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Quantification of sustainable animal manure utilization strategies in Hangzhou, China

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HIGHLIGHTS

- Regional manure utilization between animal-crop production systems.
- Collaborative optimization structure to recognize manure logistics configuration.
- Dynamics of private actions and public sustainable goals in manure utilization chain.
- Quantification of sustainable trajectories to animal manure managements.
- Decision supports to all practitioners when making policies and management strategies of animal manure recirculation.

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ABSTRACT

Context: China's livestock and poultry industries have been experiencing a transformation over recent decades, transitioning from family-size farms to larger, confined animal feeding operations. This development has significantly improved animal production capacity and reduced costs but has also created new challenges to manure management. One important concern is the conflicting interests of environmental protection and economic welfare between policymakers and manure utilization practitioners.

Objective: In this study, a regional manure utilization chain (RMUC) model was developed by recognizing optimal logistic configurations for manure and manure-based products between animal feeding operations, centralized processing facilities, and crop farms. We then use RMUC model to quantify the impact of management practices to the animal manure utilization chain of Hangzhou, China in the context of sustainable development.

Method: The RMUC model implemented an analytical target cascading structure with a multi-objective optimization algorithm to generate a set of Pareto-optimal configurations for discussing the regional economic costs and greenhouse gas (GHG) emission considering the practitioners' operational decisions to the designated manure management practices.

Results and conclusion: A comparative analysis quantified and prioritized the manure management practices (solid/liquid separation, manure reduction strategies); estimated economic and GHG emission credits of manure composition measurements; and indicated economic and GHG emission benefits of electric vehicles and the secondary infrastructures on manure distribution. The results showed sustainable metrics of the manure utilization improvement, including private costs, regional benefits, and the global impact of GHG emissions.

Significance: The RMUC model demonstrated the compromise between practitioners' interests and public sustainability benefits given a certain level of constraints in decision process. Our analysis is an example of implementing computational models to deal with agricultural systematic problems with social, environmental, and economic concerns.

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1. Introduction

China's livestock and poultry industries have been experiencing a transformation in recent years, with family farm-centered production transitioning to industrialized animal feeding operations employing sustainable manure management (Hu et al., 2017). Modern animal feeding operations (AFOs) have improved production capacity, fostered advances in breeding, and reduced production costs. However, the rapid industrialization of the Chinese livestock and poultry sectors over the past 14 years, has proceeded with little awareness to environmental impact. Recently, Chinese government officials have strengthened environmental regulations (Bai et al., 2019a; Bai et al., 2019b). In 2015, livestock production in some regions of the country were forbidden in order to prevent animal manure from polluting local water supplies. The number of pigs slaughtered on an annual basis has decreased on average by 47 million per year from 2014 to 2017 (Bai et al., 2019a). Therefore, an effective manure utilization chain is necessary for environmental well-being and a robust food supply.

Modern animal manure utilization technologies and operations are both more complex than they have been in the past. Animal manure is recognized as a fertilizer since it contains essential nutrients (nitrogen, phosphorus, and potassium) and is beneficial to soil health (Ozlu et al., 2019; Zhang et al., 2020). However, animal manure has been treated as waste in some regions. AFOs are geographically localized in order to capitalize on climate, processor availability, transportation access, labor, and proximity to market (Flotats et al., 2009; Takahashi et al., 2020). This leads to the spatial clustering of AFOs, which in turn results in challenges for local manure utilization. These challenges include high transportation costs, phosphorus runoff, and a decreasing willingness of farmers to accept manure-based fertilizers (Makara and Kowalski, 2018; Sharara et al., 2017). Most AFO owners prefer cost-effective or operation-simple practices for manure management. Large AFOs might increase the land available for manure application, reduce the pollution risks associated with manure treatment, or ship excessive manure to other facilities when prompted with environmental challenges (Keplinger and Hauck, 2006; Wesnæs et al., 2009). These strategies might solve the problem of manure utilization for a single farm, but also run the risks of reducing the value of animal manure, increasing the total operational cost, and damaging local ecosystems.

Manure nutrient management should include a set of actions that guide manure handling from source to the end-users, with considerations regarding the economy, the environment, animal welfare, and social effects. Recent research has highlighted the fact that large AFOs with stable finances, improved marketability, and credit accessibility are more empowered to implement environmental protections than small or "free-range" farms (Ren et al., 2019; Takahashi et al., 2020). Manure utilization chain expenditures could be reduced by systematic approaches, such as adjusting animal diet formulas, optimizing manure utilization networks, and changing crop combinations (Deng et al., 2020; Niles and Wiltshire, 2019; Zhang et al., 2020).

However, the holistic approach to manure nutrient management is not practical in many countries. Governments have implemented regulations to achieve environmental sustainability concerning nutrient surplus, heavy metal pollution, odor concerns, and greenhouse gas (GHG) emissions (Chadwick et al., 2020; Hansen, 2019; Moller et al., 2007). The lack of coherence between environmental protection rules and food security polices in different ministries leads to non-complementary and sometimes even contradictive to manure nutrient utilization (Teenstra et al., 2014). Such a policy creates issue of the economic sustainability to AFOs and is even not continuous to achieve environmental goals (Long et al., 2018; Qian et al., 2018). It is of critical importance that policymakers and manure management officials understand exactly how polices and management practices affect private costs and public benefits in the changes of manure utilization dynamics.

A sustainable manure utilization, in regions that are particularly sensitive to excessive nutrients, should be practical and affordable to practitioners. Then, the higher-level planning of nutrient balance could be achieved if all participants within the chain agree to follow practices which are and guided by local governments and commonly recognized as pubic benefits (Zhuo and Ji, 2019). Restricting the manure application to crop farms always means higher logistics cost to AFOs. Financial assistance and subsidies could encourage AFOs to modify their decision-making preferences to achieve both economic and environmental sustainability (Chen et al., 2016; He et al., 2016). Recent studies have pointed out the global impacts of greenhouse gas (GHG) emissions originating from livestock and have suggested mitigation strategies such as crop-livestock integration and manure management (Ma et al., 2019; Zhuang et al., 2019). However, it has proven difficult to quantify the local sustainable benefits and global impacts of some holistic manure management strategies. Many policies' standard metrics, such as setback distance, tax rates, and subsidy levels, are estimated from a set of parameters and based on the statistical average or median scenario. Few studies have included the interactions and trade-off between animal producers and manure users in these calculations (Sharara et al., 2018).

Our study was trying to address manure management issues that is specifically about the coordination of the manure utilization chain in hopes of meeting environmental and economic sustainable contexts. Logistics optimization was successfully implemented to identify optimal decisions regarding biofuel, biomass, and waste supply chain management (Díaz-Trujillo and Nápoles-Rivera, 2019; Huang et al., 2019; Mayerle and de Figueiredo, 2016). We have developed regional manure utilization chain (RMUC) models that enable the rapid configuration of an optimal manure utilization chain, while allowing for the evaluation of various economic, technical, and environmental objectives. RMUC models focus on solving one particular problem: how the units in slurry manure utilization chains decide on their flow patterns given their local objectives (minimization of their individual manure operational cost without regards to minimizing the entire chain's operation cost). This formulation guarantees that each stakeholder's operational-level decisions are made independently (Li et al., 2021). In this study, we modified RMUC model to incorporate greenhouse gas emissions as an upper-level objective as well as to the minimization of regional manure utilization costs. This approach highlights the trade-offs and enhancement effects between practitioners' interests and public environmental protection goals given a particular set of decisions and constraints.

The modified RMUC model was applied to a case study in Hangzhou, China. The Hangzhou government used to develope an *ecological plan* that had resulted in the closing of breeding operations and the establishment of prohibition zones since 2014. In recent years, the increasing demand for meat in urban areas has challenged the *ecological plan*. The sustainable manure utilization should consider both nutrient surplus issues in manure land application and the economic feasibility to all practitioners. Meanwhile, there is a new argument about the extra GHG emissions from manure transportation following the strict manure nutrient management plan. The objectives of this study are: 1) to modify the RMUC models with capability of measuring both economic costs and GHG emissions for regional manure utilization; 2) to answer "what-if" questions for quantifying and evaluating how sustainable trajectories affect manure utilization configurations and sustainable outcomes. The modeling results and scenario discussion can provide decision-makers with evidence and indicate possible future research directions.

2. Methodology

2.1. Overview of the modified slurry-manure RMUC model: widening the scope

Regional manure utilization chain (RMUC) models formulated both solid manure utilization chain and slurry manure utilization chain of animal feeding operations (AFOs) into mathematical models for optimizing the strategic decisions (capacity and locations of centralized manure processing facilities) and tactic decisions (animal manure transportation) in a target updating way that closely reflects the real decision-making processing. The optimization objective of the RMUC models is to minimize the total costs of local manure utilization (Li et al., 2021). We modified the slurry-manure model of RMUC models to address local manure nutrient utilization issues in the context of sustainability.

As shown in Fig. 1, the scope of the slurry manure utilization chain to be analyzed includes two sections: individual manure management and centralized manure management. Fresh manure is processed either at animal feeding operations (AFOs) or centralized processing facilities (CPFs). Depending on the housing types and manure processing technology, slurry manure composition varies from facility to facility (Moller et al., 2002). The slurry manure, or liquid-portion manure, from AFOs has a high moisture content and low nutrient density. This makes it more challenging to treat and transport. It is also more difficult to profitably sell, and its use is typically limited to local crop farms. The unused portion is shipped to a centralized processing facility (CPF) for further processing: energy (M-EP), fertilizer (M-FP), or wastewater (WP) (Rehl and Müller, 2011). The treatment of manure wastewater into irrigation water is costly (Wang and Serventi, 2019). The effluents from M-EP and M-FP are utilized as liquid fertilizer.

Using information regarding manure supply (AFOs), manure demand (crop farms), and existing logistic networks, modified slurry-manure RMUC models are capable of constructing an optimal logistics configuration for manure and manure-based products provided certain constraints. The optimization of the slurry manure utilization chain uses a sequential optimization approach based on the analytical target cascading structure (ATC). This structure enables the top-level design target to be cascaded down to lower levels of the modeling hierarchy (Kim, 2001). As shown in Fig. 2, this formulation guarantees that operational-level decisions for AFOs and CPFs are made independently based on their local objectives (minimization of manure operational cost), while their decisions are constrained by upper-level targets. The upper-level module is extended to optimize both total costs and GHG emissions associated with slurry manure utilization. The lower-level modules were kept as origins to reflect practitioner actions as they seek to minimize their operational costs in response to upper-level targets.

2.2. Upper-level module: economic objective

The objective of the upper-level module is to minimize total utilization cost and total deviation tolerances. The total utilization cost is comprised of slurry manure logistics cost, processing cost, land application cost, and the capital cost required to expend CPFs' slurry manure processing capacity (Eq. 1). The upper-level objective function decision variable is the amount of slurry manure flow from the AFO (Xc^{L0}) to the crop-farming village, and the slurry manure processing capacity at candidate CPF locations (CAP^{L0}). The economic parameters updated from the lower-level modules include the unit AFO-related manure utilization cost (*Cuc*), unit CPF manure collection cost at (*Ccol*), unit CPF manure processing cost (*Copl*), and unit CPF effluent distribution cost (*Clo*). The amount of slurry manure transported from AFOs to local crop farms (*Xc*) is a summation of the component flows from AFOs to crop-farming villages (*XJ*) from the lower-level module. The amount of slurry manure transported to CPFs from AFOs (*PAS*) is the operational response from lower-level modules. Unit AFO-related manure utilization costs are the average transportation cost from each individual AFO to croplands. The equality constraints (h_1) guarantee that all slurry manure from AFOs is adequately shipped to CPFs or crop-farming villages. The control constraint (g_1) ensures that the amount of slurry manure transported to local crop farms is less than the produced manure from each AFO. The target deviation tolerance (ε_x, εp) links the decision variables to the responses from lower-level modules, as shown in g_2 and g_3.

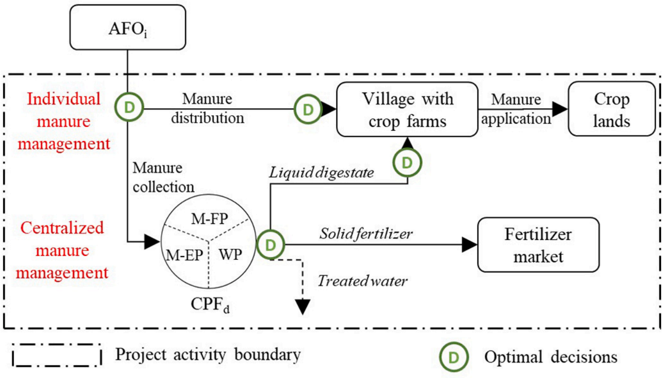

Fig. 1. System boundaries.

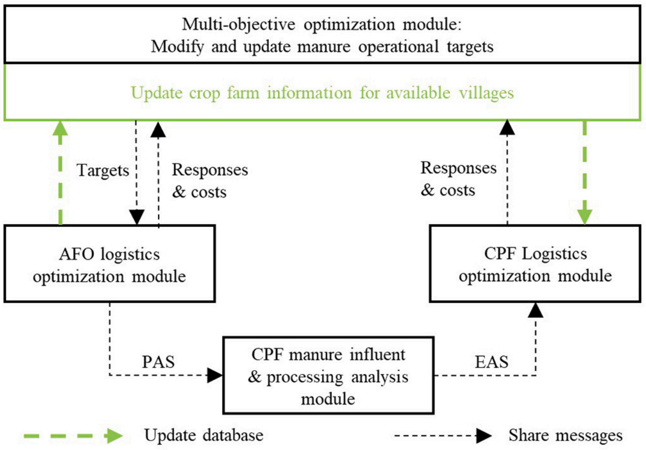

Fig. 2. Analytic target cascading (ATC) structure of modified slurry-manure RMUC model.

$$\underset{i,d}{Min}\sum_i Cuc_i Xc_i^{L0} + \sum_d (Clo_d + Copl_d + Ccol_d) CAP_d^{L0} + \sum_i \varepsilon x_i + \sum_d \varepsilon p_d$$

$$w.r.t$$

$$h_1 : \sum_i Xc_i^{L0} + \sum_d CAP_d^{L0} = \sum_i \sum_k AS_{ik}$$

$$g_1 : Xc_i^{L0} \leq \sum_k AS_{ik}$$

$$g_2 : \left(Xc_i^{L0} - Xc_i\right)^2 \leq \varepsilon x_i$$

$$g_3 : \left(Cap_d^{L0} - PAS_d\right)^2 \leq \varepsilon p_d$$

$$Xc_i = \sum_j \sum_{k=1,2} XJ_{kij}$$

$$Cuc_i = \frac{\sum_j \sum_{k=1,2} \left[Ctfl + Ctvl \times \left(DMSC_{ij} + DS_j\right)\right] XJ_{kij}}{Xc_i} \tag{1}$$

2.3. Upper-level module: environmental objective

The environmental objective is to minimize the total annual CO_2-equivalent GHG emission from animal manure utilization operations. The emission factors are taken from experimental results, a life cycle database, regulatory standards, and the previously published GREET model (IPCC, 2006; Rehl and Müller, 2011; Wang et al., 2017a; Yang et al., 2018; You and Wang, 2011). A detailed description of the emission factors is summarized in Appendix A. The formulation of this objective is based on the life cycle analysis from animal farms, transportation, manure treatment, and land application. This considers the following life cycle:

- Transportation from AFO locations to crop farms (E_{AC}, *Eq. A.1*).
- Animal manure-fertilizer land application (E_{CF}, *Eq. A.8*).
- Transportation from AFO locations to CPF locations (E_{AF}, *Eq. A.2*).
- Emissions from biogas combustion in CPFs (E_B, *Eq. A.6*).
- Emissions from treatment process in CPFs (E_P, *Eq. A.3*).
- Emissions from centralized processing and treatment facilities (E_W, *Eq. A.4*).
- Transportation of liquid products from CPFs to crop farms (E_{FC}, *Eq. A.3*).
- The land application of liquid products from centralized processing facilities (E_{CL}, *Eq. A.5*).

Total CO_2- equivalent GHG emission is estimated from AFO-related individual manure utilization and CPF-related centralized manure utilization (Eq. 2). The decision variable related to the upper-level objective function is the amount of slurry manure flow from the AFO (Xc^{L0}) to the crop-farming village and the slurry manure processing capacity at the candidate CPF location (CAP^{L0}). The GHG emission parameters include the unit AFO-related manure utilization emission factors (*Euc*) and the unit CPF-related manure utilization emission factors (*Euf*). Unit manure utilization emission factors are the average CO_2- equivalent GHG emission for each individual AFO and CPF (Eq. 3 and Eq. 4), updated from lower-level modules. The component flows from AFOs to crop-farming villages (*XJ*) and to CPFs (*PAS*) were the response from lower-level modules.

$$\begin{aligned} B_{GHG} = & \sum_k\sum_i\sum_j [credit_N(1-\varepsilon_N)NC_{ik} + credit_P(1-\varepsilon_P)PC_{ik} + credit_K(1-\varepsilon_K)KC_{ik}]XJ_{kij} \\ & + \sum_d\sum_j [credit_N(1-\varepsilon_N)ENC_d + credit_P(1-\varepsilon_P)EPC_d + credit_K(1-\varepsilon_K)EKC_d]XJD_{jd} \end{aligned} \tag{6}$$

$$\underset{i,d}{Min} \sum_i Euc_i Xc_i^{L0} + \sum_d Euf_d CAP_d^{L0} \tag{2}$$

$$Euc_i = \frac{E_{AC.i} + E_{CF.i}}{\sum_j \sum_k XJ_{kij}} \tag{3}$$

$$Euf_d = \frac{E_{AF.d} + E_{P.d} + E_{W.d} + E_{CL.d} + E_{B.d}}{PAS_d} \tag{4}$$

2.4. Lower-level modules

Three lower-level modules (*AFO logistics optimization module, CPF manure influent & processing analysis module, CPF logistics optimization module*) were used to calculate and update the economic parameters and constraint factors for optimal operation decisions in each iteration. A full description of the lower-level modules was documented in detail in our previous works (Li et al., 2021). In brief, the *AFO logistics optimization module* objective is to minimize the logistics cost of slurry manure transport from AFOs to crop farm villages and CPFs. The decision variables related to AFO slurry manure transportation costs are the amount of slurry manure going to the crop-farming village (*XJ*) and the amount of slurry manure going to CPFs (*XD*). The CPFs were expected to store, handle, and process manure for pre-determined fertilizer or energy products in order to provide a consistent format and reduce logistical loads. The *CPF manure influent & processing analysis module* will be used to calculate the component flows from AFOs to CPFs (*PAS*), the amount of liquid fertilizer delivered to crop farm villages (*XJD*), and the nutrient content of liquid fertilizer (*ENC, EPC, and EKC*). Similar to the AFO logistics optimization module, the decision variables of the *CPF logistics optimization module* are the amount of liquid fertilizer delivered to the crop farm village (*XJD*) and the amount of slurry manure processed by the waste treatment plant (*XPD*).

The economic and GHG emission benefits were calculated from the nitrogen, phosphorus, and potassium intake by crops. This was then used to show the value of manure fertilizer and anaerobic digestate in terms of synthetic chemical fertilizers (Eq. 5 and Eq. 6). The parameters of nutrient loss during manure application (ε_N, ε_P, ε_K) were taken from previous studies (Hutchings et al., 2013; Moore and Gamroth, 1991). The unit prices of synthetic chemical fertilizers are taken from a local survey. The unit GHG emissions of synthetic chemical fertilizers, including their manufacture, storage, transport, and application, were obtained from the Chinese Life Cycle Database (Wang et al., 2017b).

$$\begin{aligned} B_{value} = & \sum_k\sum_i\sum_j [p_N(1-\varepsilon_N)NC_{ik} + p_P(1-\varepsilon_P)PC_{ik} + p_K(1-\varepsilon_K)KC_{ik}]XJ_{kij} \\ & + \sum_d\sum_j [p_N(1-\varepsilon_N)ENC_d + p_P(1-\varepsilon_P)EPC_d + p_K(1-\varepsilon_K)EKC_d]XJD_{jd} \end{aligned} \tag{5}$$

2.5. Multi-objective optimization

The ε-constraint method is used to optimize the economic and environmental performance of the manure utilization chain. The first step of the ε-constraint method is to determine the optimal lower and upper bounds of the annual CO_2-equivalent GHG emission. The upper bound is obtained by solving the single economic optimization model (Eq. 1). The lower bound is obtained by replacing the economic objective function with the GHG emission objective functions (Eq. 2). The range between the upper and lower bound is divided into 19 identical intervals (20 breakpoints). The total economic cost is minimized under additional constraints (g_4, Eq. 7) requiring the GHG emission does not exceed the breakpoint (ε_{GHG}). To demonstrate the conflict interests of the economic objective and the GHG emission objective, a set of Pareto optimal solutions are generated to evaluate the degree of optimality in a way that one dimension cannot improve without a second worsening.

$$g_4 : \sum_i Euc_i Xc_i^{L0} + \sum_d Euf_d CAP_d^{L0} \le \varepsilon_{GHG} \tag{7}$$

3. Case study of manure utilization in Hangzhou

3.1. Baseline

The metropolitan area of Hangzhou, capital of Zhejiang province in China, is about 16,596 km^2 and has a population of over 20 million. The structure of animal farms is changing from family-scale operations to large-scale operations. Since 2014, many existing large-scale livestock farms located within the breeding reduction or prohibition zone were closed for environmental protection purposes (Qiu et al., 2017). Based on our previous analysis, the Hangzhou *Ecological Plan*'s manure management strategy can be adapted to balance animal husbandry and environmental protection at a lower cost (Li et al., 2021).

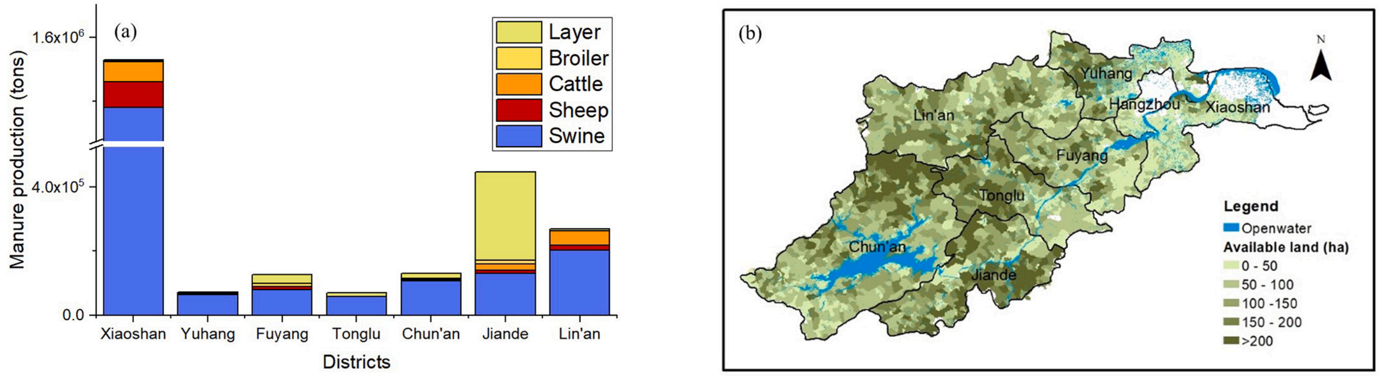

Fig. 3. (a) Statistic summary of manure production records from Animal Husbandry and Veterinary Bureau of Hangzhou and (b) land available map in Hangzhou, China.

A base case was implemented with 666 AFOs and 32 CPFs within the Hangzhou metropolitan area. As shown in Fig. 3 (a), the annual slurry manure production is 2.4 million tons. The current slurry manure processing capacity of CPFs is 1.46 million tons (additional waste treatment: 95 million tons). Hangzhou's applicable manure lands are classified and summarized (unit: administrative village) into four classes: arable land, forest, grazing land, and orchard. An overlay analysis between the standard criteria maps in Table A.3 was used to determine land use and identify manure applicable lands. As shown in Fig. 3(b), 63% of villages have arable lands and forest lands. All villages have surface water features, such as rivers, lakes, and wells. Current manure application practices utilize tank trucks to carry liquid manure fertilizer to targeted arable lands and orchards. Once these trucks arrive, they spread liquid fertilizer along roads and trails using pressurized guns. This method was deemed to be unsustainable due to eutrophication, odor problems, and sanitation issues. The base case proposes a setback policy for manure land application whereby the slurry manure is incorporated into arable land and orchards instead of surface spreading and is restricted to the land within 60 m of surface water.

3.2. *Manure management improvement*

The structure of animal production facilities is rapidly changing from family-scale farms to confined and specialized animal feed operations. As shown in Table 1, the production performance of AFOs varies greatly. Around 10% of animal farms operate on a large-scale and have good productivity. However, livestock farms, mostly swine farms, goat farms, and dairy farms, are still small-scale and have relatively low productivity.

Table 1

Summary of animal farm records from Animal Husbandry and Veterinary Bureau of Hangzhou.

Animal farms	Farm inventory statistics[a] (herds)	Sale to inventory ratio statistics[a]	Manure production statistics[a] (ton/herd)	Installation rate[b] (%)
Swine	250/800/ 5592/10000	1.5/1.75/1.72/ 2	0.7/1.08/1.12/ 1.59	81.8/84.4
Sheep	215/1000/ 1428/3000	0.4/0.0.8/0.8/ 1.3	0.22/0.47/ 0.74/1.5	50.0/53.3
Dairy cow	170/900/ 913/1580	0.13/0.5/0.49/ 0.95	17.6/22.5/ 22.4/26.5	89.0/75.0
Broiler	3000/8000/ 17636/38000	2/2.7/2.7/4.0	0.006/0.047/ 0.03/0.047	42.1/42.1
Layer	5000/13500/ 21867/49100	−/−/−/0.25	0.04/0.07/ 0.06/0.09	92.7/8.5

[a] (10%/median/mean/ 90%).

[b] Mechanical manure scraper system / Solid & liquid separation.

On-farm manure management also varies from farm to farm. The slurry manure production of swine and dairy farms account for 89% of total slurry manure production. Some animal farms prefer to use flushing water to remove manure from animal areas. Compared with mechanical manure scraper system, flushing system adds more water and results in an extra load for transportation. The broiler farms in the top 10% quantile generate 7.8 times more manure than the broiler farms in the median level, and the sheep farms in the top 10% quantile generate 6.8 times more manure than the sheep farms in the median level. The failure of proper water management in these farms has resulted in additional expenditures on manure management.

AFO owners have different opinions regarding the separation of solids from slurry manure. Some farms insist that solid/liquid separation is costly and ultimately useless in manure utilization. Other AFOs utilize mechanical manure scraper systems or solid/liquid separators to split the manure into liquid and solid portions. An advantage of solid/liquid separation is the ability to produce organic solid fertilizer, which can used elsewhere. The liquid portion of manure has lower nutrient content and can be applied to croplands. The analyses conducted herein sought to quantify the economic and environmental benefits of improvements in manure management.

- A scenario analysis was conducted to assess the impact of solid/liquid separation on manure utilization chain configuration by assuming all slurry manure was not separated into liquid and solid portions.
- A scenario analysis was conducted to quantify the economic and environmental benefits of on-farm wastewater management. The manure production level of AFOs above the median level for a given species was corrected to the median level.

3.3. *Animal manure composition measurement*

The lack of information regarding manure nutrient content is one barrier to informed nutrient recycling on agricultural land. Many organizations and agricultural extension groups recommend a regular analysis of manure samples in order to maximize nutrient efficiency and minimize nutrient losses to the environment (Marino et al., 2008; Zhu et al., 2004). However, most planners and AFO owners in Hangzhou use reference numbers or recommendation factors to determine the application rate. Laboratory tests are not widely utilized by local governments and AFO owners. A scenario analysis was conducted whereby the manure nutrient content from each AFO varied within specific ranges (10%, 30%, and 50%) while the manure application rate is calculated using standard reference numbers. An independent normal distribution was assumed for the variation level, and 100 statistic samples (N%, P%) were generated.

3.4. *Transportation alternatives*

The distribution of manure and manure fertilizer involves extensive logistics networks. The two major modes of transportation are truck and pipeline. The distribution of manure by truck transportation occurs at low-speed over a long time, resulting in lower fuel economy and low labor efficiency (Yang et al., 2018). Many organizations believe electric trucks are more suitable than diesel trucks for local distribution. Another alternative transportation method is portable pipeline pumping. This method has been used by some farms for short-distance transportation. A scenario analysis was conducted to study how these transportation options affect GHG emissions and operational cost within the manure utilization chain. Yang et al. (2018) estimated the total cost and GHG emission factors of commercial diesel trucks and electric trucks in China. In this study, we define the operational cost and GHG emission as functions of energy use (grid-electricity and petroleum diesel), maintenance cost, labor requirements, and battery replacement demands (electric vehicle only). Plug-in electric vehicles were chosen for consideration in this study because manure transportation is not time-sensitive, and night can be utilized to charge plug-in electric trucks.

Many studies have discussed pipeline transportation of animal manure (Chen and Hashimoto, 1976; Ghafoori and Flynn, 2006). The operational cost associated with this transportation method includes pipeline operator costs, pump operational costs, and booster station operational costs (Marufuzzaman et al., 2015). Here, we do not consider booster station operational costs since manure transportation pipelines operate over short distances and do not require them to function. Wang et al. (2019) estimated the electricity cost and GHG emission factors of pump operations in China. Ghafoori and Flynn (2006) summarized the breakdown of the operational cost. We assume portable pipeline pumping is used for manure and manure fertilizer distribution within a village. Long-distance transportation from AFOs to villages and AFOs to CPFs utilizes diesel vehicles or electric vehicles. The transportation cost is a function of the unit variable transportation cost and unit fixed transportation cost. Variable transportation cost is directly proportional to the amount of manure and the transportation distance. Fixed transportation cost is independent of distance traveled and includes loading and unloading activities. A list of unit costs, emission factors, and parameters are provided in Table A.2.

4. Results and discussion

4.1. *Scenario analysis of baseline case*

The Pareto-optimal curves are generated by solving the multi-objective optimization problem at 20 constraint levels of GHG emissions. As shown in Fig. 4(a), the GHG emission objective conflicts with the AFO-related and CPF-related costs. The restricted GHG emission constraint (ε_{GHG}) increases the penalty of violating the GHG emission constraint (Eq. 7), reduces the effects of target deviation to tolerance, and forces AFO logistical decisions to align the upper-level objectives. In the restricted GHG emission scenario, AFOs may ship manure to farther crop-farming villages instead of closer CPFs because that decision benefits the entire chain, as proposed in the upper-level module. However, the stricter GHG emissions constraint did not increase the average total cost. As shown in Fig. 4(b), CPFs processed more manure with relaxed GHG emission constraints. Compared with individual manure management, centralized manure management has higher processing costs and GHG emissions. Without GHG emission constraints, the regional average cost is CNY 23/ton, and the regional average GHG emission is 21.7 kg CO_2 e/ton. CPF-related costs account for a significant portion of the total cost. Although relaxing the GHG emissions constraint reduced the cost for each AFO or CPF, the utilization cost of the whole chain is higher due to the large quantity of manure processed by CPFs. Target deviations to tolerance have large impacts on the upper-level optimization module. The optimal manure utilization configuration is decided by the AFOs' logistics decisions in the lower-level module. Such a formulation illustrates how decision-making is shifting from individual interests to regional benefits under GHG emission constraints. Without a higher-level target, the manure management cost is lowest for each stakeholder, but the global optimum for the entire chain cannot be reached.

The optimal results also indicate that the land in Hangzhou available for manure land application is sufficient for current AFOs with the proposed setback policy. As shown in Fig. 4(b), 90% of manure is applied to the crops directly from AFOs when GHG emission constraints are less than 19 kg CO_2 e/ton. The economic benefits (Average: CNY 22/ton) and GHG credits (Average: 3.75 kg CO_2 e/ton) for land application remain relatively stable. The percentage of land suitable for manure application is around 11% to 12% of the total available land in different GHG emission scenarios. As shown in Fig. 5, Hangzhou's northeast district has various water networks and less croplands available for manure application. The central districts have many villages involved in manure utilization. The southwest districts of Hangzhou are

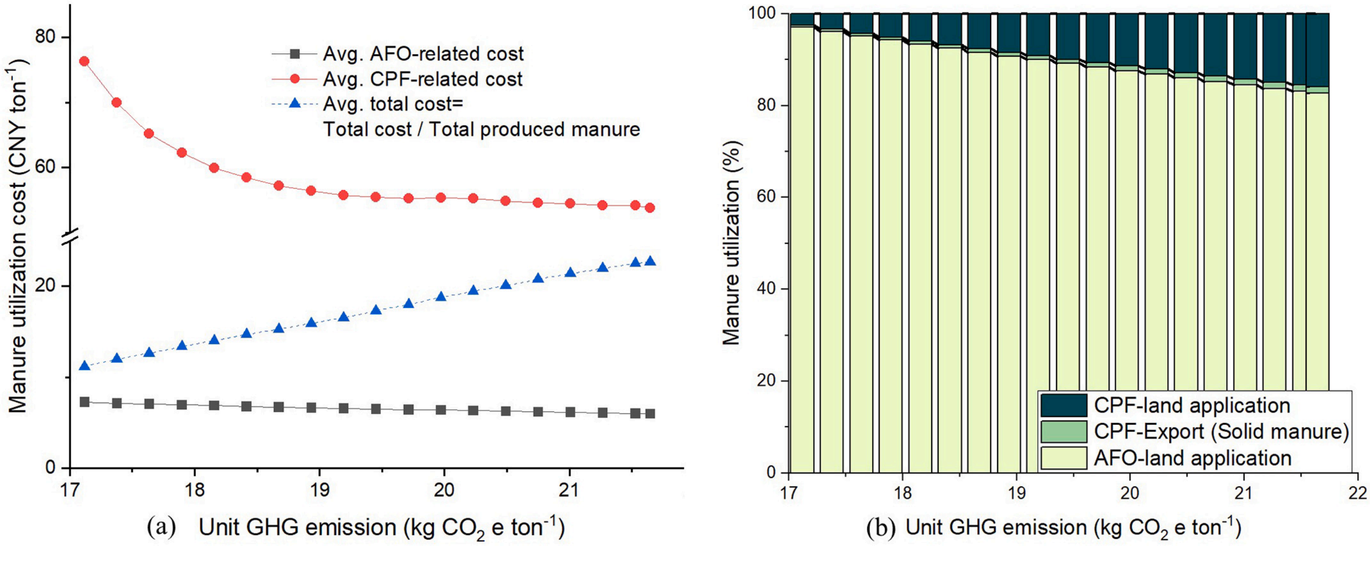

Fig. 4. Pareto-optimal curves under 20 GHG emissions levels (a) utilization cost (b) breakdown of manure utilization pathways.

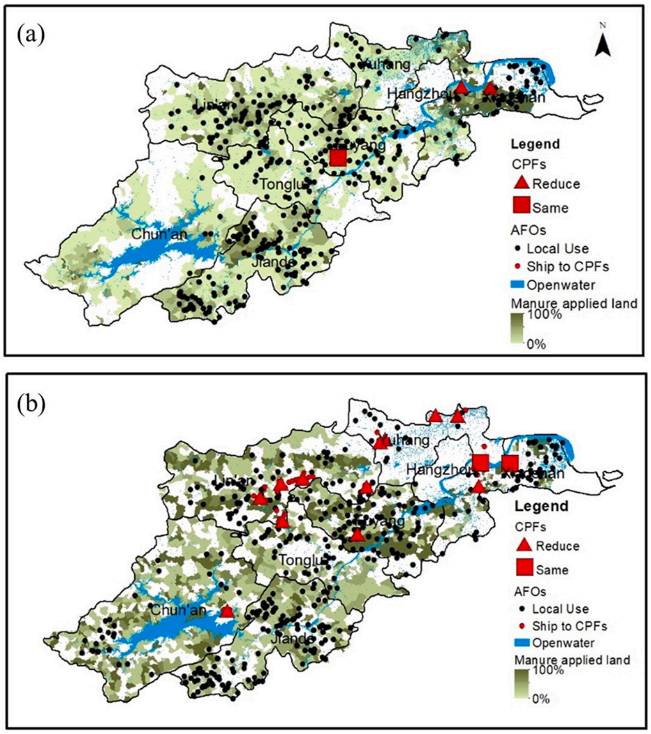

Fig. 5. The optimal slurry manure supply chain configuration at (a) $\varepsilon_{GHG.min}$ (b) $\varepsilon_{GHG.max}$.

mountainous areas with enough land resources for AFO development. The logistical behaviors change significantly in the central and northeast districts under relaxed GHG emission constraints ($\varepsilon_{GHG.max}$). The results indicate that some AFOs are very sensitive to transportation distance. The manure in Lin'an district travels around 6 km in the restricted GHG emission scenario, while it travels only 3 km in the relaxed GHG emission scenario. In other words, the available land resources are not sufficient in some local communities. This forces AFOs to decide either farther crop farms or nearby CPFs. Under relaxed GHG emission constraints ($\varepsilon_{GHG.max}$), two existing CPFs in the Xiaoshan district processed excessive manure, making them of critical attention on manure nutrient surplus issues; 13 CPFs serve for AFOs with lower logistics costs.

4.2. *Scenario analysis of animal production improvement*

Large AFOs often use manure separation mechanics, such as mechanical manure scraper systems and solid/liquid separators, in order to separate and concentrate solid mass from slurry manure. Compared with some conventional systems, like deep pits, flushing-gutters, and bedding, the investment and operational costs associated with these manure separation mechanics are relatively high, especially for small and medium-sized AFOs. To quantify the impact of solid/liquid separation on manure utilization, the slurry manure produced from each AFO was assumed to be non-separated. In other words, the 0.55 million tons of solid manure that was processed and sold elsewhere will be used locally under this assumption. The optimal configuration of the manure utilization chain was altered in this scenario with different CPF capacities and manure utilization patterns (*Fig. A.2: The optimal slurry manure supply chain configuration without solid and liquid separation*). This was especially true in the Jiande district, where cropland usage and transportation costs increased since most of the villages were operating at full manure utilization. As shown in Table 2, utilization cost and manure-applied land increase significantly. The nutrient values increase 114% and double the amount of cropland was required to compensate for the excessive nutrients from solid manure. In the GHG emission relaxed and restricted scenarios, using the solid portion of manure locally will not benefit the local economy or GHG emissions. The solid manure in the baseline scenario has high nutrient density and creates revenue for CPFs but becomes slurry manure that ultimately increases the transportation and manure application costs.

Table 2
Summary of economic, operational, and GHG emission performances considering no S/L separation and manure load reduction for high manure production farms.

	Baseline	No S/L separation	Reduction of manure production
Solid portion of manure (million ton)	0.55	0	0.5
Slurry & liquid portion of manure (million ton)	2.4	2.97	2.0
Nutrient value of solid portion (million CNY)	44.6	0	42.8
Total GHG emission credit of solid portion (Gg CO2 e)	11.3	0	10.8
Utilization cost of slurry & liquid manure (million CNY)	*20.1/37.3*	*30.6/69.7*	*16.1/32.9*
Nutrient value of land application manure (million CNY)	*53.0/50.9*	*82.1/76.2*	*48.3/46.2*
Total CPFs processing capacity (ton)	*22,318/ 427,584*	*40,275/ 542,023*	*38,942/390,446*
Number of CPFs in manure utilization chain	*3/16*	*1/18*	*2/16*
Manure applied land (%)	*12.8/11.9*	*32.3/28*	*11.7/10.8*
Total GHG emission of slurry & liquid manure utilization (Gg CO2 e)	*40/52.5*	*53/77.5*	*37.0/49.9*
Total GHG emission credit of land application manure (Gg CO2 e)	*9.0/8.44*	*15.6/14.1*	*8.2/7.6*

The manure production level of AFOs above the median level within the same species was corrected to the median level in order to quantify the impact of manure reduction strategies on manure utilization. This scenario can refer to management strategies such as reducing cleaning water usage, improving animal drinking systems, and reducing cooling systems' water use. Compared with the baseline scenario, 15% (0.45 million tons) less manure will be produced with manure reduction strategies. The manure application percentages to cropland were decreased notably for central and western districts (*Fig. A.3: The optimal slurry manure supply-chain configuration if the manure production level was reduced to the median level*). Under relaxed and restricted constraints, 41 or 70 villages (~1% prime land for manure application) would leave the manure application business, respectively. As shown in Table 2, utilization costs and GHG emissions are also decreased with less manure loading and smaller transportation distances. Wastewater reduction strategies will save CNY 4 to 4.4 million and reduce 2.6 to 3 Gg CO_2 e in different GHG emission scenarios.

4.3. *Scenario analysis of manure composition measurement*

The composition of animal manure exhibits wide variation due to differences in animal diet, housing systems, and manure management (Marino et al., 2008). However, no study has yet quantified the impact of measuring manure composition on nutrient recirculation. This analysis represents the practice of using manure nutrients noting that manure composition varies by farm; however, manure application amounts are calculated from the standard values. As shown in Fig. 6, the variation of nitrogen and phosphorus levels lead to a certain level of economic and environmental loss. In GHG emission scenarios, the land with a nutrient surplus land ranged from 110 to 140 km^2, with 54.6 to 347.6 tons of nitrogen and 9.2 to 49.2 tons of phosphorus being over-supplied if nutrient variance increased from 10% to 50%. The mismatched nutrient

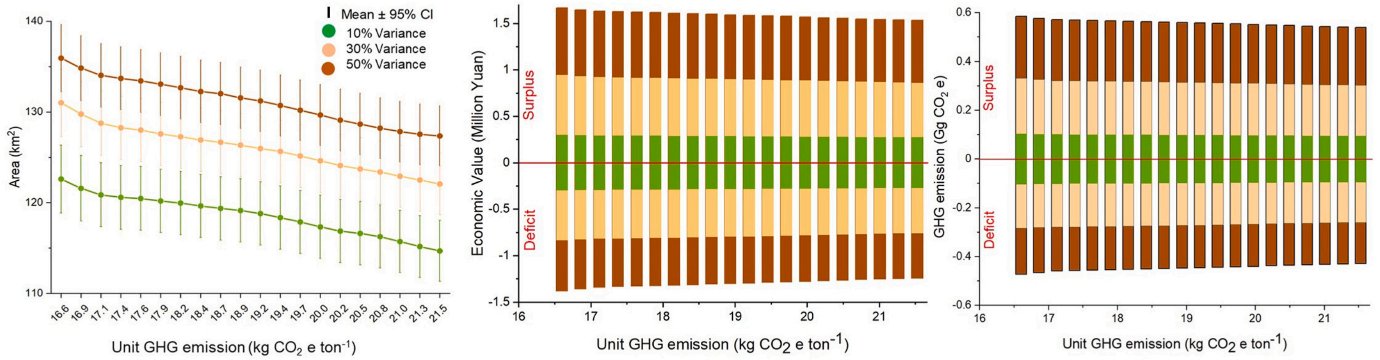

Fig. 6. Pareto-optimal curves of manure surplus land, economic values and GHG emission credits under 20 GHG emissions levels for 10%, 30%, 50% variance of nitrogen and phosphorus.

allocation also causes a direct loss in both nutrient surplus and nutrient deficit. In general, relaxing the GHG emission constraint reduces land application, economic loss, and GHG emissions. If the nutrient variance increased from 10% to 50% under restricted the GHG emission constraint ($\varepsilon_{\mathrm{GHG.min}}$), economic loss and GHG emission increased from CNY 0.6 million to CNY 3 million, and 0.2 Gg CO$_2$ e. to 1.1 Gg CO$_2$ e. These numbers can be considered as the benefits of accurate manure composition measurement. If each facility (AFOs and CPFs) measured animal manure composition each year, the average economic credit and GHG emission credit (nutrient variance: 10% to 50%, $\varepsilon_{\mathrm{GHG.max}}$) would be CNY 773 to CNY 3976 and 269 kg CO$_2$ e. to 1386 kg CO$_2$ e. In other words, if animal manure composition measurements can reduce the nutrient variance from 50% to 10%, the economic and GHG emission credit for each measurement will be CNY 3203 and 1117 CO$_2$ e. These results highlight the conceptual benefits of accurate manure nutrient composition measurement and suggest further research should be conducted into measurement strategies, cost, and related policies.

Table 3
Summary of transportation operational cost and greenhouse gas emission with different transportation modes.

	Diesel trucks only	Electric trucks only	Diesel trucks with portable pipeline	Electric trucks with portable pipeline
Average travel distance (km)[a]	**16.9/16.9**	**16.9/16.9**	**18.2/18.1**	**17.6/17.3**
AFOs manure distribution (km)[a]	11.6/10.7	11.5/10.7	9.3/8.9	9.7/9.6
CPFs manure collection(km)[a]	19/8.6	20.9/8.6	4.8/5.8	15.9/6.9
CPFs fertilizer distribution (km)[a]	7.3/10.6	9.1/10.6	7.5/8.4	9.3/9.1
Village manure application (km)[a]	5.3/4.9	5.2/4.9	8.8/8.5	7/6.8
Total transportation cost (Million CNY)	**18.9/18.3**	**13.1/13.2**	**15.1/15.2**	**11.9/11.8**
AFOs manure distribution (%)	68.3/52.5	68/51.0	63.3/55.8	61/53.4
CPFs manure collection (%)	1/9.2	1.5/9.0	3.5/7.4	6.2/8.2
CPFs fertilizer distribution (%)	0.4/10.4	0.6/10.0	4.9/9.7	3.3/9.8
Village manure application (%)	30.2/27.9	29.8/30.0	28.3/27.1	29.3/28.4
Total transportation GHG emission (Gg CO$_2$ e)	**9.4/9.4**	**8.1/8.1**	**6.2/6.3**	**5.9/5.9**
AFOs manure distribution (%)	67.5/52	66.9/52	74.5/65.2	74.7/65.3
CPFs manure collection (%)	1/9.3	1.5/9	3.9/8.4	7.8/9.8
CPFs fertilizer distribution (%)	0.4/10.2	0.6/10.2	5.7/11.3	4.1/12
Village manure application (%)	31/28.8	31/28.8	15.8/27.1	13.4/12.9

[a] Average travel distance = sum(weight*distance) / sum(weight) (Value under $\varepsilon_{\mathrm{GHG.min}}$/ Value under $\varepsilon_{\mathrm{GHG.max}}$)

4.4. Scenario analysis of transportation alternatives

Summarized operational costs and GHG emissions for the four transportation modes considered is shown in Table 3. Replacing diesel trucks with electric trucks does not affect the logistics configurations but does reduce the total transportation cost. In addition, GHG emissions are reduced by 28% and 14%, respectively. The main contributors to this are AFO manure distribution and village manure application. The transportation distance from AFOs to local crop farm villages is typically greater than 10 km. The average distance traveled for manure application is around 5 km in both the restricted and relaxed GHG emission scenarios. This demonstrates the importance of the "last-mile" distribution process in animal manure utilization. It indicates that improving the agricultural infrastructure of villages might reduce the total utilization cost.

Portable pipeline pumping is also discussed for comparison. In this case, trucks carry manure fertilizer to crop-farming villages, then unload manure fertilizer at a secondary station. Crop farm-owners use pumps and portable pipelines for land application. The results show the logistics configurations are not the same as the truck only scenario. In general, if manure and manure fertilizer are distributed using portable pipelines, the manure fertilizer travels farther within a village instead of being shipped to more distant villages. However, the average transportation distance from AFOs to crop villages or CPFs can be reduced with pipeline transportation. If portable pipelines replaced diesel trucks for manure application, the total transportation cost and GHG emissions are reduced by 21% and 34%, respectively. If portable pipelines replaced electric trucks for manure application, the total transportation cost and GHG emissions are reduced by 10% and 27%, respectively. Compared to truck transportation only, pipeline transportation within villages will introduce additional expenditures during transition. However, the results indicate that the operational cost and GHG emissions can be reduced significantly. This fact recommends adding a secondary storage station in each village to improve animal manure utilization.

5. Conclusions

In this study, a slurry-manure RMUC model was modified to analyze the operational cost and operational greenhouse gas emissions of a manure utilization chain subject to public sustainable goals in Hangzhou, China. The model could be used to assess and quantify the economic and GHG emission outcomes of sustainable trajectories in the animal manure utilization chain. These results can support and inform both the private and public sectors when making decisions to recycle animal manure nutrients in local crop-farming systems. However, an uncertainty analysis and improved data-acquisition are required to accurately measure economic costs and GHG emissions. Regular supervision of regional manure utilization behaviors is also required.

The Pareto-optimal results of the baseline scenario demonstrated how GHG emissions affect each stakeholder's decision-making process in the manure utilization chain. The GHG emission constraints increased the individual AFO-related cost and CPF-related cost, but benefited and guided the whole manure utilization chain to be more sustainable. The scenario analysis of animal production improvement discussed the economic and environmental benefits of implementing solid-liquid separation and water conservation practices on manure management. This study also quantified the importance of accurate manure composition measurement and demonstrated its benefits. Finally, we compared four different transportation modes, diesel trucks only, electric trucks only, diesel trucks with portable pipeline manure application, and electric trucks with portable pipeline manure application. The optimal results highlighted the economic and environmental potentials of electric vehicles on local manure transportation and suggested that a secondary storage station in each village would improve animal manure utilization.

Nomenclature

Indices	**Description**
i	Animal feeding operations (AFOs).
k	Manure waste types (slurry = 0, liquid = 1).
d	Manure processing facility and wastewater treatment sites (CPFs).
j	Crop-farming villages.
Input data	**Description**
$DMSP$	The distance matrix from AFO site i to CPF site d (km).
$DMSC$	The distance matrix from AFO site i to crop-farming village j (km).
$DMPC$	The distance matrix from CPF site d to crop-farming village j (km).
DS	Manure spreading distance in crop-farming village j (km).
AS	Amount of manure k produced from AFO site i (ton).
NC	Nitrogen concentration of manure k produced from AFO i (%).
PC	Phosphorus concentration of manure k produced from AFO i (%).
KC	Potassium concentration of manure k produced from AFO i (%).
CND	Nitrogen demand of crop-farming village j (ton).
CPD	Phosphorus demand of crop-farming village j (ton).
Decision variables	**Description**
CAP^{L0}	The optimal processing capacity of slurry and liquid manure at CPF site d (ton).
XC^{L0}	Amount of manure from AFOs to crop-farming villages from the AFO site i (ton, targets).
XC	Amount of manure from AFOs to crop-farming villages from the AFO site i (ton, responses).
XD	Amount of manure k transported to CPF site d from the AFO site i (ton).
XJ	Amount of manure k transported to crop-farming village j from AFO site i (ton).
XJD	Amount of liquid fertilizer transported to crop farm j from CPF site d (ton).
XPD	Amount of liquid fertilizer processed by waste treatment plant at CPF site d (ton).
Symbol	**Quantity**
$B_{value,GHG}$	Economic, GHG emission benefits of replacing synthetic chemical fertilizers (CNY, kg CO_2 e)
$Copl$	Annual unit cost of slurry manure processing at CPF site d (CNY/ton)
$Ccol$	Unit collection cost of slurry manure at CPF site d (CNY/ton).
Clo	Unit distribution cost of liquid effluent at CPF site d (CNY/ton).
Cuc	Unit AFO-related manure utilization cost of AFO i (ton).
Euc	Unit GHG emission of AFO-related manure utilization of AFO i (kg CO_2 e/ton).
Euf	Unit GHG emission of CPF-related manure utilization of CPF d (kg CO_2 e/ton).
E_{AC}	GHG emission of transportation from AFO i to crop farms (kg CO_2 e).
E_{AF}	GHG emission of transportation from AFO to CPF site d (kg CO_2 e).
E_B	GHG emission of biogas combustion in CPF site d (kg CO_2 e).
E_{CF}	GHG emission of animal manure fertilizer land application from AFO i (kg CO_2 e).
E_{CL}	GHG emission of the land application of liquid products from CPF site d (kg CO_2 e).
E_P	GHG emission of centralized processing and treatment in CPF site d (kg CO_2 e).
E_W	GHG emission of wastewater treatment process in CPF site d (kg CO_2 e).
E_{FC}	GHG emission of liquid product transportation from CPF site d to crop farms (kg CO_2 e).
PAS	Amount of collected slurry manure at CPF site d (ton).
$PSTC$	Total solid concentration of influent slurry manure at CPF site d (%).
$PSVC$	Volatile solid concentration of influent slurry manure at CPF site d (%).
PNC	Nitrogen concentration of influent slurry manure at CPF site d (%).
PPC	Phosphorus concentration of influent slurry manure at CPF site d (%).
PKC	Potassium concentration of influent slurry manure at CPF site d (%).
GF	Gas production factor influent slurry manure in CPF site d (m^3 CH_4/m^3).
ENC	Nitrogen concentration of effluent produced from CPF site d (%).
EPC	Phosphorus concentration of effluent produced from CPF site d (%).
EKC	Potassium concentration of effluent produced from CPF site d (%).
ε_{GHG}	GHG emission constraints.
ε_X, ε_P	Target deviation to tolerances.
Parameters	**Description**
Bo	The maximum rate of biogas production (m^3 CH_4/kg SV).
$Ctfl$	Fixed transportation cost for liquid and slurry manure (CNY/ton).
$Ctvl$	Variable transportation cost for liquid and slurry manure (CNY/ton km).
EFt	Unit transportation GHG emission factor (kg CO_2 e ton^{-1} km^{-1}).
EFp	Unit GHG emission factor of centralized processing and treatment (kg CO_2 e/ton).
$EFpw$	Unit GHG emission factor of wastewater treatment process (kg CO_2 e/ton).
$EFcl$	Unit GHG emission factor of manure application (kg CO_2 e/ton).
EF_{leach}	Emission factor for N_2O emissions from nitrogen leaching and runoff (kg CO_2 e).
EF_{dep}	Emission factor for N_2O emissions from atmospheric deposition of nitrogen (kg CO_2 e).
$Credit_{N,P,K}$	Unit GHG emissions of synthetic chemical fertilizers (kg CO_2 e/kg).
ε_N, ε_P, ε_K	Nitrogen, Phosphorus and Potassium loss in manure land application.
HRT	Hydraulic retention time (days).
$MCFs.land$	Methane conversion factor (%).
Os_{gas}	Percent of managed manure nitrogen volatilizes as NH_3 and NOx (%).
Os_{leach}	Percent of managed manure nitrogen that is leached (%).
$P_{N,P,K}$	Unit prices of synthetic chemical fertilizers (CNY/kg).
Nex	Annual average N excretion per head of species (kg N/ind. day).
VS	Daily volatile solid excreted (kg DM/ ind. day).

(continued on next column)

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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 A. Supplementary data

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