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Recognition on characteristics and applicability of typical modes for manure & sewage management in pig farming: A case study in Hebei, China

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A R T I C L E I N F O

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A B S T R A C T

Scale-up intensive pig farming can increase profitability by economies of large scale, but it also exacerbates environmental pollution caused by the disordered discharge of manure and sewage. Manure & sewage management (MSM) is critical to mitigate environmental pressure and reuse livestock waste. However, the corresponding MSM measures adopted by pig farmers are multitudinous in reality, due to the diversity of MSM methods and heterogeneity of farmers' characteristics and behaviors. Thus, this study empirically categorized five typical MSM modes (i.e., traditional simple mode (TSM), mixed processing mode (MPM), semi-biogas mode (SBM), professional processing with simple utilization mode (PPSUM) and professional processing with full utilization mode (PPFUM)) by clustering analysis, based on the field data from 406 pig farms, and further discriminated farmers' heterogeneous characteristics on corresponding mode adoption. Results revealed that each mode was distinctive. The applicability of the corresponding mode was reflected in the synthesis deliberation, involving farming structure, land, farmers' characteristic and their subjective awareness. Farmers' education level and pro-environmental perception are significantly promoted to adopt technology-intensive MSM modes. Scale upgrading has a positive effect on mechanization adoption and diversified strategies application. Land as an unalterable objective factor restricted the extension of MSM modes based on field returning. Conclusions clarified typical MSM modes and provided references to individual pig farms on appropriate mode selection, further enhancing the efficiency of MSM and contributing to the sustainability of green development of pig farming in China.

1. Introduction

Along with the incremental population, pork production has increased as a result of rising food demand. The global pork production rose from 109.9 million tons in 2010 to 115.6 million tons in 2019 (Food and Agriculture Organization of the United Nations, 2020). As the largest pig-breeding country globally, China dominates global pork output, with 544.19 million pigs for slaughter and 42.55 million tons of pork production (China Statistical Yearbook, 2019). 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., 2020). The future development trend of pig industry

Abbreviations: MSM, manure & sewage management; TSM, traditional simple mode; MPM, mixed processing mode; SBM, semi-biogas mode; PPSUM, professional processing with simple utilization mode; PPFUM, professional processing with full utilization mode.

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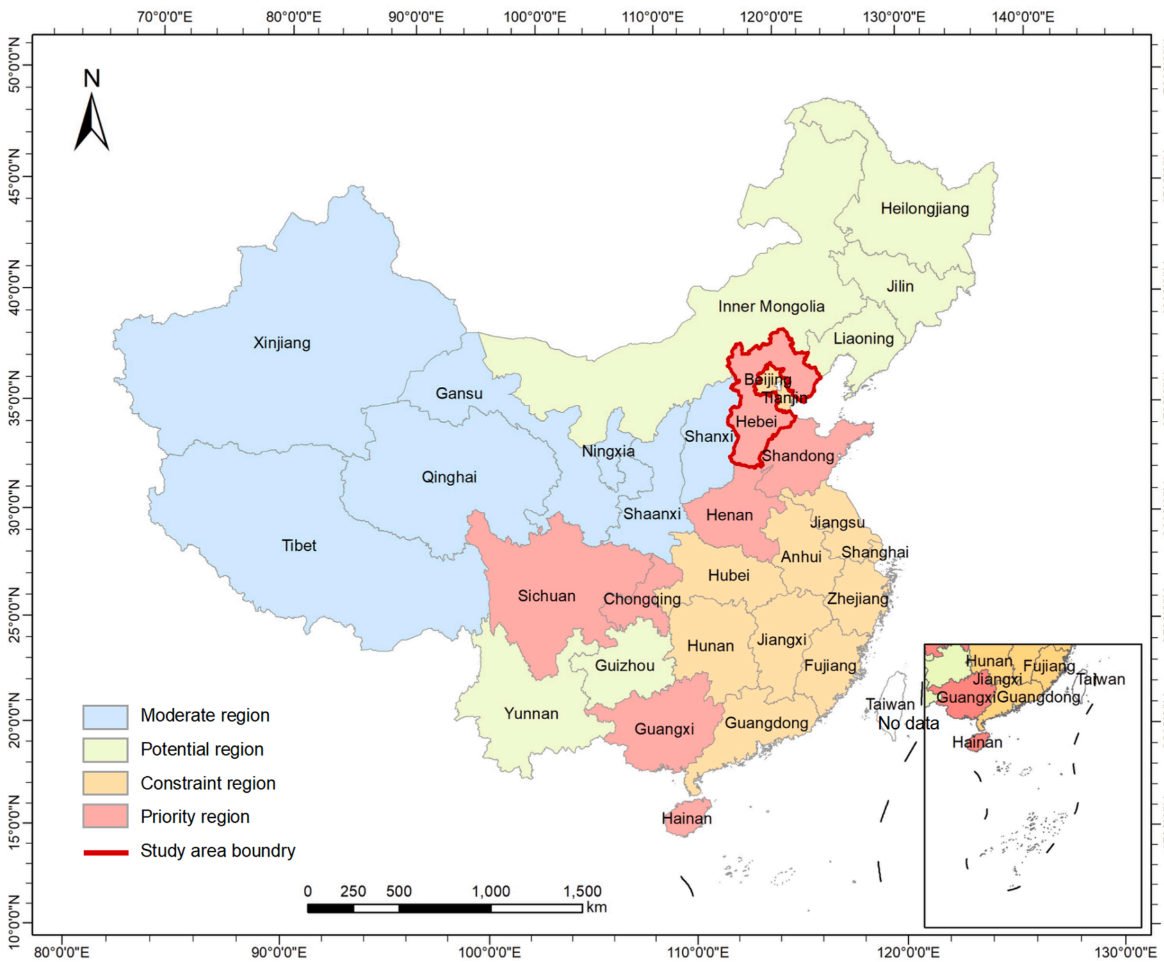

Fig. 1. Pig industry distribution, Study area in China.

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 1000 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 (Thornton and Herrero, 2015; Jin et al., 2021). 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., 2021b). The National Animal Husbandry Station has officially proposed four principal manure & sewage management (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 (Prior et al., 2013; Penha et al., 2015). 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 (Akyürek, 2018; Pexas et al., 2020), 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 (Triolo et al., 2013; Hijazi et al., 2016; Daniel-Gromke et al., 2018). 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 (Tseng and Luong, 1984; Lin et al., 2010; Yang et al., 2010), 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. (2018) 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; Hoeve et al., 2014; Cherubini et al., 2015; 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.

Currently, considering the performance subject of MSM, there are also some studies demonstrating farmers' behaviors and attitudes towards the pollution and management of livestock waste, 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 (Zhang et al., 2015; Deng et al., 2016; Pan et al., 2016; Li et al., 2021a). He et al. (2016) revealed that social capital has remarkable impacts on promoting farmers to participate in reusing agricultural waste. Some scholars have conducted research based on the theory of planned behavior to explore farmers' willingness on livestock waste management (Deng et al., 2016; Tao and Wang, 2020; Li et al., 2021b). 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. Thus, there is still a dearth of information on farmers' preference for discrepant modes. It is of great significance to identify the path selections and determine the main patterns and corresponding characteristics.

In accordance with aforementioned concerns, this study is guided by the scientific question of "what are the typical modes of pig's MSM identified by a data-driven typology, what are the factors and how do they drive farmers' adoption of various modes?" This study 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; 4) what are the characteristics and determinants of farmers towards various modes. The significance of this study 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, and discriminating farmers' heterogeneous characteristics to various modes. It is meaningful to understand the driving forces and promote the targeted implementation of MSM that will lead to the sustainable development of pig industry.

This paper is organized into 5 sections as follows. Section 2 introduces the study area, questionnaire design, data collection and research methods. Section 3 describes statistical results on MSM practices, explains and compares five MSM modes obtained, and analyses farmer' characteristics of the corresponding modes. Section 4 elaborates the empirical applications on various MSM modes and development potential. The final section summarizes the research conclusions and illustrates the research deficiencies.

2. Methodology

2.1. 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., 2018). 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 (Fig. 1).

Hebei province located in the Priority region, plays a significant role in pig breeding, with approximately 5% of the national pork production over the last five years (China Statistical Yearbook, 2016-2020). 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 with approximately 6.39 million hectares of land (China Statistical Yearbook, 2021). 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 resource, Hebei province has great opportunities for waste consumption and provide a basis for exploring the possibilities of further diversified MSM modes. Importantly, providing experience to other regions or countries confronted with similar situations in promoting circular sustainable ecological agriculture.

2.2. Data collection

The pig farm survey of this study covered all 11 cities in Hebei province, Pig farms were randomly selected and farm owners were directly investigated by anonymous questionnaires. A total of 406 valid pig farms' data were obtained, excluding duplicate questionnaires and missing-data questionnaires, which could represent the pig farming situation in Hebei province.

The questionnaire for pig's MSM investigation includes the following 6 sections. (1) Basic information of pig farm, including construction time, scale etc. (2) General situations of MSM, including the amount of manure generated, adopting technologies at collection, storage, separation, processing and utilization section. (3) Farmers' behavior and perceptions on manure disposal. (4) Environmental awareness among farmers. (5) Farmers' perceptions on government regulations and policies. (6) Basic information of pig farm owners, including gender, age and education etc.

2.3. Clustering construction

2.3.1. 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. Dellaguardia (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 is a simple and practical clustering algorithm, it generates new reassembled clusters to minimize a cost function by calculating cluster means based on Euclidean metric (Anderberg, 1973). However, K-means is only applicable to datasets with continuous data (Goyal and Aggarwal, 2017). K-modes is an extension of K-means, which is applicable to datasets with discrete attributes by altering multiple categorical attributes into binary attributes and treating binary attributes as

Table 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	Abbreviation	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%

numeric (MacQueen, 1967; Ralambondrainy, 1995). Scholar has proposed the applicability of K-modes in the application of categorical variables (Huang, 1997; Huang, 1998). Thus, K-modes algorithm can be useful to categorize individuals into groups based on quantitative typology, and identify the main typical paths.

2.3.2. 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 1).

From an overview of pig's MSM, collection mainly adopts four methods. Scraper, as the most traditional and common one, can be divided into mechanical automatic scraper and manual operation. Its advantage is convenient, but noisy. Compared with scraper, soaking and flushing avoid high frequency liquidation work and decrease electricity consumption. However, the generation of additional sewage adds burden in subsequent processing. Gravity collected saves labor and resources, but still requires discharge siphon pipes and special conditions for pigsty construction. According to the multiple collection methods and whether separation, storage section can be separated into mixed and separated. 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. The methods are mainly simple open-air, stack, slot, mulch and reactor compost. Anaerobic digestion is recognized as an available eco-friendly method, which is characterized by the conversion of waste to valuable energy and fertilizer, such as biogas and digestate. Oxidation pond is a process of aerobic biological treatment of wastewater by microorganisms. 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 aim at organic matter, nitrogen and phosphorus removal finally. Industrial treatment is the unique option with no restrictions on emissions. Sewage is treated by the anaerobic oxic pond, biochemical pond and ozonation contact reactor, and the discharge meets the "Emission Standards for Pollutants from Livestock and Poultry Farming (GB18596-2001)", which requires COD < 400 mg/L, NH_3-N < 80 mg/L, TP < 8 mg/L (Sang et al., 2010; Wang et al., 2021). Pig farms without on-site MSM capacity, choose off-site disposal to a third party through payment or grant.

Utilization mainly has four pathways, as waste returning to surrounding cultivable farmland by ditches and pipe networks, pulling away to fertilize kaleyard and orchard by transport, producing packaged

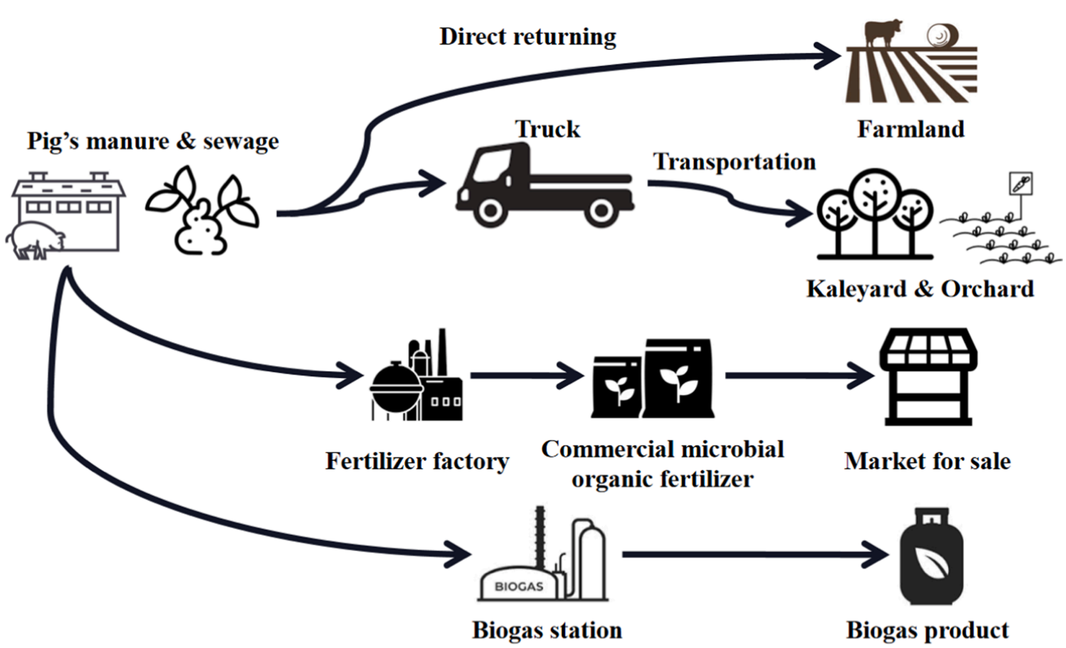

Fig. 2. Pathways of utilization of pig's MSM.

Table 2
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 (data for end of 2020)
Breeding structure	Pig slaughter for 0 = Fattening pigs, 1 = Breeding contains piglets
Cooperation	Whether as a member of pig industrialization 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).

commercial microbial organic fertilizers for sale and utilizing biogas for bioenergy (household cooking, natural gas purifying and electricity generating) (See Fig. 2).

2.3.3. Cluster characterization

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 2).

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.

3. Results

3.1. Descriptive analysis of MSM practices

A general review of type and frequency of technologies adopted at each section was obtained (Table 1.Fig. 3). 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

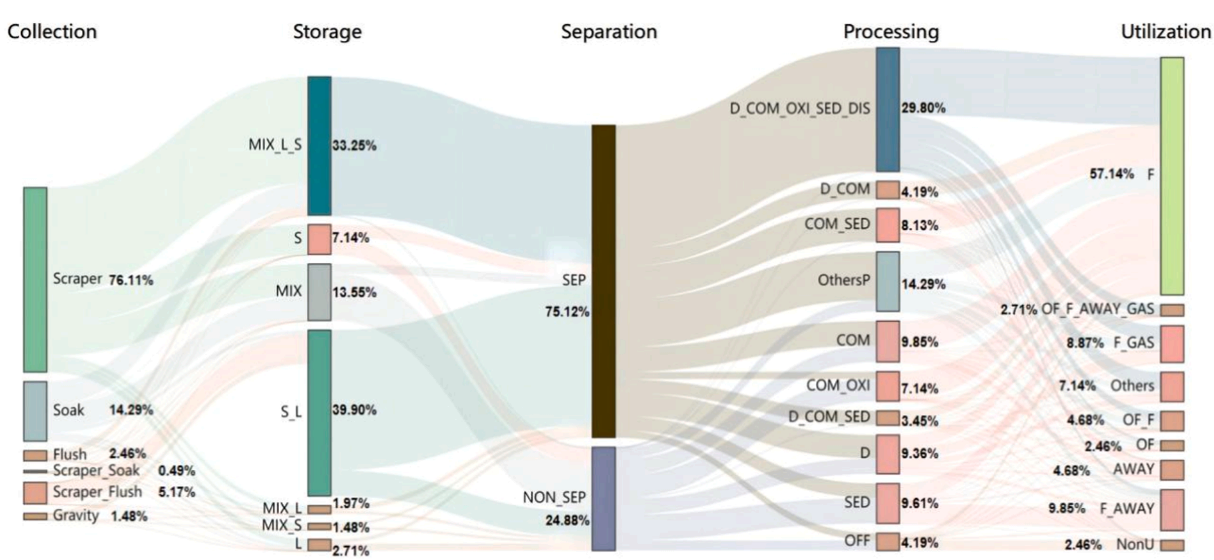

Fig. 3. Statistical description of adopted strategic options within each stage.

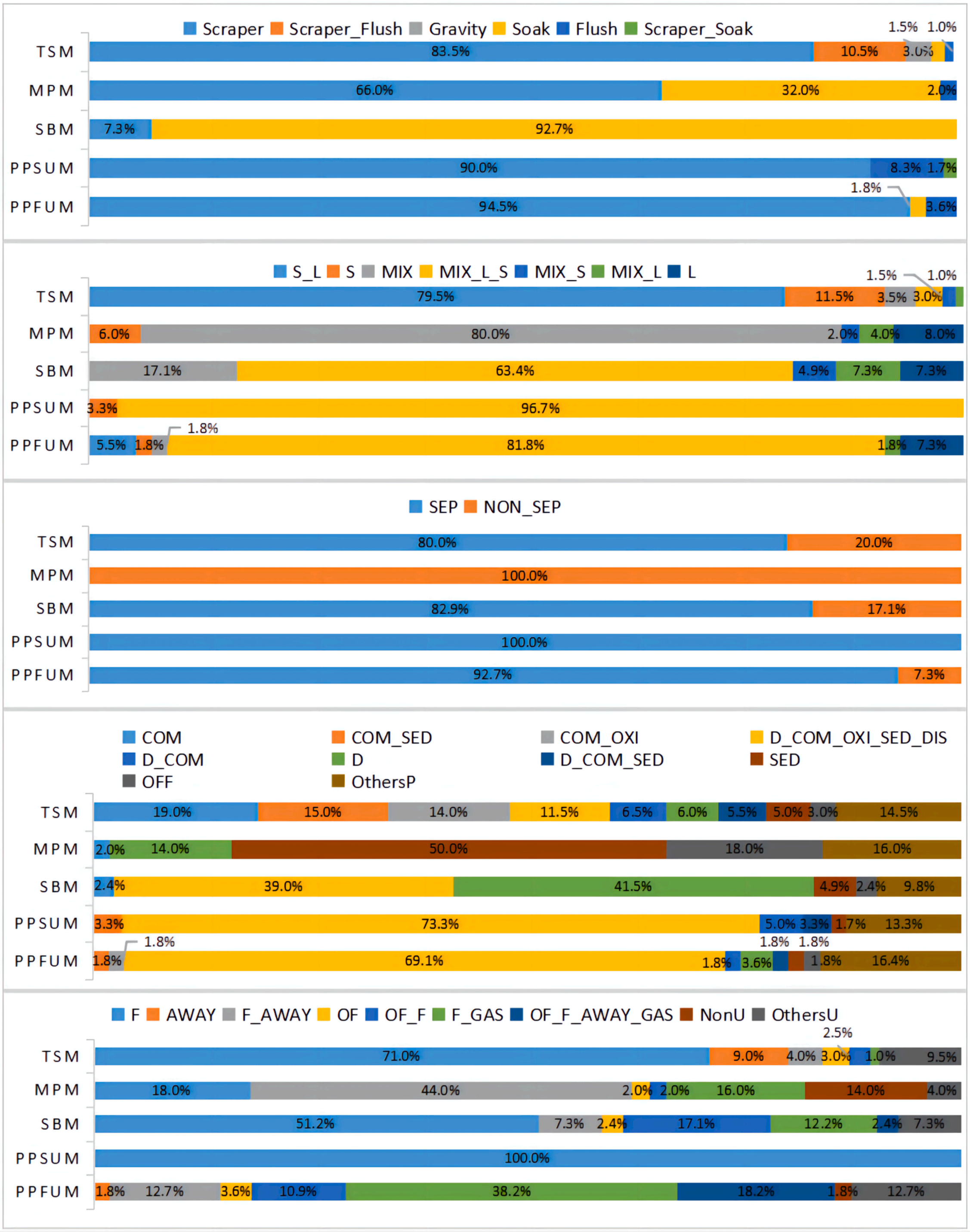

Fig. 4. Distributions of strategic options within each section for five modes.

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.

3.2. *Clustering analysis*

3.2.1. *Cluster 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 Fig. 4.

TSM: In this cluster, scraper was used during waste collection (over 94%), manure was separated stored as solids and liquids respectively.

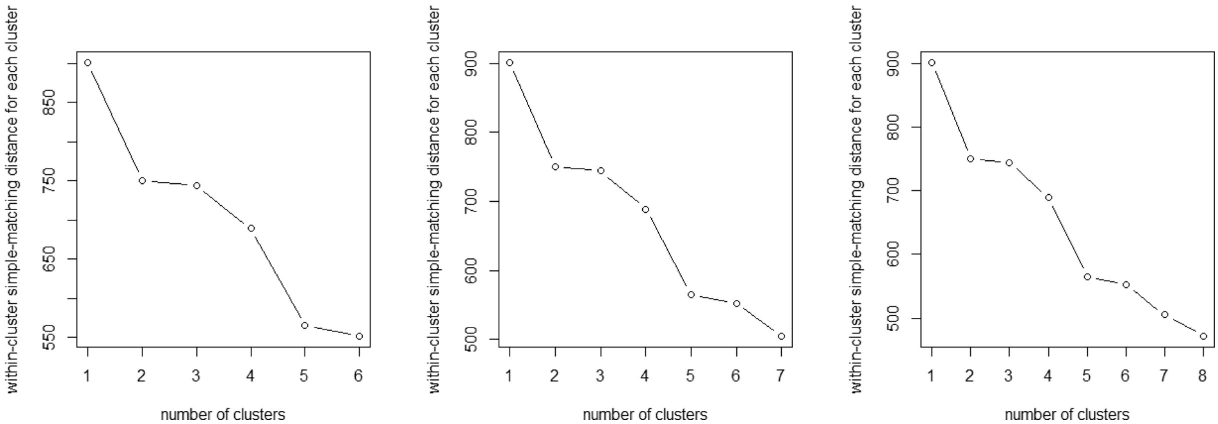

Fig. 5. Results of optimal cluster number determination by Elbow method plotting.

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)***".

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 a 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)***".

3.2.2. Heterogeneous characteristics

Significant differences among community characteristics were analyzed between five modes by Kruskal-Wallis test, Chi-square test and multiple logistic regression. 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<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

Table 3
Descriptive statistics of MSM practices adopted by 406 farms.

Section	Practice options	MSM practices	Contribution (%)
COLLECTION	Scraper	Scraper	76.11
	Soak	Soak	14.29
	Flush	Scraper_Flush	5.17
	Gravity	Flush	2.46
		Gravity	1.48
		Scraper_Soak	0.49
STORAGE	MIX	S_L	39.90
	S	MIX_L_S	33.25
	L	MIX	13.55
		S	7.14
		L	2.71
		MIX_L	1.97
		MIX_S	1.48
SEPARATION	SEP	SEP	75.12
	NON_SEP	NON_SEP	24.88
PROCESSING	COM	D_COM_OXI_SED_DIS	29.80
	D	COM	9.85
	OXI	SED	9.61
	SED	D	9.36
	DIS	COM_SED	8.13
	OFF	COM_OXI	7.14
		D_COM	4.19
		OFF	4.19
		D_COM_SED	3.45
		D_SED	2.22
		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	F	57.14
	AWAY	F_AWAY	9.85
	OF	F_GAS	8.87
	GAS	AWAY	4.68
	NonU	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

could be observed in MPM, reflected in 78% of farms with inventories of less than 2000 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 2000 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 knowledgable 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.

4. Discussion

This study attempts to categorize typical modes applied on MSM in pig farming, and discriminates farms' heterogeneous characteristics on corresponding mode obtained. Regarding to the usefulness and considerations of the modes, meaningful characteristics of modes and implementers are further demonstrated, as well as future trends in the promotion of MSM modes.

4.1. MSM modes characterization

In general, the pig farms interviewed were involved in MSM activities to varying degrees, there are no longer direct emissions without treatment. Obviously, a high policy penetration rate and systematic technology training effectively drive farmers' participation in MSM (Zhao et al., 2019b; Li et al., 2021b). 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 (Engle, 1995). As Chen et al. (2017) 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., 2017). 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.

Table 4
Descriptive statistics of MSM practices adopted of the five modes.

Section	Features	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

Farming structure as a critical factor, its impact on varying degrees of livestock MSM has been proven (Zheng et al., 2014; Huang et al., 2016; Chen et al., 2017; Li et al., 2020a; Pan et al., 2021; Zhang et al., 2021). 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., 2014). Delsart et al. (2020) also emphasized the notice of animal welfare in pig farming. Regarding pig farmers' heterogeneous characteristics, the

Table 5
Potential determinants (continuous variables) for farms' heterogeneous behaviors of five MSM modes.

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-b]Differences among five types are denoted by differing lowercase letters ($P < 0.05$).

Table 6
Potential determinants (categorical variables) for farms' heterogeneous behaviors of five MSM modes.

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)a	**30(15)[a]**	**63.4(26)[b]**	45(27)[a, b]	43.6(24)[a, b]	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 manure 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)[a, b]	**26.2(11)[c]**	48.5(16)[b, c]	**93.2(41)[d]**	82.7(43)[a, d]	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)[a]**	84(42)[a, b]	80.5(33)[a, b]	78.3(47)[a, b]	**85.5(47)[b]**	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.
[a-d]Differences among five types are denoted by differing lowercase letters ($P < 0.05$).

education level and environemntal 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 (Gao and Zhang, 2010; Pan et al., 2021). Waste discharge on compliance is determined by the nutrients (N, P) required for crops and nutrients available in excrement (Ministry of Agriculture and Rural Affairs, 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 (Wu et al., 2014; Maurer et al., 2016; Chen et al., 2017). 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

Table 7
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.

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 (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[1] 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.

4.2. MSM modes application prospects

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 cooperation of small and medium-sized farms. TSM and MPM can guarantee the basic environmental provisions for these farms. 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 (General Office of the State Council, PRC, 2020). Rising intensification levels undoubtedly create large quantities of concentrated pig waste, while increasing mechanization is more conducive to the promoting knowledge-intensive MSM modes, such as SBM, PPSUM and PPFUM.

From the perspective of land, generally, in both developed and developing countries, farmland has always been considered as 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 (National Bureau of Statistics, 2021). 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., 2020b).

Concerning 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). Data showed that small, medium and large scale pig farms accounted for 88.70%, 10.67% and 0.62% respectively in 2019 (China Animal Husbandry and Veterinary Yearbook, 2020). It could assume 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 (Lopez-Ridaura et al., 2009; Nagy and Wopera, 2012; Li et al., 2016; Corbala-Robles et al., 2018; Wang et al., 2021b). Generally, participation in MSM should not be limited to farmers, solving the hindrance of MSM requires externalities boosting by financial support from government or market means, and promoting farmers' cognition of policies, so as to establish the sustainable mechanisms (Yan et al., 2020; Wang et al., 2021a).

5. Conclusion

This study indicated a comprehensive perception of pig's MSM application in Hebei, China. Firstly, classify the existing hodgepodge of MSM methods from a macroscopic viewpoint, categorize a legible recognition of five typical MSM modes (i.e., traditional simple mode, mixed processing mode, semi-biogas mode, professional processing with simple utilization mode and professional processing with full utilization mode) from a statistic-categorized view based on quantitative typology. It has the advantage of visualizing and simplifying the variety of diversified methods combinations, contributing to the ease of administrative convenience. Substantially, MSM is an entire continuum of several sections, technical approaches adopted in a particular phase has connection to the associated phases, appropriate combination of strategies leads to the maximization of adequate allocation of resources. This study 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. Furthermore, exploring farmers' preferences for the corresponding mode by

[1] [1]CNY, Chinese yuan, 1 CNY=0.16 USD (10 December 2021).

heterogeneity analysis, may provide a reference for determining the adaptability of the mode and selecting the appropriate MSM mode for individuals. Farmers' education level and perceptions of the environment are significantly promoted MSMs technologies. Scale-up has a significant positive effect on mechanization adoption and diversified strategies application. Besides, breeding structure may affect collecting strategy. Meanwhile, land may be the critical factor that restricts manure utilization and part of MSM modes extension. Consequently, in response to the anticipated development prospects of pig industry in China, suggestions for promoting potential MSM modes are presented. Discoveries in this study contribute references and suggestions to farms and government in the aspect of the sustainability of MSM and green development of pig industry.

However, there are still limitations that need to be noticed. Firstly, 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 evidences from Constraint region are eager for our future survey because of more stringent environmental requirements. Secondly, farm scale in this study is identified by inventory numbers. Total slaughter numbers should be considered as well, due to the non-stabilization of pig production throughout the year.

Declaration of Competing Interest

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

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Appendix I. . Representativeness of the data collected - minimum sample size test

To confirm the representativeness of the survey results, the minimum sample size was calculated. X is the error rate, generally <10%, 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,

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

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

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

In 2020, there were approximately 36,484 pig farms in Hebei province with the farm size of over 100 heads for slaughtering. Thus, the minimum sample size of 381 could be representative of the pig farming situation in Hebei province. Data collected in this study covered 406 pig farms, which is statistically significant.

Appendix II

Clustering algorithms: K-means clustering and K-modes 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,

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

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). Huang 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; Huang, 1998). Thus, cluster analysis can be useful to categorize individuals to groups based on quantitative typology, and identify the rules of which to get easy identification of typical paths.

Clusters determination: 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 Fig. 5., 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 cluster is 5. Thus, MSM methods will be divided into five modes.

Appendix III. Description of adopted MSM practices in the questionnaire and contribution of adopted methods in each section among five modes

See Tables 3 and 4

Appendix Ⅳ. Kruskal-Wallis tests and significant differences for continuous variables of five MSM modes

See Table 5

Appendix Ⅴ. Chi-square tests and significant differences for categorical variables of five MSM modes

See Table 6

Appendix Ⅵ. Multinomial logistic model and significant differences of MSM modes

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:

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

See Table 7

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