of MSM in pig farming from a scientific and statistical perspective, and empirically categorizes typical pig MSM modes by clustering analysis.

Chapter 4 further discriminates farmers' heterogeneous characteristics on corresponding mode adoption by multiple independent sample tests and multiple logistic regression, providing references to individual pig farms on appropriate mode selection.

Chapter 5 systematically assesses the environmental performance and economic viability of centralized regional mode by life cycle assessment (LCA) and life cycle cost analysis (LCC), and further explores the adaptability of multi-subjects (various pig farms and biogas enterprise) and regional feasibility.

Chapter 6 is devoted to exploring the determinants affecting farmers' decision-making on sustainable MSM, elaborating on the sustainable safeguard mechanism to improve the effectiveness of pig MSM from both perspectives of endogenous and exogenous governance.

Chapter 7 summarizes the main findings and limitations, draws the major conclusions, and provides policy recommendations and perspectives.

4. Study methodology, study area and survey data collection

4.1 Study methodology

(1) Synergistic approach to literature survey and field survey

The sections in the process of MSM in pig farms are complex, and the inputs are complicated and variable. Therefore, it is necessary not only to investigate survey data such as questionnaires and field interviews, but also to draw on relevant statistical data and literature to corroborate and illustrate them with support to obtain reliable conclusions. In addition, the evaluation results of environment and economy should be compared with related research in addition to the object in this study, so as to collect literature data and practical data of pig MSM mode comprehensively as a whole, and to provide support for exploring the regularity characteristics of the mode and its future promotion.

By reviewing the literature, summarize the research progress regarding the status quo of MSM, MSM approaches, farmers' MSM behaviors, decision-making behaviors and their incentive mechanisms. Drawing on the meaningful views and methods of existing studies, sorting out the academic attention and research weakness, further combining with the situation and trend of the development of pig farming in China, the academic questions to be addressed in this study are proposed to support the subsequent research. Associated data are mainly from the China Animal Husbandry and Veterinary Yearbook, China Statistical Yearbook, National Statistical Databases, FAO and others.

Secondly, focusing on pig farmers, applying the social survey method, and designing questionnaires to conduct field surveys. Acquire direct data and messages on related issues to ensure sufficient information for empirical research. In addition, open-ended in-depth spotlight interviews are conducted, particularly with large-scale pig farming enterprises with well-established MSM systems.

(2) Combination methodology of quantitative and qualitative analysis

Explore typical MSM pathways identified by data-driven typology, and reveal the key constraints affecting the selection of pig farms. Comprehensively assess the differences in MSM modes from the perspectives of environmental and economic performance, and analyze measures to improve both benefits. Explore the influencing factors of farmers' MSM technology adoption decisions, clarify the drivers of farmers' environmental friendliness, and elucidate the driving mechanism. Discover incentives and safeguards to realize the sustainable development of pig industry.

Research methodologies include general descriptive statistics, cluster analysis, LCA, LCC, logistic regression, and the measurement software used consists of R, STATA, SPSS, ArcGIS, etc.

4.2 Study area

According to the distribution of pig industry in China, there are four regions at different levels, considering limitations and potentials (Wang et al. 2018a). Moderate region has a weak foundation for pig farming. Sufficient natural resources are the advantage of the Potential region. Constraint region is restricted by resources and environmental conditions with a severe burden on water environment management. Priority region is the core area of pork supply, and aims to improve the level of scale, specialization and informatization, thus enhancing the comprehensive production capacity (**Figure 2-2**).

Hebei Province located in the Priority region with the characteristics of intensive pig breeding, plays a significant role in pig breeding, with approximately 5% of the national pork production over the last five years (NBSC, 2020). The typical breeding technologies adopted in this Province are representative of China (Yan et al. 2020). Meanwhile, it is also the major crop-producing area, located in North China Plain, with approximately 6.39 million hectares of land (NBSC 2021a). There is great potential for achieving the efficient use of waste and establishing the integration between planting and breeding to realize circular agriculture. Due to the abundant land resources, Hebei Province has great opportunities for waste consumption and provides a basis for exploring the possibilities of further diversified MSM modes. In addition, there are 12 provinces with 67.9 million hectares of cropping area facing similar situations (NBSC 2021a), therefore, Hebei Province could be representative of other regions in northern China. Importantly, in both developed and developing countries, farmland has always been considered the final outlet for nutrient recovery (Machete and Chabo, 2020). Thus, useful processing of waste based on land disposal is demanded and meaningful (Martinez et al. 2009). (Martinez et al. 2009). This study is of great significance in providing experience to other regions or countries confronted with similar situations in promoting circular sustainable ecological agriculture. Generally, choose Hebei Province as the field study area due to its urgency, representativeness, and replicability.

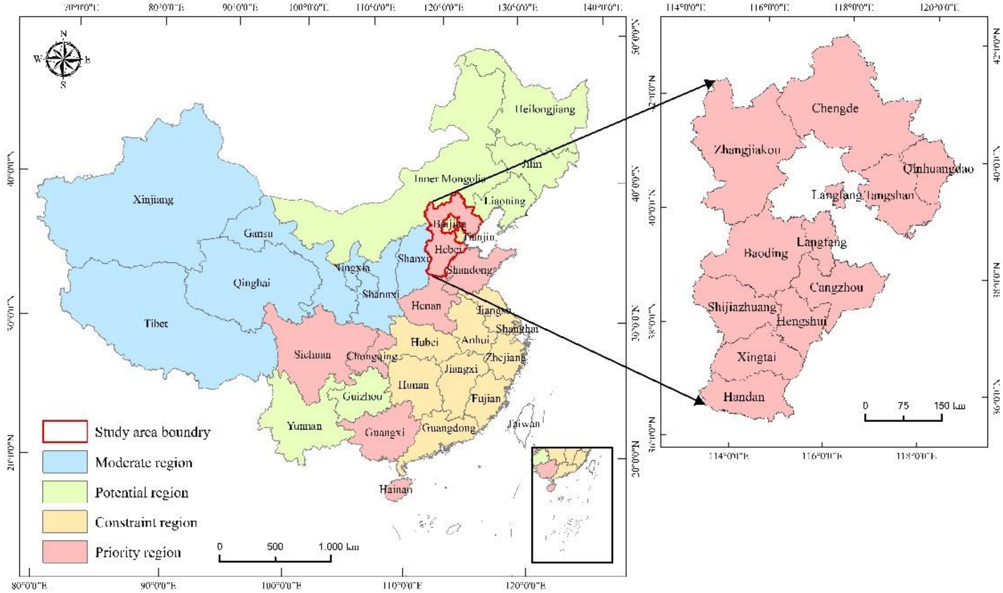

Figure 2-2. Pig industry distribution in China, and study area.

4.3 Field data collection

To investigate the current situation of MSM and farmers' MSM behaviors, it is necessary to apply the field data for empirical analysis. The following measures were taken to ensure the quality of the questionnaire:

The first is to organize this study questionnaire design based on a thorough understanding of relevant literature. The panel was composed of researchers and PhD students. Secondly, conducting pre-surveys in Hengshui City and Shijiazhuang City to assess the feasibility of the questionnaire. In response to some practical; issues, such as some questions are difficult for farmers to understand or are inducing, some do not correspond to the actual situation, and some lack precision in the examination of policies, the questionnaire is modified and improved to ensure the comprehensibility and clarity, by discussing with agricultural technicians of Hebei Provincial Animal Husbandry Station and Hebei Provincial Pig Industry Technology System. Meanwhile, accumulating experience and lessons for conducting face-to-face questionnaires with pig farmers. Thirdly, before the start of the formal survey, we provide systematic training to the interviewers (most are master and doctoral students with an agricultural background), involving the overall concept of MSM, scoping of relevant nomenclature, back-and-forth logic of questions, and communication skills with pig farmers. Lastly, summarize the field investigation and questionnaire, compare the information promptly, verify and cross-check the missing and erroneous data to ensure the authenticity and reliability of the survey content.

The questionnaire for the pig MSM investigation includes the following 6 sections. 1) Basic information of pig farm, including construction time, farm area and cost, breeding scale, etc. 2) Current situation of performed MSM practices, including the amount of manure and sewage generated, adopting methods at collection, storage, separation, processing and utilization sections, and field application information. 3) Farmers' behaviors and perceptions of MSM. 4) Farmers' environmental awareness. 5) Farmers' perceptions of government regulations and policies. 6) Personal information, including age and education, etc. The details of the questionnaire are shown in Appendix 6.

Formal surveys were conducted in two separate sessions in March and April 2021 in Hebei Province, China, encompassing all 11 cities to ensure the avoidance of sample bias resulting from regional differences. According to the scientificity, accessibility, and diversity, the field survey complied with the standard of the combination of stratified sampling and random sampling method. First of all, 3-5 counties (cities or districts) were randomly selected in each of all cities, 3-4 sample townships were selected in each county, and 3-4 villages were randomly selected in each township. Then, pig farms were randomly selected in each village using typical sampling and ensuring that a certain percentage of sizeable pig farms were included. The survey was conducted in the form of "face-to-face" interviews with pig farmers who met the following prerequisites. (1) Respondents need to meet the basic requirements of engaging in pig farming in 2020 and continuing in the future. (2) Respondents should be actually involved in pig production as well as MSM in pig farms. (3) Respondents have a clear articulation of adopted MSM practices, attitudes and perceptions of policy.

In addition, there were no ethical issues and sensitive data involved in this field survey, and conducted in a transparent manner in relation to the respondents. We have tried to ensure authenticity as much as possible during the investigation. For example, we prefaced the questionnaire by stating the purpose and use of the research, that it was only for academic research and has absolutely no relation to the politics of government. And farmers choose whether or not to be interviewed. For another, the questionnaires were anonymous, with strict confidentiality of any information submitted, and we weakened the private parts such as address, phone number, income, etc. Thus, reducing the psychological pressure on pig farmers. In addition, to avoid being influenced by other respondents, one-on-one interviews were conducted throughout the research process to ensure that farmers did not interfere with each other. All conversations were corroborated by trained professional interviewers. The field survey was conducted in accordance with the methodology of the social survey (Jackson 2011; Tan and Zhou 2020; Feng 2005; Malthus 2017) and in compliance with the General Data Protection Regulation[21]. Using EpiData 3.1 for data recording, then exporting as .xlsx format. Data filtering, editing and formatting by Office Excel by the originator of this research (Boyang Shi). We keep confidentiality, integrity and availability during data collecting and processing.

Eventually, a total of 614 questionnaires were collected (**Table 2-1**). 406 valid pig farms' data would be adapted to Chapter 3 and Chapter 4. A total of randomly valid 559 cross-sectional data were obtained for Chapter 6 excluding duplicate and missing data questionnaires. For Chapter 5, an open-ended in-depth spotlight survey of pig farms matching the system boundary description was conducted in Hebei Province, China, employing a questionnaire format (Shi et al. 2022), that included information on the methods adopted in each MSM section, such as collection, storage, processing, utilization and transport, as well as critical inputs and outputs. A total of 27 valid datasets were randomly obtained, which adhered to the individual traditional mode (ITM) system boundary description, and were subsequently used for data processing. The target pig breeding enterprise for centralized bio-energy (CBM) was located in Anping Country, Hengshui City, Hebei Province-a significant region for pig breeding. This enterprise was established in 2013, and currently operates a well-developed and stable MSM system. Enterprise provided detailed information regarding its processing procedures and inventory of inputs and outputs.

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[21] https://www.dataprotectionauthority.be/european-union

Table 2-1. Basic descriptive statistics of survey farms.

Variables	Definition	Mean
Age	Age of pig farm owner.	45.42
Education	Education level of farm owner. 1=Primary and bellow, 2=Junior, 3=Senior, 4=Vocational college, 5=Bachelor degree and above	3
Time	Year of pig farm construction.	11.02
Cooperation	Whether as a member of pig professionalization organization. 0=NO, 1=YES	0.43
Inventory	Inventory heads (data for end of 2020).	3584.17
Farm area	Pig farm construction area (mu).	97.03
Farm investment	Total investment in farm construction (ten thousand CNY).	1914.41
MSM area	Farm area for MSM (mu).	14.25
MSM investment	Investment in farm MSM (ten thousand CNY).	174.89
EIA	Whether as a member conducted Environmental Impact Assessment. 0=NO, 1=YES	0.74

4.4 Representativeness of data collected

To confirm the representativeness of the survey results, the minimum sample size was calculated. x is the error rate, generally<5%, Zc indicates the threshold value at the confidence level, usually>95%. N is the total number of pig farms in the surveyed area (Hebei Province), n is the minimum sample size required, E represents the standard deviation (SD).

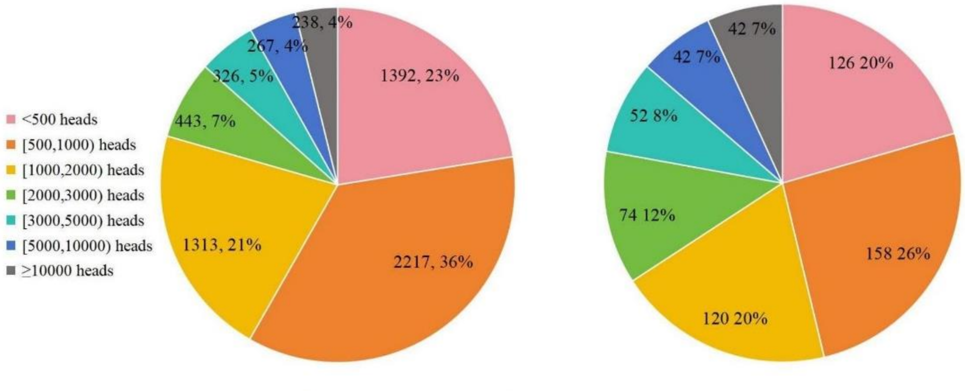
The equation is as follows,

$$x = Z_c^2 r(100 - r)$$

$$\mathrm{E} = \sqrt[2]{(N - n)/(n(N - 1))}$$

$$n = \frac{N}{((N - 1)E^2 + x)}$$

There were approximately 6196 pig farms recorded in Hebei Province. Thus, the minimum sample size of 362 could be representative of the pig farming situation in Hebei Province. The distribution of the survey sample is generally consistent with the basic situation in Hebei across to size classification, inventory heads **(Figure 2-3)**. The datasets are meaningful for this study, and could represent the pig farming situation in Hebei Province.



Farms on record in Hebei Province: 6196

Survey farms: 614

Figure 2-3. Distribution of farm scales in Hebei Province and survey farm samples.

Chapter 3

Recognition on typical MSM modes

Adapt from:

Shi, Boyang et al., (2022): Recognition on characteristics and applicability of typical modes for manure & sewage management in pig farming: A case study in Hebei, China. In Waste. Manage. 148, pp. 83–97. DOI: 10.1016/j.wasman.2022.05.018.

1. Introduction

Along with the incremental population, pork production has increased as a result of rising food demand. Meanwhile, the rapid breeding development also brings massive pressure to the environment. In China, the amount of pig manure, urine and sewage produced was about 4.37 billion tons in 2015, which accounted for 76.8% of total livestock waste discharge (Wu et al. 2018). Pollution caused by pig breeding has become the priority issue to be resolved, because of highly intensive farming with the concentrated generation of a large amount of manure and sewage simultaneously (Zhang et al. 2004). The disorderly discharge of pig manure and sewage results in a range of critical environmental problems to the atmosphere, soil and water resources, including greenhouse gas emissions, odor emanation, water eutrophication, soil acidification (Zhang et al. 2004; Prapaspongsa et al. 2010; McAuliffe et al. 2016; Wang et al. 2017; Wu et al. 2018; Liu et al. 2020a). The future development trend of pig industry towards the elimination of free-ranging and emergence of more intensive and professional breeding communities, so as to achieve the goal of scientific and efficient modern high-quality agriculture (Qian et al. 2018). It is estimated that by 2025, China's pork consumption will reach 1,000 million head (Bai et al. 2019). Consequently, dilemmas of concentrated manure and sewage generation, nutrient surplus and separation of farming and breeding are the main challenges faced by farmers and the government (Luo et al. 2014).

Though intensive pig farming poses tremendous pressure on the environment, it has mitigation potential by effective management. In terms of farming structure, according to the limitation of land carrying capacity, pig migration from the South China Water Network Area to the North Crop Producing Area with vast upland-cultivated lands is in progress, which relieves the concentration of N and P in soil (Bai et al. 2019). Establishing vital links between farms and arable land is a crucial pathway for manure recycling (Jin et al. 2021; Thornton and Herrero 2015). More importantly, a variety of resource utilization approaches for pig manure and sewage provide vital opportunities to promote green pig production as well as the upgrading of planting (Wang et al. 2021c). The National Animal Husbandry Station has officially proposed four principal MSM approaches, in terms of fertilization, energy, fodder and substrate (Wu et al. 2018). Fertilization is the most common approach in China, with an adoption rate of over 90% (Xuan et al. 2018). Manure is being promoted as an alternative to synthetic fertilizers. The nutritional contribution of pig waste reuse has been demonstrated, specifically in the enhancement of cultivated land quality as well as promotions in the production and quality of agro-products (Penha et al. 2015; Prior et al. 2013). Mechanization of fertilizer production eliminates the disadvantages of traditional uncovered composting, such as long period, large area and breeding of pathogenic bacterial (Wu et al. 2018). Biogas project is well recognized as a clean and available approach (Pexas et al. 2020; Akyürek 2018), especially in terms of mitigating greenhouse gas emissions (Prapaspongsa et al.

2010; Dhingra et al. 2011), which has promoted worldwide, such as Netherlands, Germany, Denmark, China and India (Daniel-Gromke et al. 2018; Triolo et al. 2013; Hijazi et al. 2016). Energy conversion transforms waste into heat or electricity through anaerobic digestion processes. Another utilization practice is processed into fodder, which is a consequence of high efficiencies for nutrient recovery, i.e., crude protein and mineral elements (Rao et al. 2007). Manure composting with animal proteins, such as earthworms, is valuable for feed production. This kind of regenerated feed from processed pig manure has potential for ruminant feeding and aquaculture (Wu et al. 2018). Another important use of processed manure as the substrate is for edible mushroom cultivation (Lin et al. 2010; Yang et al. 2010; Tseng and Luong 1984), which proves the economic value of waste materials.

While the variety of MSM technologies are widely presented, scholars are devoted to evaluating their environmental performance and economic benefits simultaneously. Hsu (2021) and Yuan et al. (2018a) emphasized the benefits of pig manure in energy conversion, and its potential as substitute for chemical fertilizers. However, extra environmental impacts on the production of mineral-organic fertilizer by solid separation were pointed out (Makara et al. 2019; Pexas et al. 2020). By contrast, direct use of pig manure has less environmental damage. Lopez-Ridaura et al. (2009) also revealed similar conclusions, that is the treatment option represented a worse environmental performance, especially in terms of eutrophication and acidification. Although the transparent and explicit evaluation of MSM methods provides a basis for information dissemination, the lack of relevant research on the adaptability of MSM methods impedes the promotion and popularization.

Actually, MSM in pig farming contains several phases, from the collection in pigsties to the graves on the land, including collection, storage, separation, processing and utilization. Moreover, there are various available approaches in each phase (Prapaspongsa et al. 2010; Cherubini et al. 2015; Hoeve et al. 2014; Varma et al. 2021). Thus, farmers are facing diversiform choices and most of them adopt a complex combination of approaches, rather than a single choice during one phase (Kassie et al. 2013). Furthermore, instead of following the invariable MSM mode as anticipated, farmers choose a shortcut to combine it into a variational mode according to their needs. Thus, there is a gap between the theory and practice of the MSM strategies, due to the technological complexity and behavioral diversity. Consequently, it is significant to explore the dominant MSM modes and further correlation between the modes and the pig farms to achieve environmentally friendly pig industry.

In accordance with aforementioned concerns, this chapter is guided by the scientific question of "what are the typical modes of pig's MSM identified by a data-driven typology?" This chapter systematically analyzed operational practice on pig's MSM in Hebei, China, involving 1) what is the current status of promoted pig's MSM technologies; 2) what are the typical MSM modes; 3) how to identify these MSM modes? The significance is mapping a clear current situation of MSM in pig farming from a scientific and statistical perspective, exploring empirically typical MSM pathways identified by data-driven typology.

2. Clustering construction

2.1 Clustering analysis

A systematic classification of complex permutations is significant in response to highly varied MSM methods. Clustering method is a process of dividing a collection of objects into multiple classes consisting of similar objects. Currently, cluster analysis is widely adopted in studies related to manure management. A study from Canada clustered two typical composting patterns based on the data of chemical composition, source materials, management intensity and degree of decomposition, which verified the practicability of cluster analysis (Gagnon et al. 1999). Wei et al. (2015) also employed hierarchical cluster analysis to investigate different types of composting, and proposed an optimized mode. Piot-Lepetit (2010) clustered the pig farms based on structural characteristics, then explored their economic and environmental performance at different levels respectively. In addition, clustering has also been applied to soil fertility management to evaluate various strategies and promote more effective patterns (Wawire et al. 2021).

K-means clustering

K-means is a simple and practical clustering algorithm, it generates new reassembled clusters to minimize a cost function by the calculation of cluster means. It is used as a common metric to measure the similarity between two data points. K-means bases on the Euclidean metric (Anderberg 1973), which is the shortest distance between two points in a M-dimensional space. The equation is as follows,

$$d(x,y) := \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + \cdots + (x_n - y_n)^2} = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2}$$

K-modes clustering

However, K-means is only applicable to datasets with continuous data (Goyal and Aggarwal 2017). K-modes is an extension of K-means, which applies in clustering categorical data. It is applicable to datasets with discrete attributes, replacing the means with the modes (MacQueen 1967), by altering multiple categorical attributes into binary attributes and treating binary attributes as numeric (Ralambondrainy 1995). Scholar has based on the data set of soybean disease, proposed the applicability of K-modes in the application of categorical variables, which is generally used (Huang 1997, 1998). Thus, K-modes algorithm can be useful to categorize individuals into groups based on quantitative typology, and identify the rules of which to get easy identification of typical paths.

2.2 Variables for clustering

MSM in pig farming involves five sections including collection, storage, separation, processing, and utilization, generally covering the whole process from the gate of collecting in pigsty to end-use application. Each section has corresponding options as measured variables, and the option can be a single or a combination of strategies (**Table 3-1**). Methods adopted (categorical data) in each section are selected as data variables for cluster analysis by K-modes.

From an overview of collection methods in pig farming, there are four approaches, involving scraper dry collection, water-submerging cleaning, water-flushing cleaning and gravity dry cleaning.

Scraper dry collection is the most traditional and common one, which is divided into mechanical automatic scraper and manual operation. Pigsty is equipped with slatted floor, a ditch is installed under the floor, and a catch-basin is installed at the end of the ditch (Weng et al. 2019). Feces, urine and sewage fall through the floor to the ditch and then are gathered into the catch-basin by mechanically pulling the flat scraper, and finally enter the treatment area through pipeline transportation (Schuchardt et al. 2011; Huang et al. 2021a). Compared with mechanical scavenging, manual operation is a faster and more flexible way to achieve effective separation of waste from urine and sewage, also allows for better nutrient retention. On the other hand, it saves water, has low investment costs without electricity requirements. Pollutant concentration in sewage is relatively low, less sludge is produced (Yang et al. 2019). However, manure collection and transfer are labor intensive with lower operational efficiency.

Water-soaking process is to set up a sloping cesspool under the slatted floor of the pigpen. The cesspool is filled with water (with a certain depth) and has a drain with a valve at the bottom of the cesspool (Pang 2021). Feces, urine and flushing water enter the cesspool through slatted floor, are usually stored in for 1-6 months (every batch of pigs transferred once normally) before opening the valve and dumping the mixed waste into the collection tank through the sewage pipe (Huang et al. 2021a). Compared with water-flushing, submerging saves water, generates a smaller amount of waste (Pang 2021). It has the advantages of saving energy and labor, and high efficiency of waste disposal (Huang et al. 2021a; Pang 2021). In addition, using gravity and siphoning, water-submerging saves electricity, has the benefits of reduced construction, maintenance and operating costs, easier and more stable operation and long service life, compared with mechanical scraper (Pang 2021).

Water-flushing cleaning is a method whereby water is released from a scrubber to flush pig waste from a trench into a septic tank (Pang 2021). Pig waste is then pumped through a pipe to the processing area. Setting the daily flushing frequency according to the production situation. This method requires less labor intensity, improves collection efficiency, as well as timely cleaning of manure in the barn, improving the breeding environment (Weng et al. 2019). Liquid products are applicable for fertigation (water and fertilizer integration), however, the transportation, storage and application are not convenient (Wu et al. 2018).

Gravity dry cleaning is a new modernized waste collection process developed from traditional dry removal (Zhang et al. 2020a). However, gravity dry cleaning requires special conditions for pigsty construction. Adopting the full slatted floor without flushing process, excrement enters the sealed storage collection tank directly at the bottom of the barn due to the trampling of pigs and its gravity. Pig excrement is naturally accumulated and fermented, the high temperature generated evaporates moisture, which could be directly recycled after natural air-drying, reducing the labor intensity of mechanical liquid and solid separation, and preventing pollution expansion (Zhang et al. 2018b). Besides that, adopt urinary grooves, where urine flows by gravity into a urine collection tank. Under the slatted floor, in the middle of the ground, laying slightly sloping PVC pipes throughout as urinary grooves, with a storage tank trough against the wall on the lowest side of the floor, the ground level construction into high on the sides and low in the center with a slope, both to facilitate liquid self-flow (Liang et al. 2017). There is no need to rinse the pens throughout the feeding period, the only waste sources are the feces, urine and the water used to ultimately wash the pens. No power is required for the collection process, saving kinetic and electrical energy which is innovative (Zhang et al. 2020a).

According to the multiple collection methods and whether separation, the storage section can be separated into mixed and separated (solid and liquid respectively). Due to the relevance of MSM among each section, further effective processing will be facilitated by appropriate collection and storage methods.

Processing section is essential in MSM, solid fraction can be considered for composting, and animal manure could be co-fermented with bedding, straw and rice husks (Zhu and Hiltunen 2016). Proper moisture, temperature, oxygen and pH need to be controlled. The methods are mainly simple open-air, stack, slot, mulch and reactor compost (Zheng 2014b).

Anaerobic digestion is recognized as an available eco-friendly method (Akyürek 2018; Arthur et al. 2011), which is characterized by the conversion of waste to valuable energy and fertilizer, such as biogas and digestate (Liu and Zhang 2014). Animal waste also can be anaerobically digested with crop straws and organic household waste (Croxatto Vega et al. 2014). Furthermore, anaerobic fermentation and composting can be used in combination, obtained digestate could be subsequently composted for organic fertilizer processing (Serna-García et al. 2021).

Oxidation pond is a process of aerobic biological treatment of wastewater by microorganisms (Loyon et al. 2007). Waste organic matter as culture medium, various microbial groups are mixed and continuously cultured under aerobic conditions to remove organic matter through the processes of coagulation, adsorption, oxidative decomposition, and precipitation (Nguyen et al. 2022).

Another method targeting liquid is staged sedimentation oxidation ponds: the first stage is to remove suspended solid pollutants from effluent, followed by the removal of colloids and dissolved organic pollutants and aims at the organic matter, nitrogen and phosphorus removal finally (Wang et al. 2021b). This process has the advantages of strong shock resistance, a high utilization rate of carbon source, relatively low operating cost, and effective nitrogen and phosphorus removal (Wang et al. 2021b).

Industrial treatment is a unique option with no restrictions on emissions. Sewage is treated by the anaerobic oxic pond, biochemical pond and ozonation contact reactor (Feng et al. 2024; Babu Ponnusami et al. 2023), and the discharge meets the Discharge Standard of Pollutants for Livestock and Poultry Breeding (GB 18596-2001), which requires COD<400mg/L, NH_3-N<80mg/L, TP<8mg/L (Sang et al. 2010; Wang et al. 2021b). Pig farms without on-site MSM capacity, choose off-site disposal to a third party through payment or grant.

Utilization mainly has four pathways (**Figure 3-1**), as waste returning to surrounding cultivable farmland by ditches and pipe networks (including pig farms’ own cultivated land or others' land), pulling away to fertilize kaleyard and orchard by transport, producing packaged commercial microbial organic fertilizers for sale and utilizing biogas for bioenergy (household cooking, natural gas purifying and electricity generating).

Table 3-1. Abbreviations and statistical descriptions of variables for clustering (The sum of the total probabilities is not equal to 100% due to multiple choices).

Section	Abbr.	Explanation	Percentage
Collection	SCRAPER	Feces collection by mechanical or manual operation with scrapers	81.77%
	SOAK	Manure soaking in water	14.78%
	FLUSH	Flush cleaning manure	7.64%
	GRAVITY	Manure enters the ditch at the bottom of the barn due to the trampling of pigs and itself gravity	1.48%
Storage	MIX	Mixed storage including feces, urine and sewage	50.25%
	S	Solid fraction storage	81.77%
	L	Liquid fraction storage	77.83%
Separation	SEP	Mechanical or manual solid-liquid separation	76.12%
	NON_SEP	No separation	24.88%
Processing	COM	Solid composting	69.46%
	D	Anaerobic biogas digestion	52.71%
	OXI	Sewage oxidation pond	46.31%
	SED	Staged sedimentation oxidation pond	59.36%
	DIS	Industrial treatment and discharge of sewage to standard	36.95%
	OFF	Off-site to Third-Party	4.19%
Utilization	F	Manure and sewage returning to surrounding fields	87.68%
	AWAY	Manure and sewage pulling away with no trade by transport	20.94%
	OF	Commercial organic fertilizer production	13.05%
	GAS	Biogas utilization	17.49%
	NonU	No utilization	2.46%

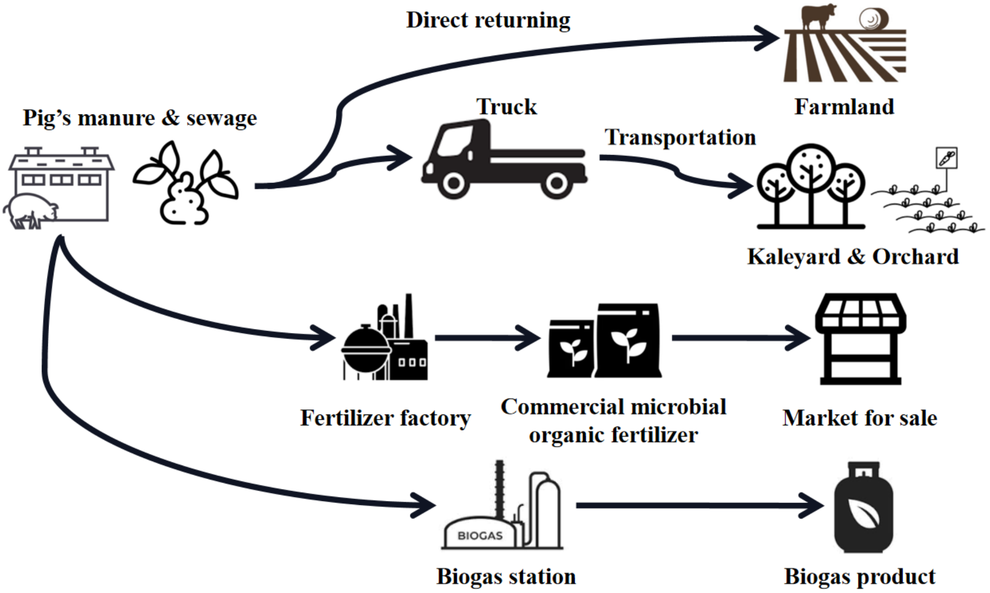


Figure 3-1. Pathways of utilization of MSM.

2.3 Clusters determination by Elbow method

Estimating the number of clusters is the foundation of clustering, which is based entirely on a quantitative analysis of data. For K-means, partitioning meaning is to define clusters such that the total within-cluster sum of distance is minimized. Elbow method is usually used to determine the number of principal components to extrapolate the distribution of the data set. It measures the compactness of the clustering and prevents over-fitting or under-fitting the model, which involves plotting the explained variance as a function of the number of clusters and selecting the elbow of the curve as the number of clusters used (Nainggolan et al. 2019).

In **Figure 3-2**, X is the number of clusters; Y represents total within-cluster sum of distance for each cluster. As the number of clusters increasing, the distance will continue to decrease. Until the slope slows down, the optimal number of clusters (K) is at the elbow, which means when adding additional cluster (K+1) has less contribution to present cluster fitting performance. In this study, we can observe that the slope of 5 to 6 is relatively flat, so the optimal number of clusters is 5. Thus, MSM methods will be divided into five modes.

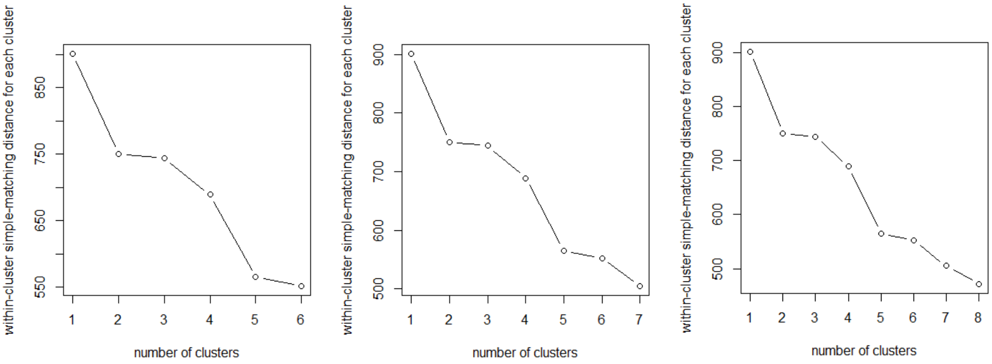


Figure 3-2. Results of optimal cluster number determination by Elbow method plotting.

3. Results on MSM practices summary and category

3.1 Descriptive analysis of MSM practices

A general review of type and frequency of technologies adopted at each section was directly obtained (**Figure 3-3**). Additionally, **Table 3-1** and **Table 3-2** indicated all-encompassing descriptive statistics of MSM practices adopted.

Results showed that the most popular collection method was SCRAPER, as 81.77% of farmers selected, of which, 29.76% chose mechanical scarper, and 57.87% adopted manual cleaning. Followed by SOCK and FLUSH occupied 14.78% and 7.64% respectively. Only 1.48% of farmers used GRAVITY which is a consequence of farm scale and building time.

During storage period, 39.90% of farmers selected separated storage (S_L), 33.25% of farmers used MIX_L_S. Other 13.55% farmers stored waste with mixed type. According to separation, 75.12% of farmers implemented solid-liquid separation, which was consistent with the results for storage (73.15% for containing S_L).

In processing section, 4.19% of farmers decided for off-site disposal by third party. The rest of farmers chose simple or multiple detoxification methods, among them, most producers preferred assorted processing methods. COM was most widely applied (69.46%), due to the characteristics of simple operation, low cost and wide applicability. It was also common to combine with other liquid technical strategies (i.e., COM_SED and COM_OXI). Adoption rates for SED and D were 59.36% and 52.71% respectively, which showed the particular importance of sewage treatment. Only 36.95% of farmers opted for DIS. It should be noted that 29.80% of farmers adopted the comprehensive approach of D_COM_OXI_SED_DIS.

Concerning utilization, F was identified as the largest contributor, which occupied 87.68%. Due to the long-distance discharge, 20.94% of farmers were forced to transfer pig waste by vehicles (AWAY). Farmers who participate in biogas utilization were in the minority, with 17.49%, which was not consistent with the application of D. In addition, only 13.05% of farmers attempted organic fertilizer production. This also differed significantly from the contribution of COM in processing stage.

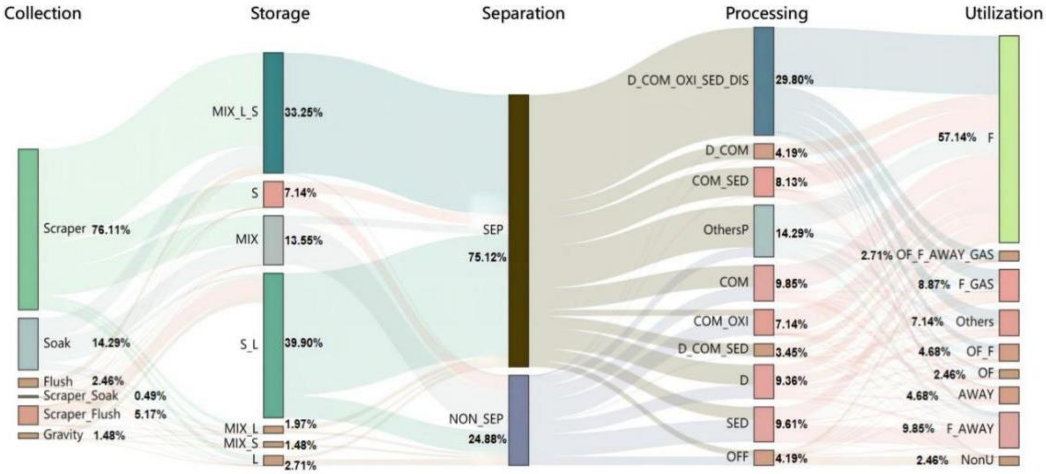


Figure 3-3. Statistical description of adopted strategic options within each stage.

Table 3-2. Descriptive statistics of MSM practices adopted.

Section	Practice option	MSM practice	Contri. (%)
Collection		Scraper	76.11
	Scraper	Soak	14.29
	Soak	Scraper_Flush	5.17
	Flush	Flush	2.46
	Gravity	Gravity	1.48
		Scraper_Soak	0.49
Storage		S_L	39.90
		MIX_L_S	33.25
	MIX	MIX	13.55
	S	S	7.14
	L	L	2.71
		MIX_L	1.97
		MIX_S	1.48
Separation	SEP	SEP	75.12
	NON_SEP	NON_SEP	24.88
Processing		D_COM_OXI_SED_DIS	29.80
		COM	9.85
		SED	9.61
		D	9.36
		COM_SED	8.13
	COM	COM_OXI	7.14
	D	D_COM	4.19
	OXI	OFF	4.19
	SED	D_COM_SED	3.45
	DIS	D_SED	2.22
	OFF	COM_OXI_SED	1.97
		COM_OXI_SED_DIS	1.97
		D_OXI	1.48
		COM_OXI_DIS	1.48
		D_DIS	0.99
		COM_SED_DIS	0.49

		D_OXI_SED	0.49
		OXI_SED_DIS	0.49
		DIS	0.49
		OXI	0.49
		D_COM_OXI_DIS	0.49
		OXI_SED	0.49
		COM_DIS	0.25
		SED_DIS	0.25
		D_COM_DIS	0.25
Utilization	F AWAY OF GAS NonU	F	57.14
		F_AWAY	9.85
		F_GAS	8.87
		AWAY	4.68
		OF_F	4.68
		OF_F_AWAY_GAS	2.71
		NonU	2.46
		OF	2.46
		F_AWAY_GAS	1.97
		OF_F_GAS	1.48
		GAS	1.48
		OF_F_AWAY	0.99
		AWAY_GAS	0.49
		OF_GAS	0.49
		OF_AWAY	0.25

3.2 Mainstream MSM modes definition

Based on clustering results, 406 pig farms were divided into five classifications in order to prevent over-fitting or under-fitting of the datasets, representing 49.3%, 12.3%, 10.1%, 14.8% and 13.5% respectively. Five modes were defined according to the typical characteristics of each section. Distributions of strategic options were sorted out in **Figure 3-4**. Descriptive statistics of MSM practices adopted of the five MSM modes were shown in **Table 3-3**.

TSM: In this cluster, scraper was used during waste collection (over 94%), manure was separated stored as solids and liquids respectively. Followed by separation processing approaches for manure and sewage. The distribution of processing strategies in this cluster was the most complicated of the five clusters, however, it is also the most straightforward approach for individual farms. Solid composting as the most popular processing approach, containing over 71.5%, was applied with a single liquid method, mainly SED, OXI and D. Land consumption was the final destination, for more than 75% of farmers adopt F in utilization stage. Farms presented the characteristics of traditional pig farming with relatively minimum automation level and affordable costs during MSM process, mainly utilized through low-technology methods. Labor endowment was the core element in this mode, which was a primary MSM mode based on simple processing methods and convenient access, namely as "***traditional simple mode (TSM)***".

MPM: Collection method in this type was a combination of SCRAPER and SOAK, which was the unique approach with significant differences from the remaining four groups. Samples were all adopted NON_SEP, which accommodated MIX for storage (80%). SED dominated processing section (50%), and followed by D with 14%. Interestingly, apart from this, 18% of the farms still decided for off-site handling, which is unprecedented in other classifications. This is possibly due to the limitation of surrounding land area, which echoes AWAY (44%) when utilizing. The mechanization degree of this mode is the lowest, which was considered to be a labor-intensive saving mode. This category was defined as "***mixed processing mode (MPM)***".

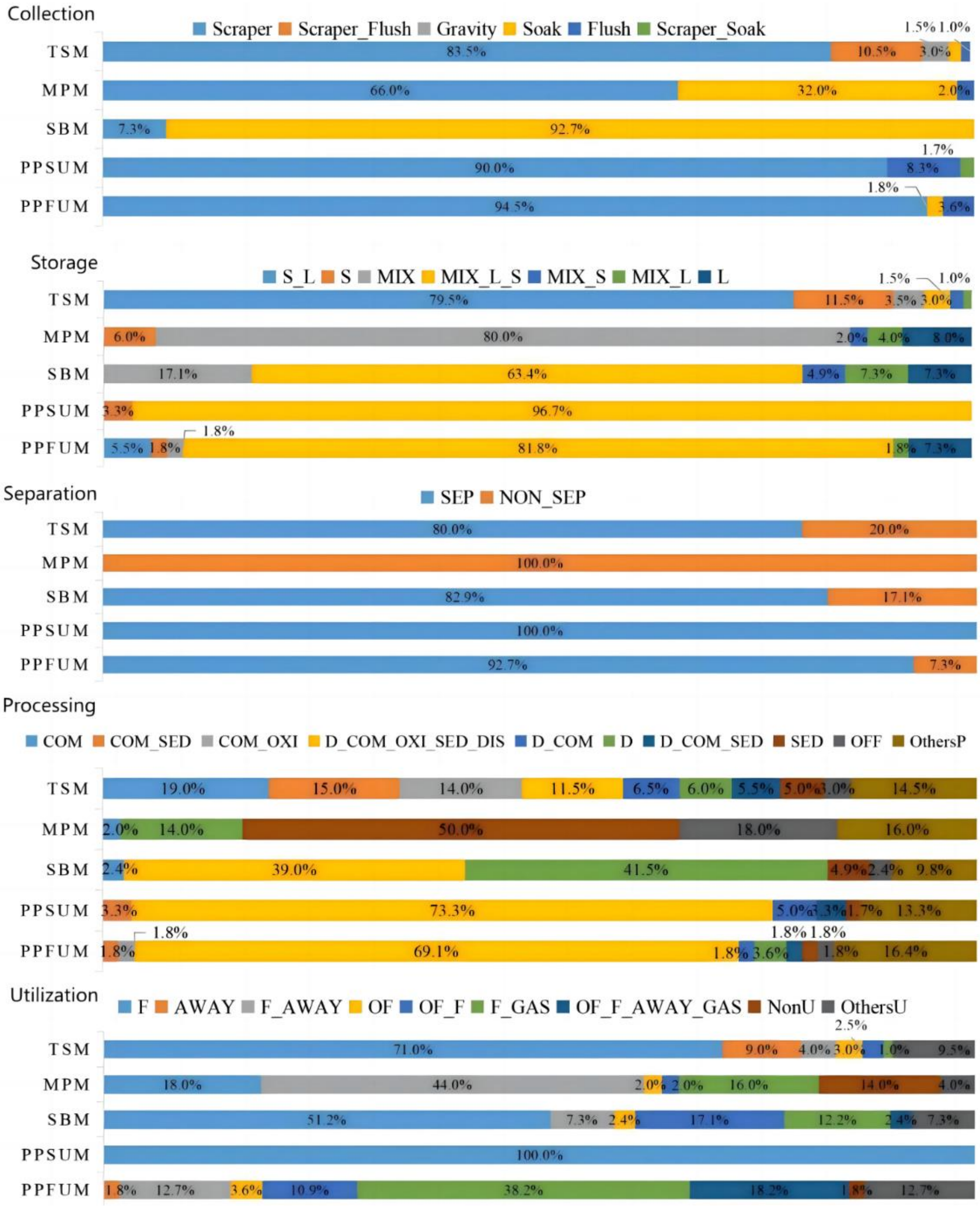


Figure 3-4. Distributions of strategic options within each section for five MSM modes.

SBM: This cluster exhibited significant differences when collecting, as about 93% of farmers chose SOAK. Considering the entire continuum of MSM sections, a majority of farmers adopted mixed storage, of which, 63% of them opted for MIX_L_S. Processing mainly guided two pathways, D_COM_OXI_SED_DIS and D, accounting for 39% and 41% respectively. For utilization, F still remained dominant, additional strategies of OF and GAS were chosen with slight probabilities (17% and 12% respectively). Obviously, anaerobic digestion was the guide approach in this cluster, however, biogas utilization was incompleted and neglected as well as the production of commercial fertilizers. Exploration of the conversion on waste-to-profit is premature. Consequently, "***semi-biogas mode (SBM)***" was used to identify it.

PPSUM: Waste was completely separated in all farms in this cluster, followed by the adoption of MIX_L_S with 96.7%. Applied methods during processing section were more comprehensive and professional than in previous three clusters. D_COM_OXI_SED_DIS was mostly found with an adoption rate of 73.3%. However, utilization was entirely represented by F. Generally, this mode was significant in mitigating environmental pressures by comprehensive treatments, besides, undoubtedly contributing to the reduction of synthetic fertilizer application. Thus, "***professional processing with simple utilization mode (PPSUM)***" was used to name this cluster.

PPFUM: Approaches in each section in PPFUM were quite similar to PPSUM except utilization. The choice of SCRAPER, MIX_L_S and D_COM_OXI_SED_DIS were in the majority at each section respectively. Comprehensive processing technologies certainly laid a secure basis for upgraded utilization. Obviously, PPFUM had the highest speciality grade of utilization strategy, which contained not only F, but also OF for 32.7% and GAS for 56.4%. This type was characterized by a strengthened utilization factor compared with PPSUM, which was an integrated mode that well-performing in both aspects of the detoxification of pig waste and the multi-utilization of resource. Accordingly, it was identified as "***professional processing with full utilization mode (PPFUM)***".

Table 3-3. Descriptive statistics of MSM practices adopted in five MSM modes.

Section	MSM practices	TSM	MPM	SBM	PPSUM	PPFUM
Collection	Flush	1	2	0	8.3	3.6
	Gravity	3	0	0	0	0
	Scraper	83.5	66	7.3	90	94.5
	Scraper_Flush	10.5	0	0	0	0
	Scraper_Soak	0.5	0	0	1.7	0
	Soak	1.5	32	92.7	0	1.8
Storage	L	0	8	7.3	0	7.3
	MIX	3.5	80	17.1	0	1.8
	MIX_L	1	4	7.3	0	1.8
	MIX_L_S	3	0	63.4	96.7	81.8
	MIX_S	1.5	2	4.9	0	0
	S	11.5	6	0	3.3	1.8
	S_L	79.5	0	0	0	5.5
Separation	NON_SEP	20	100	17.1	0	7.3
	SEP	80	0	82.9	100	92.7
Processing	COM	19	2	2.4	0	0
	COM_DIS	0.5	0	0	0	0
	COM_OXI	14	0	0	0	1.8
	COM_OXI_DIS	0.5	0	0	8.3	0
	COM_OXI_SED	2	0	0	1.7	5.5
	COM_OXI_SED_DIS	2	0	9.8	0	0
	COM_SED	15	0	0	3.3	1.8
	COM_SED_DIS	0.5	0	0	1.7	0
	D	6	14	41.5	0	3.6
	D_COM	6.5	0	0	5	1.8
	D_COM_DIS	0	0	0	0	1.8
	D_COM_OXI_DIS	0	0	0	1.7	1.8
	D_COM_OXI_SED_DIS	11.5	0	39	73.3	69.1
	D_COM_SED	5.5	0	0	3.3	1.8
	D_DIS	0	6	0	0	1.8

	D_OXI	0.5	8	0	0	1.8
	D_OXI_SED	0.5	0	0	0	1.8
	D_SED	4	0	0	0	1.8
	DIS	0.5	2	0	0	0
	OFF	3	18	2.4	0	1.8
	OXI	1	0	0	0	0
	OXI_SED	1	0	0	0	0
	OXI_SED_DIS	1	0	0	0	0
	SED	5	50	4.9	1.7	1.8
	SED_DIS	0.5	0	0	0	0
Utilization	AWAY	9	0	0	0	1.8
	AWAY_GAS	0.5	2	0	0	0
	F	71	18	51.2	100	0
	F_AWAY	4	44	7.3	0	12.7
	F_AWAY_GAS	3	0	0	0	3.6
	F_GAS	1	16	12.2	0	38.2
	GAS	1.5	0	4.9	0	1.8
	NonU	1	14	0	0	1.8
	OF	3	2	2.4	0	3.6
	OF_AWAY	0.5	0	0	0	0
	OF_F	2.5	2	17.1	0	10.9
	OF_F_AWAY	2	0	0	0	0
	OF_F_AWAY_GAS	0	0	2.4	0	18.2
	OF_F_GAS	0.5	2	2.4	0	5.5
	OF_GAS	0.5	0	0	0	1.8

Chapter 4

Clarify farmers' heterogeneity and behaviors towards MSM modes

Adapt from:

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1. Introduction

Pig farmers as the direct handlers of pig waste, are the most basic and widespread micro subjects of pig MSM. Therefore, their individual behaviors are intimately related to environmental issues and resource recycling. An adequate acquaintance of farmers’ MSM status and behavioral characteristics is necessary for more proper MSM approach promotion and policy formulation (Wang and Tao 2020). Since market-oriented outlets for waste resource utilization have not been fully developed, farmers are responsible for the proper management on their farms. Whereas the key to willingness-led MSM actions, and improving utilization rate is to increase farmers' attitudes and willingness, and the focus is on identifying the determinants of farmers' preferences to MSM. Therefore, explore pig farmers’ preferences to MSM is relevant to promoting pig waste resource utilization (Li et al. 2021c).

Currently, considering the performance subject of MSM, there are some studies demonstrating farmers' attitudes, willingness and behaviors towards the pollution and management of livestock waste, and mostly explained by the factors of farmers’ characteristics, individual perceptions to the environment, human health and policy, farms’ characteristics, surrounding conditions, prevalence of MSM, policy instruments and so on (Li et al. 2021a; Zhang et al. 2015b; Deng et al. 2016; Pan et al. 2016). Furthermore, the study conducted based on the will-to-behavior perspective by Zhao et al. (2019b) clarified the internal mechanisms for the transformation of will to behavior. Zanu et al. (2012) analyzed crucial factors that contributed to the farmers’ attitudes towards the application of new MSM technology. Moreover, He et al. (2016) revealed that social capital has remarkable impacts on promoting farmers to participate in reusing agricultural waste. And the positive effectiveness of management policies has also been confirmed (Ji et al. 2014; Zheng et al. 2014a). In addition to this, the efficacy of external environmental factors such as insurance and social services have also been explored (Kumar et al. 2011; Khan et al. 2013).

Additionally, previous researches based on the theory of planned behavior (TPB) to explore farmers’ willingness on livestock waste management (Li et al. 2021c; Tao and Wang 2020; Deng et al. 2016). And there are also some studies that build on the Unified Theory of Acceptance and Use of Technology (UTAUT) model (Wang and Tao 2020). Relevant studies use a variety of research perspectives and provide detailed theoretical findings.

However, most of the studies focused on the MSM adoption for whether or not. In fact, due to the environmental constraint, MSM is a compulsory requirement in China, instead of willingness behavior. In this situation, manure disposal practices must be implemented even if farmers are reluctant, which may lead to coping or shortcutting behaviors. In addition, the diffusion of specific new technologies is not necessarily appropriate for all farmers, whether they adopt or not, the benefits may not be optimal. Therefore, when farmers voluntarily choose the most suitable MSM method for them to ensure the smooth progress of the utilization of waste resources, meanwhile, the occurrence of such proactive behavior can alleviate the pressure of governmental supervision and market dependence. Thus, there is still a dearth of information on farmers' preference for discrepant modes. Furthermore, pig farmers make choices after considering the complexity of their situation, study covering more comprehensive characterization factors are closer to reality. Overall, it is of great significance to identify the mode selections and characterize the corresponding farmer groups.

This chapter is guided by the scientific question of "what are the factors and how do they drive farmers' adoption of various MSM modes?" based on the five mainstream modes obtained in the previous chapter. In this chapter, the farm owner characteristics, farm characteristics, land characteristics, farmers' awareness towards MSM & environment, and their policy awareness are comprehensively considered in the regression model, which brings the model more in line with reality. This provides a better understanding of the current situation and behavioral characteristics of farmers' pig waste disposal. Offer theoretical support and scientific basis for various farmers to select appropriate MSM mode, relevant government departments to formulate policies as well as fine-tune and optimize existing policies.

2. Clustering characterization

2.1 Multiple independent sample tests

After clustering, the next step is to identify the obtained MSM modes, as well as explore application characteristics among individual farms and determinants of corresponding MSM mode application. In this study, 18 variables are considered, involving farm owner characteristics, farm characteristics, land characteristics, farmers' MSM & environmental awareness and policy awareness (**Table 4-1**).

Firstly, multiple independent sample tests are examined by non-parameter Kruskal-Wallis test for continuous variables and ordered categorical variables, and Chi-square test for unordered categorical variables. Both are subsequently followed by pair-wise comparisons to demonstrate the differences between each two clusters. Test levels have been adjusted according to Bonferroni correction. Subsequently, multiple logistic regression is conducted for further exploration of the correlation between modes and farms. Results are considered significant when the P-value is less than 0.05.

Table 4-1. Definitions and descriptive statistics of explanatory variables.

Variables	Definition
FARM OWNER CHARACTERISTICS	
Age	Age of pig farm owner
Education	Education level of pig farm owner. 1=Primary and bellow, 2=Junior, 3=Senior, 4=Vocational college, 5=Bachelor degree and above
Training	Whether you have received MSM training. 0=NO, 1=YES
FARM CHARACTERISTICS	
Time	Year of pig farm construction
Scale	Inventory heads (data for end of 2020)
Breeding structure	Pig slaughter for 0=Fattening pigs, 1=Breeding contains piglets
Cooperation	Whether as a member of pig professionalization organization. 0=NO, 1=YES
LAND CHARACTERISTICS	
Land consumption*	Do you think surrounding land is enough for waste consumption? 1=quite not enough ~ 5=quite enough
Land price*	What do you think of the transfer price of land? 1=extremely low ~ 5=extremely high
Land use	Cultivable land is for 0=Manure disposal only, 1=Disposal and planting
MSM & ENVIRONMENTAL AWARENESS	
MSM standard*	To what level do you know MSM technologies & standards. 1=completely unknown ~ 5=completely know
MSM difficulty*	To what level do you think MSM treatment is difficult. 1=extremely difficult ~ 5=extremely easy
Transport difficulty*	To what level do you think waste transport is difficult. 1=extremely difficult ~ 5=extremely easy
Farm EI*	To what level do you think MSM damages farm environment. 1=no affects ~ 5=extremely high affects
Pig growth*	To what level do you think MSM damages pig growth. 1=no affects ~ 5=extremely high affects
MSM investment*	To what level are you willing to invest in MSM. 1=completely unwilling ~ 5=completely willing

POLICY AWARENESS	
MSM policy*	To what level do you know MSM regulations & policies. 1=completely unknown ~ 5=completely know
EIA	Whether as a member conducted Environmental Impact Assessment. 0=NO, 1=YES

* According to the Likert scale, degree is divided into five levels to indicate the strength of the attitude, all statements are positive (Likert 1932).

2.2 Multinomial logistic model

Multinomial logistic regression is actually a simultaneously estimation of multiple Binary logistic regressions.

The equation is as follows,

$$\ln\left(\frac{\pi_{ij}}{\pi_{ib}}\right) = \ln\left(\frac{P(y_i = j|x)}{P(y_i = b|x)}\right) = x_i'\beta_j$$

b is the selected benchmark group, and set J to be the total number of groups contained in the category variable (j=1, 2, 3, ..., J). When j=b, $\ln 1 = 0$, $\beta_b = 0$. $P(y_i = j|x)$ represents the probability that farmers choose MSM mode j. Thus, obtain the predicted probability of each choice:

$$\pi_{ij} = P(y_i = j|x) = \frac{\exp(x_i'\beta_j)}{\sum_{m=1}^{J} \exp(x_i'\beta_m)}$$

3. Heterogeneous characteristics of typical modes

Significant differences among community characteristics were analyzed between five modes by Kruskal-Wallis test (**Table 4-2**), Chi-square test (**Table 4-3**) and multiple logistic regression (**Table 4-4**). Variables indicated significant effects at 1%, 5% and 10% level respectively. All the variables have passed the multicollinearity test with 1.65 of the mean Variance Inflating factor (VIF).

From farmers' perspectives, age and education level, significantly influenced the preference for mode selection. With the rise in age, farmers are more likely to accept relatively more traditional and simple modes, i.e., TSM>MPM>SBM>PPFUM>PPSUM. Farmers with higher education level were preferred knowledge-intensive modes of technology, such as SBM, PPSUM and PPFUM. In terms of farmers' awareness of MSM and environmental performance, individuals in SBM, PPSUM and PPFUM have a relatively higher degree of environmental awareness and professional cognition. Approximately 84.7 % of farmers have already received MSM technical training. Farming scale and breeding structure demonstrated significant effects on adopted modes, up-scaling farm level expressively promoted the acceptance of comprehensive technologies. In addition, the surrounding land conditions were also an indicator that could not be ignored (e.g., *Land price*, *Land use*). In particular, its vital contribution to multiple pathways in utilization stage should be noted.

TSM was the most common mode, approximately half of the respondents adopted it. It was adapted to a wide range of breeding scales. Particularly, a larger percentage of small-sized farms of less than 2000 heads was significant. Farmers who adopted TSM had the maximum mean age and relatively low education level. However, the implementation rate of Environmental Impact Assessment (EIA) was the minimum compared to other modes.

MPM was the only one without solid-liquid separation, which simplified treatment processes. Farms with longer construction time were more prefer MPM to TSM. Farmers who applied MPM demonstrated the lowest education level and generally lack of relevant knowledge of MSM standards and faced treatment difficulties, which reflected in lowest degree of *MSM standard* and *MSM difficulty* among all modes. In addition, MPM was confirmed by the lowest recognition level of waste pollution. The majority of farms regarded land for the univocal purpose of manure disposal. Small-scaled and mono-breeding farms could be observed in MPM, reflected in 78% of farms with inventories of less than 2,000 and around 70% of farms only raise fattening pigs. Farms who employed MPM illustrated the most negative investment intentions in terms of MSM.

Compared to MPM, SBM was more appropriate for larger scale farms. Pig farms with a stock of over 2,000 heads account for 70.8%, larger scale farms have a higher probability of choosing SBM compared to TSM. In a macro situation dominated by fattening pigs, SBM was considered particular with the characteristic of piglet breeding, with 63.4% of the farms involving piglets in their breeding structure, which represented a significant difference from TSM and MPM. The characteristics of the highest education level and relatively strong environmental awareness of farmers can be observed. Farmers’ willingness to invest in waste management also presented a significantly positive result, showing the strongest intentions among the five groups.

PPSUM was applicable for almost any size of farms. Farm sizes are mainly concentrated between 500 and 3000 heads. Compared to TSM, farms of different sizes prefer SBM, probably because of the higher farmers' awareness levels. Meanwhile, as the youngest group on average, farmers in PPSUM were more knowledgeable on MSM standards. More importantly, an apparent percentage of farms (93.2%) have conducted planting in parallel with manure disposal, which could explain the full rate of returning to land.

PPFUM was the most technically comprehensive and optimally utilized mode. It was the most comprehensive group for performing pig farm *EIA*, with 85.5% coverage rate. Farmers’ characteristics were essentially similar to those of PPSUM and SBM. Because of the diversity of utilization, PPFUM was the least sensitive to changes in land prices. Involving farm scale, although PPFUM had the largest stocking capacity, medium scale farms occupied a large proportion in terms of individual distribution.

Table 4-2. Potential determinants (continuous variables) for farms' heterogeneous behaviors of five MSM modes by Kruskal-Wallis tests.

Variable	Mean						Sig.
	TSM	MPM	SBM	PPSUM	PPFUM	Total	
Age	**46.8**	46.38	45.39	**42.75**	43.51	45.56	**0.030**
Education	2.97$^{a, b}$	**2.68^{b}**	**3.44^{a}**	3.12$^{a, b}$	3.24$^{a, b}$	3.04	**0.004**
Time	10.97	10.84	10.88	11.73	10.51	11	0.816
Scale	5006.96^{a}	**2244.68^{a}**	4633.15^{b}	2889.32$^{a, b}$	**14245.15^{a}**	5567.55	**<0.001**
Land consumption	3.38	3.66	3.37	3.43	3.33	3.41	0.280
Land price	3.45^{b}	**3.84^{a}**	3.74$^{a, b}$	3.55^{b}	**3.37^{b}**	3.53	**<0.001**
MSM standard	3.5^{a}	**3.14^{b}**	3.54$^{a, b}$	**3.65^{a}**	3.33$^{a, b}$	3.46	**0.009**
MSM difficulty	2.78^{a}	**2.34^{b}**	2.68$^{a, b}$	**3.03^{a}**	2.96^{a}	2.78	**<0.001**
Transport difficulty	2.91	3.2	2.73	3.13	3.11	2.99	0.058
Farm EI	4.1$^{a, b}$	**3.92^{b}**	4.02$^{a, b}$	**4.45^{a}**	4.07$^{a, b}$	4.12	**0.013**
Pig growth	4.06^{a}	**3.64^{b}**	3.85$^{a, b}$	**4.25^{a}**	3.87$^{a, b}$	3.99	**0.005**
MSM investment	3.79^{a}	**3.22^{b}**	**4.15^{a}**	3.85^{a}	3.84$^{a, b}$	3.77	**0.001**
MSM policy	3.09	3.08	3.25	3.38	3.07	3.15	0.361

Non-parametric Kruskal-Wallis tests were conducted, followed by the post-hoc test pairwise comparisons. Adjustment of alpha levels according to the Bonferroni method. The statistics is Kruskal-Wallis Chi-squared value.

The variable categories, marked in bold, were the key variations of maximums and minimums, identified to distinguish the types.

$^{a\text{-}b}$ Differences among five types are denoted by differing lowercase letters (P<0.05).

Table 4-3. Potential determinants (categorical variables) for farms’ heterogeneous behaviors of five MSM modes by Chi-square tests.

Variable		%(N)						Sig.
		TSM	MPM	SBM	PPSUM	PPFUM	Total	
Training	NO	17.5(35)	10(5)	9.8(4)	15(9)	16.4(9)	15.3(62)	0.582
	YES	82.5(165)	90(45)	90.2(37)	85(51)	83.6(46)	84.7(344)	
Breeding structure	Only fattening pigs	62.5(125)^{a}	**70(35)^{a}**	**36.6(15)^{b}**	55(33)$^{a, b}$	56.4(31)$^{a, b}$	58.9(239)	**0.014**
	Contain piglets	37.5(75)	**30(15)**	**63.4(26)**	45(27)	43.6(24)	41.1(167)	
Cooperation	NO	61(122)	72(36)	58.5(24)	56.7(34)	45.5(25)	59.4(241)	0.087
	YES	39(78)	28(14)	41.5(17)	43.3(26)	54.5(30)	40.6(165)	
Land use	Only disposal	33.6(48)^{a,b}	**73.8(31)^{c}**	51.5(17)$^{b, c}$	**6.8(3)^{d}**	17.3(9)$^{a, d}$	34.4(108)	**<0.001**
	Disposal and planting	66.4(95)	**26.2(11)**	48.5(16)	**93.2(41)**	82.7(43)	65.6(206)	
EIA	NO	**35(70)^{a}**	16(8)$^{a, b}$	19.5(8)$^{a, b}$	21.7(13)$^{a, b}$	**14.5(8)^{b}**	26.4(107)	**0.003**
	YES	**65(130)**	84(42)	80.5(33)	78.3(47)	**85.5(47)**	73.6(299)	
Scale	<500	25.5(51)^{a}	28(14)^{a}	7.3(3)^{a}	10(6)^{a}	14.5(8)^{a}	20.2(82)	**<0.001**
	[500,1000)	27(54)^{a}	32(16)^{a}	9.8(4)^{a}	33.3(20)^{a}	27.3(15)^{a}	26.8(109)	
	[1000,2000)	21.5(43)^{a}	18(9)^{a}	12.2(5)^{a}	11.7(7)^{a}	25.5(14)^{a}	19.2(78)	
	[2000,3000)	5.5(11)^{a}	8(4)$^{a, b}$	17.1(7)$^{a, b}$	20(12)^{b}	10.9(6)$^{a, b}$	9.9(40)	
	[3000,5000)	7.5(15)^{a}	6(3)^{a}	29.3(12)^{b}	5(3)^{a}	12.7(7)$^{a, b}$	9.9(40)	
	[5000,10000)	1.5(3)^{a}	4(2)$^{a, b}$	9.8(4)^{b}	13.3(8)^{b}	3.6(2)$^{a, b}$	4.7(19)	
	⩾10000	11.5(23)^{a}	4(2)^{a}	14.6(6)^{a}	6.7(4)^{a}	5.5(3)^{a}	9.4(38)	

Chi-square tests of independence and followed by multiple pairwise comparison using Chi-square goodness of fit tests were performed; otherwise, Fisher’s exact test followed by goodness of fit exact test was conducted.

The variable categories, marked in bold, were the key variations of maximums and minimums, identified to distinguish the types.

$^{\text{a-d}}$ Differences among five types are denoted by differing lowercase letters ($P<0.05$).

Table 4-4. Results of Multinomial logistic regression analysis.

Variables		MPM [a]		SBM [a]		PPSUM [a]		PPFUM [a]	
		Coef.	RRR	Coef.	RRR	Coef.	RRR	Coef.	RRR
Time		0.05*	1.05	0.02	1.02	0.06**	1.07	0.00	1.00
Scale	<500	-	-	-	-	-	-	-	-
	[500,1000)	0.30	1.35	0.09	1.10	1.02*	2.79	0.75	2.12
	[1000,2000)	-0.13	0.88	0.22	1.25	0.38	1.46	0.72	2.05
	[2000,3000)	0.52	1.67	2.05**	7.80	2.53***	12.54	1.15*	3.15
	[3000,5000)	-0.29	0.75	2.37***	10.65	0.70	2.00	1.35**	3.88
	[5000,10000)	1.71	5.50	3.25***	25.78	4.24***	69.44	2.18**	8.83
	⩾10000	-0.12	0.89	1.41	4.10	0.53	1.70	-0.17	0.84
Age		-0.05**	0.95	-0.03	0.97	-0.08***	0.93	-0.04**	0.96
Education		-0.20	0.82	0.16	1.17	-0.28	0.75	0.17	1.19
MSM standard		-0.55*	0.58	-0.64*	0.53	-0.26	0.77	-0.75**	0.47
MSM difficulty		-0.83***	0.44	-0.12	0.88	0.28	1.32	0.48*	1.61
Transport difficulty		0.53**	1.70	0.04	1.04	0.21	1.23	0.23	1.26
Farm EI		-0.06	0.94	0.11	1.12	1.03***	2.80	0.44	1.55
Pig growth		-0.27	0.76	-0.52	0.60	-0.47*	0.62	-0.53**	0.59
Land consumption		0.51**	1.67	0.14	1.16	0.12	1.13	-0.16	0.85
Land price		1.32***	3.73	0.85***	2.35	0.27	1.32	-0.17	0.84
MSM policy		0.82***	2.27	0.52*	1.69	0.15	1.16	0.04	1.04
MSM investment		-0.33*	0.72	0.48*	1.61	-0.14	0.87	0.01	1.01

Note:“*”significant at the 10% level;“**”significant at the 5% level;“***”significant at the 1% level.

[a] the reference category is TSM, because it is the most common mode with maximum sample size.

4. Discussion

In general, the pig farms interviewed were involved in MSM activities to varying degrees and adopted several MSM methods, there is no direct discharge without waste treatment currently. Obviously, a high policy penetration rate and systematic technology training effectively drive farmers' participation in MSM (Zhao et al. 2019b; Li et al. 2021c). However, mode characterization and differentiation need further research. The clarity of advantages towards modes, and the discrepancies among five modes in terms of individual characteristics can be further explored.

Capital investment, mechanization level and operational complexity are the crucial features to distinguish various modes. Regarding the factors of farmers’ willingness to participate in MSM, previous studies mentioned that economic factor may be more important than technical on environmental technologies application (Engel 1988). As Chen et al. (2017a) indicated, cost-benefit is the key constraint that influences farmers' behavior on MSM. However, most of existing MSM patterns are uneconomical, accompanied by a severe financial burden on farmers (Huang et al. 2016). Small-size farms are more concerned with the cost associated with extra labor hiring and MSM operating (Chen et al. 2017a). As aforementioned, MPM has the lowest mechanization level and simplifies processing steps, thus, it effectively saves labor and cost. In addition, funding savings are generated in MSM infrastructure construction and facility procurement. Advantages of MPM of unattended execution and relatively low capital requirements attract small farms with a stocking capacity of less than 2000 heads. In addition, because of operation convenience, MPM operates in favor of elderly farmers who are weak in skills learning and neglect potential pollution risks to cater for environmental compliance. Followed by TSM, which is a traditional applicable mode. The striking characteristic of TSM is twofold. Firstly, separation is observed, in order to execute solid fraction for composting, liquid fraction for harmless treatment in a single way according to local constrains. TSM presents the widest range of applicability, which has greater compatibility among different farm sizes. Meanwhile, it also satisfies the development of integration of planting and breeding.

Farming structure as a critical factor, its impact on varying degrees of livestock MSM has been proven (Zhang et al. 2021b; Chen et al. 2017a; Pan et al. 2021; Li et al. 2020b; Huang et al. 2016; Zheng et al. 2014a). As Pan et al. (2021) and Wu et al. (2018) concluded, as farm scale increasing, waste management was more comprehensive and professional, capital-intensive and knowledge-intensive methods were gradually accepted. In this study, SBM, PPSUM and PPFUM have distinctive features of multiple approaches in processing stage, especially on liquid treatment and gather relatively larger scale farms. Furthermore, probabilities of these modes being adopted increase significantly as the scale rises compared to TSM. Anaerobic digestion, an advanced and efficient approach of livestock waste treatment technology that has been promoted in recent years (He et al. 2013), has a higher adoption rate in the aforementioned three modes. Surprisingly, the influence of breeding structure on MSM is novel. Concerning collected methods, SOAK has advantages of being less noisy and fewer working frequency, which is perfect for piglets’ features of physical sensitivity, small amount of manure production and brief feeding cycle (Zheng et al. 2014a). Delsart et al. (2020) also emphasized the notice of animal welfare in pig farming. Regarding pig farmers’ heterogeneous characteristics, the education level and environmental perceptions are positively correlated, which is consistent with Harvey et al. (2014). Producers with high knowledge and environmental responsibility are inclined towards technological sophistication and professionalization (Wang and Tao 2020).

Farms' characteristics of PPSUM and PPFUM are essentially similar to SBM, nevertheless, they have more comprehensive technical diversity. A certain amount of management flexibility is built into multiple combinations of processing approaches, when manure volume changes or utilization strategy modifications. Considering the diversity of usage pathways, PPSUM<SBM<PPFUM. PPSUM prefers full volume land dissipation, which demonstrates farmers' determination on planting simultaneously. However, the dilemma of mismatch between stocking and land limits land application, especially for large farm on an intensive scale (Pan et al. 2021; Gao and Zhang 2010). Waste discharge on compliance is determined by the nutrients (N, P) required for crops and nutrients available in excrement (MOA 2018). Data indicated that stocking capacity that exceeded the boundary of land carrying capacity would lead to secondary pollution (Wu et al. 2014). Thus, adequate cultivable land is the prerequisite for the implementation of PPSUM, which would otherwise cause hindrances, such as additional transportation and loading work (Hsu 2021). Researches have confirmed that various processing technologies correspond to different elements (COD, N, P) collection rates, which could effectively relieve land pressure (Chen et al. 2017a; Maurer et al. 2016; Wu et al. 2014). Thus, any section has a strong connection to the others, the optimal MSM mode is an organizing operation after discussing the entire continuum of MSM sections with appropriate approaches.

Obviously, PPFUM is an upgrade of PPSUM according to a more comprehensive utilization. It is more conducive to achieve the goal of contributing to environmental benefits and converting waste to economic value. However, only large-scale farms can profit from MSM, because of available skill acquisition and adequate financial support. Actually, the biogas produced is supplied free of charge by surrounding farmers for cooking and heating. Due to the unstable nature of the seasonal reason, biogas production is faced with the dilemma of unstable yield and unsustainable supply. As a result, nonstandard prices restrict fair market transactions. Only a few qualified enterprises are eligible for paralleling electricity generation. Bottleneck on commercial organic fertilizer production is that powder processing from pig manure has the lowest net present value among livestock waste (Hsu 2021). It should be noticed that the internalization of negative externalities of utilization, the government may be the contributor to overcoming unsatisfactory earnings. Recent studies on subsidy supported this conjecture, Feng et al.(2012) and Zhao et al. (2019b) clarified the role of government policy and financial support in promoting waste utilization. Cucchiella et al.(2019) assessed the potential for bio-methane production from animal waste. The unit gas production and net present value are substantial but are dependent on subsidy support. In China, subsidy for biogas power generation acquisition increase to 0.75 CNY per kWh, which relieves cost pressure by about 0.4 CNY. Gebrezgabher et al. (2010) also pointed out that subsidies was the reason for the continuous operation of biogas program.

Chapter 5

Opportunities for centralized mode at regional level

Adapt from:

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1. Introduction

As a powerful competitor in the global pig market, China occupies the largest share and boasts impressive figures. However, rising breeding resulted in the generation of massive amounts of manure and sewage, causing environmental hazards such as terrestrial acidification, water eutrophication and global warming (McAuliffe et al. 2016; Liu et al. 2020a). In response to this pressure, Chinese government and research institutions have proposed a variety of manure MSM strategies to relieve the environmental burden (Bai et al. 2019). It is worth noting that small-sized pig farms are the predominant pig breeding communities in China, occupying over 88.7% (MOA 2020). Local farmers prefer MSM modes characterized by operational convenience, low-cost, and proximity to nearby fields. This approach is particularly attractive to individuals who have sufficient arable land, as it allows for simultaneous breeding and cropping (Shi et al. 2022). This facilitates nutrient recovery and contributes to circular farming at the household level.

Nowadays, the pig industry in China is undergoing intensified development, with professional breeding scaling up rapidly (Qian et al. 2018; Hu et al. 2017). Meanwhile, integrated generation of pig waste is accompanied by this transform. Moreover, the percentage of farms participating in the breeding-cropping mix has dropped to 12% in 2017, with 37% of them exceeding the suitable stocking densities for farmland (Jin et al. 2021). Small and medium-sized pig farms are suffering from unstable operation of waste treatment facilities and unregulated reutilization of by-products (Chen et al. 2017a). With accelerating urbanization, the suburban distribution of livestock farming is generally dense, coupled with a scarcity of surrounding arable land area (Deng et al. 2014). As aforementioned, the separation of breeding and cropping has become more prevalent in regions with high rearing density and intensive concentration due to the mismatch between the original MSM modes and corresponding farmland (Luo et al. 2014). As a result, most of the pig farms struggle with high waste nutrient loading and other environmental pollution, making optimization and strategic adjustments of MSM in pig farms a pressing necessity within the pig industry.

The term “centralized MSM pattern” refers to the centralized regional collection within a specific radius and unified disposal, facilitating resource integration to improve processing and utilization efficiency. It could effectively address the issue of excessive waste production, and additionally cover a wider range of pig farms lacking MSM and presenting the risk of secondary contamination. In contrast to land-dependent individual MSM, centralized MSM is a modern, specialized approach that optimizes land utilization, energy for environmental control, and labor, while also incorporating knowledge-intensive technologies. Currently, one specific example of centralized MSM is the proposed large-scale biogas program, which offers prominent advantages in terms of mitigating environmental impacts, producing organic fertilizer and generating renewable energy (He et al. 2013; Holm-Nielsen et al. 2009). The relatively lower marginal disposal cost, combined with the benefits obtained from the sale of processed commercial organic fertilizer and renewable energy, could support the transport of by-products to further destinations. Verified and guaranteed organic fertilizers are more readily accepted by cultivators, thus widening the path of off-site consumption, and consequently reestablishing connections between breeders and cultivators.

Biogas utilization is widely promoted as a dedicated solution for biowaste management (Hijazi et al. 2016; Arthur et al. 2011). Currently, the technical approaches are relatively sophisticated, with numerous scholars studying its potential for mitigating greenhouse gas emissions and its commendable economic performance in renewable energy production (DeVries et al. 2012b; Ramírez-Islas et al. 2020; Vu et al. 2015; DeVries et al. 2015; Duan et al. 2020; Deng et al. 2014; Pérez et al. 2014; Balcioglu et al. 2022). Relevant research emphasized the logistics that limit access to fermentable feedstocks (Dieter and Angelika 2010; Menna et al. 2018; Sharara et al. 2019). However, most of the studies focused on scientific experiments specific to a particular technology, restricting the research objective to the household level, such as a single farm or plant, thus excluding the upstream portion. Considering the intensive transformation of pig farming, there is an opportunity to expand the scope of MSM from a farm to an entire region. However, comprehensive studies examining the overall performance of the centralized MSM mode appear to be lacking, as there remains a dearth of research conducted on collective forms based on the regional perspective. Such studies would be of great magnitude to fully understand the preponderances of contrasting individual mode.

In accordance with aforementioned concerns, this chapter aims to answer the academic question of “what are the environmental and economic performances of a centralized bio-energy mode, what is the potential for resource reintegration and effective allocation in pig’s MSM at the regional scale?” Presented from a regional perspective, this study conducts a systematic analysis of the comprehensive evaluation of centralized MSM on biogas projects, and further explores its applicability and possibility in various regional contexts. Specifically, it is guided by 1) differentiating between individual MSM mode at the household level and centralized mode at the regional scale; 2) evaluating and comparing the environmental and economic performance of both modes; 3) further detecting potential trade-offs in optimizing the economic and environmental aspects of the centralized mode. Significance lies in providing and quantifying a specific comprehensive evaluation that reveals the contrasting characteristics of traditional and centralized MSM modes, contributing to a transparent understanding of the interests of relevant muti-subjects. Furthermore, it scrutinizes the adaptability and feasibility of the centralized mode, which is critical for exploring the possibility of resource reintegration and effective allocation in pig MSM, facilitating coordinated breeding and cropping, and achieving circular agriculture at the regional level. Ultimately, this study contributes to providing a visualized and reliable MSM strategy to adapt to the transformation of the pig industry in China.

2. Methodology

Life cycle assessment (LCA), as defined by ISO 14040 and ISO 14044 standards (ISO 2006b, 2006a), is an authoritative and internationally recognized methodology for assessing environmental impacts, which is widely applied in various fields, including waste management (Duan et al. 2020; Corbala-Robles et al. 2018; Cherubini et al. 2015; Reich 2005), bio-energy (Balcioglu et al. 2022; Kotagodahetti et al. 2023), bio-fertilizer production (Kamilaris et al. 2020; Styles et al. 2018) and bio-products (Sánchez 2022). LCA evaluates the environmental performance of products, services or activities, taking into account resource consumption and environmental impacts throughout their entire life cycle. It is often employed to identify potential environmental mitigation strategies for various systems or individual components within a system (Lopez-Ridaura et al. 2009; Makara et al. 2019). Calculations in this study were quantified by the ReCiPe 2016 Midpoint (H) V1.07 method developed in 2008 by RIVM, based on the most common policy principles with regards to consensus model (Huijbregts et al. 2016), and analyzed using SimaPro 9.4.0.2 software, ensuring an adequate comparison of the environmental impacts of two MSM modes.

Life cycle cost (LCC) is a methodological approach that considers all economic costs associated with products, services or activities along their life-cycle (Martinez-Sanchez et al. 2015). LCC provides a comprehensive evaluation, is designed to explore the profitability, reliability, availability, serviceability and security of the product or activity, incorporating costs related to investment, operation, maintenance, faulty performance and disposal (Sharma and Chandel 2021). Results from LCC analysis could highlight the economic conflicts of interest among stakeholders, enabling the evaluation of cost-effectiveness between different alternatives.

Although LCA and LCC are conceived to analyze diverse aspects, they can share the same assumptions and system boundaries, making them complementary in the decision-support process (Swarr et al. 2011; Reich 2005).

2.1 Goal and scope definition

As McAuliffe et al. (2016) mentioned, numerous studies of LCA related to swine production could be categorized into three main streams, feed for pig breeding, whole-system production and pig waste management. System boundary in this study focuses on a localized LCA study concerned with value-added processes in the waste production chain. The aim is how waste products can realize resource reuse value and what is the environmental impact of this process. Therefore, consideration of pig’s MSM boundary is from the cradle (generation of excrement leaving the pig) to the grave (waste land use and conversion to emissions) as Prapaspongsa et al. (2010) and DeVries et al. (2015), encompassed waste collection, storage, processing, utilization and transport. Kuhn et al. (2018) started the boundary from manure storage to crop utilization, focusing on transportation, same boundaries were chosen by Lopez-Ridaura et al. (2009), Brockmann et al. (2014) and DeVries et al. (2012a). Although this is a phased LCA, it contains a complete list within this phase, such as products and by-products of the unit process, natural resource and secondary energy sources consumption, and environmental emissions. The overlap of the system boundaries guarantees results comparability.

Actually, the current situation in China is that the pig reproduction system and MSM system are separated. Waste from different pig pens will be centrally collected and uniformly disposed of. For upstream stages, pig rearing, housing and feeding are excluded from this boundary evaluation because they are not altered by MSM changes (Prapaspongsa et al. 2010; Croxatto Vega et al. 2014). This research focuses on the impacts of changes in its pathways following waste production. Main purpose is to make comparisons based on the existing operative MSM modes and the changes. Given that the assessment mode is already in operation, with a program for ongoing functioning, the environmental influence of waste disposal facilities construction and decommissioning are not considered.

This study aims to apply LCA and LCC to evaluate the environmental performance and economic viability of a centralized bio-energy pig's MSM mode (CBM) on a regional scale. Furthermore, the potential feasibility will be assessed by the comparison with the individual traditional mode (ITM). System boundary encompasses pig waste collection, storage, processing, utilization and transport. Measure adoption, resource consumption, inputs, intermediate outputs and resulting products in both MSM modes were illustrated in **Figure 5-1** and **Table 5-1**.

Table 5-1. Mass flows and chemical compositions of raw pig waste, waste-based intermediate outputs and final products of two MSM modes.

	Mass(kg)	TN(kg)	TP(kg)	TK(kg)	COD(mg/L)
INPUTS					
ITM: Solid waste (manure)	285.71[a]	8.46[b]	3.19	4.68[b]	-
ITM: Liquid waste (urine and sewage)	714.28[a]	1.13[c]	0.57[c]	0.23[c]	-
CBM: Mixed waste	1000	9.59	3.76	4.91	15000-25000
CBM: Water	1165.35	-	-	-	
INTERMEDIATE OUTPUTS					
ITM: Solid waste after storage	-	7.36[d]	-	-	-
CBM: Sludge after digestion	2165.35	8.44[e]	3.76[i]	4.72	-
CBM: Solid fraction	378.34	7.01[e]	2.69[f]	4.54[f]	-
CBM: Liquid fraction	1787.01	1.43[e]	1.07[f]	0.18[f]	-
PRODUCTS					
ITM: Farmyard fertilizer	227.21	6.03[d]	2.57	3.96	-
ITM: Aerated slurry	635.42	0.68[d]	0.57	0.23	440
CBM: Mineral fertilizer	378.34	5.92[g]	2.27[g]	3.84[g]	-
CBM: Digestate water	893.51	0.72	0.54	0.09	400
CBM: Effluent after treatment	893.51	0.37[h]	0.24[h]	-	50

[a] The mass ratio of solid fence to liquid urine and sewage is about 2:5.

[b] The mass fraction of TN is 2.96% in solid waste as measured, TK is 16.39g/kg.

[c] Assumptions based on Corbala-Robles et al. (2018), 1.58g/kg, 0.8g/kg and 0.32g/kg for TN, TP and TK.

[d] Assumed that 13% reduction during storage,18.1% during composting >20°C (Chang et al. 2013), and 40% during oxidation pond as estimated.

[e] TN in sludge after digestion is reduced by 12%. Nitrogen content in solid fraction is reduced by 28%, while in the liquid increased by 10.7% (Chang et al. 2013).

[f] Distributions of TP and TK are 0.71% and 1.20% in solid fraction; and 0.06% and 0.01% in liquid fraction.

[g] Mineral fertilizer composition of N:P:K is 20:8:12 approximately.

[h] N and P in effluent is 0.04% and 0.03% respectively as measured.

[i] Phosphorus content remains unchanged during anaerobic digestion (DeVries et al. 2015; DeVries et al. 2012a).

2.2 Functional unit and harmonization

The functional unit (FU) of this study is defined as 1 ton of untreated mixed raw pig waste (with a solid fence to liquid urine and sewage ratio of approximately 2:5, as measured). The characteristics of pig waste were specified in **Table 5-1**. Relevant inputs data for ITM calculations were obtained from field research. While CBM was based on a large-scale pig farming operation, incorporating a MSM facility with an annual processing capacity of 75153 tons of pig manure and 167024 tons of sewage. Results have been normalized based on the FU.

To calculate the energy consumption per FU of managed pig waste, the total annual electricity consumption was determined by multiplying the mechanical power and daily working hours*365. This value was then divided by the total amount of waste treated annually.

$$E_{annual} = P_{MSM\ machine} * H_{daily\ working\ hours} * 365$$
$$E_{FU} = E_{annual}/N_{annual\ waste\ treated}$$

For transportation, details were showed in **Table 5-2**.

Table 5-2. Details on transport distance, vehicle and diesel use at different stages of transportation.

Mode	Stage	Road transport (tkm)	Stage diesel use (kg)
ITM [a]	On-site transport for manure composting	285.71kg*0.5km	0.02
	Transport of farmyard fertilizer to the field	635.42kg*5km	0.34
	Transport of aerated slurry to the field	227.21kg*5km	0.12
CTM [b]	Transport to the biogas plant	1t*27km	1.96
	Transport of mineral fertilizer	378.34kg*100km	2.74
	Transport of digestate water	893.51*10km	0.65
CTM_Scenario return transport [c]	Transport to the biogas plant	1t*27km	1.33
	Transport of mineral fertilizer	378.34kg*100km	1.86
	Transport of digestate water	893.51*10km	0.44

[a] Vehicle used in ITM is [Transport, truck <10t, EURO5, 80%LF, empty return {GLO} Economic, U], 1tkm requires 0.106kg diesel.

[b] Vehicle used in CTM is [Transport, truck 10-20t, EURO5, 80%LF, empty return {GLO} Economic, UU], 1tkm requires 0.0725kg diesel.

[c] Vehicle used in CTM_Scenario is [Transport, truck 10-20t, EURO5, 80%LF, default {GLO} Economic, U], 1tkm requires 0.0491kg diesel.

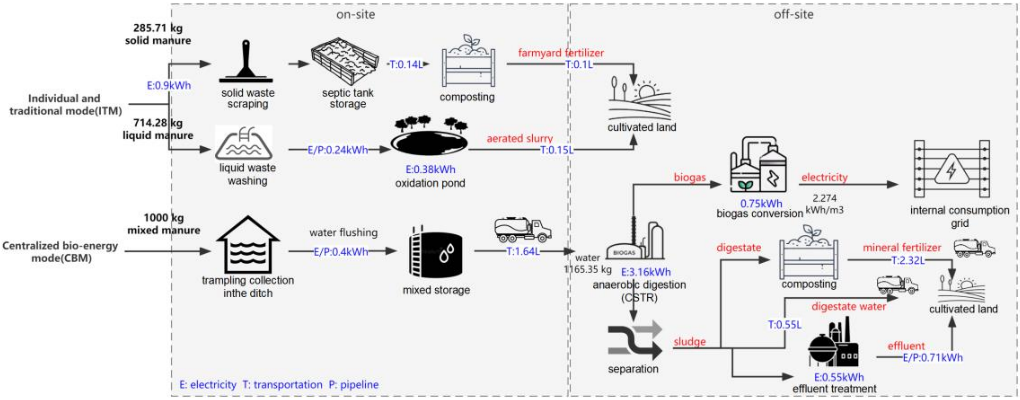

Figure 5-1. System boundary of considered Individual and traditional mode (ITM) Centralized bio-energy mode (CBM), which is indicated by a gray box. The dashed box represents the processing location, left is on-site operating section, right is off-site section. Black arrows indicate induced processes, blue for energy consumption and red for products.

2.3 System boundaries and definitions

2.3.1 Individual and traditional mode

As a conventional decentralized management approach, ITM is regularly favored by small and medium-sized pig farms for its simplicity in on-site management. It is characterized by the treatment in close proximity to the farm, and with the advantages of saving labor, lower processing costs, and avoiding transport hassle. ITM involves the separate handling of solids and liquids, with feces collected using electric scrapers, and briefly stored in septic tanks. Liquid waste and flushing water are stored in a ditch beneath the pigsties through slatted floors, and subsequently pumped into intermittently heated oxidation ponds for around 6 months. Meanwhile, feces are transferred to the drying yard for composting by forklift. The resulting farmyard fertilizer and aerated slurry obtained are then used for nearby cultivation on their own arable land or surrounding neighborhood planters for off-site utilization. Organic fertilization potentially replaces synthetic fertilizers, thereby affecting soil quality and fertility leading to an improved environment, as well as increasing crop quality and yields, resulting in better market prices and economic performance. Given the aforementioned situation of the declining proportion of farms that adopted breeding-cropping integrated pattern, and the dilemma of mismatch between waste production and land, pig waste off-site utilization was considered in life cycle assessment. Additionally, the self-sufficient mode with on-site utilization on pig farms' own land will be briefly discussed.

2.3.2 Centralized bio-energy mode

CBM aims for higher energy conversion efficiency and nutrient recovery compared to ITM. The pattern is a summary of the experience of cooperation relying on a typical large-scale pig farming enterprise, supported by the Chinese government. CBM involves MSM divided into two stages, on-site waste collection at pig breeding farms, and centralized off-site processing in disposal enterprise. During on-site collection, waste accumulates in the ditches at the bottom of the pigsties due to pig trampling, and is subsequently scoured into on-site covered septic tanks. Mixed waste and flushing water are transported to the centralized treatment facility by a suction-type sewer scavenger for further processing, which includes homogenization, anaerobic fermentation, gas liquefaction, desulphurisation and digestate separation. Waste is converted into biogas and digestate slurry in a completely sealed condition using a stirred tank reactor (CSTR). Produced biogas (consisting of 60% CH_4, 38.95% CO_2 and 0.97% N_2) is partially combusted for electricity generation for internal consumption. Surplus electricity could be sold to the national grid, used for household heating and cooking, or pressurized as compressed natural gas (CNG) for transport purposes. For this study, biogas conversion is assumed to be used for electricity generation only. Separated solid digestate and slurry can be utilized as an alternative to synthetic fertilizers for cultivation, while the treated effluent can be directly used for irrigation.

2.4 Life cycle inventory analysis

Life cycle inventories (LCI) for MSM modes were constructed from pig farms' measurements and relevant literature. The mass flows and chemical compositions of raw pig waste, waste-based intermediate outputs and final products were expressed in **Table 5-1**. Calculation details for transportation were explained in **Table 5-2**. Energy consumption involving electricity and diesel usage, was derived from field research and the Ecoinvent database (EC), is explained in **Table 5-3**. Emissions' (CO_2, CH_4, N_2O, NH_3, etc.) calculations were further elaborated in Appendix **Table A1** in Supplementary information.

The calculation of substituted production of synthetic fertilizer was primarily based on the conversion of nitrogen (N) content, considering its nutritional contribution and potential environmental impacts such as volatilization and leaching (Makara and Kowalski 2018). In accordance with the conservation of N, the available N provided in the by-product should be equivalent to that contained in the synthetic fertilizer, according to the total N provided by fertilizer and the corresponding nitrogen-use efficiency (NUE). The calculation could be interpreted as

$$M_{\text{synthetic fertilizer}} * N\% * NUE_{\text{synthetic fertilizer}} = M_{\text{by-product}} * N\% * NUE_{\text{by-product}}$$

The NUE for farmyard fertilizer, aerated slurry, and mineral fertilizer was estimated at 37%, according to Baral et al. (2017), while the NUE for digestate water was slightly lower at approximately 30%. The NUE of synthetic fertilizer was 25% (Zhang et al. 2015a).

Environmental benefits refer to the reduction in environmental impacts achieved by the pig's MSM, including two components: (i) the production of secondary electricity from biogas, replacing electricity generated in power plants, and (ii) the production of natural fertilizers for field applications, that could replace chemical synthetic fertilizers.

Table 5-3. Inventory of energy consumption of electricity and diesel at each stage of two MSM modes.

Stage	Unit energy consumption*	
	Electric Power/kWh·FU^{-1}	Diesel/kg·FU^{-1}
ITM		
Scraping for collection	0.9 (0.51)	
On-site transport for manure composting (500m on average)		0.02
Pumping to the oxidation pond	0.24 (0.15)	
Oxidation pond heating	0.38 (0.55)	
Transport of farmyard fertilizer to the field (5km on average)		0.34
Transport of aerated slurry to the field (5km on average)		0.12
CBM		
Collecting and pumping to the storage tank	0.4 (0.25)	
Transport to the biogas plant (27km on average)		1.96
Anaerobic digestion (CSTR)	3.16	
Biogas conversion	0.75	
Effluent treatment	0.55	
Transport of mineral fertilizer (100km on average)		2.74
Transport of digestate water (10km on average)		0.65
Transport of effluent by pump	0.71	

*Applied [Electricity, low voltage {CN}| market group for | Cut-off, U (kWh)] for electric power, and [Diesel {BR}| diesel production, petroleum refinery operation | Cut-off, U (kg)] for diesel used (Ecoinvent 3-allocation, cut-off by classification-unit). Standard deviation in parentheses.

2.5 Life cycle impact assessment

LCI analysis sorted out the corresponding emissions for each section of the MSM modes. To achieve a comprehensive understanding of environmental performance of both MSM modes, the midpoint characterization method from Hierarchist perspectives was employed, enabling visual comparison of five environmental categories, involving global warming (GW), fine particulate matter formation (FPMF), terrestrial acidification (TA), marine eutrophication (ME) and fossil resource scarcity (FRS), which were crucial parameters associated with the agricultural environment, and relevant with two MSM modes (Lopez-Ridaura et al. 2009; Prapaspongsa et al. 2010; Hoeve et al. 2014; Corbala-Robles et al. 2018). They could express the relative severity on an environmental impact category, the environmental differences can be clearly compared. Operation impact and total impact of both MSM modes will be compared separately. Operation impact focused on pollutants released into the environment across the five sections, while total impact additionally considered the environmental mitigation potentials of avoided synthetic fertilizers and renewable electricity generation.

A sensitivity analysis of the impact assessment results was carried out to evaluate the influence of changes in important parameters, involving the MSM-section indicators for GW, FPMF, TA, ME and FRS, with respective variations between ±30% (Jiang et al. 2022). Additionally, electricity consumption was also an important factor in the environmental performance of MSM (Corbala-Robles et al. 2018). Thus, the effect of switching to renewable sources of electricity mix was tested, specifically transitioning from China low voltage electricity production to biomass electricity generation, as specified in the Ecoinvent database (EC).

2.6 Life cycle costing analysis

The application of the joint LCA and LCC analysis method requires the harmonization of system boundaries. As Reich (2005) mentioned, it is necessary to apply the same time dimension to match the economic computations with the LCA calculations. If the functional unit of LCA handles the waste in one year, the economic calculation shall also be based on an annual average. The economic system studied thus tends to become a hypothetical system, more or less different from the existing economic regime (Swarr et al. 2011).

In this study, FU is 1 ton of untreated mixed raw pig waste, normalized by the annual handling capacity of the two MSM modes. Thus, economic viability is calculated by the costs of treating pig waste and benefits from MSM during one year rather than the whole life. Therefore, the initial construction and end-of-life decommissioning are not considered in the system boundary. Ruviaro et al. (2020) also did not consider the construction fixed costs of a farm when comparing the environmental economics of three dairy farms. However, MSM infrastructure and equipment are long-term consumables with a certain life span, so the steady-state cost model is not appropriate for this study (Luo et al. 2009). The economic viability calculation of volume FU treated should consider facility abrasion.

Therefore, as the system boundary began at the existing built infrastructure, both MSM modes have already been established and are in operation. Operating expense (OpEx), involving maintenance cost, energy cost and labor salary, is considered to meet the system boundary of LCA, to calculate the marginal economic performance per FU. Besides, in order to comprehensively and objectively present the changes in the residual value of fixed assets, management expense (MgEx) is also structured considering the variable operating cost and sunk cost (depreciation expense) (Chen et al. 2017a; Lian 2017), and thus to explore the possibilities for mode optimization. For each life cycle process, the inventories of OpEx and MgEx expressed in monetary terms were combined to evaluate LCC.

Biogas enterprises have established centralized waste collection agreements with pig farmers to ensure the reasonable trade of raw materials. The settlement mechanism states that waste with a concentration between 3% and 8% is provided free of charge, eliminating material costs from this study [22]. Depreciation expense was calculated by multiplying the fixed assets by a depreciation rate of 5% assuming a life expectancy of 20 years (Sharma and Chandel 2021; He et al. 2013; Ruiz et al. 2018). Capital expenditures (CapEx) of two modes were detailed in Appendix in Supplementary information (**Table A2**). Maintenance costs were calculated at 20% of the depreciation expense of fixed assets (Zhang et al. 2016b). The maintenance cost of anaerobic digestion and power generation equipment was estimated to be 0.06 CNY per kWh of electricity produced according to the survey by interviewed experts. Energy and labor costs were based on market prices, and would be further explored for sensitivity analyses.

Economic revenues were determined by (i) savings from electricity generation and (ii) income by selling manure by-product organic fertilizer, from the perspective of MSM managers. Procurement price for generated electricity in CBM was 0.75/kWh CNY[23]. Farmyard fertilizer and aerated slurry were mostly gifted to surrounding cropping farmers on a free basis. Mineral fertilizer and digestate water were sold for profit at market prices, with prices ranging from 100-500 CNY/t and 10 CNY/t respectively.

3. Comprehensive evaluations and optimized solutions

3.1 Environmental performances

Using the ReCiPe 2016 Midpoint method, the environmental performances of ITM and CBM were obtained. Results showed that, for operation impact, CBM had greater potential for GW, TA and ME, compared with ITM, and decreased by 38.89%, 5.68% and 4.65% respectively. However, CBM also exhibited higher environmental implications on FPMF and FRS, with increases of 3.47% and

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[22] According to the survey, waste collection price depends on the concentration: biogas plants purchase waste with a concentration greater than 8% at a price of 50-80 CNY/t; 3%~8% is acquired for free; and waste concentration less than 3%, farmers pay an MSM fee of 20 CNY/t.

[23] As stated in the "Renewable energy law" issued by National Development and Reform Commission, PRC.

875.54% respectively. Moreover, CBM exhibited more pronounced declines in characteristics regarding the total impact, with 49.49%, 6.8% and 4.67%, as well as increases of 3.35% and 38.55% in respective environmental categories (**Figure 5-2**). The corresponding environmental categories and sub-section contributions were proved in **Figure 5-3**, statistics and percentages were further elaborated in Appendix 3 in Supplementary information.

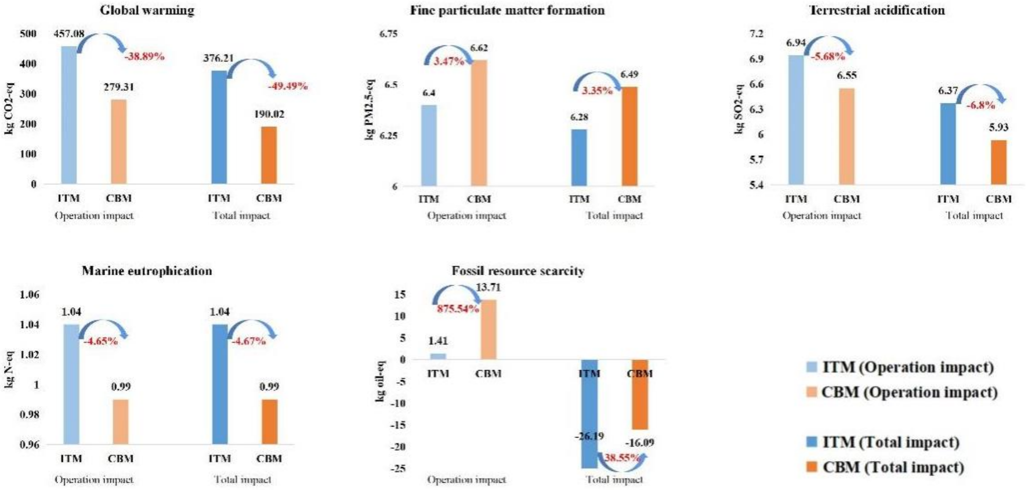

Figure 5-2. Environmental performance expressed per function unit for ITM (blue) and CBM (orange). Comparisons between operation impacts and total impacts were also included, total impact additionally contained net reductions in impact for avoided synthetic fertilizers and renewable electricity generation. Numbers above the bars present the net results. Red figure indicates decreased percentage of CBM impacts compared with ITM. Impacts were calculated at midpoint using the ReCiPe 2016 v1.1 method from Hierarchist perspective.

The GW per FU in ITM was 376.21 kg CO_2-eq, the main greenhouse gas (GHG) emissions were concentrated in the processing section (234.84 kg CO_2-eq.), occupied approximately 51.38% of the total output emissions, mainly due to CH_4 emissions from composting. Followed by storage and utilization, accounting for 25.93% and 22.01% accordingly. Contributions of collection and transport were negligible in ITM. In comparison, GHG emissions in CBM was 190.02 kg CO_2-eq, with this apparent decline attributed to the more sealed storage and processing conditions. More importantly, in contrast to ITM, GW potential of utilization was significantly lower in CBM. This was due to the consequence of the reduced N_2O production from mineral fertilizer and slurry after anaerobic fermentation. The greenhouse effects of using alternative organic fertilizer created in ITM and CBM were significantly lower than the production and utilization of synthetic fertilizers equivalencies, resulting in reductions of 17.69%

and 29.61%. The difference between the two modes was the renewable energy generated by CBM, which helped avoid an additional 2.36% of GHG emissions caused by electricity production.

For FPMF, the pollutants for treated FU were 6.28 and 6.49 kg PM2.5-eq for ITM and CBM severally. NH_3 and NO were the major contributors, mainly concentrated in the storage and processing stages. Results showed that in the storage stage, ITM accounted for 5.04 kg PM2.5-eq, which represented 78.73% of the whole system. In CBM, the emissions in the storage phase were relatively low, with 3.28 kg PM2.5-eq. However, it is worth thinking of the NH_3 emissions from digestate dewatering, CBM processing generated 2.96 kg PM2.5-eq, accounting for 42.14% of the total FPMF.

CBM provided a 6.8% lower TA relative to ITM (6.37 kg SO_2-eq) based on FU, with 5.93 kg SO_2-eq. In terms of pollutants, NH_3 was the most significant contributor for TA, while in terms of disposal stages, storage was the main stage responsible for TA, accounting for 64.92% in ITM. While in CBM, storage followed by processing accounted for 44.62% and 40.32% respectively. NH_3 emissions from digestate dewatering were significant and might be due to open-air exposure and heating during anaerobic digestion. Regarding by-products application, CBM showed significantly lower levels than ITM. It should be mentioned that both MSM modes shared a key feature, which was the significant mitigation potential for reducing the use of synthetic fertilizers, with reductions of 8.3% and 9.01% separately. Results indicated that controlling NH_3 emissions was responsible for achieving TA reduction in pig's MSM.

CBM showed a more favorable result on ME with 0.99 kg N-eq relative to ITM (1.04 kg N-eq). Releases were mainly concentrated in the utilization section due to the NH_3 emissions and NO_3^- losses in water. Application of composted digestate resulted in more environmental benefits, because of lower TAN. Conditions of storage and processing were cement-hardened and impermeable, reducing N leaching.

Obviously, the difference in FRS between the two MSM modes was considerable, with -26.19 kg oil-eq for ITM and -16.09 kg oil-eq for CBM. The contribution of electricity consumption was insignificant, while off-site transport was the vital factor. Extensive regional collection range in CBM required more transportation. It should be noticed that, the effect of substituting synthetic fertilizer production was remarkable, with -27.59 and -28.66 kg oil-eq. separately. Thus, the optimal response is to recycle alternative organic fertilizer in the vicinity of cultivated fields of the pig farm. Identifying the most suitable transfer distance is of great relevance. Since ITM did not involve energetic resource generation, the professional expertise with a high conversion rate in CBM brought exceptional value to electricity production, with approximately 40.86 kWh, which could cover much more than the operating power consumption.

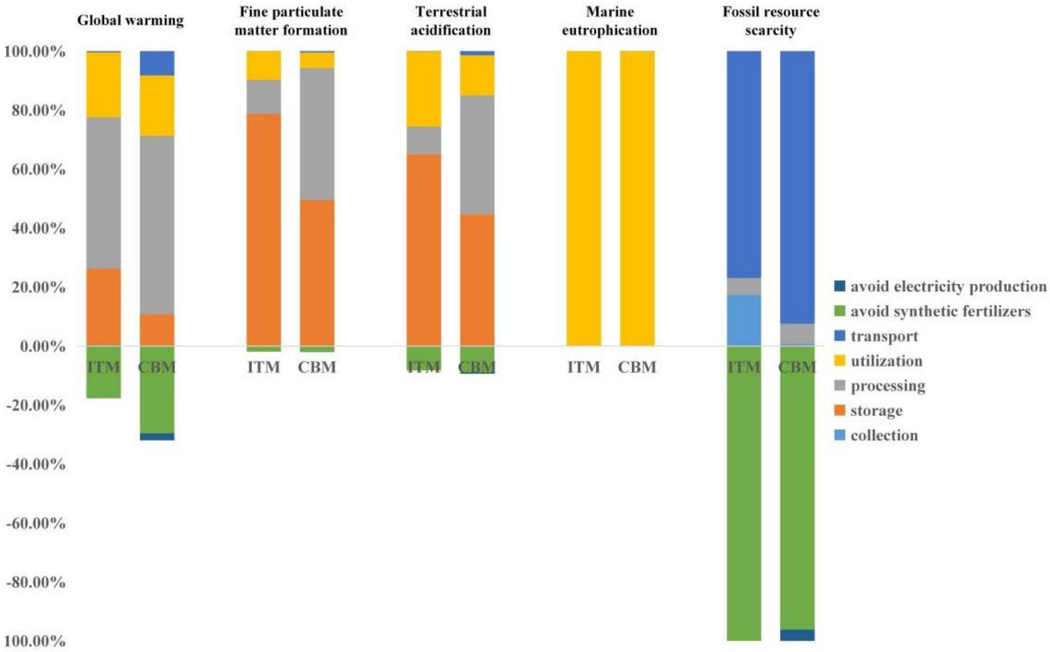

Figure 5-3. Contribution of the considered sections to 5 impact categories at midpoint level in ITM and CBM. Negative contributions indicate a net reduction in impact. Impacts were calculated at midpoint using ReCiPe 2016 v1.1 method from Hierarchist perspective.

Results of sensitivity analysis were conducted varying the percentages of each MSM section, with the varied range of ±30% (**Figure 5-4**). In addition, the restructuring of the energy mix was also considered (**Figure 5-5**). The variation in waste collection displayed no significant effects. GW was most sensitive to MSM processing both in ITM and CBM, with a varied range of 386.63~527.53 kg CO_2-eq and 228.64~329.97 kg CO_2-eq severally. Moreover, in CBM, processing also played a critical role for FPMF and TA, with a variability of approximately ±13.42% and ±12.1%. In both MSM modes, storage significantly impacted on FPMF and TA, and more strongly in ITM, with a range of 4.89~7.91 kg PM2.5-eq and 5.59~8.3 kg SO_2-eq respectively. Utilization contributed to ME by ±30% approximately. FRS was most sensitive to transport. For electricity, switching to renewable sources generation mainly improved two categories pinpointed above: FRS with a reduction of 22.99% and 8.64% for ITM and CBM respectively, followed by GW with a reduction of about 0.35% and 2.1%. The considerable sensitivity of the MSM practice necessitates further improvements, which will be discussed in Section 3.3 and 4.1.

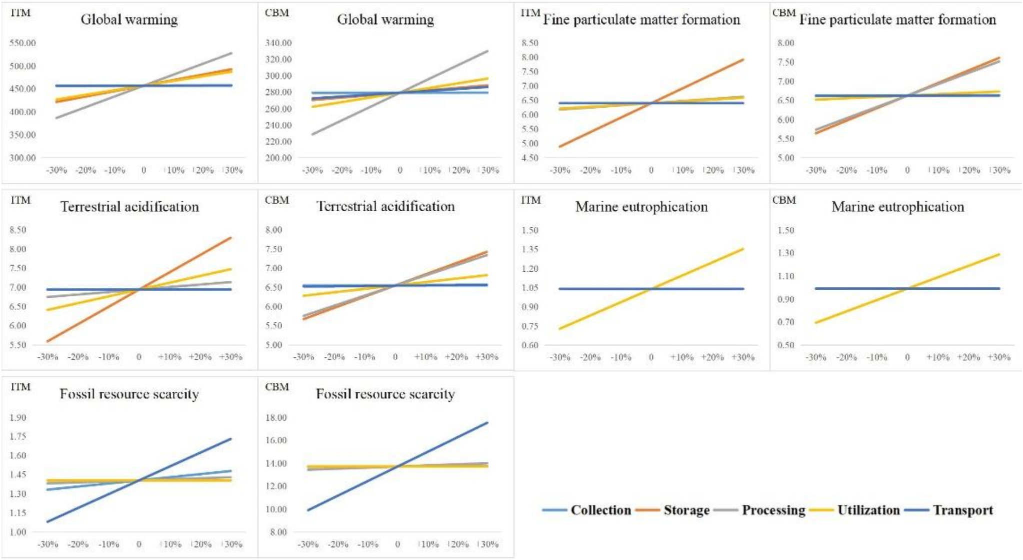

Figure 5-4. Sensitivity results of varying the percentages of each MSM section to GW, FPMF, TA, ME and FRS respectively.

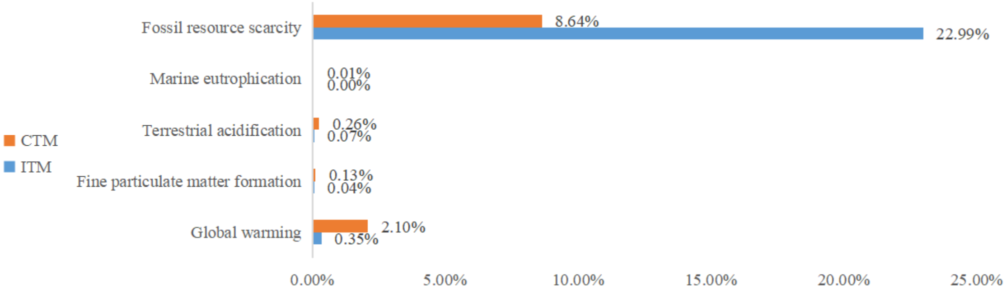

Figure 5-5. Sensitivity of changing to the renewable sources of electricity mix.

3.2 Economic viability

Economic viability of MSM modes was evaluated by comparing OpEx, MgEx, economic benefits, net incomes, and respectively specified contributions (**Figure 5-6** and **Table A6**). Overall, both in terms of OpEx and MgEx, CBM was much higher than ITM. For ITM, the OpEx and MgEx of treating FU was 11.66 and 13.81 CNY with negligible benefit, because the manure by-products of primary processing are only freely available to surrounding growers. This was consistent with previous research in China, ranging from 12.3 to 22.88 CNY (Chen et al. 2017a; Yan and Luo 2020). CBM was significantly more profitable than ITM, with a net income of 48.5 CNY because of the commoditized transactions. MgEx and OpEx of CBM were 87.68 and 66.09 CNY/FU respectively. Previous studies have shown that the costs of livestock waste management for biogas power projects were approximately from 27.97 to 90.83 CNY due to handling capacity (Liang 2019; Wang and Li 2018).

In ITM, OpEx accounted for 84.43% of total MgEx. The overall MgEx was mainly attributed to labor costs, accounting for 51.19% with 7.07 CNY, far exceeding all other expenditures. This phenomenon since family members are the main workforce in family farms and traditional farms, short-term workers are hired only during slaughter and selling time. Generally, implementing MSM as a continuous daily work requires at least 1-2 additional people with a monthly salary of 3500-6500 CNY. Therefore, the hiring fee may not be affordable for pig farms with lower daily waste generation. Energy consumption and depreciation followed as significant expenses, accounting for approximately 30.12% and 15.57% of MgEx respectively. Maintenance cost was minimal, with only 0.43 CNY, mainly due to the relatively low cost of infrastructure construction and equipment procurement. The most striking finding from ITM was that its technology-intensive level was relatively backward, since the machinery-related costs accounted for only 18.68% of the total MgEx.

For CBM, energy consumption became the primary expense in CBM with 63.37% of the MgEx, of which, diesel expense accounted for 59.42%, equivalent to 52.1 CNY. This high proportion of energy inputs may significantly affect OpEx due to market price fluctuations. Depreciation charge was relatively higher, reaching 21.59 CNY, which even exceeded the total expenditure of ITM. OpEx accounted for 75.38% of the total MgEx, which was lower than ITM. In contrast to ITM, labor cost was not noticeable in CBM, although the amount was similar at around 6.44 CNY, however, it occupied only 7.34% of the MgEx. Maintenance cost was relatively low, representing 4.66%. According to the economic benefits based on the current operation of CBM and CapEx (**Table A2** & **Table A7**), the net present value for biogas enterprise over 20 years is approximately 27.06 million CNY (considering a social discount rate of 8% per year on future revenues and expenses[24]), as well as an internal rate of return of 11.6%. The payback time is around 8.66 years.

Figure 5-6. Economic viability analysis including economic costs and net incomes based on per function unit. (a) Comparisons between MSM modes (ITM, CBM and CBM traffic optimization scenario). (b) Based on the perspective of biogas enterprise of CBM, the original operation pattern and up-scale scenario were contrasted. Black numbers indicate the operating expenses of subitems. Bolded indicate total cost, red is net income. The major changes are represented by gray arrow.

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[24] According to the “Economic evaluation method and parameters for constructions”, the nominal discount rate of 8% is adopted for the assessment of all types of construction projects in China (Li et al. 2016a).

What stands out in the preliminary results is the contribution of labor and energy in waste handling. Sensitivity analyses of labor and energy prices to market fluctuations are significant (**Figure 5-7**). The prevailing price range for labor hire is from 3500-6500 CNY, fluctuating at ±30% of the average salary. Rural electricity prices range from 0.45-0.8 CNY/kWh, varying from -15% to 30%. The variation in the market price of diesel is ±3%.

Sensitivity results illustrated that variations in labor cost had the greatest impact on the OpEx for ITM, with the range of 9.54~13.78 CNY/FU, the variability of approximately ±18.19%. Contributions of electricity and diesel were inconspicuous, with the variation only between -1.2%~2.39%. For CBM, labor salary and diesel consumption were obvious for sensitivity analysis, with a varied range of 64.16~68.02 CNY/FU. However, its variability was relatively lower compared to ITM, with ±2.92%. It followed that, from the perspective of OpEx, the stability of CBM was superior to that of ITM, which was attributable to the higher degree of mechanization. Manpower was most sensitive to ITM because of its labor-intensive character.

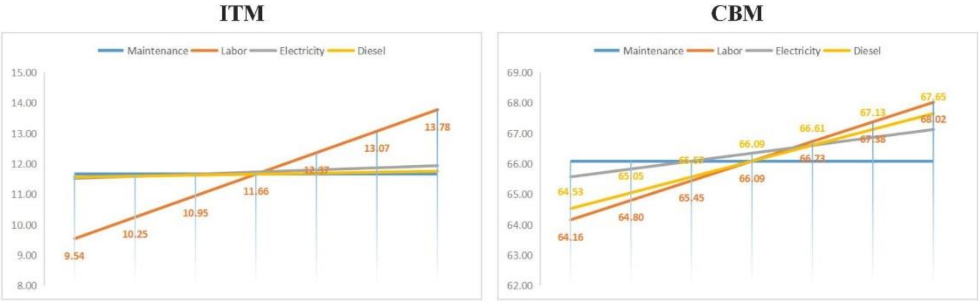

Figure 5-7. Economic sensitivity of OpEx according to labor, electricity and diesel costs.

3.3 Scenarios on transport optimization and up-scaling in CBM

This study performed a preliminary estimation of environmental performances as well as economic viability for two MSM modes. The potential for environmental implications mitigation and marginal cost reduction would be further discussed to explore the preponderance and applicability of CBM (**Figure 5-6**).

3.3.1 Scenarios on transport optimization

As aforementioned, CBM demonstrated better environmental performance and promising economic feasibility. Regardless of the existing CBM or the upgraded scenario, however, the environmental impact and economic burden caused by transport deserve to be investigated.

Transport optimization could be conducted in two aspects, firstly by improving transport efficiency, and secondly by restructuring transport distances. Currently, waste transfer during the non-cultivation season is unidirectional, including empty runs (Schnorf et al. 2021). To reduce transport frequency and improve efficiency, maintaining synchronization between suppliers and receivers is efficient. Establishing sufficient storage space for both waste and prepared fertilizer was an attractive solution (Schnorf et al. 2021). Compared to CBM, return transport could save 3.96 kg oil-eq for FRS, simultaneously, obviously contributing to a 29.93% reduction in transport in terms of GW and a 32.28% decrease in transport costs. Consequently, net revenue increased by 34.68%, reaching 65.32 CNY per FU.

This study also explored other possibilities to strengthen the association between pig breeding, biogas plant and cropping. Currently, the by-products manufactured by CBM were sold to organic fertilizer markets and contracted cultivation sites located far away. The lack of widespread promotion and credibility within the cropping community may explain this. Technical standard for preventing pollution in livestock and poultry breeding (HJ/T 81-2001) stipulated that farms should be sited away from densely populated areas, industrial zones, and tourist areas, therefore most breeding communities were scattered around planting areas. Popularization of CBM could enhance farmers' willingness to use organic fertilizers, providing an opportunity for spatial arrangement and reducing the transit distance. The appropriate amount of digestate water irrigation was found to be 30 t/hm^2 of farmland, applied 5 times annually, in line with prior studies (Chen et al. 2019; Wu et al. 2018). Therefore, gathering pig waste from farms of a similar size as ITM (between 2 to 3.67 ha and breeding 3000 pigs), would necessitate approximately 51 hm^2 of land for disposal. Generally, as the distance successively increases between the collected pig farm and the applied cultivated land, more diesel consumption and collection expenses are incurred. The optimal collection radius should be less than 31.45 km, as this ensures the highest net benefit per FU of waste treated, with approximately 92.4 CNY. The threshold load distance for a positive marginal effectiveness per FU of waste treated is roughly 187.7 km, which covers the complete region of the pig waste collection, consequently, is more conducive to promoting regional operating MSM mode.

3.3.2 Scenarios on up-scaling

CBM is characterized by extensive waste collection and subsequent centralized scale processing. A more favorable approach is to involve more substantial waste to be handled by anaerobic digestion, which has preferable environmental impacts, as well as reduces marginal management cost in terms of attendance time. Based on volume and hydraulic retention time calculations, the capacity of the biogas plant could be increased to handle 370,000 tons annually. According to the investigation, there are sufficient pig farms and abatement cultivable fields nearby, eliminating the need for additional transportation. Although vehicle acquisition and personnel hiring increase correspondingly, the marginal MgEx decreases by approximately 8.53%, including a 33.5% reduction in depreciation expense, as well as, a 10.83% reduction in labor cost. As a result, net income improves by 13.89%, accordingly, the payback time is shortened to 5.47 years. Furthermore, the regional pig rearing generates 930,000 tons of pig waste annually, the most obvious finding to emerge from the up-scaling scenario leads to a total net saving of -23,799 tons of CO_2-eq., representing an apparent 7.81% mitigation on GW. Simultaneously, a reduction of -6.19 tons of N-eq. for ME is observed in this breeding region.

4. Discussion

The objective of this chapter is to comprehensively evaluate the environmental performance and economic viability of two MSM modes. The research explores the potentials and challenges associated with transitioning from individual behaviors to cooperative processing, akin to the shift from spot practices to a more systematic approach. Furthermore, the feasibility and experiential insights gained from this study are further demonstrated to popularize and generalize the improved MSM mode in a larger scope aiming to facilitate effective resource allocation and create sustainable pig production activities.

4.1 Contribution and improvements of crucial sections on environmental performance

Livestock and poultry manure treatment has the characteristics of complexity and coherence. MSM of pig is an aggregation encompassing collection, storage, processing, utilization and transportation (Prapaspongsa et al. 2010; Lopez-Ridaura et al. 2009). From an environmental perspective, it is significant to ascertain which segment contributes the most and make targeted improvements, with the intention of constructing an optimized MSM mode.

According to the results of LCA, collection and transport had relatively lower environmental impacts. Modern pigsties are equipped with well-developed infrastructure and reinforced anti-seepage measures, which facilitate the cleaning and removal of pig’s manure and sewage (DeVries et al. 2012a). Compared to manual operations, the use of electric scavenger boards not only increases the clearance efficiency, but also reduces the manure retention rates (Xu et al. 2020). This significantly reduces the duration of exposure of untreated pig waste to the atmosphere and mitigates the infiltration of sewage into the soil and water bodies. In terms of transport, compromise is possible because of the inconspicuous contribution to environmental performance except for FRS. Emission originating from livestock waste is minimal, due to the short transportation time and relatively airtight containers. Thus, its contribution to environmental performance is inconspicuous, even this has been neglected in relevant researches (Schnorf et al. 2021; Hoeve et al. 2014).

Applications of various measures in storage, processing and utilization showcased especially important differences and warranted further discussion. In general, controlling CH_4, N_2O and NH_3 emissions could optimize environmental performance (Lopez-Ridaura et al. 2009). Storage, in particular, has large environmental impacts on GW, FPMF and TA, primarily induced by NH_3 emissions. Residence time and exposure level are all critical influencing factors (Wang et al. 2017). In pig farms that rely on seasonal cultivation and fertilization, the duration of manure stacking may extend to five months or longer, definitely leading to increased gas release. Studies have revealed that N loss occurs more rapidly during the first 60 days of storage, in particular, with NH_3 volatilization resulting in a loss of up to 29% of nitrogen, furthermore, 0.8-4% of nitrogen was lost through runoff, with about 22% entering the water column (Wolter et al. 2004; Oenema et al. 2007). Additionally, Styles et al. (2018) demonstrated that NH_3 volatilization could vary between 2% and 10% due to the various degrees of containment of storage conditions. Thus, minimizing the contact area with air can effectively reduce gas release.

Also, in relation to the different techniques adopted for waste processing, contrasting consequence on environmental impacts was revealed. Composting, regardless of the mode used, was a major contributor to the greenhouse effect. Approximately 9.6% to 46% of total organic nitrogen was lost in the form of NH_3 during composting (Fukumoto et al. 2003; Jiang et al. 2013), accompanied by the release of N_2O, and subsequent impacts on GW and TA. According to Chang et al. (2013), the height of the composting stack inversely affected the rate of nitrogen loss. Stirring and forced-air techniques accelerated manure decomposition, but also generated more NH_3 and CH_4 (Jiang et al. 2013). However, nitrogen loss can negatively impact microbial degradation and reduce compost quality (Gao et al. 2014). Many researchers have focused on optimizing composting processes, nitrogen retention techniques, the extraction and use of microbial agents, as well as compost maturity indicators (Barthod et al. 2018). As aforementioned, aerated slurry decantation and digestate dewatering also provide significant impacts on GW, FPMF and TA. One reason is that the large contact area with air during operating and residence time. On the other hand, anaerobic digestion, compared to composting, demonstrated better environmental performance in terms of GW for equivalent raw materials (Morsink-Georgali et al. 2022; Aguirre-Villegas and Larson 2017), with a relatively lower nitrogen loss of approximately 1.2% to 12.2%. Maintaining more nitrogen represents a source of nutrients, allowing for a reduction in the use of chemical fertilizers (He et al. 2013). Nevertheless, ammonium nitrogen is increased in the liquid digestate, which poses the risk of NH_3 volatilization upon application (Chen et al. 2019). Nkoa (2014) has also emphasized potential risks associated with digestate application, such as leaching and runoff of nutrient-rich elements into water bodies. Therefore, storing liquid digestate prior to utilization has been shown to benefit the environment by resulting in a 10% decrease in GW (Zeshan and Visvanathan 2014). Minimizing N release when applying fertilizer to cultivated fields can circumvent environmental damage. Nevertheless, Wang et al. (2017) and Prapaspongsa et al. (2010) also emphasized the relevance of fertilizer form and application methods, liquid fraction had a notably higher emission potential compared to solid forms, liquid injection demonstrated better performance compared to surface broadcast application (Aguirre-Villegas and Larson 2017). Prapaspongsa et al. (2010) indicated that the emission factors of different liquid application methods were various. Broadcast spreading had relatively high NH_3 emissions, with lower N_2O and N_2 compared with deep injection. Deep injection showed better environmental performances than shallow injection, with the lowest NH_3 emissions, however, waste injection utilization produced 2.7 times more N_2O and N_2 emissions than surface application. In addition, fertilizer type, soil type, irrigation approach and crop type may affect emission factors (Yoshida et al. 2016; DeVries et al. 2015).

4.2 Adaptability of multi-subjects to both MSM modes

In general, ITM had significantly lower operational costs compared to CBM, it possessed the characteristics of being cost-effective and providing convenient access. For pig farms that manage both breeding and cropping, ITM could potentially reduce feed purchases and synthetic fertilizer use. According to the estimation from survey data, the pig farms adopted a breeding-cropping pattern with their own arable land could save feedstock costs in the range of 15-200 CNY/mu, with an average of 91.29 CNY/mu, and the reduction rate was 11.77%, with the range of 1.06%-31.25%, due to the variations in farm stocking, manure generation and supporting land area. Additionally, organic fertilizer application reduces synthetic fertilizer use by 5.9% to 22.5% compared to crop-only households (Jin et al. 2021). It follows that the promotion of breeding and planting integration contributes to the development of organic agriculture, as it is beneficial for nutrient recycling and offers an accessible outlet for livestock waste. Additionally, the close combination of animals and crops reduces the transport of commercial fertilizers and fodder from distant production sites. Thus, the self-sufficient nature of ITM minimizes the need for extensive machinery operation and long-distance transportation due to the relatively small waste volumes processed. It is appropriate for the pig farms involved in both breeding and cropping, as well as has sufficient nearby farmland for consumption, which is a dual initiative with environmental and economic merits.

In contrast to the practice of solely breeding, although the substitution of by-products compensates for the impacts incurred by synthetic fertilizers and shows potential for mitigating environmental effects, it is not profitable for pig farmers. ITM products have only undergone natural biological treatment, and lack verification of nutrient content. As a result, planters are hesitant to pay for unverified information and face inconveniences in utilization (Huang et al. 2021b). The absence of industry standards for primary processed natural fertilizers and the lack of a well-developed market prevents ITM products from participating in market transactions. Continuously applying an uneconomical mode will impose financial burdens on farmers, especially for small-scale pig farmers, because of the stationary cost of hiring (Chen et al. 2017a; Poffenbarger et al. 2017), thereby, restricting the expansion of breeding activities. Furthermore, rapid urbanization, combined with a declining younger population with high learning abilities in rural areas, which hinder the diffusion of knowledge-intensive technology. Currently, the appearance of third-party centralized processing may present an opportunity, the striking characteristic is twofold. Firstly, declining MSM handling cost is identified, because of the omission of the subsequent processing, resulting in a reduction of approximately 37% in original expenditure, of which, labor hiring cost has been reduced by about 30%. Meanwhile, timely waste removal guarantees a positive habitat for pig breeding. Thus, CBM is applicable to farmers who lack sufficient land for spreading, are unfamiliar with MSM technologies, or suffer from financial burdens regarding MSM. However, some farm owners are anxious about the access to the superintendent of transportation and vehicles, the additional cost of disinfection may constrain their cooperation.

From the perspective of biogas enterprises, the net income was impressive. However, the operational cost was comparatively high, resulting in prolonged payback times. Scenario on up-scaling indicated that collecting more substantial waste leads to lower marginal cost. Biogas plants are preferably located in areas with a dense distribution of pig farms, considering the collection radius, with an optimal range between 30km to 50km, allowing for fluctuations in slaughter volume.

The government should take responsibility for establishing trust and cooperation between biogas plants and pig farms. Efforts to enhance publicity or establish demonstration areas to increase farmers' awareness and acceptance, as well as provide subsidies for biogas plants. Meanwhile, improving organic fertilizer standards and expanding the corresponding market could effectively broaden outlets of by-products.

Chapter 6

Driving forces and innovative incentives for sustainable MSM

Adapt from:

Shi, Boyang et al., Understanding pig farmers' intentions across farm scales to improve eco-friendliness of waste management for sustainable pig industry.

1. Introduction

Intensive and up-scaling development of pig breeding has resulted in the generation of a large amount of pig waste. Due to the huge amount of effluent produced, pig manure, urine and sewage constituted 76.8% of the total livestock waste discharge, with 4.37 billion tons in China (Wu et al. 2018). The indiscriminate and excessive release of pig excrement and sewage causes a slew of serious ecological problems for the soil, water and atmosphere resources (Zhang et al. 2004; Prapaspongsa et al. 2010; McAuliffe et al. 2016; Wang et al. 2017; Wu et al. 2018; Liu et al. 2020a). Manure and sewage management (MSM) is an increasingly important concern, which has been proposed to solve these accompanying environmental pollutions. Additionally, it is considered to be a fundamental approach to explore potential pathways of converting resource value from pig waste, and relieve the pressure on land (Qian et al. 2018). Therefore, the Chinese Government has promulgated environmental policies to restrain the behavior of pig farmers, and promoted relevant MSM technologies. These initiatives had positive outcomes to some extent, however, the MSM in China remains at the primary stage with limited adoption. In Europe, 70%-80% of the manure is treated by suitable processing methods (Pan et al. 2021). In 2017, pig manure generation exceeded 600 million tons, however, the rate of the comprehensive resource utilization of pig manure was less desirable, being less than 50% (Li et al. 2020b).

Given the low initiative and low level of education of farmers, and their incomplete understanding of MSM approaches may not be up to the standard promoted by the technology sector. Application of a single technology or shortcutting behaviors with limited processing capacity may lead to secondary contamination. Several farmers still adopt simple extensive MSM methods such as open-air composting, tank storage with natural fermentation due to the high operating cost and unsystematic knowledge of MSM technologies (Gu and Du 2020). This is one of the immediate contributors to the disordered discharge of waste (Jiang et al. 2018). For example, although anaerobic fermentation is considered to be a more environmentally friendly processing method, direct application of the resulting digestate will result in secondary pollution (Shi et al. 2023), and a more favorable option is to return it to the field after composting. Accordingly, these not only diminished waste treatment efficiency, but also increased the burden of subsequent product handling (Tsapekos et al. 2017). Thus, comprehensive combined applications contribute to compensating for the shortcomings of single MSM technologies, enhancing on-farm management and fertilizer use efficiency, and achieving more environmentally friendly utilization standards.

Existing studies on integrated MSM approaches adopted by pig farmers have four limitations.

Firstly, there is a dearth of information on pig farmers' decision-making on comprehensive combined MSM approaches adoption. The scope of existing research is mainly focused on farmers' willingness or behaviors on MSM adoption for whether or not (Li et al. 2021c; Tao and Wang 2020; Deng et al. 2016). Or exploring the influencing factors in the application of a new specific methodology (Wang and Tao 2020). In fact, due to environmental constraints and cyclic economy, MSM is a compulsory requirement instead of willingness behavior, the most basic minimum threshold of environmental access is insufficient (Baumol and Oates 1988). It is necessary to improve individuals' levels of environmental obligations and eco-friendly behaviors. The application of comprehensive MSM approaches is significant to improve the efficiency of waste treatment and utilization, enhance the adaptation to different environments and requirements, promote the recycling of valuable resources in pig waste, spread risk and improve system stability, as well as an important technical support to promote the green and high-quality development of pig industry. Therefore, it is meaningful to explore how to get pig farmers to actively apply the comprehensive MSM approach.

Secondly, most previous studies investigated breeding farmers as a homogeneous group, ignored the heterogeneity across farm scales, research on the effects of farm scale has not yet been explored in depth. Traditional economic theory holds that production scale determines farmers' behavior (Welsh and Rivers 2011), and conducts a preliminary study on the issue of scale affecting breeding waste pollution. Small-scale breeding can effectively play the role of resource recycling and realize positive waste utilization. However, they produce serious environmental issues due to the shortage of MSM facilities and equipment and simple handling methods. On the other hand, large-scale farms are supported by the state in terms of facilities and funds, although the facilities and equipment are sound with scientific and professional treatment methods, the operating costs are high with poor feasibility (Lian 2017). Pan and Kong (2015) and Zhu et al. (2016) also emphasized the significant impact of breeding scale and economic income on farmers' MSM behavior. It has also been found that the willingness for waste disposal grows stronger as the scale of farming increases (Zhang et al. 2011; Bin et al. 2017b). It has been demonstrated that the environmental awareness and technology adoption of scale farmers are generally higher than that of non-scale farmers. Furthermore, the degree of pollution caused by scale breeding is relatively low because of the scale economy in MSM and farmers' motivation (Zheng et al. 2014a). Thus, breeding scale as a key factor affecting pig farmers' MSM behaviors should be careful differentiation.

Thirdly, few studies considered the impact of land characteristics on adoption decisions. Generally, the key to effective pig waste resource management is to access the field, and establish a close link between breeding and cropping (Shi et al. 2022). Of which, arable land consumption is the dominant outlet (Machete and Chabo 2020). Studies have concluded that scale farming is constrained by the supporting land for manure disposal, and that breeding and cultivation cannot be effectively integrated, the pollution from breeding is instead more serious (Gao and Zhang 2010). Importantly, Willems et al. (2016) indicated that the degree of land fragmentation and the difference in land price may be the influencing factors for the variability in the effectiveness of manure utilization in the Netherlands and Denmark. Therefore, land as an essential endowment, should be investigated in the application of comprehensive and sustainable MSM. Currently, in China, pig farmers access complex land types during manure utilization, such as own land for cropping (own land), cultivated land acquired through transfer and lease transactions (transfer land), and someone else's land in the vicinity for waste consumption following permission and agreement of the landowner (agreed-upon land). Various types of land lead to waste returning convenience, applying expenditure, and individual social relations, thus affecting pig farmers’ MSM practice. Whereas, the lack of relevant research on the influence of land characteristics, blurs farmers' attitudes toward comprehensive MSM.

Fourthly, lack of a unified framework involving internal factors and externalities impacts, and their interactions. Pig farmers, builders of the connection between waste and land, their behaviors are fundamental to achieving sustainable manure management. Currently, studies on the behaviors and influencing factors have focused on the individual characteristics of farmers, farming characteristics, psychological perceptions and social factors (Bernath and Roschewitz 2008). Jiang et al. (2014) showed that age negatively affected farmers’ agricultural waste usage intention, educational level had a significant positive impact on livestock waste controlling (Bin et al. 2017b). Zhang et al. (2011) and Lin et al. (2018) concluded that individuals’ psychological and environmental cognition had critical active impacts on pollution control behavior. However, few studies focus on how resource endowments influence the MSM application. A comprehensive waste management system requires additional labor, and handling feasibility is affected by labor availability and expense (Xiaokaiti and Zhang 2023). Senyolo et al. (2018) pointed out that technology characteristics impacted farmers’ application behaviors and puzzles, and technology familiarity directly affects utilization efficiency. MacLeod et al. (2010) believed that cost-benefit analysis was a prerequisite for farmers' decision-making. In addition, household economic income level was also corroborated had significantly positive effects on farmers' behaviors toward agricultural waste recycling (Jiang et al. 2014). In general, pig farmers, as rational economists, tend to weigh all aspects of benefits before making behavioral decisions, such as manpower, skilled and financial resources, to maximize the benefits by allocating acquired several elements. Thus, multiple resource endowments become critical in shaping farmers' MSM behaviors.

Furthermore, externalities analysis of pig farming is also important. Environmental pollution from pig breeding is an external diseconomy caused by "cost spillovers" (Brown 2002) with significant negative externalities. Unused manure is a "misplaced resource" while the "positive externality" is created if the waste is turned into a resource with increasing revenue (Peng 2009). Externalities can be internalized through government intervention.

Policies have a role in guiding, coordinating and controlling socio-economic development. Rational policies provide guidance for human behavior, coordinate and balance relationships in society, as well as play a positive role in constraining and regulating human and organizational behaviors (Wu 2023b). The emphasis and sensitization of government departments play an instrumental role in promoting MSM among farmers (Bin et al. 2016). Study revealed that the degree of breeding and cropping integration, government environmental constraints and subsidies were the main reasons for the discrepancy in the factors contributing to the influence of waste utilization among breeding farmers (Wang and Yang 2017). The Chinese Government has adopted a top-down schema of environmental regulation and governance to adjust farmers' production behavior, implemented regulations were categorized into constrained and incentive environmental regulation. Langpap (2006) indicated that incentives, especially compensation policies, could be effective in promoting farmers' environmental behaviors. Government subsidies compensate to a certain extent for the positive externalities of waste management by farmers (Zhang and Qiao 2014), and it is a more effective implementation process than command-and-control instruments (Khanna et al. 2002).

In addition, the same factor may have different effects on separate farms. Such as government intervention had a significant impact on the willingness of small and medium-scale farms to the environmentally MSM, while it exhibited less sensitivity to large-scale farms (Kong et al. 2016). Furthermore, the perception and attitude of various farms towards the corresponding environmental regulation differ depending on the information acquisition and knowledge level. These indicated that scale variations may affect the policy rationality of the same exogenous means. There are interactions between internal factors and external factors, thereby affecting policy effectiveness and private behaviors.

In accordance with the aforementioned concerns, this chapter is guided by the academic issue of "How to improve the adoption of comprehensive combined MSM approaches by pig farmers across farm scales?" It will be explained by 1) What are the differences in the characteristics of various farm scales? 2) From the perspective of scales, what are the impacts of land, resource endowments and policy rationality on farmers' eco-friendly behaviors? 3) What are the effective paths to improve farmers' eco-friendly MSM behaviors by adopting more comprehensive MSM approaches? Establish a systematic and analytical framework with land factors, resource endowments, policy rationality and individual characteristics as the factors influencing farmers' decision-making on comprehensive combined MSM approaches adoption (**Figure 6-1**). From the perspective of farm scales, analyze the effect and intensity of each factor respectively, and further explore the matching targeted initiatives.

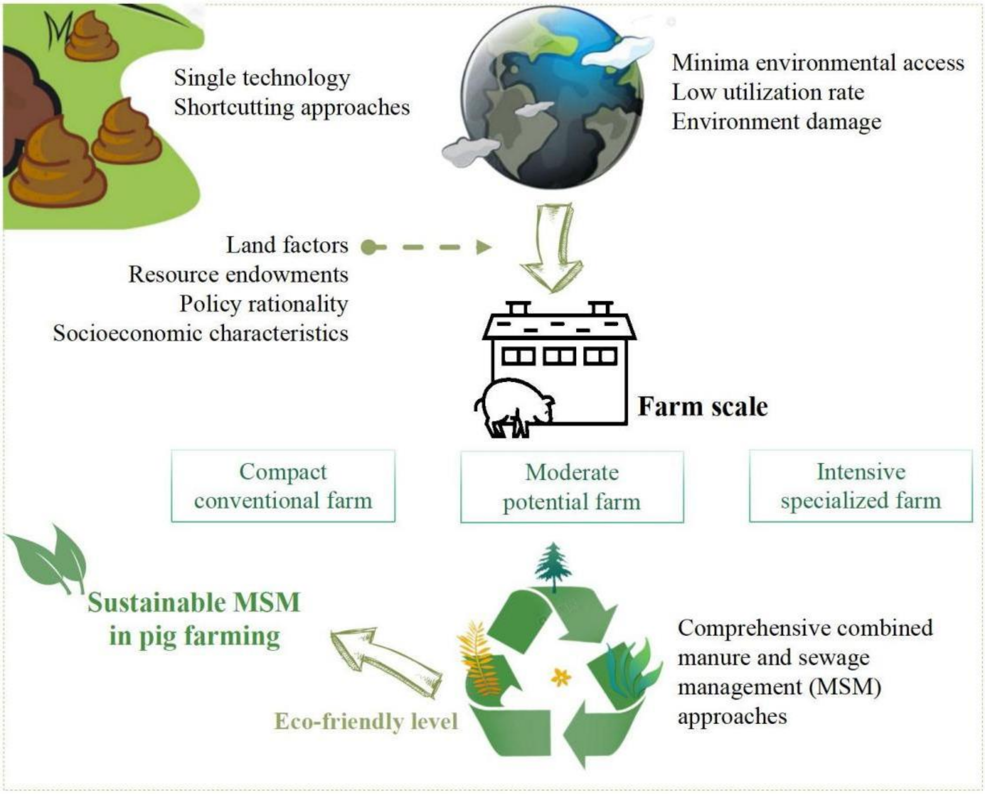

Figure 6-1. Framework of factors influencing farmers' decision-making on comprehensive combined MSM approaches adoption.

This chapter aims to fill the aforementioned gaps with four contributions. Firstly, cluster analysis was used to categorize farms into three types by considering the inventory pig numbers, pig farm area, and farm MSM area. This compensates for the one-sidedness of the scale differentiation only based on pig population, and avoids the deviation mismatch between breeding numbers and MSM capacity. Secondly, one more comprehensive systemic and contextualized framework was established to approach the reality of farmers' exposure to MSM technologies. Thirdly, analyzing policy rationality along three dimensions, policy perception, policy execution and policy request, to harmonize instrumental and value rationality in environmental policy (Hou and Su 2019). More importantly, heterogeneity assessments across various farm scales were significant in clarifying the effectiveness of various internal factors and responsiveness of policy, and ferreting out the driving forces in the pathway involved in the promotion of comprehensive combined MSM approaches. In general, it contributes to developing tailored implications to targeted farm scales, improving waste availability and utilization rate to establish more effective innovative incentives for pro-environmental and sustainable MSM. Furthermore, it provides a suasive reference for the Chinese government and other developing countries on the flexible and responsive policy formulation, to promote policy rationality, and achieve policy legitimacy, effectiveness and resilience.

2. Methodology

2.1 Farm scale clustering analysis

Clustering analysis could effectively reduce the dimensionality of diverse data, integrate similar data, reduce intra-group differences while highlighting inter-group variation.

Previous categorization was determined solely on slaughters or stocks, however, this may be biased, farm construction as a prerequisite for waste management is significant to incorporate. Furthermore, the Chinese government has issued special standards for the *Construction of intensive pig farms GB/T 17824.1-2022*, which presented the standards of land area and environment. To encompass a more comprehensive characterization of farm scale, combined with the variables of inventory pig numbers, pig farm area and farm MSM area, this study redefined farm scale into three tiers to adapt actual situation. A total of randomly valid 559 cross-sectional data were obtained for clustering by k-means.

This is significant to avoid the one-sidedness of determining the farm scale based only on inventory numbers or slaughter numbers, since the constantly changing number of pigs. Therefore, avoid the decision deviation of high breeding density caused by large inventories with small areas, and the mismatched MSM capacity.

2.2 Farm heterogeneous characteristics

After grouping, it is meaningful to distinguish the characteristics of different scale pig farms. Multiple independent sample tests were verified through two tests due to the differing properties of the variables, and both were subsequently followed by pairwise multiple comparisons of means. Using non-parameter Kruskal-Wallis test for ordered variables, and Chi-square test for dichotomous variables. Then, for pair-wise comparison, all the significance levels would be modified according to the Bonferroni correction. Variables showing significant differences between groups were selected for further study.

2.3 Variable definitions and Ologit model construction

MSM practices involve diverse approaches and technologies, which could be applied singly or in combination. Adopting more practices contributes to the more scientific MSM and more comprehensive utilization of waste resources subsequently, and the harmonization of environment and pig breeding. Thus, comprehensive and diversified MSM applications indicate higher levels of eco-friendly behavior, which is the dependent variable in this study. It is explained by the question "*How many MSM technology practices do you adopt?*", and be measured by the combined value of applied MSM practices. Values are 1, 2, 3, 4, 5 with a clear progressive relationship.

Independent variables are presented in four dimensions, of which the core variables are *Land characteristics*, involving Land property (Own land, Transfer land and Agreed-upon land), Land convenience and Land transfer price. *Policy rationality* involve Policy perception, Policy execution (Constrained and Incentive environmental regulation) and Policy request. Additionally, *Resource endowments* are considered, including labor abundance, technology acquisition, and economy convenience. Furthermore, *Individual socioeconomic characteristics* are also included. Detailed sub-variables and definitions are shown in **Table 6-1**.

For empirical model building, ologit model is more appropriate since *Eco-friendly behavior* is an ordered multi-categorical variable, which has a natural ordering (low to high) under the assumption. However, the distances between adjacent levels are unknown. The model could be expressed as follows,

$$Y = \alpha_0 + \alpha_1 X_{LC} + \alpha_2 X_{PR} + \alpha_3 X_{RE} + \beta C + \mu_i$$

Y indicates *Eco-friendly behavior*; X_{LC} is the Land characteristics, which are represented by five variables, α_1 represents corresponding coefficients of the effect of Land characteristics on farmers' eco-friendly behaviors; X_{PR} is Policy rationality, X_{RE} is Resource endowments, α_2 and α_3 are corresponding coefficients; C represents the set of observable independent variables, β represents coefficients of the effect of observable independent variables on farmers' eco-friendly behaviors. α_0 is constant term, μ_i represents the stochastic perturbation term for pig farmers.

Since the meaning of the coefficient terms in the Ologit model is not intuitive and only contains information on the statistical significance of the independent variables and the direction of action, such as positive or negative. Therefore, by calculating proportional odds ratios, the degree of influence of each independent variable on the dependent variable is further obtained.

Considering data effectiveness, by calculating Cook distance for anomaly detection. The maximum Cook's distance value is 0.1<0.5. Prompt that there are no significant outliers. For multiple collinearity concerns between the variables, the maximum variance inflation factor (VIF) is 1.32 with the average VIF of all variables being 1.15. Therefore, the model does not have multicollinearity risk.

Table 6-1. Descriptive statistics and variables definitions.

Variables	Definition	Mean	Std.
Dependent variable			
Eco-friendly MSM behaviors	How many MSM technology practices do you adopt?	3.05	1.10
Land characteristics			
Own land	Whether you have your own cultivated land. 0=NO, 1=YES	0.30	0.46
Transfer land	Whether you have transferred land. 0=NO, 1=YES	0.17	0.38
Agreed-upon land	Whether you have come to agreements with surrounding planters for waste disposal. 0=NO, 1=YES	0.20	0.40
Land convenience*	Do you think the surrounding land is enough for waste consumption? 1=quite not enough ~ 5=quite enough	3.4	0.92
Land transfer price*	What do you think of the transfer price of land? 1=extremely low ~ 5=extremely high	3.56	0.66
Policy rationality			
Policy perception*	To what level do you know MSM regulations and policies. 1=completely unknown ~ 5=completely know	3.16	0.84
Constrained regulation	Whether you have been asked to rectify because of rejected MSM? 0=NO, 1=YES	0.21	0.41
Incentive regulation	Whether you have received an MSM subsidy? 0=NO, 1=YES	0.46	0.5
Policy request*	To what level do you need policy supports. 1=completely without ~ 5=completely have	2.91	1.31
Resource endowments			
Labor abundance*	Persons for MSM in pig farm.	2.22	2.91
Technology acquisition*	To what level are you proficient in MSM technologies? 1=extremely difficult ~ 5=extremely easy	2.75	0.87
Economy convenience*	To what level are you willing to invest in MSM? 1=completely unwilling ~ 5=completely willing	3.75	0.99
Individual socioeconomic characteristics			
Age	Age of pig farm owner.	45.31	9.33
Education	Education level of pig farm owner. 1=Primary and bellow, 2=Junior, 3=Senior, 4=Vocational college, 5=Bachelor degree and above	3.02	1.05

MSM cost ratio	Proportion of MSM construction cost to total pig farm cost.	0.13	0.11
Social influence	Whether you are influenced by other pig farmers. 0=NO, 1=YES	0.42	0.49
Environmental perception*	To what level do you think MSM affects farm environment? 1=no affects ~ 5=extremely high affects	4.10	0.88

* According to the Likert scale, the degree is divided into five levels to indicate the strength of the farmers' attitudes and perceptions, all statements are positive (Likert, 1932).

3. Results and discussions

3.1 Sample overview and current situation

A general view (**Table 6-1**) revealed that pig farmers' eco-friendly behavior was at a medium level, with 3 MSM methods adopted. From the perspective of utilized land property, farmers preferred own land> agreed-upon land >transfer land, this might be due to the demand for resource recycling for cropping, and the constraint of the additional transfer expenditures. In a situation of relatively matching available land in the surrounding area, farmers perceived the price of transferred land to be slightly expensive. This might be related to the field location, soil quality, land right and the transfer trading market. However, the percentages of farmers with access to land were all below 30%, regardless of the land properties. It indicated that there were further opportunities to strengthen the combination of pigs and lands, as well as develop the integration of breeding and planting.

Along with an overview of policy rationality, farmers' policy recognition was relatively satisfactory, with more than 85.88% of respondents having a clear understanding of relevant environmentally friendly breeding policies. For policy execution, incentive regulation reached a significantly larger audience than constrained regulation. There were currently 46% of farmers benefiting from incentive regulation, farmers who have faced constrained regulation represented about 21%. The overall response to the survey indicated medium-level policy aspirations.

For resource endowments, on average, approximately two people were involved in MSM, over 88% of the farms interviewed had fewer than three people handling manure. However, there was a noticeable fluctuation in the total sample which was related to farm scale. Farmers' understanding of MSM technology knowledge was unsatisfactory, only 15.92% of farmers were better informed, and 45.08% were at a basic level of understanding. Technical support requirements emerged from this analysis. However, they were positive regarding economic devotion, about 65.65% of respondents had a positive investment intention. Governmental agencies and relevant scientific research institutions should be responsible for publicizing and educating farmers to compensate for the lack of technical knowledge.

Individual socioeconomic characteristics showed that the average age of interviewees was 45 years old, with a senior level of education. On average, the investment in MSM facilities accounted for about 13% of total farm expenditure. Social influences affected farmers' attitudes toward MSM participation to some extent, with 42% of responders influenced by other peers. In general, pig farmers had a relatively positive environmental attitude toward MSM surprisingly.

3.2 Farm characterization based on farm scale

Pig farms were classified into compact conventional farm, moderate potential farm and intensive specialized farm according to cluster analysis, based on the characteristics of inventory, breeding density, area and investment, occupying 42.93%, 42.93%, and 14.13% respectively (**Table 6-2**). Compact conventional farms and moderate potential pig farms accounted for about 85% of the total sample, which was in line with the current situation in China. Compact conventional farms are relatively small farms with an average annual stock of less than 1,000 heads, have relatively small footprints and low capital investment but possess a high breeding density. Category II is moderate potential farms, mainly for family farms and a small portion of farming communities, which are developed by local small-scale farms with capital accumulation. And it is a transitional phase for breeding communities expansion. Intensive specialized farms are most mature and professional special large-scale farms, with robust financial reserves and technical support, mainly subsidiaries of listed companies and local large sprawling breeding enterprises.

Table 6-2. Farm scale based on clustering analysis.

Scale	No.	(%)	Inventory	Farm area	Breeding density	MSM area	Farm investment	MSM investment
			(head)	(mu)	(head/mu)	(mu)	(ten thousand CNY)	(ten thousand CNY)
CCF	240	42.93%	731.38	8.92	81.99	0.86	211.11	22.36
MPF	240	42.93%	2406.83	49.14	48.98	5.3	1061.09	114.43
ISF	79	14.13%	25768.18	556.4	46.31	90.13	10390.93	922.93
Total	559	100%	4989	103.76	48.08	15.44	2026.37	186.91

CCF: Compact Conventional Farm; MPF: Moderate Potential Farm; ISF: Intensive Specialized Farm
* 15 mu = 1 ha; 1 CNY = 0.14 USD.

Farm characterization would be further explored to distinguish the heterogeneity between clusters based on farm scale, and clarify the remarkable driving force on farmers' eco-friendly MSM behaviors (**Table 6-3**).

Results showed that, as farm size rose, the diversification of MSM practices adopted by farmers increased, exhibiting better environmental behavior. Especially for intensive specialized farms had an apparent multiplicity in approaches application, compared with compact conventional farms and moderate potential farms. However, compact and moderate-scale farms indicated insignificant differences.

For land property, there were no significant differences in the proportions of own land and agreed-upon land of various farm scales. Objectively, this may be related to the system of field distribution in China. Among them, the proportion of compact conventional farms owning land was relatively high at 33%, which was in line with the reality of self-circulation by socialized household farms. Meanwhile, compared to larger farms, smallholder farmers also accounted for a higher proportion in the selection of land under the agreement. This may be due to its manageable amount of waste, which is more likely to meet the abatement requirements of the cropping site, and favorable neighborly relations between household farms. For land transferring, there has been a slight rise in the probability of land transaction as farm size increases. Approximately 27% of intensive specialized farms opted for land leases because of the requirement of more land area for waste consumption, and the stricter environmental controls they faced. Furthermore, specialized communities also had a certain financial capability, which tended to develop more towards a complete eco-park that encompasses breeding and planting. Attitudes toward available land area and transferred land prices were similar regardless across the hierarchical farm scales, whereas it appeared that the high transaction price might be a hindrance for manure utilization.

In addition, policy rationality also varied considerably for different farm scales. Policy perception showed insignificant differences across farms scales, which confirmed that the scope and intensity of policy popularization was relatively balanced. The effectiveness of policy execution varied greatly among farm sizes by hierarchy. Of these, under the constrained regulation, compact conventional farms and intensive specialized farms had relatively higher proportions of non-compliant farms, with about 24% and 27% respectively. This may be because of the invisibility of compact farms, therefore, owners may have fluke minds. Moreover, they had the worst tolerance for market risk, resulting in economic burden leading to substandard MSM. Intensive farms may neglect to upgrade supporting MSM facilities when expanding the breeding scale, resulting in insufficient MSM capacity. From the perspective of incentive regulation, compact farms had the highest subsidy rate of 55%, which was followed by moderate farms with 43% and intensive farms with only 27% approximately. Since the considerable initial investment for large intensive farms, the government usually subsidizes progressively with strict environmental acceptance inspection. Additionally, intensive farms also had significant policy demands, which suggested that larger-scale farms were in dire need of government support for future development.

Scale up-grading had superiority in access to all resource endowments, whether in terms of labor, technology or capital. **Table 6-3** illustrated that both labor abundance and economic convenience showed significant differences between farm scales. Although the fund availability for compact conventional farms was inferior to that of larger ones, it was at a neutral level of willingness for MSM investment. In contrast, moderate and intensive-scale farms had a stronger willingness to contribute. It was apparent that, the technology acquisition of intensive farms was significantly different compared to the other farm types. It reached only a basic level of technological proficiency, however, the other two smaller-scale farms expressed worrisome results. Obviously, the unfamiliarity with the technology directly affected MSM operations, which could lead to incomplete treatment of pig waste, resulting in environmental pollution, moreover, this would cause secondary contamination due to improper technical practices.

In terms of individual socioeconomic characteristics and attitudes, rancheros on intensive farms were characterized by being younger and more educated, which suggested that they had a greater capacity to learn and were more likely to master a multitude of methods. And they were more receptive to the advanced opinions because of their ability to reflect. Thus, they generally had more positive environmental attitudes and perceptions along with stronger perceived behaviors toward MSM. What stands out in the table was the share of MSM expenses. Intensive-scale farms had the smallest proportion of MSM cost, with only 11%. This represented twofold, firstly, they had the capital strength to ignore the waste handling cost. Secondly, the benefits they received from waste resource utilization might offset their expenditures and therefore did not have a significant impact on the overall negative efficiency gains.

Table 6-3. Farm characterization across three farm scales.

Variable	Mean			Sig.
	CCF	MPF	ISF	
Eco-friendly MSM behaviors	2.86^a	2.98^a	3.86^b	**<0.001**
Own land	0.33	0.28	0.29	0.420
Transfer land	0.13^a	0.18^{ab}	0.27^b	**0.024**
Agreed-upon land	0.23	0.20	0.13	0.146
Land convenience	3.44	3.39	3.30	0.406
Land transfer price	3.49	3.63	3.57	0.139
Policy perception	3.14	3.21	3.09	**0.595**
Constrained regulation	0.24^a	0.16^b	0.27	**0.039**
Incentive regulation	0.55^a	0.43^b	0.28^c	**<0.001**
Policy request	2.76^a	2.91^a	3.35^b	**0.002**
Labor abundance	1.24^a	2.09^b	5.59^c	**<0.001**
Technology acquisition	2.74^a	2.67^a	3.03^b	**0.005**
Economy convenience	3.50^a	3.84^b	4.20^c	**<0.001**
Age	46.54^a	45.94^a	39.65^b	**<0.001**
Education	2.57^a	3.17^b	3.91^c	**<0.001**
MSM cost ratio	0.13^a	0.14^a	0.11^b	**0.003**
Social influence	0.36^a	0.44^{ab}	0.53^b	**0.016**
Environmental perception	4.00^a	4.10^a	4.41^b	**<0.001**

CCF: Compact Conventional Farm; MPF: Moderate Potential Farm; ISF: Intensive Specialized Farm
$^{a-c}$ Differences among the three farm scales are denoted by differing lowercase letters (P<0.05).
Chi-square tests of independence followed by multiple pairwise comparisons using Chi-square goodness of fit tests were performed; otherwise, Fisher's exact test followed by goodness of fit exact test was conducted. Non-parametric Kruskal-Wallis tests were conducted, followed by the post-hoc test pairwise comparisons. Adjustment of alpha levels according to the Bonferroni method. The statistics is Kruskal-Wallis Chi-squared value.

3.3 Driving forces on farmers' MSM eco-friendly behaviors based on farm scale

Regression analysis in **Table 6-4** aimed to predict the factors influencing farmers' eco-friendly behaviors towards MSM and passed the robustness test. Overall, the eco-friendly levels were influenced by a wider range of essential factors, with a scope for further enhancement. However, fewer driving forces could affect intensive specialized farms, and they have probably developed fixed MSM patterns of established superiority.

Table 6-4. Influencing factors on farmers' MSM eco-friendly level.

Variables	CCF		MPF		ISF	
	Odds ratio	Std. err.	Odds ratio	Std. err.	Odds ratio	Std. err.
Own land	2.34**	0.82	1.73*	0.54	0.80	0.64
Transfer land	0.92	0.40	0.54*	0.19	3.76*	2.85
Agreed-upon land	0.68	0.25	0.91	0.32	0.99	1.12
Land convenience	0.61***	0.11	0.65***	0.08	1.16	0.44
Land transfer price	0.52***	0.12	0.90	0.16	0.16***	0.09
Policy perception	1.34*	0.23	1.18	0.16	0.93	0.38
Constrained regulation	0.44**	0.16	0.59	0.22	0.13***	0.10
Incentive regulation	2.17***	0.60	1.83**	0.48	1.44	0.96
Policy request	0.96	0.09	1.11	0.12	1.51*	0.37
Labor abundance	1.00	0.19	1.13*	0.07	0.90**	0.04
Technology acquisition	1.33*	0.21	1.21	0.19	1.35	0.51
Economy convenience	1.24*	0.19	1.26	0.18	0.84	0.43
Age	0.99	0.02	0.96***	0.01	0.96	0.03
Education	0.83	0.14	0.98	0.13	0.75	0.25
MSM cost ratio	0.70*	0.13	0.78	0.13	1.12	0.46
Social influence	1.66*	0.51	1.41	0.36	1.88	1.17
Environmental perception	1.40**	0.23	0.76	0.13	2.22	1.00

CCF: Compact Conventional Farm; MPF: Moderate Potential Farm; ISF: Intensive Specialized Farm
Note:"*"significant at the 10% level;"**"significant at the 5% level;"***"significant at the 1% level.

From the perspective of various land types, two of significant land types were own land and transfer land. Own land had positive impacts on MSM practice adoption. Compared to farms without farmland, the increases in eco-friendly level of those with farmland were 2.34 times and 1.73 times for compact and moderate-scale farms respectively. Farms with their land were more likely to realize synergies between breeding and cropping (Materechera 2010), and also took extra care of soil quality and crop production, so they paid more attention to waste management and fertilizer application. Thus, adapted own farmland promoted flexibility in waste handling and diversity in technology adoption.

Furthermore, surprisingly, for intensive specialized farms transferring land, the odds of more MSM practices adopted versus relatively simple processing reached 3.76 times higher than for no-transfer farms. This represented the future development of the Modern Circular Agriculture Park encompassing ecological breeding and cropping. Intensive specialized farms, with the security of adequate capital and land, are in a more favorable position to realize organic fertilizer production and utilization, thus obtaining both economic and environmental benefits from cultivation. Nevertheless, transferring land had a disincentive effect on moderate-sized farms, with the odds of 0.54 lower. Two reasons might contribute to this adverse situation. Firstly, the sole purpose of farms in initially transferring land may be for excess waste consumption. Therefore, the additional cost of land transferring caused a reluctance to continue to pay for the overhead of more comprehensive MSM technologies. Likewise, wider land utilization reduced the pressure on waste consumption, meanwhile, controls on the MSM practices had been slightly relaxed to a certain extent. As Materechera (2010) mentioned, cropland areas impeded farmers' application of manure for soil fertility management.

In addition, significant negative evidence of land convenience was also found in compact and moderate-scale farms. A consequence of the drained away pressure on land-carrying capacity and lower environmental obligations was the decreasing adoption of MSM skills. However, it should be noted that if lax environmental standards and lower sewage charges are the main means by which a region develops its environmental endowment, this endowment advantage is not sustainable (Yu et al. 2011; Levinson 2018). Currently, in China, the awareness of compact and moderate-scale farms in handling waste is still at the primary level, which is forced by government requirements to meet environmental standards. Their MSM behaviors may be regressive when there is sufficient land area available for elimination. Meanwhile, higher land transfer prices could discourage MSM practices on compact conventional farms and intensive specialized farms. Similarly, as the price of the surrounding transferred land was lower, farmers could afford to lease more fields, resulting in a subsequent decline in the emphasis on MSM.

Environmental regulation is a kind of institutional or consciousness constraint on relevant subjects with the goal of ecological environmental protection (Zhang et al. 2021d), which is mainly formulated and implemented by the government to achieve the goal of environmental protection employing both mandatory constraints and economic incentives (Zhao et al. 2009). Mapping farmers' policy rationality contributes to policy construction and adjustment. In general, farmers’ policy perception was significant in enhancing their environmentally friendly behaviors in compact conventional farms. Appropriate policy advocacy is necessary, especially for these groups with low levels of education. For policy implementation effects, constrained environmental regulations indicated a negative result on farmers' eco-friendly decisions, especially in intensive pig farms with the odds of 0.13 lower. It could be speculated that penalized regulations could restrain farmers' manure disposal behavior in the short term, but they do not fundamentally improve their proactive pro-environmental behavior. Surprisingly, incentive regulation was different from constrained types, as the positive effects of economic incentive-based regulations on compact and moderate-scale farms were significant at 1% and 5% levels, the probabilities of higher environmental friendliness were 2.17 and 1.83 times greater respectively, compared to the comparatively lower level of environmental duties. This is consistent with Tang et al. (2020) finding and is in line with the basic idea of rational smallholder theory. The financial burden caused by uneconomical MSM modes is a major concern, as well as the key factor that hinders decision-making by rational economic agents. A certain level of subsidy can compensate for the increased breeding marginal cost due to MSM and thus incentivize farmers to undertake waste management. In addition, subsidies for some specific technologies will motivate farmers to adopt more MSM technologies. Additionally, eco-friendly behaviors in intensive specialized farms appeared to be affected by policy demands.

In terms of various resource endowments, results demonstrated that labor, technology and economics perceptions contributed to farmers' environmental friendliness of MSM on compact and moderate-scale farms to some extent. Following the improvement of technology acquisition, a significant increase in diversified approaches adoption in compact-scale farms was recorded. Moreover, economic strength could contribute to possibilities for attempting more MSM practices for them, the relatively higher proportion of MSM expenditure impeded farmers' higher levels of pro-environmental behaviors. For moderate-sized farms, which were facing expansion, the more abundant the labor force, the more available manpower for comprehensive MSM practices application. This has been confirmed that labor availability is important for the collection and application of manure field use (Materechera 2010). On the other hand, smallholder farmers were characterized by their susceptibility to the influence of others. Wu et al. (2017) also confirmed that farmers had a strong herd mentality in their production behavior and social reference norms influenced their manure treatment behaviors (Barr 2003). Beneficial social impacts had positive spillovers and could favorably influence farmers' environmental awareness (Tang et al. 2020). Besides, environmental perceptions positively affected farmers' MSM behavior, as Wu et al. (2017) mentioned, the higher the ecological awareness, the greater the willingness of farmers for MSM. Obubuafo et al. (2008) and Afroz et al. (2009) also emphasized that environmental knowledge and environmental perception were vital determinants of MSM practices adoption. Reciprocal determinism by Albert Bandura also describes the dynamic interaction between behavior, cognition, and environment.

4. Implications and perspectives

This chapter, from both government-level and farm-level perspectives, explores the driving forces of efficient and sustainable MSM. In general, pig farmers' eco-friendly behavior is the result of a combination of their characteristics and policy rationality, with land and other resource endowment availability. The effectiveness of the key factors varies for different farm scales. Furthermore, the corresponding innovative incentives and implications are further demonstrated.

4.1 Attentions on land and labor resources

Large-scale agricultural operation is a common trend in global agricultural development, which is also an important direction for the transformation and innovation of China's agricultural management system and approach. Land resources have a positive significant effect on pig farming, moreover, land has an increasing impact on its production layout with the developing industry (Zhao et al. 2019a).

Collective ownership of land in China was launched in 1949, farmers contract land from the collectives for cultivation, without secure land tenure and transfer rights (Cheng and Chung 2018). Household Contract Responsibility System started in 1980 resulting in decentralized management of arable land (Cao et al. 2022). Compared with the modern agricultural development requirements and international standards, the scale of land management in China is still on the small side. The proportion of farmers with cultivated land area less than 10 mu remained stable between 84%~86%. This land fragmentation is not conducive to mechanical operations and greatly reduces fertilization efficiency and productivity (Hao et al. 2023).

In this situation, the priority is avoiding cultivator withdrawal to guarantee effective and sustainable farmland production. *Outline of the National General Land Use Plan (2006-2020)*[25] implemented the "requisition and compensation balance" to maintain the amount of farmland, and optimize the structure and layout of cultivated land use (Gao et al. 2022; Fei et al. 2021). The Land Certificated Program was conducted to clarify and stabilize land property rights and accelerate lease transactions (Cao et al. 2022), as well as enhance farmers’ confidence in land investments and agricultural productivity (Ma et al. 2015). The government should devote to the preservation of high-quality, concentrated and contiguous high-yield farmland. Thus, increasing the machinery use for organic fertilizer application, and alleviating the plight of manpower-dependent utilization. Promoting the pattern of “Grain-to-Fodder Crop Conversion” cultivation to encourage pig farmers with existing arable land to practice integrated planting and breeding (Wang et al. 2022b). Likewise, strengthening the regulation of land carrying capacity in areas of adequate arable land, to avoid the subsequent risk of over-fertilization and secondary pollution. Yu et al. (2012) identified that farms in densely populated areas, the more environmental pressure they are exposed to, the more they stimulate the demand for environmentally friendly technologies.

In terms of land transfer transactions, land circulation has created important conditions for intensive agricultural operations (Fei et al. 2021). Since 2008, rural land transfer across the country has steeply accelerated, land transfer area expanded rapidly from 109 million mu in 2008 to 532 million mu in 2020 (Shi 2024; Huang et al. 2022). However, such wholesale land transfers lead to

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[25] https://www.gov.cn/guoqing/2008-10/24/content_2875234.htm?eqid=95dceb7e0004a34000000003646ae031

significant rental hikes. In part of plain areas, annual land rent has climbed to 700-800 CNY/mu, with some even exceeding 1000 CNY/mu (Du 2019). Rising land prices increase economic pressures on producers engaged in agriculture, which is detrimental to the stabilization of food production and the sustainability of agriculture as a whole (Wang and Wang 2022). Therefore, it is crucial to balance the respective interests of breeding farmers and cropping growers by coordinating the price of transferable land through administrations such as local governments and village collectives. However, land usability and transfer prices face a double-edged sword. Overly cheap turnover prices or sufficient field consumption may lower the environmental and social obligations of farms. Gao et al. (2011) found that farmers had worries on applying organic fertilizers on transferred land. A fair trading market is instrumental in preventing crop farmers from dropping out of land leasing, while also providing opportunities for breeding farmers to seek environmentally friendly technologies by saving land transfer costs (Yuan et al. 2018b). Effective land transfer contributes to the promotion of waste consumption and concentrated cultivation, facilitates farmers' adoption of labor-saving technologies for farmyard fertilizer application, and contributes to the integrated production of cropping and breeding (Wu and Li 2016). In general, rational land planning can not only alleviate the environmental pollution problems caused by livestock waste, but also realize carbon emission reduction and guarantee food production (Weindl et al. 2017; Hao et al. 2023; Xu et al. 2023).

Land transfer not only promotes land structure, but also reallocates labor resources (Yuan et al. 2018b). Nguyen and Warr (2020) indicated that land consolidation contributed to reducing dependence on labor, as well as promoting mechanized production. Results showed that labor resources significantly affected farmers’ enthusiasm to adopt agricultural technologies. However, China is currently facing a shortage of agricultural labor, and the foremost is rural labor outflow. The promulgation of the Labor Contract Law, which stipulates the minimum wage, has attracted more rural labor to the urban areas, with 220 million rural migrants by 2020 (Lu and Xie 2018; Chen et al. 2023). On the other hand, aging and feminization of the rural population cause a decline in the productive labor force and cropland utilization intensity (Liu et al. 2016; Ren et al. 2023). Traditional artisanal agriculture is a less attractive job option for young people (Liu et al. 2016). With the dual challenges of the declining rural labor force and the widening income gap between urban and rural areas, the rising agricultural labor costs are simultaneously boosting agricultural commodity prices (WANG and FU 2019). Furthermore, an important negative effect is a significant decline in the international competitiveness of agriculture (Zhang et al. 2016a). Labor migration stagnates agricultural productivity, while additional fertilizers and pesticides inputs can mitigate the effects of labor shortages, this initiative is unsustainable because at the cost of the environment (Liu et al. 2016). One solution is to upgrade mechanized agriculture, or to develop a service-driven business model (Gao et al. 2020a). Mechanical inputs not only free up labor, but also facilitate the modernization and transformation of agriculture, increasing individual incomes while improving yields (Ji et al. 2012).

Studies indicated that, for the future of agriculture, labor and machinery elasticities were the highest, followed by land elasticity (Gong 2020). Integration of land resources is conducive to farmland high-efficient use and mechanization application. Machinery-intensive modernized agriculture can attract talents to seek employment opportunities in the agricultural sector, which is conducive to the concentration of capital and technology in rural areas.

4.2 Improvements of environmental regime

Findings were obvious that adjusting farmers' behaviors through internalization of externalities by policy and regulation was effective. In the process of formulating and implementing specific environmental regulatory policies, the government should ensure the consistency and stability of the promotion of waste resource utilization policies, to provide stable psychological expectations for farmers (Yu and Yu 2019).

Previous research has established that farmer's pollution prevention behavior is the result of the joint action of their psychological cognition and environmental regulation, when the pollution prevention behavior is more difficult to implement, the farmers' reliance on the psychological variables will be weakened (Pan et al. 2016), and the influence of environmental regulation on the pollution prevention behavior will be strengthened (Guo and Zhao 2014; Kumar et al. 2013). In the process of practice, farmers have a low level of awareness of policies and regulations, which to a certain extent weakens the implementation of relevant policies (Yang 2013). Therefore, it is feasible to improve both the environmental perceptions of pig farmers and the institutional context simultaneously (Zeng et al. 2024).

For policy implementation, the insights gained from this study indicated that farms that have been penalized have not upgraded their pro-environmental behaviors. This was in line with Zhao et al. (2009), that overly rigorous and "one-size-fits-all" approaches may jeopardize the efficiency of farms and inhibit their incentives for technological innovation. That is because, the government strengthens the restrictive supervision of pig farms to counteract the negative environmental externalities by taking command-and-control measures. Nowadays, most of the means applied in China are fines, rectification and relocation, which undoubtedly add to the woes of small-traditional farms that have low incomes and are exposed to high-risk markets. And the moratorium creates huge daily financial deficits for intensive large-scale farms (Zhang et al. 2022; Ren et al. 2018; Zeng et al. 2024). Risk aversion theory suggests that farmers conform to the assumption of rational economic agents to maximize returns from production and operation, however, when farmers are in an environment of uncertainty or risk, their goal is to minimize production losses (Werner 2008). These could significantly slash farmers' enthusiasm for scientific

MSM, impelling them to take shortcuts to obtain environmental permits and quickly resume production for profit. However, it cuts both ways, as punitive policies also have a deterrent effect to some extent. In the face of the potential risk of huge financial losses due to environmental sanctions, the economist will take certain environmental measures to prevent this damage before it occurs.

As a result, the implementation of constrained-oriented regulations requires attention to modalities and enforcement efforts. Farmers need to be guided to participate in environmental governance, rather than focusing only on prohibiting their behaviors. Implementation intensity should be progressively strengthened, and the orientation should be flexibly and effectively adjusted in the light of the actual situation. The passive impacts of restrictive rules like stocking restriction, farm abandonment or relocation revealed that the government should reasonably control the interference with the livelihoods of farmers. Recognize the indispensability of informal rules, strengthening the binding force of the resulting implicit environmental regulations, such as intangible environmental ideas, concepts, awareness, attitudes and perceptions. Improving ecological and policy rationality can be accomplished by awareness-raising and education. Strengthening the publicity and education of green-ecological breeding development employing village assemblies, study manuals and eye-catching slogans, etc., committed to enhancing farmers' ecological awareness and responsibility, and promoting the conscious transformation and optimization of sustainable MSM behaviors.

On the other hand, incentive regulations were effective in improving farmers' eco-friendly behaviors. The view was echoed by Mueller (2013) that government incentives, particularly compensation, were more effective than disciplinary and constraint policies. Subsidies have a stimulating effect on production and investment activities with externalities, which could compensate to some extent for the shortfall caused by manure treatment. Therefore, there is a need to implement the dissemination and implementation of subsidy policies, and complete more diversified, multi-type breeding subsidy policies, regarding construction, technology adoption, processing product production, fertigation transportation, etc. The more comprehensive subsidies farmers receive and the more inclusive policies they enjoy, will increase their earnings and lead to a higher willingness of farmers to respond positively to national policies and try more scientific MSM practices. Moreover, providing pinpoint and targeted subsidy schemes for specific breeding groups to improve policy effectiveness. While strengthening the subsidy policy publicity, establishing a platform for information exchange between farmers and the government is significant, focusing on the subsidy implementation and effectiveness for timely adjustments.

4.3 Implications on target pig farm across scale types

In addition to the land and policy rationality impacts, farmers' MSM behavior is a rational choice under their individual survival rationale, which needs to be further internalized (Lin et al. 2018). A combination of external incentives and internal guidance should be used to translate into autonomous behaviors of farmers.

For compact conventional farms, given the positive role of economic and technical conditions on farmers’ MSM behaviors, technical knowledge should be promoted in the form of skill manuals and information materials. Considering the lower education level and the generally older age group, actively conducting sci-tech training by visiting households and providing face-to-face guidance. In addition, strengthen the innovation and improvement of MSM methods and promote the implementation of various technologies to enhance the effectiveness (Truelove et al. 2015). For economy acquisition, there is a significant positive correlation between individual income and their environmental awareness (Liu et al. 2014). Increasing farmers' MSM motivation can therefore be achieved through the considerable benefits from by-products production and policy subsidies. Dilemmas of insufficient product recognition, weak production technology and poor supporting services are the main challenges to the realization of the value chain of MSM (Zhang et al. 2021c; Zheng et al. 2017). Further publicize the benefits of organic fertilizer application for regional soil quality and crop quality (Pampuro et al. 2018; Case et al. 2017). Provide subsidies and technical support to organic fertilizer manufacturers to optimize production processes. More importantly, develop quality standards for organic fertilizers processed from livestock waste to facilitate fair market transactions. From the perspective of individuals, pig farmers have a stronger sense of ownership in the environmental management of the pig industry, and the probability of implementing standard-compliant and environmentally friendly MSM practices increases as they recognize their responsibilities and obligations (Lin et al. 2018). Therefore, it should be a long-term strategic task and central mission to improve farmers’ ecological awareness. Firstly, to increase publicity on the environmental hazards of casual disposal of livestock waste, to effectively raise environmental knowledge level and environmental protection responsibilities among farmers. It is feasible to organize cooperatives or farming communities to strengthen exchanges and communication among farmers. Thereby, through social networks, stimulating positive attitudes towards eco-friendly breeding, and developing better pro-environmental behaviors (Wang et al. 2024). Thirdly, innovative and effective use of regulatory mechanisms, taking full advantage of the surrounding masses of public opinion and informal monitoring functions to enhance responsibility awareness and strengthen subjective normative pressure. Residents are encouraged to monitor and investigate the polluting behaviors of neighboring farms (Wang et al. 2024), meanwhile, the exemplary role of model pig farms should be utilized to form a good culture for the pig breeding industry.

In terms of moderate potential farms, the study indicated that there was a clear inverted U-shaped curve relationship between up-scaling and livestock pollution (Pan 2015). Medium-scale farms are in the expansion stage facing greater pollution risk and MSM difficulty. Promoting labor-saving technologies that facilitate factors of production such as machinery to address the challenges of labor shortages and rising labor costs (Wu and Li 2016). Besides, transfer of complementary land and mechanized application can alleviate the reliance on manual labor. Bin et al. (2017a) pointed out that the ease of fertilizer production and use affected farmers' willingness to adopt MSM practices. Moreover, developing appropriately scaled operations contributes to the efficiency advantage (Li 2021b), and improving the degree of organization can alleviate the pressure of MSM to a certain extent (Pan 2015). The government could create conditions to encourage and guide moderate farms to participate in various forms of industrial organizations, standardize the MSM methods and enhance pollution treatment capacity through the provision of additional training courses on clean pig waste treatment technologies. Strengthening the cooperation with third parties, and adopting agricultural socialized services can provide convenience for waste processing, farmyard manure handling, transporting and applying, and enhance productivity (Zhang et al. 2024; Shu et al. 2019). Additionally, pig farmers and neighboring growers sign an agreement for field waste utilization, which in theory and in practice is a relatively low transaction cost and low government regulatory cost scheme of governance (Shu et al. 2019). Li (2021b) presented that increasing financial support for medium-sized farms had a positive impact on farmers' MSM behavioral improvement, because of its weak capital accumulation capacity, and the difficulty in fully deploying MSM facilities in a short period, thus financial subsidies could appropriately bridge the economic shortfalls.

For intensive specialized farms, farmers already have a well-developed level of literacy and mastery of technology, in addition, two of the greatest strengths are capital and labor. While perfecting the MSM behavior on their own farms, expanding the service area when they have the ability, and relying on their own strengths to drive the regional pig waste treatment, utilizing the radiation-driven role of demonstration households adopting more comprehensive MSM technologies (Liu et al. 2015; Yu et al. 2011). The policy demands showed positive effects on eco-friendly MSM adoption. In formulating innovative policies and subsidies, local agricultural governments and departments should through consultation and dialogue, understand their facilities and equipment supports, environmental assessment procedures, waste utilization channels, supporting land area and other specifics, and the main problems, to reach a reasonable and applicable range, and improve the effectiveness of targeted and flexible policies (Wang et al. 2024). Furthermore, it can actively promote government-social capital cooperation, government-purchased services, socialized services and other ways to establish a beneficiary-payment mechanism and a market-oriented construction and management mechanism, and leverage financial and social capital into the livestock waste resource utilization industry to maintain long-term stable operation (Zheng et al. 2017). Thereafter, the relevant departments should further refine the institutional arrangements focusing on key aspects such as environmental access, law enforcement and supervision, implementation of responsibilities and performance assessment (Jin et al. 2018). Simultaneously, highlighting the means of informatization and regular scheduling of progress. It is meaningful to induce large-scale farms to strengthen self-restraint and self-management. Driving media power to monitor the environmental behavior of sewage enterprises (Wang et al. 2024). In addition, through preferential policies in finance, taxation and credit, supporting the development of large-scale pig farms with advanced environmental and technological levels, taking into account social and environmental benefits while meeting consumer demand (Yu et al. 2011).

Chapter 7

General discussions, perspectives and conclusion

1. General discussions and perspectives

1.1 Status, opportunities and challenges for MSM approaches

Scaling-up intensive pig farming can increase profitability, but it also exacerbates environmental pollution caused by the disordered discharge of manure and sewage. MSM is critical to mitigating environmental pressure and reusing waste resources. According to Chapter 3, normally, the entire chain of MSM contains several sections, including collection, storage, processing and utilization. Moreover, there are various available approaches in each section, the integrality and coherence of MSM should be noticed because the practices at the upstream stage affect the composition and amount of waste at subsequent stages (Petersen et al. 2013). And it is significant to notice that cleaner breeding should start with waste source control, focus on prevention, and eliminate contaminants as much as possible before it is produced. Collection is the upstream of MSM, technology adoption has significant implications for the difficulty and efficiency of subsequent processing and final utilization.

Based on the MSM practices in Chapter 3, water consumption, infrastructure investment and power consumption are relatively high in flushing cleaning method (Pang 2021). Additional sewage and mixed fecal wastewater generation significantly increase the cost and difficulty of subsequent treatment, especially for fertilization processing, because of the high moisture content of 95%-98% and a low-nutrient solid fraction (Huang et al. 2021a; Pang 2021). Furthermore, it is ineffective for biogas production due to insufficient concentration of organic matter (Weng et al. 2019). Therefore, the flushing practice is not compatible with the technological needs of large-scale pig farms.

Water-submerging process decreases the stress impact on animals compared to scraper scavenging process, which is better for pig welfare. However, long-time waste remaining may produce harmful gases (such as hydrogen sulfide) affecting animal health (Pang 2021), therefore, ventilation and environmental monitoring are particularly important. Chronically mixed waste can significantly increase the difficulty of separating solids and effluent during subsequent steps, whereas prolonged maceration of soluble organic matter facilitates subsequent treatment, such as anaerobic biogas digestion in MPM and SBM (Weng et al. 2019). In terms of resourcing, water-submerging should be used in conjunction with follow-up resource utilization, such as fertigation. Immersion method applies to farms surrounded by cultivated farmland. The Southern Water Network region is not applicable to this approach, because of the constraints on successive dryland resources and environmental conditions (Huang et al. 2021a).

The most common method, mechanical scraper dry collection has the advantage of improving work efficiency, reducing labor needs and sewage yield (Huang et al. 2021a). The amount of effluent produced by scraper is less than half that of waste submerging practice (Chang and Yang 2015). Collected fecal mixture contains high levels of solids and organic matter, which contributes to the organic fertilizers production, TSM, PPSUM and PPFUM are befitting. However, the disadvantage is that it requires equipment investment with a machine failure rate, and certain maintenance and operating costs (Huang et al. 2021a; Schuchardt et al. 2011). In general, mechanical scraper could be the preferred choice, nevertheless, it still requires improvement regarding reduction of equipment damage to animals, improvement of cleaning efficiency and effectiveness and the decline in MSM cost (Pang 2021; Weng et al. 2019).

Table 7-1. Comparison of manure collection technologies.

Method category	WU	EU	LU	MC	IC	PD	PE
Manual scraper	Less	Less	More	Less	Less	Easy	Medium
Mechanical scraper	Less	More	Medium	More	More	Easy	Medium
Water-flushing	More	Less	Less	Less	Medium	Difficult	Good
Water-submerging	Medium	Medium	Less	Less	More	Difficult	Bad
Mattress bed	Less	Less	More	More	Medium	Easy	Medium

WU: Water use, EU: Electricity use, LU: Labor use, MC: Maintenance cost, IC: Investment cost, PD: Processing difficulty, PE: Pigsty environment.

Nowadays, ecological farming has emerged as a compelling topic. Microbial fermentation mattress bed is an environmentally-friendly, safe and effective ecological pig breeding method proposed by combining modern microbial fermentation treatment technology (Chen et al. 2017b). Microorganisms are mixed with straw and fermented at high temperatures to make organic bedding fermentation beds, which results in the direct decomposition of animal waste (Weng et al. 2019). The advantage is that there is no need to wash pigsty, realizing clean production with no pollution and no discharge. Nevertheless, manure requires to be hand-filled and bedding needs to be regularly turned. This is favored for chicken rearing because of the chicken's rummaging habit (Yang et al. 2019). Besides, bedding produces heat, which is not favorable to pigs' health, especially in summer (Zhang et al. 2013). It is difficult to control temperature and humidity, therefore, stocking density must be strictly controlled (Gao et al. 2020b; Sun et al. 2023). This technique will enlarge farm MSM area, applicable to smaller farms (Gao et al. 2020b; Weng et al. 2019). In addition, because of the direct contact with feces, bacterial strains are more affected by antibiotics and other drugs, which can increase the difficulty of epidemic prevention in pig farms (Zhang et al. 2013). Therefore, the application of mattress beds to pig breeding is limited in China.

Heterotopic fermentation bed is proposed to solve the aforementioned problems (Hao 2024). The layered pigsty can effectively alleviate the problem of large footprint, bedding laid on the sublayer of the leaky floor can avoid direct contact between animals and bedding, and facilitate mechanized flipping (Liu et al. 2020b). Waste soaking combined with ectopic fermentation bed practice contributes to the reduction of animal waste generation, utilization of straw, mitigation of disease transmission probability, and improvement of organic fertilizer quality simultaneously (Yao 2021; Liu et al. 2020b; Chen et al. 2021). Fermented mattresses can be used for vermiculture (Xie 2018). In addition, the benefits of reducing GHG emissions, improving air quality in the enclosure and animal welfare have also been demonstrated (Ruckli et al. 2024). China has plenty of straw with 8.3t annually, promotion of fermentation bed process can effectively realize the comprehensive utilization of a variety of agricultural wastes (Jing et al. 2024). Furthermore, the application of algal pond with aerobic biological processes contributes to the production of activated sludge and construction of constructed wetlands, which strengthens the nexus of food-water-energy and realizes ecological farming (Nguyen et al. 2022; Milledge et al. 2019). Microalgal remediation could also recover nutrients from waste for carbon cycle and circular bioeconomy (Ngo et al. 2022; Goveas et al. 2022).

China is trying other solution for “Building-type pig raising”, which realizes the upgrade from single-floor to multi-storey rearing (Zhang et al. 2020a; Liu 2022). Exploiting spatial production effectively alleviates the constrains of land tension and high rearing densities, as well as provide opportunities for layered scraper and heterotopic bedding. However, special construction techniques for impermeability and load bearing are particularly important.

To sum up, sustainable MSM should be closely aligned with resource recycling and respecting ecological criteria, PPFUM is best suited to multiple uses of resources. Most importantly, each link should match the subsequent processing and terminal application (Huang et al. 2021a). Based on the farms’ surrounding conditions and resource utilization outlets, forward extrapolate interconnected collection and processing approaches (Niles et al. 2022). For composting, a scraper dry collection is preferred. Large intensive pig farms that follow the biogas anaerobic fermentation can tend to use water-soaking or mechanical scraper. Rationalizing the combination of MSM approaches to form an integrated application that maximizes the effectiveness of technologies by making the individual methods fully operational (Gao et al. 2020b).

1.2 MSM feasibility among farmers with application prospect

Chapter 3 summarized five key MSM pathways and their features, although the transparent and explicit evaluation of promoted MSM methods provides a basis for information dissemination, the corresponding MSM measures adopted by pig farmers are multitudinous in reality. Decision-making processes of individual pig farmers for deciding MSM strategies are complex and inherently dynamic depending on their socioeconomic circumstances and available resource endowments (Meyer et al. 2011).

Effective implementation of MSM requires not only weighing the characteristics of methods, but also adapting it to individuals' characteristics and regional conditions. Chapter 4 discriminated farms' heterogeneous characteristics on various MSM modes to enhance the efficiency of waste resource utilization. The synthesis consideration of farm scale, breeding structure, available land and farmers' awareness, influences the appropriate mode selection. Higher education levels and greater pro-environmental perception among farmers significantly promoted technology-intensive MSM modes such as SBM, PPFUM and PPFUM. Scale upgrading had a positive effect on mechanization adoption and diversified strategies application.

Consideration of resources and environmental conditions is also particularly important. Water resource availability and land carrying capacity in the region are essential conditions for MSM mode selection (Varma et al. 2021). For example, water is scarce in the arid and semi-arid regions of Northwest China, so it is necessary to minimize the water consumption and ecological environment impact, by choosing less water-intensive practices such as scraping cleaning or fermentation mattress bed (Zhang et al. 2013). From the perspective of land, generally, in both developed and developing countries, farmland has always been considered the final outlet for nutrient recovery (Machete and Chabo 2020). However, there is also a challenge of less available land, with a reduction of 7.53 million ha of national arable land in recent 10 years (NBSC 2021b). Waste disposal with appropriate treatment processing is particularly important to avoid secondary pollution. Thus, only in the main producing areas of dry crops, PPSUM is the preference to promote integration of planting and breeding. For economic performance, farmyard manure can replace 43% of synthetic fertilizers with constant wheat yield, which even has the potential to increase yield, and it also saves the cost of synthetic fertilizers (LI et al. 2020). In addition, MSM adoption should be integrated with regional economic levels and labor resources. In economically developed areas such as the Eastern coast of China, where labor forces are scarce and expensive, the modernization process should be preferred, with low labor intensity and high production efficiency.

Moreover, although this study contemplated the waste treatment of swine, more insights could be used in other livestock and poultry farming. MSM efficiency is closely related to the raw waste characteristics. Anaerobic lagoons, flushing and scraping were widely used for pig and dairy waste management, their waste has high water content, which is suitable for biogas fermentation (Varma et al. 2021). Bedding is more common for dairy rearing (Ferraz et al. 2020; Fregonesi et al. 2007), and bedding materials quality directly affects cow stall comfort and milk production. Forklift was a special collection method for dairy manure collected (Zhang et al. 2021b). Most importantly, differences in waste collection methods are related to breeding conditions and feedings, the processing and utilization are determined based on the waste composition. And poultry manure is mostly used for feeding, because of the high nutrient content in excreta. Poultry has a short digestive tract, 70% of the nutrients in the feed are excreted without being digested and absorbed (Gao et al. 2020b). On the premise that human, material and financial resources are permitted, optimize feed formulas, improve feeding techniques, and adopt cleaner production processes that can reduce the amount of livestock waste generated, MSM difficulty and save costs.

Frontier thinking of the development trends of pig farming, although the proportion of small-scale farms has been declining continuously in the last two decades (Zhao et al. 2019a), it is imperative to improve the standardization level and strengthen the cooperation of small and medium-sized farms. TSM and MPM can guarantee the basic environmental provisions for these farms. In developed countries, for example, there are only four large farms in the Netherlands, the entire agricultural and livestock industry is dispersed among 137,000 family farms across the country, generating animal waste that is digested on their own farms. Denmark relies on the country's 80,000 yeoman farmers who produce both crops and meat. Although there are large livestock farms in the U.S., the dominant role in hog raising is performed by small integrated subsistence farms with 200-500 hogs annually (Benecke 2024; Zhao et al. 2024). The key to sustainable breeding is to realize the integration of animals and land, and nutrient cycling.

Meanwhile, large-scale farms and pig farming communities are becoming the continuous trend of pork production. Scale-up rate of livestock is anticipated to reach over 75% by 2030 (GOSC 2020). Rising intensification levels undoubtedly create large quantities of concentrated pig waste, while increasing mechanization is more conducive to promoting knowledge-intensive MSM modes, such as SBM, PPSUM and PPFUM. Furthermore, with the farm expansion and increased labor costs, pig industry will gradually transform from manual culture to mechanized farming, and progressively to intelligent farming development (Huang et al. 2021a). Along with the progress of modern electronic information technology, big data and artificial intelligence, informatization platform with automatic manure cleaning equipment will be the future orientations (Marques-dos-Santos et al. 2023; Wang et al. 2021a). It can realize automatic and precise management, including real-time status, historical data, statistical analysis and fault alarms. Automatic acquisition of information as well as the system remote control and debugging contribute to the improvement of MSM stability, reduce workforce cost, and promote the informatization, intelligence, cleanliness and sustainable development of livestock production (Wu et al. 2023a).

Concerning the environment, carbon neutrality is gaining more attention nowadays. China is committed to a reduction of 65% of carbon emissions by 2060 at the Climate Ambition Summit. Modes containing anaerobic digestion (SBM, PPSUM and PPFUM) should be promoted as mainstream. Theoretically, methane production is 0.30~0.39 Sm^3CH_4/kg VS (Lee et al. 2018), 1-ton pig manure can obtain 26.81 kg of natural gas (Duan et al. 2020). It could be assumed that all scale farms are considered to implement the appropriate modes mentioned above. The consequence is tremendous for both environmental performance and economic benefits, represented by reducing environmental pollution, decreasing synthetic fertilizer use, and enhancing bio-energy production (Corbala-Robles et al. 2018; Lopez-Ridaura et al. 2009; Nagy and Wopera 2012; Wang et al. 2021c; Li et al. 2016b).

In general, the livestock MSM in China has undergone stages of backyard recycling-unit expansion-resource circular economy (Liu and Zhang 2014). Future MSM will comply with the modern eco-agriculture concept, emphasizing the modern, efficient and cyclic agriculture development, and forming a natural management system. Agroforestry was considered an ecological pattern to balance livestock breeding and environmental preservation (Rojas-Downing et al. 2017). In pastoral and semi-pastoral areas with adequate land, promote free-range breeding for pigs and cows. Adopt forest farming, which is an ecological approach to raising chickens by utilizing food such as insects or pasture in the forest. However, wild rearing should pay attention to rotational grazing to maintain the ecological balance of food supply and manure consumption among chickens, grasses and forests (Yang et al. 2019). “Agro-ecological zones” or “eco-breeding parks” were put forward for the establishment of ecological complexes (Wu et al. 2023a). It has a complete industry chain, involving breeding, feeding, slaughtering, environmentally friendly energy producing, planting, even tourism (**Figure 7-1**). Animal waste is used for fertilizing and energy production, cropping contributes to animal feeding, the cultivation of vegetables and fruits can promote the picking industry, the biogas project is a significant link, to realize waste recycling.

Figure 7-1. Aggregation production of Eco-breeding parks.

1.3 Evaluation and prospect on comprehensive centralized regional mode from environmental and economic perspectives

Currently, pig breeding is moving toward more intensive development and is accompanied by the integrated generation of pig waste. This has disrupted the synergy between the original MSM mode and corresponding farmland at the household level. The aforementioned chapters obtained the dominant MSM modes, among them, the most comprehensive scheme was PPFUM, covering scientific technologies and an integrated approach to resource utilization. However, its implementation requires financial and technical support and it is not practical to achieve wide-scale replication. Centralized bio-energy mode (CBM) relying on capable MSM plants may be a solution in response to the transformation of pig farming. It is significant to explore its comprehensive evaluation, applicability and feasibility.

Therefore, compared to the individual and traditional mode (ITM) at the household level, Chapter 5 was conducted using life cycle assessment and life cycle cost analysis, systematically assessed the environmental performance and economic viability of CBM at the regional scale, and further explored the adaptability of multi-subjects (various pig farms and biogas enterprise). Results that compared with ITM, CBM appeared to be a better alternative in terms of global warming, terrestrial acidification and marine eutrophication, with decreases of 49.49%, 6.8% and 4.67% respectively. The contribution of fossil resource scarcity was significant in CBM because of additional transfer, but it could be reduced by improving transport efficiency and restructuring transport distances. Simultaneously, CBM indicated a substantial profit of 48.5 CNY for managing per ton of pig waste. Furthermore, both environmental and economic performance could be improved by scale expansion and transport optimization, with the optimal collection radius less than 31.45 km. In general, ITM was appropriate for the pig farmers who manage both breeding and cropping, as it is beneficial for nutrient recycling and accessible outlet for livestock waste. CBM was a preferable solution for regional scattered small and medium-sized farms that are suffering from financial burdens, or insufficient farmland, as a more efficient, cost-effective, controlled and regulated manner for resource recovery. Furthermore, critically assessing the applicability and feasibility of implementing CBM.

Frontier thinking in the development of agriculture aims to strengthen the coupling of breeding and cropping. The proportion of scale livestock and poultry breeding has increased rapidly from 21.8% to 58.3% over the past decade, which is anticipated to reach over 75% by 2030 (GOSC 2020). The construction of regional ecological recycling agriculture and specialized large and medium-sized biogas projects have become key strategies for national implementation in China, to achieve a comprehensive utilization rate of over 90% of livestock and poultry waste by 2025. Increasing mechanization and specialization is more conducive to mitigating the risk of secondary contamination and improving nutrient cycling efficiency. Regional MSM modes like CBM contribute to broader coverage and further enhance the sustainability of the system.

From the perspective of environment, according to the measurement of available cultivated land area, livestock and poultry population and corresponding discharge coefficients by region (Zhang et al. 2020b), 7 provinces nationwide are at risk of exceeding their land allocation capacity (**Table A7**). Therefore, it could be assumed that these regions should consider implementing CBM, the consequence is tremendous for both environmental performance and economic benefits, represented by minimizing environmental pollution, and strengthening bio-energy production. In particular, it could lead to a reduction in GHG emissions ranging from 1.15% to 14.35% based on regional scope (Table A5), accompanied by 13.04 million CNY to 354.87 million CNY for carbon trading[26]. Undoubtedly, the extension of CBM contributes to the acceleration of China's carbon reduction targets. The IPCC 3rd Assessment Report stated that global warming was projected to increase by 1.4 to 5.8℃ between 1990-2100 (Allen et al. 2000; Wigley and Raper 2001). Moreover, more developing countries facing similar challenges may also consider CBM as a means to alleviate this critical pressure.

Regarding organic fertilizer, its use has been prioritized in China, since 2015, the country has been implementing the initiative of stable use of chemical fertilizers. As a major consumer of fertilizers, China accounted for approximately 30% of worldwide consumption (IFIA 2022). The organic fertilizer market shows promising prospects. Further, the unique properties of digestate produced by CBM have been proven to be highly effective in enhancing crop productivity, pest-resistant and soil-improving (Chen et al. 2019; Xia et al. 2017), which can ensure food security, increase farmers' income, and undoubtedly tap into the enormous potential market. Furthermore, in the recent decade, the Chinese government has introduced various policies to support bio-energy, including the Renewable Energy Law and the Biomass Power Project Construction Work Plan (Wu 2020b; Feng et al. 2012). Firstly, these policies strongly facilitate the development of renewable energy enterprises, secondly, prioritize the use of renewable energy sources, thereby guaranteeing the production and market availability of regenerative energy. Annual biogas production is expected to exceed 300×10^{27} m^3 by 2030 (Giwa et al. 2020), establishing biogas projects as the mainstream waste treatment solution for the future.

In Chapter 5, we clarified the potential of CBM and provided valuable references for its implementation, expanded the system boundary of MSM, and enriched the application of LCA at the regional level in agricultural system. While explored the possibility of resource reintegration and effective allocation in pig's MSM. Conclusions provided a visualized and reliable MSM strategy to

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[26] Average trading cost was 40 CNY/t according to Chinese Certified Emission Reduction (CCER) in 2021.

adapt to the transformation of the pig industry in China, and references to various regions on centralized mode extension. Ultimately, further contributing to a more efficient, cost-effective, controlled and regulated manner for resource recovery, culminating in the sustainability of pig farming and achieving regional environmental-friendly agriculture.

1.4 Construction of eco-friendly and sustainable MSM safeguard mechanism

In China, the relationship between the livestock industry and the environment has gone through three stages. Initial stage was the smallholder self-circulation pattern. With the expansion of the breeding sector and the rise of professional households, environmental problems have gradually emerged, the Government's attention and the introduction of relevant environmental policies mitigated these ecological tensions. However, with the intensification of breeding and the popularity of the concept of circular farming, the resourceful use of fecal matter has become the most promising initiative to approach eco-agriculture. Focusing on technology and scientific approaches and targeting resource utilization replace the reliance on nature, which is a sustainable measure to avoid the "pollution sanctuary hypothesis", and gradually improve the threshold of environmental access (Levinson 2018).

Guiding farmers to adopt more holistic technologies is key to improving farmers' environmental friendliness behaviors and achieving sustainable MSM. Due to the environmental externalities of pig breeding, which could be achieved through the dual role of intrinsic enhancement of initiative and extrinsic implementation of environmental regulations. From the perspective of three scales of pig farms, Chapter 6 established an objective theoretical framework with land factors, resource endowments, policy rationality and individual characteristics as the factors influencing farmers' decision-making on MSM strategies adoption, exploring respective effectiveness and intensity shown by key factors. Clarify the both effective paths of individual improvement and government intervention for the utilization of manure resources on different-sized pig farms, and provide relevant detailed recommendations.

Intensive specialized farms were more environmentally friendly, applying more comprehensive MSM methods, having relatively higher levels of knowledge and environmental perceptions, and better resource endowments. However, their demand for land transfer and policy support was relatively higher. Targeted and effective policies, such as preferential policies in finance, taxation and credit, can assist them in leveraging their strengths to achieve regional excreta treatment. It can actively promote government-social capital cooperation, to establish a market-oriented management mechanism. This inclusion of social capital can guarantee sustainable MSM.

Compact conventional farms and moderate potential farms still need to strengthen their green production behaviors by land readjustment, policy incentives and awareness-raising. However, in comparison, moderate-scale farms were in the expansion stage facing greater pollution risk and MSM difficulty, and compact farms had more possibilities and optimizing upside potential. Land as the dominant outlet, its properties, size and transaction price influence farmers' behaviors, the government should optimize the structure and layout of cultivated land use, and balance the land-transfer market transaction prices. Preserving concentrated and contiguous high-yield farmland to improve the availability of machinery for waste field utilization, further alleviates the limitation on labor dependence, especially for moderate-scale farms. Allocation of reasonable land area and coordination of transferable land prices contribute to the efficient use of fields and controlled MSM expenses. Most importantly, encourages pig farmers with arable land to practice integrated breeding and cropping to enhance nutrient cycling, thus raising their awareness of crop production, land conservation and green breeding. Additionally, strengthening the regulation of land carrying capacity in areas of adequate arable land is important to avoid over-fertilization and secondary pollution.

The improvement of technology and economy favors compact farm approaching more environmentally friendly methods. Promoting technical knowledge and conducting technical training, in order to enhance farmers' ability to distinguish flexible measures, and carry out more comprehensive MSM strategies. Furthermore, increasing farmers' MSM expected returns through the considerable benefits of resource utilization and policy subsidies, to stimulate their willingness and motivation (Gao et al. 2020). Local governments and village collectives could develop quality standards for organic fertilizers processed from local livestock waste to facilitate fair market transactions and provide security for commercial value. Characterized by dispersed distribution, lower level of education and less access to information among compact farms. Local governments can organize cooperatives or breeding communities to expand the channels of information dissemination, strengthen communication among farmers to improve their perceptions of technology, environment and policy. Strengthen normative pressure to enhance farmers' awareness of responsibility and positive attitudes toward breeding environmental protection, thus, participating in scientific and comprehensive MSM.

In the process of formulating and implementing specific environmental regulatory policies, it is crucial to improve the construction of livestock and poultry pollution control regulations and systems. Strengthening the convergence of policy objectives, the orientation and intensity should be flexibly and effectively adjusted in the light of the actual situation. For incentive regulations, complete more diversified, multi-type pig breeding subsidy policies and detailed subsidy programs. Establishing and reinforcing the concept of "utilization as the most effective pollution control measure". Policy implementation should be based on economic incentives complemented by command-and-control policy instruments. Constrained regulation should be discreetly administered and progressively strengthened. Correcting excessive no-farming policies in a few areas and reducing the cost of enforcing binding instruments. A reasonable definition of binding instrument boundaries is significant to avoid the issue of “one-size-fits-all” or the non-equity of wide variations in enforcement behavior (Jin et al. 2018) .

1.5 Development of friendly animal welfare and appropriate environmental protection: Insights from Europe

Given the outbreak of COVID-19 globally, public recognition of the harmonious development of humans, animals and the ecological environment is increasing (Liang et al. 2023). With the intensification of livestock farming, high-density-productivity breeding is considered to be potentially detrimental to animal welfare (Ducrot et al. 2024). Besides, with the accelerated agriculture development and stressful environmental pressures, the balance between production and the environment is skewed. Strict regulations constrain producers' behaviors at environmental risk, but they also place economic plight on production. The violent protests in Europe prove this contradiction. Agricultural producers, especially small and family farmers stated that harvest had tiny margins, accumulated production restrictions made financial difficulties and put livelihoods in peril. Conflicts between intensive breeding and animal welfare, and contradictions between strict environmental regimes and agricultural benefits have become the globally valued challenges

Livestock production with Animal welfare in Europe and China

The World Organization for Animal Health (WOAH) guided animal welfare work with the principle of “Five Freedoms”, announced the first standard in 2005, which has been continually refined (Ducrot et al. 2024; Li et al. 2023; Guevara et al. 2023; Zeng et al. 2023). EU has the most advanced animal welfare legislation worldwide (Simonin and Gavinelli 2019). Spain, Germany and Denmark are the major pig-producing countries in the EU, pay considerable attention to animal welfare policies and regulations. Spain introduced the *Support Plan for the Development of Large-Scale Pig Farms (2017)* and the *Reduction of Antibiotic Use in Pigs Plan (2018)*. The German government implemented the *Animal Protection Act (2019)*. Denmark is steering a green and sustainable way for pig industry, launching the *Sustainable Development of the Pig Industry Policy*, and *Quality Assurance of the Whole Pig Chain Policy* (Zhao et al. 2024).

Nevertheless, these pro-animal protection policies also raise economic concerns and especially accelerated small-scale farms' exit from the market. Free-ranging and extensive agriculture may increase the risk of animal contact with disease and exposure to weather extremes, e.g. heat stress (Ducrot et al. 2024). In Belgium, the primary driver of non-transfer of pregnant sows is associated with economic consequences (Tuyttens et al. 2011), however, repeated flock shifting may lead to a stress response (Li and Chen 2024; Wang

2020). Furthermore, conflicts with other legislation and knowledge gaps may act as barriers to the implementation of animal welfare (Temple et al. 2015).

China's concern for animal welfare started relatively late compared to developed countries (Xiao 2015). There is not yet comprehensive legislation related to animal welfare currently (Guevara et al. 2023). Less than 80% of animal husbandry practitioners are aware of animal welfare-related knowledge, 30% are wise to related policies (Lu et al. 2022). Moreover, Chinese consumers have little knowledge of the concepts and information on animal welfare (Liang et al. 2023). China has relatively high pig breeding densities with 0.6-0.8 m^2/pig, due to high population demands and land constraints (Fu et al. 2016). This overstocking may result in poorer air quality and high ambient humidity, thus reducing pigs’ exploratory behavior and increasing stress response (Cornale et al. 2015).

Studies indicated that stocking density was less important than other environmental factors (Li et al. 2023). China is devoted to pigsty scientific construction, e.g. ventilation enhancement and underfloor heating adoption in winter (Li et al. 2023). Apply automatic temperature control and mechanical wet curtains to maintain the temperature, humidity and air quality (Qiao 2021). Increasing environmental enrichment to reduce pigs’ boredom and eliminate their aberrant behaviors (Qiao 2021). Wallgren and Gunnarsson (2021) found that offering straw for arching feeding was effective in reducing pigtail injury rates. Environmental enrichment has positive effects on pig physiology, growth and metabolism performance, and meat quality (Li and Fu 2020). Moreover, optimizing feed formulation and drinking performance can control heat stress in pigs (Montnach 2019).

Agricultural production with environmental regulation in Europe

Rules for agricultural environmental protection are also strict in Europe. The European Green Deal aims to be climate neutral by 2050, including cutting fertilizer use by 20%, devoting more land to non-agricultural use, and doubling organic production to 25% of all EU farmland (European Commission 2019). The New York Times (2022) reports that the Dutch government has announced a 50% reduction in nitrogen emissions by 2030, some places should stop livestock farming entirely and over 3000 farms near environmentally sensitive areas are planned to be bought or closed (Dowling 2022). Furthermore, the political office proposes the possibility of taxing nitrogen emissions, and Berlin aims to phase out tax breaks for agricultural diesel fuel. In addition, the EU’s Common Agricultural Policy (CAP) encouraged consolidation, since 2005, the number of farms has fallen by a third, large farms faced debt in low-margin businesses and small ones become less competitive (Henley 2024). If farmers want to survive, they are forced to adapt more rules and costs (Casert and The Associated Press 2024). A survey by the German Farmers' Association in 2021 showed that nearly 70% of pig farms believed that environmental standards reduced their revenue margins and they were willing to exit from the farming industry (Zhao et al. 2024). In addition to the pressure caused by superimposed environmental policies, import bugbear also adds a burden on farmers. Globalization increases the imports from cheaper locations like New Zealand and Chile. For Ukraine, the EU waived quotas and duties following Russia's invasion, which depressed prices and fuelled resentment about unfair competition (Henley 2024). Wide-ranging trade deals between the EU and South America's Mercosur trading bloc decreased EU farmers' confidence (Henley 2024). The importers do not necessarily comply with stringent environmental regulations and costly production as EU farmers and are therefore more price-competitive. EU farmers complain that the environmental policies are unfair, unrealistic, and economically unviable. Conflicts between environmental protection and agricultural production are becoming more pronounced.

Conflict mitigation measures by adjusting market role

Increased production costs with unsatisfactory earnings appear to be the major obstacle to the implementation of animal welfare and environmental protection efforts. Higher levels of animal welfare products are accompanied by higher production costs, excess costs paid for by producers are unsustainable. Consumers may be able to ease the pressure of additional costs because of the close causality between better animal welfare and higher-quality meat (Liang et al. 2023). The survey in Australia indicated that 34% of interviewees were willing to pay an extra 10% of the product price for animal welfare (Taylor and Signal 2009). American consumers also could accept a 20% premium to create a more comfortable living environment for animals, such as involving gestation crates or cages (Tonsor and Wolf 2011). In Japan and Korea, consumers were concerned about whether products were labeled for animal welfare or not, and they were willing to pay for welfare-friendly products (Sonoda et al. 2018; Kitano et al. 2022; Hong et al. 2018). In China, respondents who were aware of animal welfare, their payment level for additional prices increased from 16.2% to 21.3% (Wang and Gu 2014). As Liang et al. (2023) mentioned, consumers in economically developed regions were willing to pay a premium of 27.8-37 CNY/kg for pork with better animal welfare attributes. Studies showed that Chinese consumers were willing to pay a premium for enhanced food safety measures, environmental practices and animal welfare, of these, packaging with food safety claims had the greatest potential for premiums (Lai et al. 2018). In addition, people could pay an appreciation of up to 44.5% for products with traceability information (Jin et al. 2017). It follows that the pressure on producers to pay for animal welfare could be alleviated through market role. Livestock breeding should be closely linked to the food value chain, which promotes the transition to animal welfare farming (Ducrot et al. 2024).

Insights from European agriculture for China

Animal welfare and environmental regulations in Europe are ahead of China in laws, regulations, government finance and market self-awareness, which is of good reference significance (Lu et al. 2022). In response to agricultural producers' dissatisfaction with strict environmental regulations, European countries have offered measures to ease farmers' concerns and anger. The European Commission makes three key proposals, to limit imports of cheap agricultural products from Ukraine, to exempt farmers from the obligation to keep 4% of their land fallow in 2024, and to sidestep an environmental measure (Casert and The Associated Press 2024). The French president is pledging to delay the EU-Mercosur trade deal (Bounds and Harris 2023). On the economic front, Berlin plays down the plans to cut diesel subsidies. Paris cancels diesel tax increase and postpones other measures, promising €150 million in subsidies and restricting imported food (Henley 2024).

For policy establishment, the EU countries have a well-developed system of legislation with a strong legal deterrent effect, combined with effective encouraging and punitive provisions. Animal welfare as an example, the Animal Welfare Act is highly operational, providing clear and detailed provisions on animal welfare concepts, violations and the liability to be incurred. Meanwhile, specialized government agencies or social organizations have also been established to carry out these tasks, e.g., the Royal Society for the Prevention of Cruelty to Animals (RSPCA) in the UK. The enforcement in Germany is handled by the Anti-Animal Cruelty Association (Deutscher Tierschutzbund), the Food Inspection Agency and the Police (Xiao 2015; Guevara et al. 2023). For subsidies, the EU invested over £700 million to support animal welfare in 2015, with 71% of this financial outlay directly subsidizing farmers (Lu et al. 2022).

Implications of the conflict between farmers and environmental regimes are all-encompassing. First, constrained environmental regimes should be implemented based on the adequate supply of food and meat. The practice in Canada of seeking a 30% reduction in nitrogen pollution through reducing fertilizer use, even reducing food yield is unsustainable (Shellenberger 2022). The worst consequences of the synthetic fertilizer ban in Sri Lanka in 2021 led to a massive drop in food production of up to 50%, even sparking starvation and an economic crisis (Dowling 2022). There are 500 million farmers in China, and environmental measures that ignore people's livelihoods may result in social unrest. Second, promoting coordinated progress is necessary according to “The Five-Sphere Integrated Plan” with Chinese characteristics, including economy, politics, culture, society and eco-environment.

Third, for policy establishment, the government should clarify the purpose and boundaries of legislation on particular production to avoid contradictions (Liang et al. 2023), by formulating checklist-type regulations to regulate the type, scope and extent. For example, it is necessary to incorporate welfare rules into the industry production standard, which is conducive to production structure optimization and product quality improvement.

Fourth, considering locally adapted regulations and production realities is essential for policymaking. Or else, it will widen the gap between farmland and political office. Coercive measures may provoke a revolt among farmers. Tailored and customized measures are more likely to be willingly accepted by farmers rather than being standardized. In the long run, sustainable environmentally-friendly agriculture requires a conscious awareness of agricultural producers.

Fifth, a lack of knowledge seems to be a significant barrier to policy implementation (Temple et al. 2015). Relevant departments should establish a vocational training system for education and guidance for agricultural practitioners and drive social consciousness. In addition, establishing certification systems to eliminate information asymmetry, especially in emerging markets (Liang et al. 2023). Lessons from Temple et al. (2015) emphasized that information on legislation implementation was not enough, relevant expected benefits (economic and other) should also be considered.

Most importantly, it is recommended for government to provide financial support for the initial stage of livestock sector structure upgrading or the green agriculture transformation, to alleviate farmers' negative sentiment about the increased additional environmental costs. Including special funds in the agricultural departments' budgets, and gradually increasing this proportion to ensure sufficient policies, systems, funds and talents (Lu et al. 2022).

Furthermore, adequate mobilization of market resources and consumers' possibilities is necessary for the special value realization of animal welfare products and other pro-environmental agricultural products (Uehleke, Huttel 2016). Optimize the value chain of eco-friendly products, strengthen the supervision of upstream and downstream processing chains (Liang et al. 2023). Uniform production standards are conducive to achieving the brand effect, thereby enhancing consumer trust and purchase intention to share producers’ economic burden (Liang et al. 2023; Sans and Sanjuán-López 2015). Consumer purchases of animal welfare, eco-friendly services contribute to facilitate the rational and sustainable agricultural development in China (Lu et al. 2022).

Lastly, strengthen research and development of pro-environmental agricultural production technologies. Sustainable agriculture is supposed to seek a solution based on the protection of food supplies and livelihoods. Reducing pollution at source can be achieved by improving advances in farming techniques, not just by reducing breeding numbers. Farmers should be comfortable in the harmony between communal food needs and climate-friendly processes.

In general, improving animal welfare and environmental protection, both from the perspective of the substance of food quality and the spirit of ethical requirements, is conducive to the improvement of human welfare (Boyle and O’Driscoll 2011; Phillips et al. 2010). Future, the development of big data, video surveillance, sensors and other technologies could better track and identify animal growth and health status, the adoption of precise smart agriculture technologies can improve the green agriculture level in China.

2. Limitations

Nonetheless, there are still limitations that warrant further consideration. Firstly, methodological improvements and innovations are sustaining, we should consider more newly available technologies from developed countries. Although the differences between China and developed countries in terms of breeding structures and conditions will affect the application of MSM technologies, it can trigger thinking and promote technological innovation so that it can be adapted to local conditions.

Secondly, from the perspective of data source, the field investigation in this study is only in Hebei province, which has a good interpretation for pig MSM in the potential area (including Moderate region, Potential region and Priority region). On the other hand, more concrete evidence from the Constraint region is eager for the future survey because of more stringent environmental requirements. In addition, this study only estimated the land-carrying capacity at the provincial level due to the unavailability of county-level data, a more detailed database will be created in future studies.

Moreover, the farm scale in Chapter 4 was identified by inventory numbers. Total slaughter numbers should be considered as well, due to the non-stabilization of pig production throughout the year. Therefore, in Chapter 6, we try to address this problem, combined with more indicators for farm classification to adapt actual situation.

Fourthly, while the boundaries for targeting waste management are clear in Chapter 5, we weakened the effects of feeding, breeding and housing on MSM. Since the main object of this study is the stage of waste treatment, we attenuate the focus on inputs in the cultivation chain. In addition, the environmental impacts of the construction and decommissioning of MSM infrastructure will be explored in the subsequent study. And the ratio of digestate water to treated effluent is seasonally variable, but an equal distribution ratio of 50% was assumed for calculation. In addition, the application of by-products from both MSM modes was only considered for grain cropland in chapter 5. Future studies should explore the possibility of utilizing these by-products in kaleyards and orchards.

3. Conclusions

China's breeding industry has gradually transformed from traditional scattered-raising to modern scale-breeding. Recognition and optimization of MSM patterns, exploration of regional schemes, and investigation of farmers' behaviors are critical to improving eco-friendly and sustainable pig breeding. This study indicated a comprehensive perception of pig MSM application in Hebei, China, which was representative of a region with a well-developed pig sector and can provide useful reference learned. Four significant consequences emerged from this analysis.

Firstly, the dominant MSM modes have been classified and identified from a macroscopic viewpoint, categorizing a legible recognition of five typical MSM modes by data-driven typology from a scientific and statistical perspective. Five mainstream MSM modes were obtained to simplify the high diversity of MSM strategies, involving traditional simple mode (TSM), which was based on simple processing methods and convenient access, mixed processing mode (MPM), which is a labor-intensive saving mode with the lowest mechanization degree, semi-biogas mode (SBM) is guided by anaerobic digestion with incompleted utilization, professional processing with simple utilization mode (PPSUM) has comprehensive treatments with unified field application, professional processing with full utilization mode (PPFUM) is an integrated mode that well-performing in processing and resource multi-utilization. Substantially, MSM is an entire continuum of several sections, technical approaches adopted in a particular phase have connections to the associated phases, appropriate combination of strategies leads to the maximization of adequate allocation of resources. Recognition of modes provides a comprehensive overview of the possibilities of all sections, accordingly, avoiding capital waste due to over-processing and environmental damage caused by simplified treatment. It enhances the efficiency of MSM and contributes to the ease of administrative convenience by the government.

Secondly, the heterogeneity of farmers' characteristics and behaviors towards five MSM modes was identified to reveal the underlying determinants that might affect individual decision-making on MSM mode selection. Applicability of the respective mode was reflected in the synthesis deliberation. Farmers' education level and pro-environmental perception significantly promoted the adoption of technology-intensive modes, such as SBM, PPSUM and PPFUM. Breeding structure may affect the collecting strategy. Scale upgrading had a positive effect on mechanization and diversified strategies application. Land may be the critical factor that restricts manure utilization and some MSM modes extension based on field returning. Consequently, in response to the anticipated development prospects of the pig industry in China, suggestions for promoting potential MSM modes are presented. Understanding these driving forces contributes to the design of an optimal and tailor-made MSM scheme with greater adaptability, meanwhile, providing credible experience and qualification to individual pig farms on appropriate mode selection to enhance effective MSM in pig farming.

Considering the trend towards more intensive breeding, PPFUM seems to be a more scientific, comprehensive and green MSM mode. The possibility of a newly planned centralized MSM pattern is proposed to relieve environmental pressure, increase resource recovery efficiency and rebuild the coupling effect of cropping and breeding. A comparative evaluation between individual and traditional mode (ITM) at the household level and centralized bio-energy mode (CBM) at the regional scale was conducted, by life cycle assessment (LCA) and life cycle cost analysis (LCC), dual objectives of economy and environment were quantified based on comprehensive coverage of all sections of MSM. CBM appeared to be a better alternative in global warming, terrestrial acidification and marine eutrophication, with significant reductions of 49.49%, 6.8% and 4.67% respectively compared with ITM. While CBM showed a slightly higher impact on FPMF because of additional transportation, which could be reduced by optimizing transportation. From an economic perspective, ITM was appropriate for the pig farms involved in both breeding and cropping, or has adequate nearby farmland for consumption, because of the lower MgEx and savings in synthetic fertilizer and fodder. Although CBM exhibited a relatively higher MgEx, it offered substantial profits, with 48.5 CNY/FU. Furthermore, both environmental and economic performance could be improved by scale expansion and transport optimization, with an optimal collection radius of less than 31.45 km, and a decrease in marginal cost in the range of 7.2-16.82 CNY. Generally, with comprehensive consideration of pig breeding structure, land availability, market prospects, and policy recognition, the implementation of CBM demonstrates great potentiality and advantages in activating the industry chain, elevating the value chain and restoring the ecological chain, and contributing to both environmental and economic performance. Conclusions provided a visualized and reliable MSM strategy to adapt to the transformation of the pig industry in China, and references to various regions on centralized mode extension, further contributing to a more efficient, cost-effective, controlled and regulated manner for resource recovery, culminating in the sustainability of pig farming and facilitating the development of regional environmental-friendly agriculture.

Lastly, from the perspective of pig farmers, the exploration of underlying determinants affecting their decision-making on scientific and comprehensive MSM practices was conducted to cater to the goals of ecologically sustainable farming. Improving the threshold of environmental access could be realized by the modulation of land factors, resource endowments, policy rationality and individual characteristics, but required the consideration of the various characteristics across farm scales. Compact conventional farms had more possibilities and optimizing upside potential, by improving land utilizing, technology acquisition and economic convenience, strengthening neighborhood cooperation. Moderate potential farms were in the expansion stage facing greater pollution risk and MSM difficulty, the promotion of mechanized technology was significant to address the challenges of labor shortages and rising labor costs.

Intensive specialized farms were more environmentally friendly, applying more comprehensive MSM methods. Targeted and effective policies can assist them in leveraging their strengths to achieve regional excreta treatment. In addition, the government should guide farmers to adopt the integration of breeding and cropping pattern. Government intervention for land rezoning and harmonization of prices to trade-off within the price range acceptable to farmers, and the creation of linkages for abatement. Strengthen land transfer and integration contribute to the adoption of combined MSM practices, thus enhancing waste resource utilization level and further forming the green sustainable pig industry. For policy-making, it is noticed that to strengthen the convergence of policy objectives, the orientation and intensity should be flexibly and effectively adjusted considering the actual situation. For policy implementation, incentive regulations were effective, diversified and targeted subsidy policies were required, but constrained regulation should be discreetly administered and progressively strengthened, to avoid cutting farmers' motivation and confidence with excessive force.

In general, this study analyzes the current situation of MSM in China, and conducts a comprehensive study from the perspective of MSM modes, regional application and pig farms. Summarize five mainstream modes and distinguish corresponding application characteristics and adaptability. Explore the possibility of regional centralized treatment by adopting the optimal mode of integrated resource utilization, to maximize various resource values and achieve both environmental and economic benefits. Clarifying the driving force for improving farmers' environmental friendliness across farm scales, and further puts forward tailor-made policy recommendations. It contributes to providing a persuasive reference for pig farmers to select appropriate MSM mode to improve effectiveness, theoretical support for the replication of regional models proposed in response to breeding restructuring in the future, and suggestions to muti-subjects in the aspect of pollution prevention and control and waste resource utilization in pig farming to achieve the sustainability of MSM and eco-friendly development of pig industry. Furthermore, this paper provides insights for developing countries in similar situations, in terms of MSM strategic innovations and policy recommendations.

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Supplementary Information

Appendix 1. LCA Emissions calculations

The emission steps in ITM conclude solid storage, liquid storage, solid composting, biological aerobic treatment, aerated slurry decantation, biological sludge storage, composted manure storage, farmyard fertilizer application and aerated slurry application. CBM contains mixed storage, digestate dewatering, solid fraction storage, solid fraction composting, sludge storage, mineral fertilizer storage, effluent treatment, mineral fertilizer application, digestate water application and effluent application.

Considering the significance of the research topic, immediate research subject and data availability, cite validated data by screening, comparing the relevant emission factors in the published literature, by choosing emission factors in the following steps: Firstly, identify the related literature regarding pig manure/waste treatment by web searching and keyword screening, carried out using Web of Science, Scopus and Google Scholar, etc. The following keywords were used, “pig/swine/hog waste management”, “swine manure treatment”, “Life Cycle Assessment”, “pig manure utilization/recycling”, “environmental impacts on pig waste use”. Secondly, screening MSM methods consistent with those used in my study, and sorting out corresponding emission factors, and chemical compositions of raw material (pig waste) also tend to be close. Then, select emission factors that are relatively close to the average and China's situation. For example, for waste storage, the details of whether it was covered or not, storage duration, and surface area in contact with air were noted, in response to the actual situation in my study. Most importantly, I avoided selecting some official data, such as IPCC, because it was not updated in time, and lack of clarity in the description of method definitions.

Table A1. Emission factors for calculating environmental impacts in MSM modes.

	Value		Unit	Reference
ITM				
Solid storage	$^{a}CO_2$	0.2	kg CO_2-C/kg TC	(Ramírez-Islas et al. 2020)
	$^{a}CH_4$	0.008	kg CH_4-C/kg TC	(Ramírez-Islas et al. 2020)
	N_2O	0.005	kg N_2O-N/kg TN	(Ramírez-Islas et al. 2020)
	^{b}NO	0.005	$N_2O/NO/N_2$=1:1:5	(Oenema et al. 2000)
	$^{b}N_2$	0.025	$N_2O/NO/N_2$=1:1:5	(Oenema et al. 2000)
	NH_3	0.31	kg NH_3-N/kg TN	(Ramírez-Islas et al. 2020)
Liquid storage	$^{c}CO_2$	41.9	g CO_2-C/m^3 day	(Ramírez-Islas et al. 2020)
	$^{c}CH_4$	49.8	g CH_4-C/m^3 day	(Ramírez-Islas et al. 2020)
	N_2O	0.0012	kg N_2O-N/kg TN	(Ramírez-Islas et al. 2020)
	^{b}NO	0.0012	$N_2O/NO/N_2$=1:1:10	(Oenema et al. 2000)
	$^{b}N_2$	0.012	$N_2O/NO/N_2$=1:1:10	(Oenema et al. 2000)
	NH_3	0.31	kg NH_3-N/kg TN	(Ramírez-Islas et al. 2020)
Solid composting	$^{d}CO_2$	0.26	kg CO_2-C/kg OM degraded	(Ramírez-Islas et al. 2020)
	$^{a}CH_4$	8.12%	kg CH_4/ kg TC	(Duan et al. 2020)
	N_2O	1.4%	kg N_2O-N/kg TN	(Duan et al. 2020)
	$^{e}NH_3$	20%	kg NH_3-N/kg NH_4-N	(Duan et al. 2020)
	H_2S	0.003	kg/t composted solid	Measurement
Biological aerobic treatment	$^{f}CO_2$	12.1	g CO_2-C/m^3 day	(Loyon et al. 2007)
	$^{f}CH_4$	0.87	g CH_4-C/m^3 day	(Loyon et al. 2007)
	$^{f}N_2O$	0.015	g N_2O-N/m^3 day	(Loyon et al. 2007)
Aerated slurry decantation	$^{f}CO_2$	4.8	g CO_2-C/m^3 day	(Loyon et al. 2007)
	$^{f}CH_4$	7.6	g CH_4-C/m^3 day	(Loyon et al. 2007)
	$^{fg}NH_3$	0.16	g NH_3-N/m^2 day	(Loyon et al. 2007)
Biological sludge storage	$^{f}CO_2$	6.7	g CO_2-C/m^3 day	(Loyon et al. 2007)
	$^{f}CH_4$	5.6	g CH_4-C/m^3 day	(Loyon et al. 2007)
	$^{fg}NH_3$	0.26	g NH_3-N/m^2 day	(Loyon et al. 2007)
Composted manure storage	N_2O	0.017	kg N_2O-N/kg N	(Wang et al. 2017)
	NH_3	0.249	kg NH_3-N/kg N	(Wang et al. 2017)
Farmyard	N_2O_{dir}	0.034	kg N_2O-N/kg N	(Yoshida et al. 2016)

fertilizer application	NH_3	0.016	kg NH_3-N/kg N	(Yoshida et al. 2016)
	NO_3^-	0.1257	kg NO_3^--N/kg N	(Yoshida et al. 2016)
	N_2O_{ind}	0.0026	kg N_2O-N/kg N	(Corbala-Robles et al. 2018)
	NO_X	0.0013	kg NO_X-N/kg N	(Brockmann et al. 2014)
	PO_4-	0.096%	kg PO_4-P/kg P_2O_5	(Brockmann et al. 2014)
Aerated slurry application	N_2O_{dir}	0.012	kg N_2O-N/kg N	(Brockmann et al. 2014)
	NH_3	0.09	kg NH_3-N/kg N	(Brockmann et al. 2014)
	NO_3^-	0.111	kg NO_3^--N/kg N	(Brockmann et al. 2014)
	N_2O_{ind}	0.0024	kg N_2O-N/kg N	(Corbala-Robles et al. 2018)
	NO_X	0.0012	kg NO_X-N/kg N	(Brockmann et al. 2014)
	PO_4-	0.185%	kg PO_4-P/kg P_2O_5	(Brockmann et al. 2014)
CBM				
Mixed storage	$^{c}CO_2$	41.9	g CO_2-C/m^3 day	(Ramírez-Islas et al. 2020)
	$^{c}CH_4$	49.8	g CH_4-C/m^3 day	(Ramírez-Islas et al. 2020)
	N_2O	0.0012	kg N_2O-N/kg TN	(Ramírez-Islas et al. 2020)
	^{b}NO	0.0012	$N_2O/NO/N_2$=1:1:10	(Oenema et al., 2000)
	$^{b}N_2$	0.012	$N_2O/NO/N_2$=1:1:10	(Oenema et al., 2000)
	NH_3	0.31	kg NH_3-N/kg TN	(Ramírez-Islas et al. 2020)
Digestate dewatering	CO_2	60/40	CH_4/CO_2 ratio	Measurement
	CH_4	0.028	Fraction of CH_4	(UNFCCC/CCNUCC, 2012)
	N_2O	0.1%	kg N_2O-N/kg N	(IPCC 2013)
	$^{e}NH_3$	52%	kgNH_3/kg NH_4-N	(Styles et al. 2018)
Solid fraction storage	CO_2	60/40	CH_4/CO_2 ratio	(Vu et al. 2015)
	CH_4	0.17	kg/t solid fraction	(DeVries et al. 2012b)
	N_2O	0.02	kg N_2O-N/kg N	(DeVries et al. 2015)
	NO	0.02	kg NO-N/kg N	(DeVries et al. 2015)
	N_2	0.2	kg N_2-N/kg N	(DeVries et al. 2015)
	NH_3	1.4	kg NH_3-N/kg N	(DeVries et al. 2015)
Solid fraction composting	$^{b}CO_2$	0.26	kg CO_2-C/kg OM degraded	(Ramírez-Islas et al. 2020)
	$^{b}CH_4$	0.01	kg CH_4-C/kg OM degraded	(Ramírez-Islas et al. 2020)
	N_2O	1.4%	kg N_2O-N/kg N	(Duan et al. 2020)
	$^{e}NH_3$	20%	kg NH_3-N/kg NH_4-N	(Duan et al. 2020)
Sludge storage	N_2O	0.005	kg N_2O-N/kg N	(Prapaspongsa et al. 2010)
	N_2	0.015	kg N_2-N/kg N	(Prapaspongsa et al. 2010)

	NH_3	0.02	kg NH_3-N/kg N	(Prapaspongsa et al. 2010)
Mineral fertilizer storage	CH_4	0.014	kg/t mineral fertilizer	(DeVries et al. 2012a)
	NH_3	0.04	kg NH_3-N/kg N	(DeVries et al. 2012a)
Effluent treatment	CH_4	0.6	kg CH_4/g BOD_5 treated	Measurement
	NH_3	0.002	g NH_3/g BOD_5 treated	Measurement
	NO_X	0.001	kg NO_X/g BOD_5 treated	Measurement
	H_2S	0.000005	g H_2S/g BOD_5 treated	Measurement
Mineral fertilizer application	N_2O	0.017	kg N_2O-N/kg N	(Yoshida et al. 2016)
	NH_3	0.016	kg NH_3-N/kg N	(Yoshida et al. 2016)
	NO_3^-	0.078	kg NO_3^--N/kg N	(Yoshida et al. 2016)
	PO_4-	0.096%	kg PO_4-P/kg P_2O_5	(Brockmann et al. 2014)
Digestate water application	N_2O	0.024	kg N_2O-N/kg N	(Yoshida et al. 2016)
	NH_3	0.016	kg NH_3-N/kg N	(Yoshida et al. 2016)
	NO_3^-	0.216	kg NO_3^--N/kg N	(Yoshida et al. 2016)
	PO_4-	0.185%	kg PO_4-P/kg P_2O_5	(Brockmann et al. 2014)
	NH_4^+	0.075	kg NH_4^+-N/kg N	(Yoshida et al. 2016)
Effluent application	N_2O	0.012	kg N_2O-N/kg N	(Brockmann et al. 2014)
	NH_3	0.09	kg NH_3-N/kg N	(Brockmann et al. 2014)
	NO_3^-	0.111	kg NO_3^--N/kg N	(Brockmann et al. 2014)

TS=total solid, VS=volatile solid, OM=organic matter, TN = total nitrogen, TC=total carbon, N_2O_{dir}=direct N_2O emission, N_2O_{ind}=indirect N_2O emission

[a] TC was calculated as VS*0.552 (Vu et al., 2015),VS was calculated at 78% of TS, TS for solid and liquid waste were 25% and 1% as measured

[b] Calculated as a ratio of the N_2O-N emission (ratio N_2O:NO:N_2 = 1:1:10 for liquid manure and 1:1:5 for solid manure).

[c] Storage for two days.

[d] 74.5% of OM degraded, 66.7% of the TS was OM.

[e] 80% of TN as NH_4 for liquid fractions, and 25% for solid fractions (Croxatto Vega et al. 2014).

[f] Biological aerobic treatment for 180 days. Decantation for around 30 days. Biological sludge storage for 50 days.

[g] Contact area was 100 m^2.

Appendix 2. MSM construction economic inputs, operating expenses and management expenses

As a result of the definition of system boundary in this study, was from the cradle (generation of excrement leaving the pig) to the grave (waste land use and conversion to emissions).The upstream stages of the MSM process, such as pig rearing, housing and feeding were excluded. Because both MSM modes were previously been established completely with safe and stable operation, evaluating the facilities and modes that currently exist was the purpose of this study. Management expense (MgEx) and operating expense (OpEx) were closely associated with the initial capital expenditure (CapEx), **Table A2** showed the investments in detail at initial construction to calculate MgEx and OpEx for LCC analysis. It should be noted that the economic performance was calculated on an annual basis and divided by the annual capacity of MSM to get the LCC per functional unit.

Table A2. Inventory of CapEx, MgEx and OpEx of two MSM modes.

ITM (Treated pig waste 8677.24 t/a)	
CapEx	372,800 CNY
Infrastructure cost	270,800 CNY
Equipment cost	102,000 CNY
MgEx	
Depreciation cost	18,640 CNY/a
OpEx	
Maintenance cost	3728 CNY/a
Labor cost	5112 CNY/month
Electricity cost	0.615 CNY/kWh
Diesel cost	8.28 CNY/L
CBM (Treated pig waste 242,177 t/a)	
CapEx	104,583,600 CNY
Waste collection & Waste storage & Transportation	8,433,600 CNY
Anaerobic digestion & Electricity production	96,150,500 CNY
MgEx	
Depreciation cost	5,229,180 CNY/a
OpEx	
Maintenance cost	991,416 CNY/a
Waste collection & Waste storage & Transportation	84,336 CNY/a

Anaerobic digestion & Electricity production	907,080 CNY/a
Labor cost	1,560,000 CNY/a
Waste collection	20000 CNY/month
Anaerobic digestion	40000 CNY/month
Sewage management	30000 CNY/month
Transportation	40000 CNY/month
Electricity cost	0.621 CNY/kWh
Diesel cost	8.28 CNY/L

Appendix 3. Midpoint environmental impacts

The LCA system boundary included operation section (collection, storage, processing, utilization and transport), and mitigation potential (avoid synthetic fertilizers production and application, and avoid electricity production). The environmental impacts of entire MSM linkage and subsection, and the contribution of each subsection were described in **Table A3**, **A4** and **A5**.

Table A3. Environmental performance from the management of 1-ton untreated mixed raw pig waste (285.71kg solid waste and 714.28 liquid waste) calculated at midpoint with the ReCiPe 2016 v1.1, Hierarchist perspective – ITM.

Impact category	Total	Collection	Storage	Processing	Utilization	Transport	Avoid synthetic fertilizers
GW	376.21	1.25	118.51	**234.84**	100.59	1.89	-80.88
(kg CO_2-eq)		(0.27%)	(25.93%)	(51.38%)	(22.01%)	(0.41%)	(-17.69%)
FPMF	6.28	0.00	**5.04**	0.73	0.63	0.00	-0.12
(kg $PM_{2.5}$-eq)		(0.03%)	(78.73%)	(11.44%)	(9.77%)	(0.03%)	(-1.92%)
TA	6.37	0.00	**4.51**	0.65	1.77	0.01	-0.58
(kg SO_2-eq)		(0.06%)	(64.92%)	(9.36%)	(25.56%)	(0.09%)	(-8.3%)
ME	1.04	0.00	0.00	0.00	**1.04**	0.00	0.00
(kg N-eq)		(0%)	(0%)	(0%)	(100%)	(0%)	(-0.1%)
FRS	-26.19	0.24	0.00	0.08	0.00	**1.08**	-27.59
(kg oil-eq)		(17.3%)	(0%)	(5.77%)	(0%)	(76.93)	(-1962.91%)

*Proportions are given in parentheses. The greatest contributions were highlighted in bold.

Table A4. Environmental performance from the management of 1-ton untreated mixed raw pig waste calculated at midpoint with the ReCiPe 2016 v1.1, Hierarchist perspective – CBM.

Impact category	Total	Collection	Storage	Processing	Utilization	Transport	Avoid synthetic fertilizers	Avoid electricity production
GW (kg CO_2-eq)	190.02	0.44	29.63	**168.89**	57.30	23.05	-82.71	-6.58
		(0.16%)	(10.61%)	(60.47%)	(20.51%)	(8.25%)	(-29.61%)	(-2.36%)
FPMF (kg $PM_{2.5}$-eq)	6.49	0.00	**3.28**	2.96	0.35	0.03	-0.13	-0.01
		(0.01%)	(49.47%)	(44.73%)	(5.34%)	(0.45%)	(-1.9%)	(-0.13%)
TA (kg SO_2-eq)	5.93	0.00	**2.92**	2.64	0.89	0.09	-0.59	-0.03
		(0.02%)	(44.62%)	(40.32%)	(13.65%)	(1.39%)	(-9.01%)	(-0.38%)
ME (kg N-eq)	0.99	0.00	0.00	0.00	**0.99**	0.00	0.00	0.00
		(0%)	(0%)	(0.01%)	(99.97%)	(0.02%)	(-0.11%)	(-0.01%)
FRS (kg oil-eq)	-16.09	0.09	0.00	0.95	0.00	**12.68**	-28.66	-1.14
		(0.62%)	(0%)	(6.94%)	(0%)	(92.44%)	(-209.01%)	(-8.34%)

*Proportions are given in parentheses. The greatest contributions were highlighted in bold.

Table A5. Environmental performance from the management of 1-ton untreated mixed raw pig waste calculated at midpoint with the ReCiPe 2016 v1.1, Hierarchist perspective - CBM_Scenario return transport

Impact category	Total	Collection	Storage	Processing	Utilization	Transport	Avoid synthetic fertilizers	Avoid electricity production
GW (kg CO_2-eq)	183.13	0.44	29.63	168.89	57.30	**16.15**	-82.71	-6.58
FPMF (kg $PM_{2.5}$-eq)	6.48	0.00	3.28	2.96	0.35	**0.02**	-0.13	-0.01
TA (kg SO_2-eq)	5.9	0.00	2.92	2.64	0.89	**0.06**	-0.59	-0.03
ME (kg N-eq)	0.99	0.00	0.00	0.00	0.99	**0.00**	0.00	0.00
FRS (kg oil-eq)	-20.04	0.09	0.00	0.95	0.00	**8.72**	-28.66	-1.14

Appendix 4. Economic viability of economic costs, benefits and net income

To compare the economic viability and relevant improvement potentials, clarify the economic changes of multi-subjects in choosing different MSM modes, **Table A6** illustrated more details regarding the alterations. Including economic costs, economic benefits and net income of different modes (ITM and CBM), alternative scenarios (Traffic optimization CBM and Up-scale CBM), and multi-subjects in CBM.

Appendix 5. Promotion prospect of CBM

The significant environmental mitigation potential of CBM had been demonstrated in **Chapter 5 Section 3.1 and 3.2**. Its opportunities and effectiveness would be further explored in other regions. Firstly, calculating the theoretical environmental carrying capacity of regions to identify the areas with promotional value. Secondly, it was assumed that the excess volume of waste would be treated according to CBM. Finally, resulting in the corresponding environmental emission reductions for each region. The equation is as follows,

$$\text{Land capacity} = \text{Pig waste equivalent} \times 10^4 \div \text{Cultivated land area}$$

$$\text{Warning value R} = \text{Land capacity} \div \text{Theory maximum pollutant load}$$

$$\text{Excess warning value} = \text{Warning value R} - 0.4$$

Table A6. Economic costs, economic benefits, net incomes of MSM modes, alternative scenarios and multi-subjects of per FU.

	ITM	**CBM**	**Traffic optimization CBM**	**CBM pig farmers**	**CBM biogas enterprise**	**Up-scale CBM biogas enterprise**
Economic costs						
Depreciation	2.15 (15.57%)	21.59 (24.62%)	21.59 (30.47%)	1.74 (52.25%)	19.85 (23.53%)	13.2 (17.11%)
Maintenance	0.43 (3.11%)	4.09 (4.66%)	4.09 (5.77%)	0.35 (10.51%)	3.75 (4.45%)	3.79 (4.91%)
Labor	7.07 (51.19%)	6.44 (7.34%)	6.44 (9.09%)	0.99 (29.73%)	5.45 (6.46%)	4.86 (6.30%)
Energy (electricity)	0.93 (6.73%)	3.46 (3.95%)	3.46 (4.88%)	0.25 (7.51%)	3.21 (3.81%)	3.21 (4.16%)
Energy (diesel)	3.23 (23.39%)	52.1 (59.42%)	35.28 (49.79%)	0 (0%)	52.1 (61.76%)	52.1 (67.52%)
Total cost	**13.81**	**87.68**	**70.86**	**3.33**	**84.36**	**77.16**
Economic benefits						
Farmyard fertilizer	0	-	-	-	-	-
Aerated slurry	0	-	-	-	-	-
Mineral fertilizer	-	96.59	96.59	-	96.59	96.59
Digestate water	-	8.94	8.94	-	8.94	8.94
Electricity	-	30.65	30.65	-	30.65	30.65
Total benefit	**0**	**136.18**	**136.18**	**0**	**136.18**	**136.18**
Net income	**-13.81**	**48.5**	**65.32**	**-3.33**	**51.82**	**59.02**

*Proportions are given in parentheses. The unit is CNY.

Table A7. Measurement on exceeding capacity for land allocation at the regional level.

Region [a]	Cultivated land area (hm^2)	Pig waste equivalent (*10^4 t/a)	Land capacity ($t/hm^2/a$)	Theory maximum pollutant load of land (t/hm^2)	Warning value R[b]	Level	Environmental impact	GHG emission reduction (*10^4 t/a)	GW potential reduction
Hebei	8716640	8612.63	9.88	45	0.220	I	No impact		
Shanxi	3720810	2826.61	7.60	45	0.169	I	No impact		
Inner Mongolia	7921900	11004.6	13.89	45	0.309	I	No impact		
Liaoning	4064100	7809.22	19.22	45	0.427	II	Slight impact	91.9	3.13%
Jilin	5676320	4994.8	8.80	45	0.196	I	No impact		
Heilongjiang	12426540	6346.89	5.11	45	0.114	I	No impact		
Jiangsu	7676920	4956.31	6.46	30	0.215	I	No impact		
Zhejiang	2274440	1475.11	6.49	30	0.216	I	No impact		
Anhui	8893610	5122.25	5.76	30	0.192	I	No impact		
Fujian	2327310	2635.99	11.33	30	0.378	I	No impact		
Jiangxi	5560670	5432.4	9.77	30	0.326	I	No impact		
Shandong	10973180	13041.43	11.88	45	0.264	I	No impact		
Henan	14472320	17346.63	11.99	45	0.266	I	No impact		
Hubei	7843510	8010.21	10.21	30	0.340	I	No impact		
Hunan	8793280	10964.89	12.47	30	0.416	II	Slight impact	76.85	1.86%
Guangdong	4830830	6296.08	13.03	30	0.434	II	Slight impact	92.88	3.92%
Guangxi	6145310	7549.52	12.29	30	0.410	II	Slight impact	32.6	1.15%
Hainan	823260	1354.6	16.45	30	0.548	II	Slight impact	68.24	13.39%

Chongqing	3600740	3965.34	11.01	30	0.367	I	No impact		
Sichuan	9728610	16441.57	16.90	30	0.563	II	Slight impact	887.18	14.35%
Guizhou	5596810	5863.74	10.48	30	0.349	I	No impact		
Yunnan	7164460	9966.37	13.91	30	0.464	II	Slight impact	254.77	6.8%
Shaanxi	4276920	3210.88	7.51	45	0.167	I	No impact		
Gansu	4253840	5570.07	13.09	45	0.291	I	No impact		
Xinjiang	5867520	5892.51	10.04	45	0.223	I	No impact		

a The measurement excludes areas with relatively weak agricultural development and grazing areas (Beijing, Tianjin, Shanghai, Hainan, Ningxia, Qinghai and Tibet) (Shi et al. 2022).

b Warning value R<0.4, no impact to environment (I); 0.4-0.7, slight impact (II); 0.7-1.0, obvious impact (III); 1.0-1.5, serious impact (IV); 1.5-2.5, more serious impact (V); >2.5, extremely serious impact (VI) (Zhang et al. 2018c).

Appendix 6. Questionnaire for field survey

Questionnaire for Research on Waste Management and Resource Utilization in Pig Breeding

Dear Respondent:

Hello! We are the scientific researchers of the Chinese Academy of Agricultural Sciences and Hebei Pig Industry Technology System. To further comprehend the current situation, issues and requirements of waste management and resource utilization of pig breeding waste in Hebei, and to provide a reference basis for the government to formulate relevant policies, in your region to carry out field investigation on the manure and sewage management (MSM) of pig breeding. Results collected are only intended for academic research, please answer all the questions according to the actual situation, thank you for your cooperation and support!

1. Basic information of pig farm

1) Name, address and construction time of the pig farm.
2) Whether as a member of pig professionalization organization.
3) Construction of pig farm: total land occupation area and cost of pig farm, land area and cost of MSM, MSM infrastructure facilities cost and MSM processing equipment cost.
4) Employer situation: number of total employees, number of MSM employees and salary per month.
5) Annual fuel consumption for MSM, and farm electricity unit price.
6) Breeding scale in 2020,

	Sow	Boar	Fattening pig	Piglet
Inventory (head)				
Raising time (day)				

	Sow	Cull pig	Fattening pig	Piglet	Pigs die of illness
Slaughter (head)					
Body weight (kg)					
Selling price (CNY/kg)				CNY/head	Agricultural insurance compensation (CNY/head)

2. Current situation of performed MSM practices

1) Daily manure (ton), urine and sewage (m^3) generation.

2) Farm MSM practices adoption,

Collection section

Method*	Operation time (hour/day)	Equipment power (kW)	Labor cost (CNY/month)	Equipment cost (CNY)	Government subsidy (CNY)	Durable years (year)	Annual power consumption (kWh)	Annual fuel consumption (L)

*Collection method: **A. Scraper**, Feces collection by mechanical or manual operation with scrapers, **B. Soak**, Manure soaking in water, **C. Flush**, Flush cleaning manure, **D, Gravity**, Manure enters the ditch at the bottom of the barn due to the trampling of pigs and itself gravity.

Storage section

	Yes/no	Method*	Storage time (day)	Effective capacity (m^3)	Superficial area (m^2)	Construction cost (CNY)	Government subsidy (CNY)	Durable years (year)
Mix storage								
Solid storage								
Liquid storage								

*Storage method: **A. Open-air septic tanks**, **B. Semi-covered septic tanks**, **C. Full-coverage septic tanks**.

Primary processing section

	Yes/no	Method*	Operation time	Equipment power (kW)	Labor cost (CNY/month)	Construction cost (CNY)	Government subsidy (CNY)	Durable years (year)	Annual power consumption (kWh)	Annual fuel consumption (L)	Transportation range (m)
Solid and liquid separation			(hour/day)								-
Anaerobic biogas digestion			(day)								-
Solid composting			(day)								-
Sewage oxidation pond			(day)								-
Staged sedimentation oxidation pond			(day)								-
Industrial treatment and discharge of sewage to standard											
On-site transportation			(hour/day)	-					-		
Off-site transportation			(hour/day)	-					-		
Off-site to Third-Party		Trading style: A. Depends on time period, B. By inventory, C. By volume of waste. Trading price: (CNY/ton, m^3, head, month, year) Who pay the waste: A. Pig farm, B. Third-party, C. Free.									

*Solid and liquid separation method: **A. Mechanical solid-liquid separation**, **B. Separated by scraper**.
Anaerobic biogas digestion method: **A. Tank fermentation**, **B. Film fermentation**, **C. Digester fermentation**.
Solid composting method: **A. Simple open-air**, **B. Stack**, **C. Slot**, **D. Mulch**, **E. Reactor compost**.
Sewage oxidation pond method: **A. Mulch**, **B. Open air**.
Staged sedimentation oxidation pond method: **A. Two stages**, **B. Three stages**.
Transportation type: **A. Forklift**, **B. Septic tanker**.

Deep processing section

		Yes/no	Annual production (ton)	Cost (CNY/ton)	Labor cost (CNY/month)	Equipment cost (CNY)	Government subsidy (CNY)	Durable years (year)	Annual power consumption (kWh)	Annual fuel consumption (L)
Processing of commercial organic fertilizers										
Processing of bio-organic fertilizers										
Processing of commercial liquid fertilizers										
Other										
Biogas	Agricultural (combustion)		(m^3)							
	Natural gas purification		(m^3)							
	Electricity generation		(kWh)							

Utilization section

	Yes/no	Selling price (CNY/ton)	Transportation range (km)	Transport cost (CNY/ton)	Labor cost (CNY/month)	Vehicle and Equipment cost (CNY)	Government subsidy (CNY)	Annual power consumption (kWh)	Annual fuel consumption (L)
Organic fertilizer for sale									
Waste returning to surrounding fields		-							
Waste pulling away with no trade by transport		-						-	
Biogas for agricultural use		(CNY/m^3)		-					-
Natural gas use		(CNY/m^3)		-					-
Electricity		(CNY/kWh)		-					-

3) Field application information,

Total field area of waste consumption (ha)			
	Own land	Transfer land	Agreement land
Area (ha)			
Types of cultivation			
The average distance from pig farm to field			
Cost (CNY/ha)	-		

Own land: own cultivated land, Transfer land: transferred land, Agreement land: meet agreements with surrounding planters for waste disposal.

4) Do you think the surrounding land is enough for waste consumption?
**1=quite not enough ~ 5=quite enough

5) What do you think of the transfer price of land?
**1=extremely low ~ 5=extremely high

6) The purpose for transferring land.
A. Combination of planting and breeding (for feed producing), B. Develop planting industry (for fruit and vegetable planting), C. Waste consumption.

3. Farmers' behaviors and perceptions of MSM

1) Reasons for the construction of MSM facilities.
A. Requirement of laws and regulations, B. Subsidies from government, C. Protect pig farm environment, D. Develop the combination of planting and breeding, E. Follow the example of the other farms.

2) Whether your MSM behaviors are influenced by other pig farmers?

3) To what level do you know MSM technologies & standards?
**1=completely unknown ~ 5=completely know

4) To what level do you think MSM treatment is difficult?
**1=extremely difficult ~ 5=extremely easy

5) To what level do you think waste transport is difficult?
**1=extremely difficult ~ 5=extremely easy

6) To what level are you willing to invest in MSM?
**1=completely unwilling ~ 5=completely willing

7) Difficulties faced in MSM.
A. Lack of MSM construction land, B. High MSM cost, C. High labor cost, D. Lack of treatment technology, E. Low price of organic fertilizer, F. Lack of field for waste consumption, G. Transport problems.

4. Farmers' environmental awareness

1) Do you know that pig breeding ban or restriction is related to waste pollution?
2) To what level do you think MSM damages farm environment?
   **1=no affects ~ 5=extremely high affects
3) To what level do you think MSM damages pig growth?
   **1=no affects ~ 5=extremely high affects
4) To what level do you think MSM damages human health?
   **1=no affects ~ 5=extremely high affects
5) Whether as a member conducted an Environmental Impact Assessment?

5. Farmers' perceptions of government regulations and policies

1) To what level do you know MSM regulations & policies?
   **1=completely unknown ~ 5=completely know
2) Whether the relevant government departments have carried out publicity and education on waste prevention and control measures?
3) Whether you have received MSM training?
   If YES, what department provides training?
   A. Government, B. Large-scale pig farms, C. Feed or veterinary pharmaceutical companies, D. Organic fertilizer factory, E. Others.
4) What do you think of the current subsidy standard for MSM?
   **1=very low ~ 5=very high
5) Whether you have been asked to rectify because of rejected MSM?
6) Whether you have received MSM subsidies?
7) To what level do you need policy support.
   **1=completely without ~ 5=completely have

6. Personal information

1) Respondent information: age, address and contact information.
2) Education level of respondent,
   1=Primary and bellow, 2=Junior, 3=Senior, 4=Vocational college, 5=Bachelor degree and above.
3) Annual income from breeding, net profit margin, and proportion of income from pig breeding to total household income.

**Note: The ordered categorical variables in this questionnaire were all based on Likert scale, degrees were divided into five levels to indicate the strength of the attitude, all statements are positive (Likert, 1932).