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# Regional integrative benefits of converting livestock excrements to energy in China: An elaborative assessment from life cycle perspective

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## Abstract

Livestock excrements (LEs) are important biomass, whose utilization for energy conversion can potentially ameliorate environmental problems and create economic profits. The integrative benefits contributed by LEs utilization have not been adequately explored especially from life cycle perspective. Due to different levels of husbandry development, LEs utilization in China's provincial regions may present spatial disparity. We construct an integrated assessment model that is capable of elaborating the life cycle energy, environmental and socioeconomic benefits of utilizing LEs from commercial scale husbandry feedlots. The model is applied to 30 provincial regions in China to reveal the spatial features of the benefits. On the national level, the theoretical reserve of LEs shows an increasing trend during 2008-2017, reaching 200.36 Mt in 2017. 11.30 Mt coal-eq net energy benefits can be generated. The eutrophication potential is most significant as -9.08E+08 kg $PO_4$-eq, accounting for 96.77% in total potential followed by the potentials of climate change, photochemical oxidation and acidification. Sichuan has the largest mitigated potentials of climate change and photochemical oxidation, and Henan has the largest mitigated potentials of eutrophication and acidification. In total 1.88 billion USD net profit and 73.06 thousand employments could be created. There overall forms a consistency among the three types of benefits spatially, with Sichuan, Yunnan, Shandong, Henan, Heilongjiang, Inner Mongolia, Hunan and Hebei more advantageous. These regions should be prioritized when deploying LEs utilization. The comprehensive benefits and their spatial features presented by this study are expected to offer better support in formulating region-specific planning regarding LEs utilization and development.

**Key words:** livestock excrements; bioenergy; biogas; integrative benefits; spatial features; life cycle.

## 1. Introduction

In the context of rapid economic development, the crises of energy shortage and environmental pollution are increasingly severe due to the heavy reliance on fossil fuels worldwide (Song et al., 2016). Bioenergy, as a potential substitute for fossil fuels, is one of the best options for alleviating the crises (Wang et al., 2019a). However, massive biomass is being discarded or unreasonably utilized, causing emissions of greenhouse gases and air pollutants, as well as discharges of water pollutants (Pratt et al., 2015). Livestock excrements (LEs) as typical biomass contain a mass of organic matters and nutrients, which could contaminate water environment if improperly disposed (Schlegel et al.,2017).

With the flourishing development of husbandry industry in China, tremendous LEs can be potentially converted to biogas and fertilizer through energy conversion projects (Liu et al., 2015; Zhang et al., 2019b). The 13th five-year plan of National Rural Biogas Development announced by Chinese government reported that 56% of the LEs produced by commercial scale husbandry feedlots are under improper management, amounting to 1.15 billion t (NDRC and MOA, 2018). In 2015, chemical oxygen demand (COD), ammonia nitrogen ($NH_3$-N) and total phosphorus (TP) discharged by commercial scale husbandry feedlots amounted to 3.13 million tons (Mt), 1.63 Mt and 0.27 Mt, accounting for 14.08%, 35.3% and 49.37% of total agricultural discharges in China, respectively (NBS and MEE, 2016). Based on the above situation, it is necessary to propel energy-oriented utilization of LEs through energy conversion projects such as biogas plants (Deng et al., 2017). Not only energy and environmental benefits, but also certain benefits for enterprise and society (incomes from electricity and fertilizer, employments) could be created, if LEs could be fully utilized to realize industrial development. Due to the vast territory of China, the provincial regions have different levels of husbandry development and thus different levels of LEs potentials, affected by the quantity of livestock, excrement generation rate (the quantity of excrements produced by one livestock per day), constituents of excrements, etc. It is of great help to clarify the spatial disparities regarding the above benefits in deploying region-specific target and planning for LEs utilization and the industrial development.

Accurate estimation of the theoretical reserve and collectible quantity of LEs and the energy potential is the premise for assessing the integrative benefits of LEs utilization. Such estimation has been conducted in previous studies, however, there are some deficiencies to improve. Scarlat et al. (2018) adopted the same coefficients for livestock from different regions to estimate the theoretical reserve of LEs in Europe as 1346.9 Mt, the collectible quantity as 941.6 Mt. However, different values of the coefficients should be considered to correspond to different levels of husbandry development of regions, which would otherwise induce inaccuracy. Bao et al. (2019) refined the weight of LEs into fresh weight and dry weight and estimated the theoretical reserve of LEs (the LEs of cattle, swine, poultry and other animals are considered) as 414.9 Mt on a dry weight basis in China. Ersoy and Ugurlu (2020) evaluated the energy potential of LEs utilization in Turky, indicating that 4.18 billion $m^3$ biogas could be produced which could meet up to 2.0% of annual electricity demand of the country. These studies considered LEs from almost all types of livestock while ignored that not all livestock's excrements are probable for biogas production due to difficulty in collection or low efficiency in energy conversion process.

Based on the theoretical reserve and energy potential, an optimal mode for LEs utilization needs to be identified considering the performances of effective energy conversion, lower emissions and discharges, and economic feasibility, which have been involved in some studies. (Chowdhury and Freire, 2015; Pergola et al., 2018; Ramírez-Islas et al., 2020; Zhang et al., 2013). For the environmental aspects, Burg et al. (2018) evaluated that 159 kilo tons (kt) of $CO_2$ could be prevented if exploitable amount of LEs in Switzerland were used for energy production. Ramírez-Islas et al. (2020) assessed the environmental benefits of energy production from swine excrement treatment, finding that biogas plant combined with composting generated the lowest $CO_2$ emissions. These studies focused primarily on greenhouse gas emissions, without incorporating the avoided emissions of $SO_2$ and $NO_x$ contributed by the replacement of fossil fuels with biogas. Pedizzi et al. (2018) evaluated the energy and nutrient recovery from LEs and indicated that the process of separating biogas residue and biogas slurry could improve the environmental profile, however ignored the water pollutants contained in biogas slurry. Qian et al. (2018) analyzed the pollutants generated from the excrements of five kinds of livestock in different breeding practices and presented that large-scale industrial breeding results in less pollutants but has larger intensity of pollution compared with conventional household breeding. One of the distinguishing characteristics of LEs is that it can lead to serious water pollution compared with agricultural and forestry residues (Zhang et al., 2019a), which has not been adequately discussed or quantified in the reviewed studies on LEs utilization.

LEs utilization through biogas plants can create significant socioeconomic benefits, which has been discussed in studies using multiple methods. For example, Zhang and Xu (2020) proposed an economic analysis method and applied it to a biogas power generation plant, finding that the net profit could increase from 11.03 to 59.40 million yuan by monetizing the environmental benefits as the income. Joshi and Wang (2018) integrated Life Cycle Assessment (LCA), cost-benefit analysis and sensitivity analysis to evaluate the economic benefits of LEs management, clearing that fertilizer production could significantly improve the economic benefits of LEs utilization. Mostafa et al. (2019) proposed that sale price of biogas and electricity production are the key parameters to determine the profitability of LEs utilization for small to medium dairy farms. Some studies also argued that biogas plants are uncompetitive in the case without incentives, which means the subsidy from government is a critical factor in economic analysis of LEs utilization (Federica et al., 2019; Lauven et al., 2019).

Previous researches have largely focused on only one aspect of LEs utilization such as energy potential, environmental emissions/discharges, economic profits and so on, without integrating the energy, environmental and socioeconomic benefits of LEs utilization comprehensively, particularly from a life cycle perspective. Some researchers have made such studies on other types of biomass. For instance, Wang et al. (2018b) predicted the quantity of straw available for energy production by 2030 and assessed the energy, environmental and socioeconomic benefits of straw utilization for energy production in China. Song et al. (2019) developed an integrated model to quantify energy, environmental and economic benefits of straw utilization from life cycle perspective and applied the model to 30 provincial regions in China to reveal regional features of the benefits. Wang et al. (2019b) developed a hybrid LCA model that integrates the multi-regional input-output approach and specific production data to evaluate the social, environmental and economic benefits of agricultural wastes utilization for bioethanol production in Henan province in China, the results are indicated by employment creation, energy production and economic stimulus. There still lacks an integrative assessment of the energy, environmental and socioeconomic benefits of regional energy-oriented LEs utilization in the whole country considering the spatial disparities.

In this study, we construct an integrated model for comprehensively assessing the energy, environmental and socioeconomic benefits of LEs utilization from life cycle perspective. The model is then applied to the 30 provincial regions in China to highlight the integrative benefits of LEs utilization and the spatial patterns of the benefits. The energy benefits are indicated by the net energy output; the environmental benefits are indicated by the mitigated environmental impact potentials; the socioeconomic benefits are indicated by the net profits, employments and workers' income. The quantified integrative benefits and the revealed spatial features can assist in formulating targeted policies on LEs utilization to accelerate the industrialization of regional bioenergy utilization.

The remaining of the paper is structured as follows: Section 2 details the formulation of the integrated model for assessing the integrative benefits of LEs utilization. Section 3 describes the data sources and data processing for the life cycle energy, environmental and socioeconomic parameters. Section 4 presents the results of the integrative benefits for 30 provincial regions. The discussions, uncertainties of results and policy implications are provided in Section 5. Finally, some conclusions are drawn in Section 6.

## 2. Methods and data

### *2.1 Life cycle Modeling framework*

*(1) Goal and scope*

The goal of the assessment is to measure the life cycle energy benefits (indicated by biogas production and power generation), environmental benefits (indicated by mitigated environmental impact potentials) and socioeconomic benefits (indicated by net profit, employment and workers' income) of converting LEs to energy in each region. Considering the complete process of LEs utilization, the life cycle system boundary is depicted as in Fig. 1. It incorporates four stages as (a) LEs acquisition and pretreatment (including LEs transportation, LEs storage and preprocessing), (b) energy conversion (including anaerobic digestion and combined heat and power (CHP)), (c) digestate utilization (including the production of solid and liquid fertilizers (bio-fertilizers), and wastewater treatment), and (d) final consumption of products (including the consumption of electricity and fertilizers).

First, the collected LEs are transported to the biogas plants. After preprocessing, they are converted into biogas which is then utilized for CHP generation. The produced heat is utilized for warming the digester. The produced electricity is connected to local grid. Power from local grid is used to maintain stable plant operation to avoid the instability of self-power supply. Meanwhile, biogas slurry and biogas residue are used to produce liquid and solid fertilizers. Both the electricity and fertilizers produced can be for sale. Also, the newly built biogas plant can provide chances of employment.

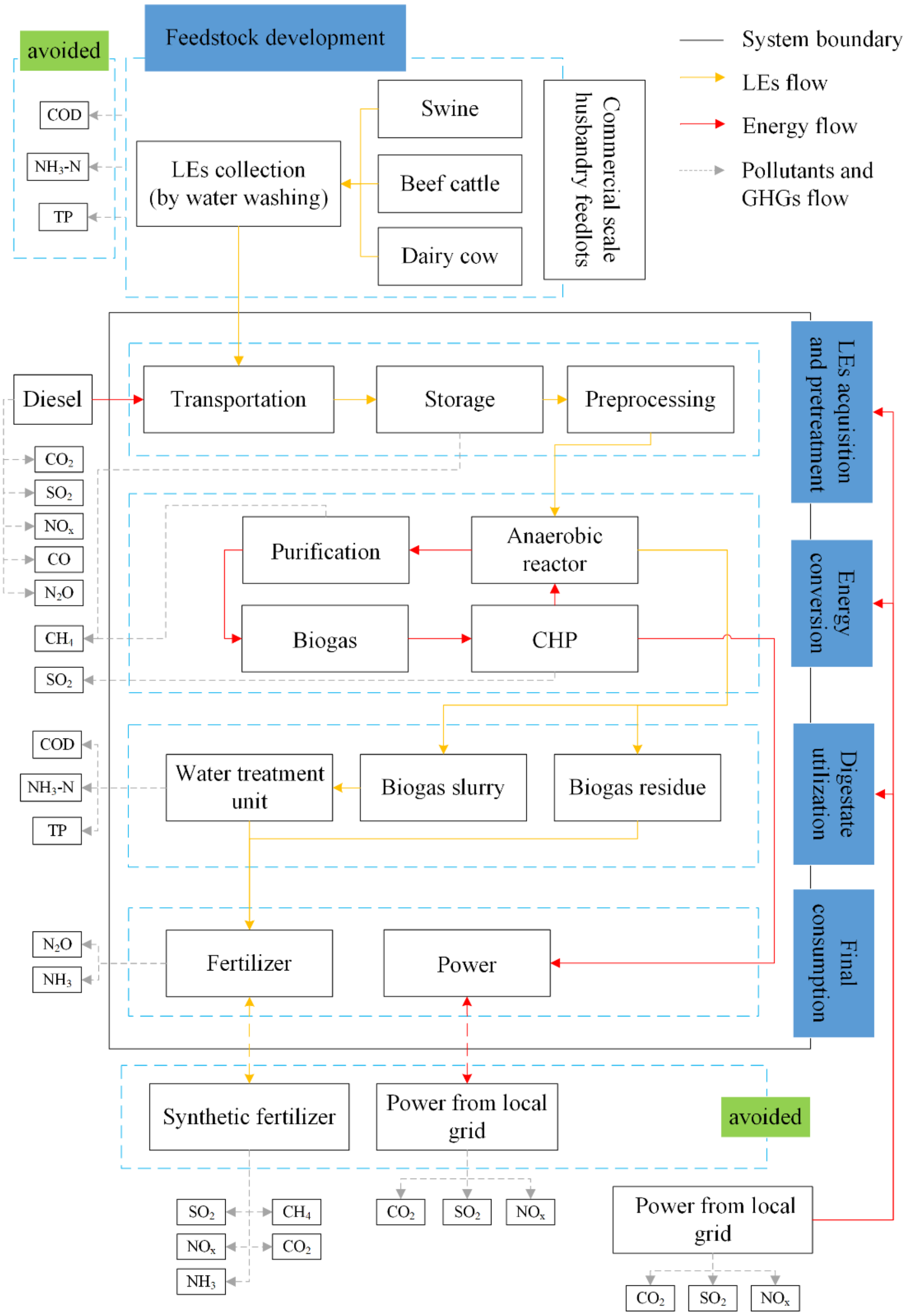


**Fig. 1.** System boundary of energy-oriented LEs utilization.

*(2) Life cycle inventory*

The inputs into the system and the outputs out of the system are listed in Table 1. The inputs into the system include the raw materials LEs and the energy consumed. Diesel is consumed during LEs transportation. Power from local grid is consumed during plant operation. The outputs out of the system include the products of LEs utilization, i.e. electricity and bio-fertilizers, as well as the water pollutants, atmospheric pollutants and GHGs generated through the system.

During LEs transportation, there are $CO_2$, CO, $NO_x$, $SO_2$ and $N_2O$ emissions from diesel consumption. During LEs storage, some $CH_4$ is generated and escapes. During digestion process, more $CH_4$ is produced, part of which escapes during the subsequent purification process. Considering the “$CO_2$-neutral” nature of biomass, the $CO_2$ generated due to burning biogas during CHP process is not included. During CHP process, as $H_2S$ is contained in biogas, there are $SO_2$ emissions. Additional $CO_2$, $SO_2$ and $NO_x$ emissions are induced due to power consumption for plant operation. During digestate utilization, COD, $NH_3$-N and TP are contained in biogas slurry and discharged after treatment. During final consumption of bio-fertilizers, there are $N_2O$ and $NH_3$ emissions.

We additionally set another three substitution assumptions: (a) If the LEs are not utilized for energy conversion, the LEs-containing wastewater from husbandry feedlots would be discharged into water environment, leading to COD, $NH_3$-N and TP discharges; (b) If no power generated from LEs utilization, the equivalent quantity of power would be from local grid, leading to $CO_2$, $SO_2$ and $NO_x$ emissions; (c) If no bio-fertilizers produced by LEs utilization, the equivalent quantity of fertilizers would be produced by synthetic fertilizer plants. Thus attributed to LEs utilization, certain quantity of water pollutants, atmospheric pollutants and GHGs could be potentially avoided. The substitution assumptions are aimed at quantitatively maximizing the environmental benefits contributed by LEs utilization.

**Table 1.** Life cycle inventory of LEs utilization (inputs and outputs).

| | | LEs acquisition & pretreatment | Energy conversion | Digestate utilization | Final consumption |
|---|---|---|---|---|---|
| Inputs | **Raw material** | | | | |
| | LEs | √ | | | |
| | **Energy** | | | | |
| | Electricity | | √ | √ | |
| | Fuel (diesel) | √ | | | |
| Outputs | **Products** | | | | |
| | Electricity | | √ | | |
| | Bio-fertilizers | | | √ | |
| | **Emissions to air** | | | | |
| | $CO_2$ | √ | √ | | |
| | CO | √ | | | |
| | $CH_4$ | √ | √ | | |
| | $NO_x$ | √ | √ | | |

| | | | | |
|---|---|---|---|---|
| $SO_2$ | √ | √ | | |
| $N_2O$ | √ | | | √ |
| $NH_3$ | | | | √ |
| **Discharges to water** | | | | |
| COD | | | √ | |
| $NH_3$-N | | | √ | |
| TP | | | √ | |

### *2.2 Sub-model for energy benefits*

We choose the LEs from swine, beef cattle and dairy cow as the target feedstock due to larger scale of feedlots and the applicability to anaerobic digestion. Subscript $i$ denotes the type of LEs. The quantities of different types of LEs are summable. The dry matter within LEs is used to estimate the potential of biogas production. We use superscripts $f$ and $d$ to denote the fresh mass and dry mass of LEs. The energy potential of LEs is obtained based on three levels: theoretical reserve on a fresh mass basis ($Q_i^f$) (the theoretical quantity of excrements directly generated by livestock on a fresh mass basis), theoretical reserve on a dry mass basis ($Q_i^d$) (the quantity of dry matter contained in fresh excrements), collectible quantity ($Q_c^d$) (the quantity of LEs that can be collected from commercial scale husbandry feedlots). $Q_i^f$ is expressed as the number of the livestock ($W_i$) multiplying the excrement generation coefficient of livestock ($k_i$) (the quantity of excrements generated by one livestock per day) and the feeding cycle ($T_i$) (the days that the livestock stays in feedlot within a year).

$$Q_i^f = W_i \times k_i \times T_i \quad (1)$$

$Q_i^d$ is expressed as $Q_i^f$ multiplying the proportion of dry mater content in excrements 1-$M_i$ ($M_i$ denotes the proportion of moisture content in excrements). $Q_c^d$ is expressed as the sum of $Q_i^d$ multiplying the collection coefficient ($\varepsilon_i$) (the proportion of LEs available for energy conversion) and the coefficient of commercial scale husbandry ($\lambda_i$) (the proportion of livestock from commercial scale husbandry feedlots in total livestock in a region).

$$Q_i^d = Q_i^f \times (1 - M_i) \quad (2)$$

$$Q_c^d = \sum_i \left(\varepsilon_i \times \lambda_i \times Q_i^d\right) \quad (3)$$

Then, the net energy benefits (*EN*) can be calculated by total bioenergy production deducting the coal-fired power consumed during biogas plant operation:

$$EN=\sum_i\left(\eta_i\times\varepsilon_i\times\lambda_i\times Q_i^d\right)-F^{diesel}-F^{mix}=F^{bio}-F^{diesel}-F^{mix} \quad (4)$$

where $\eta_i$ denotes the energy conversion coefficient of LEs; $F^{bio}$, $F^{diesel}$ and $F^{mix}$ and denote the quantity of biogas power produced, consumption of diesel during LEs transportation and consumption of power from local grid during plant operation (with the unit unified as tons of coal-equivalent (tce)).

The fertilizers produced are in either solid or liquid form, derived from biogas residue and biogas slurry, respectively. LEs feedstock enters biogas plant in the form of liquid-residue mixture. Part of the dry matter of LEs contained in the mixture is converted into biogas and the rest is remained in the mixture. After finally separating the liquid and residue in the mixture, the biogas slurry (almost without residue) and biogas residue can be obtained. The quantity of solid fertilizer ($D_r^f$) and liquid fertilizer ($D_s^f$) can be formulated as:

$$D_r^f=\mu\times Q_c^d\times\left(1-M_r\right)^{-1} \quad (5)$$

$$D_s^f=Q_c^d\times\left(1-M_s\right)^{-1}-\theta\times Q_c^d-D_r^f \quad (6)$$

where subscripts $r$ and $s$ denote solid fertilizer and liquid fertilizer; $\mu$ denotes the proportion of dry matter of LEs remaining in the biogas residue; $M_r$ and $M_s$ denote the moisture content of biogas residue and liquid-residue mixture, respectively; $\theta$ is the proportion of dry matter of LEs converted into biogas.

### *2.3 Sub-model for environmental benefits*

The environmental benefits of energy-oriented LEs utilization are evaluated considering three aspects as (i) avoided water pollutant discharges according to substitution assumption (a), (ii) discharges/emissions from the life cycle of LEs utilization, and (iii) avoided GHG and atmospheric pollutant emissions according to substitution assumption (b) and (c).

*(1) Avoided water pollutant discharges*

As is assumed, if the LEs are not utilized for energy conversion, they would be contained in the wastewater of husbandry feedlots that is finally discharged into water environment. If the LEs are utilized for energy conversion instead, the discharges of certain quantity of COD, $NH_3$-N and TP could be avoided. The avoided discharges of a certain type of water pollutant ($E^{(1)-water}$) can be calculated as:

$$E^{(1)-water}=\sum_i\left(d_i\times W_i\times T_i\times\varepsilon_i\times\lambda_i\right) \quad (7)$$

where $d_i$ is the discharge factor of water pollutants corresponding to each type of LEs.

*(2) Discharges/emissions from the life cycle of LEs utilization*

According to the life cycle inventory as listed in Table 1, the quantity of a certain type of water pollutant ($E^{(2)-water}$) and GHG/atmospheric pollutant ($E^{(2)-air}$) during the life cycle of LEs utilization can be calculated as:

$$E^{(2)-water} = d^{LEs} \times Q_c^d \quad (8)$$

$$E^{(2)-air} = e^{LEs} \times Q_c^d + e^{pow} \times F^{mix} + e^{bf}\left(\alpha_r \times D_r^f + \alpha_s \times D_s^f\right) \quad (9)$$

where $d^{LEs}$ is the discharge factor of water pollutants (discharges of COD, $NH_3$-N and TP corresponding to unit quantity of LEs); $e^{LEs}$ is the emission factor of GHGs/atmospheric pollutants (emissions of $CO_2$, CO, $NO_x$, $SO_2$, $N_2O$ and $CH_4$ corresponding to unit quantity of LEs); $e^{pow}$ is the emission factor of power consumption during plant operation (emissions of $CO_2$, $SO_2$ and $NO_x$ from unit power consumption); $\alpha$ is the proportion of nitrogen within bio-fertilizers; $e^{bf}$ is the emission factor of bio-fertilizer consumption (emissions of $N_2O$ and $NH_3$ corresponding to unit quantity of bio-fertilizers).

*(3) Avoided GHG/atmospheric pollutant emissions*

It is assumed that the biogas power could substitute power from local grid, making emissions due to power generation avoided; the bio-fertilizers could substitute synthetic fertilizers, making emissions due to producing synthetic fertilizers. We use $F^{sub}$ ($F^{sub}$=$F^{bio}$) to denote the quantity of power from local grid substituted by equal quantity of biogas power. Fertilizer substitution relates to the nutrient content (nitrogen, phosphorus and potash) within bio-fertilizers and synthetic fertilizers. The avoided emissions of a certain type of atmospheric pollutant ($CO_2$, $SO_2$ and $NO_x$) due to power substitution and fertilizer substitution ($E^{(3)-air}$) can be calculated as:

$$E^{(3)-air} = e^{pow} \times F^{sub} + \sum_j e_j^{sf}\left[\left(\alpha_{rj} \times D_r^f + \alpha_{sj} \times D_s^f\right)/\delta_j\right] \quad (10)$$

where $e_j^{sf}$ is the emission factor of synthetic fertilizer production corresponding to the *j*-th kind of synthetic fertilizer (i.e. nitrogen fertilizer, phosphorus fertilizer or potash fertilizer) (emissions of $CO_2$, $NO_x$, $SO_2$, $NH_3$ and $CH_4$ corresponding to unit quantity of synthetic fertilizers); $\delta_j$ is the proportion of nutrient *j* within the *j*-th kind of synthetic fertilizer.

*(4) Additive avoided discharges and emissions*

Total avoided discharges of water pollutants ($EV^{water}$) and total avoided emissions of GHGs/atmospheric pollutants ($EV^{air}$) contributed by LEs utilization can be calculated combing the above three aspects:

$$EV^{water} = E^{(1)-water} - E^{(2)-water} \quad (11)$$

$$EV^{air} = E^{(3)-air} - E^{(2)-air} \quad (12)$$

*(5) Mitigated environmental impact potentials*

We choose the following four categories of environmental impact potentials: climate change (expressed as $CO_2$ equivalent), acidification (expressed as $SO_2$ equivalent), eutrophication (expressed as phosphate equivalent) and photochemical oxidation (expressed as ethylene equivalent). According to the life cycle inventory and the quantity of water pollutants, atmospheric pollutants and GHGs, the mitigated environmental impact potentials can be calculated following three steps as characterization, normalization and weighting.

Characterization involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category:

$$CP^{(m)} = \sum_n \left( CF_n^{(m)} \times EV_n^{(m)} \right) \quad (13)$$

where $CP^{(m)}$ is the characterized mitigated environmental impact potential for category $m$; subscript $n$ is the type of pollutants/GHGs responsible for impact category $m$; $EV_n^{(m)}$ is the quantity of avoided discharges/emissions of pollutant or GHG $n$; $CF_n^{(m)}$ is the characterization factor.

Normalization is the calculation of the magnitude of an impact category relative to some reference information, which is aimed at better understanding the magnitude of each indicator:

$$NP^{(m)} = CP^{(m)} / NF^{(m)} \quad (14)$$

where the $NP^{(m)}$ is the normalized mitigated environmental impact potential for category $m$; $NF^{(m)}$ is the normalization factor.

Weighting is the process of converting different categories of environmental impact potentials using numerical factors based on value-choices. It may include aggregation of the weighted potentials:

$$WP = \sum_m \left( NP^{(m)} \times WF^{(m)} \right) \quad (15)$$

where *WP* is the weighted total mitigated environmental impact potential; $WF^{(m)}$ is the weighting factor.

***2.4 Sub-model for economic benefits***

*(1) Total cost of LEs utilization*

LEs, as a kind of waste generated by husbandry feedlots, are totally useless for the husbandry feedlots, based on which we assume no procurement cost (for buying LEs from husbandry feedlots). Total cost contains the cost for transportation ($C_{tran}$), materials ($C_{mate}$) (desulfurizer, bacteria agent, etc.), coal-fired power ($C_{power}$), labor for plant operation ($C_{labor}$), depreciation of fixed asset ($C_{depr}$), maintenance ($C_{main}$) and enterprise tax ($C_{tax}$). Each kind of cost is calculated by corresponding unit price (the cost corresponding to unit quantity of LEs) multiplying $Q_c^d$.

$$\begin{aligned} C &= C_{tran} + C_{mate} + C_{power} + C_{labor} + C_{depr} + C_{main} + C_{tax} \\ &= \left(\rho_{tran} + \rho_{power} + \rho_{labor} + \rho_{depr} + \rho_{main} + \rho_{tax}\right) \times Q_c^d \end{aligned} \quad (16)$$

*(2) Total income from LEs utilization*

The income from LEs utilization is composed of the sales of biogas power and fertilizers. Total income from LEs utilization ($I$) is expressed as:

$$I = \rho^e \times F^{bio} + \rho^r \times D_r^f + \rho^s \times D_s^f \quad (17)$$

where $\rho^e$, $\rho^r$, $\rho^s$ denote unit price of biogas power, solid fertilizer and liquid fertilizer, respectively.

*(3) Total profit contributed by LEs utilization*

The net profit ($EC$) is yielded by total income deducting total cost as:

$$EC = I - C \quad (18)$$

## 3. Data presentation

### *3.1 Study area*

Three kinds of livestock are considered in this study including swine, beef cattle and dairy cow. 30 provincial regions of China are the case study areas. According to their spatial locations in china, they can be divided into six large areas as the northern area (Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia), the northeastern area (Liaoning, Jilin and Heilongjiang), the eastern area (Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi and Shandong), the central and southern area (Henan, Hubei, Hunan, Guangdong, Guangxi and Hainan), the southwestern area (Chongqing, Sichuan, Guizhou and Yunnan) and the northwestern area (Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang). Tibet is excluded due to data inefficiency. Considering the latest data availability, we choose 2017 as the study year. The data on the number of livestock in 30 regions are obtained from China Animal Husbandry and Veterinary Yearbook (CAHVYEC, 2008-2017). The data on gross product of husbandry industry come from China Rural Statistical Yearbook (NBSC, 2009-2018). In Table 2, the excrement generation coefficient ($k_i$) and the discharge factor of water pollutants ($e_i^{be}$) corresponding to each type of LEs in six areas are extracted from the manual of the first national pollution census of livestock and poultry breeding industry in China (IEDA, 2009); the emission factors of power consumption ($e^{pow}$) for GHGs and atmospheric pollutants correspond to the regional power grids (Cao et al., 2010).

**Table 2.** Parameters corresponding to different regions.

| Area | GHGs/pollutants | Emission factors corresponding to power grids ($e^{pow}$) (t/MWh) | Area | Livestock | Excrement generation coefficient ($k_i$) (kg/head/day) | COD ($e_i^{COD}$) (g/head/day) | $NH_3$-N ( $e_i^{NH_3-N}$ ) (g/head/d) | TP ($e_i^{TP}$) (g/head/day) |
|---|---|---|---|---|---|---|---|---|
| North | $CO_2$ | 0.9680 | North | Swine | 3.39 | 247.93 | 10.95 | 3.17 |
| | $SO_2$ | 0.0077 | | Beef cattle | 22.10 | 1761.26 | 47.41 | 8.80 |
| | $NO_x$ | 0.0046 | | Dairy cow | 46.05 | 3612.58 | 156.71 | 37.32 |
| Northeast | $CO_2$ | 1.1082 | Northeast | Swine | 4.09 | 235.55 | 19.74 | 3.28 |
| | $SO_2$ | 0.0065 | | Beef cattle | 22.67 | 867.81 | 33.58 | 6.43 |
| | $NO_x$ | 0.0055 | | Dairy cow | 48.49 | 4750.82 | 214.49 | 45.19 |
| East | $CO_2$ | 0.8046 | East | Swine | 2.97 | 154.62 | 10.34 | 2.09 |
| | $SO_2$ | 0.0057 | | Beef cattle | 23.71 | 1321.19 | 75.28 | 9.86 |
| | $NO_x$ | 0.0037 | | Dairy cow | 46.84 | 3958.06 | 165.78 | 33.28 |
| Center & South | $CO_2$ | 0.9014 | Center & South | Swine | 3.74 | 152.06 | 14.98 | 2.59 |
| | $SO_2$ | 0.0100 | | Beef cattle | 23.02 | 2045.46 | 60.42 | 9.84 |
| | $NO_x$ | 0.0050 | | Dairy cow | 50.99 | 6265.32 | 264.77 | 60.71 |
| Southwest | $CO_2$ | 0.8367 | Southwest | Swine | 3.56 | 129.17 | 8.23 | 1.05 |
| | $SO_2$ | 0.0075 | | Beef cattle | 20.42 | 930.20 | 34.90 | 3.91 |
| | $NO_x$ | 0.0039 | | Dairy cow | 46.84 | 3549.57 | 148.13 | 29.83 |
| Northwest | $CO_2$ | 0.9155 | Northwest | Swine | 3.54 | 136.06 | 13.43 | 1.56 |
| | $SO_2$ | 0.0093 | | Beef cattle | 20.42 | 1886.84 | 81.19 | 9.09 |
| | $NO_x$ | 0.0045 | | Dairy cow | 31.39 | 2708.85 | 150.01 | 11.76 |

### *3.2 Data on energy conversion of LEs*

The feeding cycle of livestock, proportion of moisture content in excrements, proportion of livestock from commercial scale husbandry feedlots in total livestock, and collection coefficient of LEs are provided in Table 3 (Bao et al., 2018; Scarlat et al., 2018; Angelis-Dimakis et al., 2011; Wang et al., 2018a). The biogas generation coefficient of LEs is unified as 347.73 $m^3$/t-LEs. The main content of biogas is $CH_4$ (50%-70%) and $CO_2$ (30%-50%) and it is assumed that the proportions of $CH_4$ and $CO_2$ are 60% and 35%, respectively. During CHP process, power generation from unit quantity of biogas ranges within 1.6-2.0 kWh/$m^3$. It is assumed that the CHP process operates stably with the parameter as 1.7 kWh/$m^3$ (Dong et al., 2019; Ramos-Suárez et al., 2019; Rico et al., 2011; MEE, 2018). The relevant energy conversion coefficients corresponding to 1 t-LEs are also listed in Table 3.

**Table 3.** Parameters for energy conversion of LEs.

| | Swine | Beef cattle | Dairy cow |
|---|---|---|---|
| Feeding cycle within a year ($T_i$) (days) | 179 | 365 | 365 |
| Moisture content of excrements ($M_i$) (%) | 84.2 | 81.0 | 81.3 |
| Coefficient of commercial scale husbandry ($\lambda_i$) (%) | 42.6 | 28.1 | 48.3 |
| Collection coefficient ($\varepsilon_i$) | 0.9 | 0.6 | 0.6 |
| Biogas generation ($m^3$/t-LEs) | | 347.73 | |
| Standard coal-equivalent conversion (tce/t-LEs) | | 0.25 | |
| Power generation (kWh/t-LEs) | | 591.14 | |

### *3.3 Data on environmental parameters*

It is assumed that there are 6.43 $m^3$/t-LEs $CH_4$ leaks during LEs storage and 8% of $CH_4$ generated from digestion escapes during subsequent $CH_4$ purification (Dong et al., 2019; Ramos-Suárez et al., 2019). The emission factors of diesel consumed during LEs transportation, the discharge factors of wastewater treatment unit during digestate utilization, and the parameters relevant to bio-fertilizer consumption and fertilizer substitution are provided in the Appendix (Table A-1). With Jilin Province as an example, we provide the detailed information of the life cycle inventory of LEs utilization (with the substitution assumptions considered) as in Table 4.

**Table 4.** Life cycle inventory of LEs utilization with 1 t-LEs as functional unit (with Jilin Province as example).

| | | Unit | Value |
|---|---|---|---|
| **Inputs** | LEs | t-LEs | 1 |
| | Electricity | kWh/t-LEs | 67.08 |
| | Fuel (diesel) | MJ/t LEs | 194.19 |

| | | | |
|---|---|---|---|
| | Electricity | kWh/t-LEs | 606.62 |
| | Solid fertilizer | t/t-LEs | 1.00 |
| | Liquid fertilizer | t/t-LEs | 10.90 |
| | $CO_2$ | kg/t-LEs | -1050.42 |
| | CO | kg/t-LEs | 0.092 |
| | $CH_4$ | kg/t-LEs | 15.42 |
| **Outputs** | $NO_x$ | kg/t-LEs | -5.66 |
| | $SO_2$ | kg/t-LEs | -4.85 |
| | $N_2O$ | kg/t-LEs | 0.12 |
| | $NH_3$ | kg/t-LEs | 1.05 |
| | COD | kg/t-LEs | -292.07 |
| | $NH_3$-N | kg/t-LEs | -17.95 |
| | TP | kg/t-LEs | -3.22 |

With the information in Table 4 and the parameters for normalization and weighting of environmental impact potentials in Table 5 (Sleeswijk et al., 2008; Mayer et al, 2020; Ertem et al., 2017), the environmental benefits represented by four categories of mitigated environmental impact potentials can be calculated.

**Table 5.** Parameters for normalization and weighting of environmental impact potentials.

| Impact category | Impact potential | GHGs/pollutants | Normalization factor ($NF^{(m)}$) | Weighting factor ($WF^{(m)}$) |
|---|---|---|---|---|
| Climate change | -2.70E+10 kg $CO_2$-eq | $CO_2$, $CH_4$, $N_2O$, CO | 4.18E+13 | 0.357 |
| Photochemical oxidation | -1.67E+07 kg $C_2H_4$-eq | CO, $NO_x$, $SO_2$, $CH_4$ | 3.51E+11 | 0.214 |
| Eutrophication | -9.07E+08 kg $PO_4$-eq | $NH_3$-N, $NO_x$, $N_2O$, COD, TP | 3.77E+09 | 0.214 |
| Acidification | -2.19E+09 kg $SO_2$-eq | $SO_2$, $NH_3$, $NO_x$ | 3.18E+11 | 0.214 |

### *3.4 Data on socioeconomic parameters*

The socioeconomic parameters of LEs utilization are presented in Table 6. The parameters are calculated according to the commercial data obtained in multiple references associated with different scales of biogas plants (e.g. biogas plants that produce 12000, 2000, 1000 and 300 $m^3$ biogas per day) (Song et al., 2016; Joshi and Wang, 2018; Mostafa et al., 2019; NEA, 2018). These parameters are expected to reflect the average level of various economic variables corresponding to unit quantity of LEs. Government subsidies for biogas plant are reflected in investment subsidy, higher electricity price and fertilizer price. The quantity of employment created and workers' income are calculated according to the energy benefits (quantity of biogas produced) and the commercial data of labor requirement by biogas plant (e.g. three workers whose income is 426

USD/month/person work in one biogas plant that generates 2000 $m^3$ biogas per day).

**Table 6.** Socioeconomic parameters for LEs utilization.

| Items | Unit | Values |
|---|---|---|
| **Initial investment** | USD/t-LEs | 493.93 |
| **Total cost** | USD/t-LEs | 83.55 |
| Transportation | USD/t-LEs·km | 0.29 |
| Materials | USD/t-LEs | 2.26 |
| Energy consumption | USD/t-LEs | 4.06 |
| Labor | USD/t-LEs | 7.31 |
| Maintenance | USD/t-LEs | 12.35 |
| Depreciation | USD/t-LEs | 24.70 |
| Tax | USD/t-LEs | 17.99 |
| **Unit price of product** | — | — |
| Solid fertilizer | USD/t | 42.61 |
| Liquid fertilizer | USD/t | 1.42 |
| Electricity | USD/kWh | 0.10 |
| **Total income** | USD/t-LEs | 119.97 |
| **Net profit** | USD/t-LEs | 36.80 |
| **Employment** | Number/t-LEs | 0.0014 |
| **Workers' income** | USD/t-LEs | 7.31 |

## 4. Results

### *4.1 Theoretical reserve of livestock excrements*

According to Table 2 and Table 3, regional theoretical reserve of LEs in China can be attained. Relying on the development of husbandry industry, the theoretical reserve of LEs shows an increasing trend. As illustrated in Fig. 2, theoretical reserve of LEs varies from 176.4 Mt in 2008 to 200.36 Mt in 2017 with an average growth rate of 1.4%, and gross product of husbandry increases from 292.37 billion USD to 417.04 billion USD. Total reserve of LEs on a dry mass basis amounts to 226.56 Mt in 2015, reaching the peak level during 10 years. We can recognize that the trend in theoretical reserve of LEs roughly follows the track of gross product of husbandry industry. The theoretical reserve structure is dominated by LEs from beef cattle and swine which account for 48% and 32%, respectively, for average during 10 years.

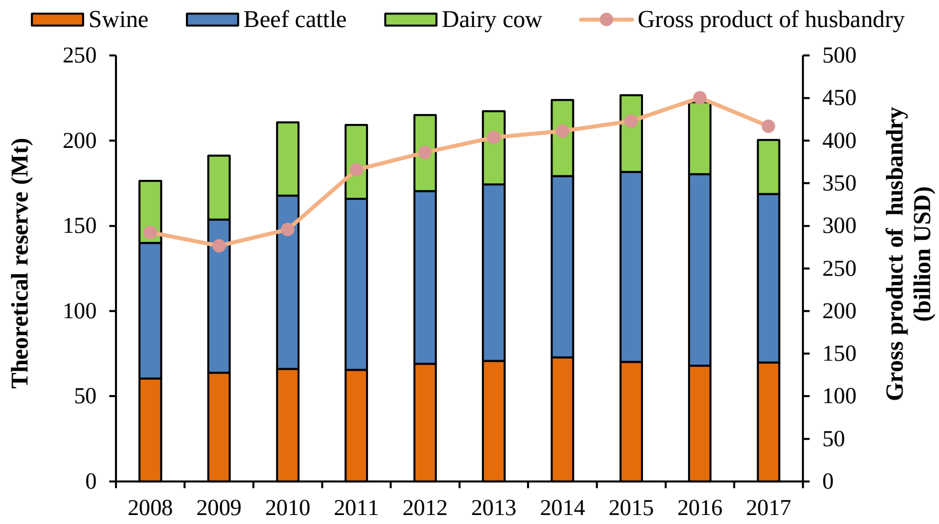


**Fig. 2.** Theoretical reserve of LEs and gross product of husbandry in China (2008-2017)

Generally, the distribution of theoretical reserve of LEs in different regions is also roughly in compliance with the gross product of husbandry industry. The spatial distribution of theoretical reserve of LEs and gross product of husbandry industry for 30 regions in 2017 is depicted in Fig. 3. The top five regions in terms of gross product of husbandry industry are Shandong, Henan, Sichuan, Hebei and Heilongjiang. While the top five regions in terms of theoretical reserve of LEs are Sichuan, Yunnan, Heilongjiang, Inner Mongolia and Shandong, with the quantity ranging from 11.84 Mt to 16.15 Mt. What primarily results in the divergence is that the large quantity of livestock is not promoting prosperity of husbandry industry in some regions, such as Qinghai and Yunnan.

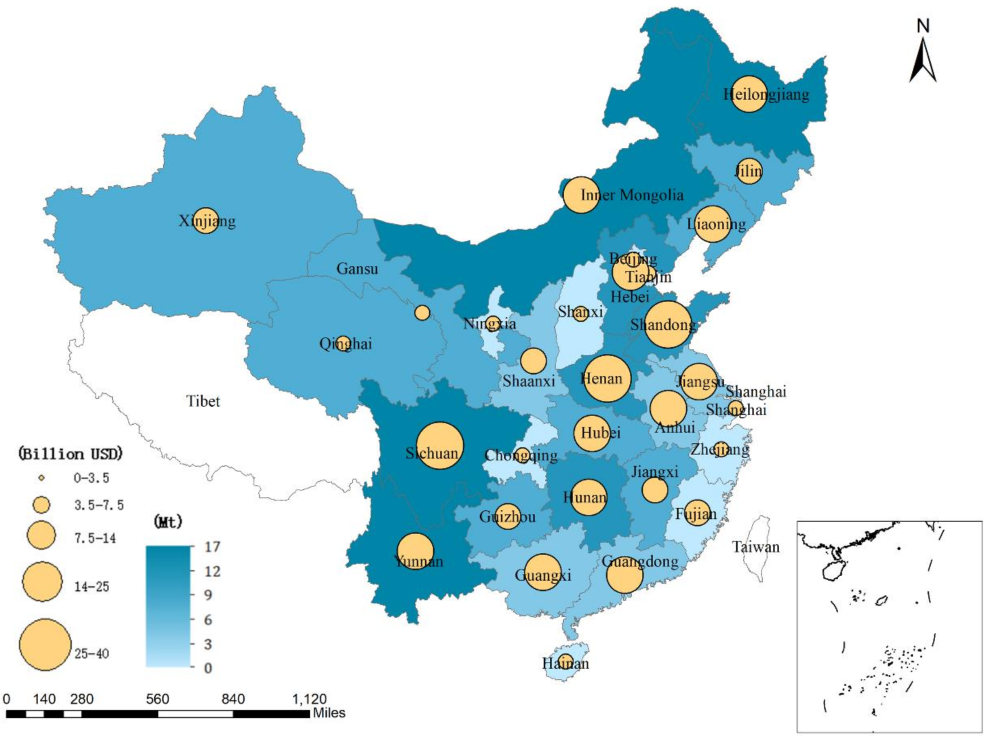

**Fig. 3.** Theoretical reserve of LEs and gross product of husbandry industry in 30 regions.

### *4.2 Energy benefits of livestock excrements utilization*

According to the theoretical reserve of LEs, coefficient of commercial scale husbandry feedlots and collection coefficient (see Table 3), the quantity of collectible LEs on a dry mass basis in each region in 2017 is calculated, with the results presented in Fig. 4. Total quantity of collectible LEs could reach 51.12 Mt, accounting for around a quarter of the theoretical reserve. Among 30 regions, Sichuan has the largest quantity of collectible LEs which is larger than 4 Mt. Henan, Yunnan, Hunan, Shandong, Heilongjiang and Hebei belong to the second level, with the quantity larger than 3 Mt. There are six regions with less than 0.5 Mt collectible LEs, including Ningxia, Zhejiang, Hainan, Tianjin, Beijing and Shanghai. In terms of the contribution of livestock type to collectible LEs, swine, as the main source of meat for Chinese, contributes to half of the collectible LEs. LEs from beef cattle and dairy cow account for 30.42% and 17.31%, respectively. The difference in the quantity of three types of LEs is caused not only by different quantity of livestock, but also the specific scale of husbandry feedlots and collection coefficient as in Table 3. Some spatial features can be revealed from the structure of LEs. The collectible LEs in the center & south and east, which contribute 41.19% in total collectible LEs, is dominated by LEs from swine. The northwestern area, and Inner Mongolia have a larger proportion of LEs from beef cattle and dairy cow (larger than 85% collectively) due to local traditional culture and customs.

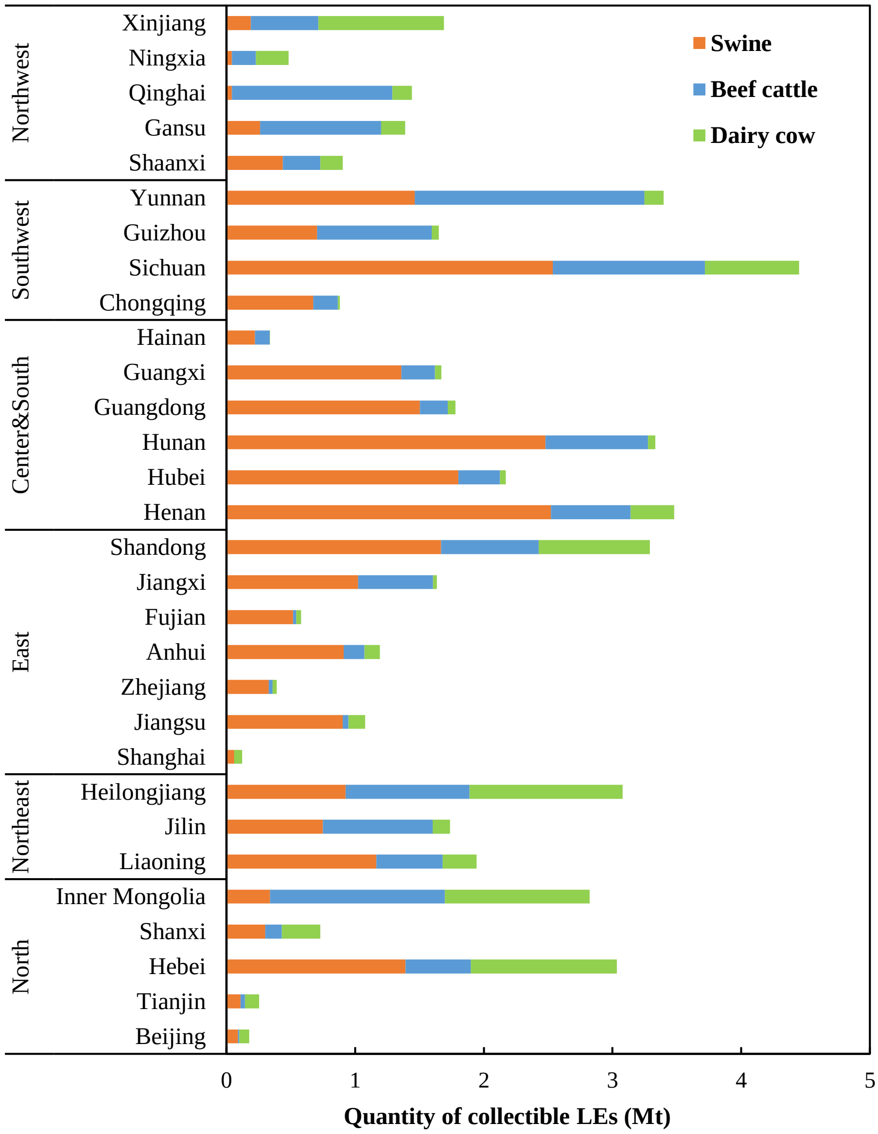


**Fig. 4.** Quantity of collectible LEs in 30 regions.

The spatial distribution of the energy benefits for 30 regions is depicted in Fig. 5. Total quantity of biogas produced amounts to 16.92 billion m$^3$, equivalent to 28.76 billion kWh electricity, with the net energy benefits as 11.30 Mtce. Similar to the condition for collectible LEs, Sichuan has the greatest energy benefits as 1.0 Mtce. The energy benefits for Yunnan, Shandong, Henan, Heilongjiang, Inner Mongolia, Hunan and Hebei are larger than 0.7 Mtce. The most disadvantageous regions are Zhejiang, Hainan, Tianjin, Beijing and shanghai. It is worth noting that Inner Mongolia enters the second level due to its larger proportion of LEs from beef cattle and dairy cow which have higher energy conversion efficiency (see Table 3). Total biogas power produced by LEs utilization could potentially account for 0.47% of the total power consumption on the national level. Such proportion in Heilongjiang, Jilin, Qinghai, Sichuan, Hunan and Yunnan could be even larger than 1%.

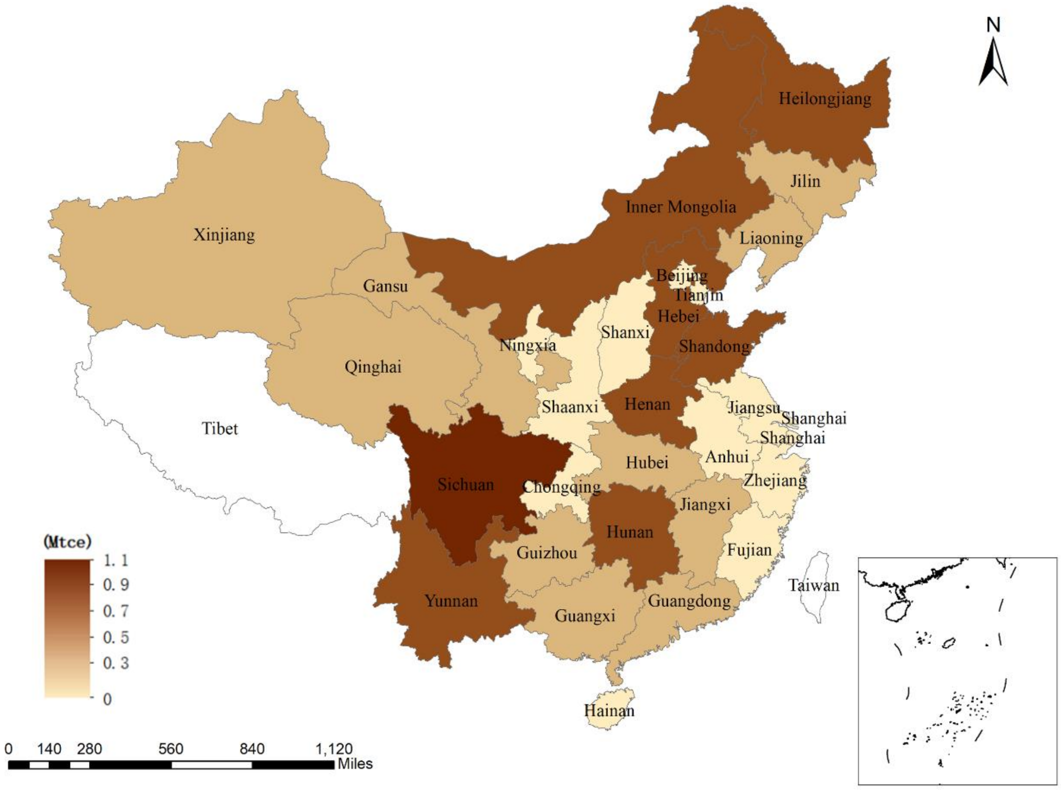


**Fig. 5.** Energy benefits of LEs utilization in 30 regions.

### *4.3 Environmental benefits of livestock excrements utilization*

In order to highlight the merits of LEs utilization, considering the outputs within the life cycle boundary, the avoided discharges/emissions according to the substitution assumptions, four categories of environmental impact potentials are calculated according to total avoided discharges/emission (see Table 4 and Table 5). As illustrated in Fig. 6, all the values of environmental impact potentials on the national level are negative, indicating that the environmental benefits of LEs utilization are positive. Total weighted environmental impact potential amounts to -0.053. Attributed to LEs utilization, the main pollutants for eutrophication COD and $NH_3$-N and TP (originally would be discharged into water environment) are substantially substituted. The eutrophication potential is most significant, amounting to -9.08E+08 kg $PO_4$-eq and accounting for 96.77% in total potential. The values for the potentials of climate change, photochemical oxidation and acidification are -2.70E+10 kg $CO_2$-eq, -1.66E+07 kg $C_2H_4$-eq, and -2.19E+09 kg $SO_2$-eq, which account for 0.43%, 0.02% and 2.77% in total potential, respectively.

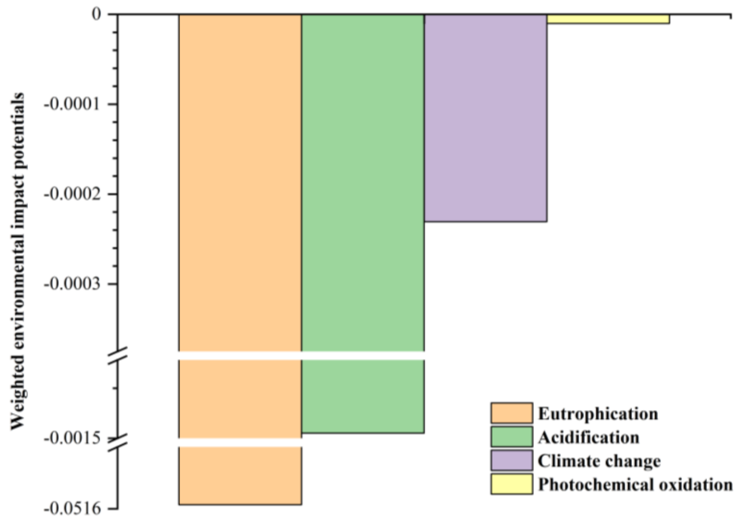


**Fig. 6.** Environmental impact potentials on the national level.

The spatial features for the environmental impact potentials are overall consistent with the quantity of collectible LEs and energy benefits. As presented in Fig. 7, Henan has the most remarkable environmental benefits, whose total potential amounts to -0.0040. LEs utilization in Hunan, Hebei, Shandong, Heilongjiang and Sichuan are also more environmentally advantageous, whose total potential is between -0.004 and -0.0030. Like the energy benefits, the environmental benefits in Zhejiang, Hainan, Tianjin, Beijing and Shanghai are tiny. Sichuan has the largest mitigated potentials of climate change and photochemical oxidation, as 2.29E+09 kg $CO_2$-eq and 1.65E+06 kg $C_2H_4$-eq, respectively. Henan has the largest mitigated potentials of eutrophication and acidification, as 6.81E+07 kg $PO_4$-eq and 1.76E+08 kg $SO_2$-eq, respectively.

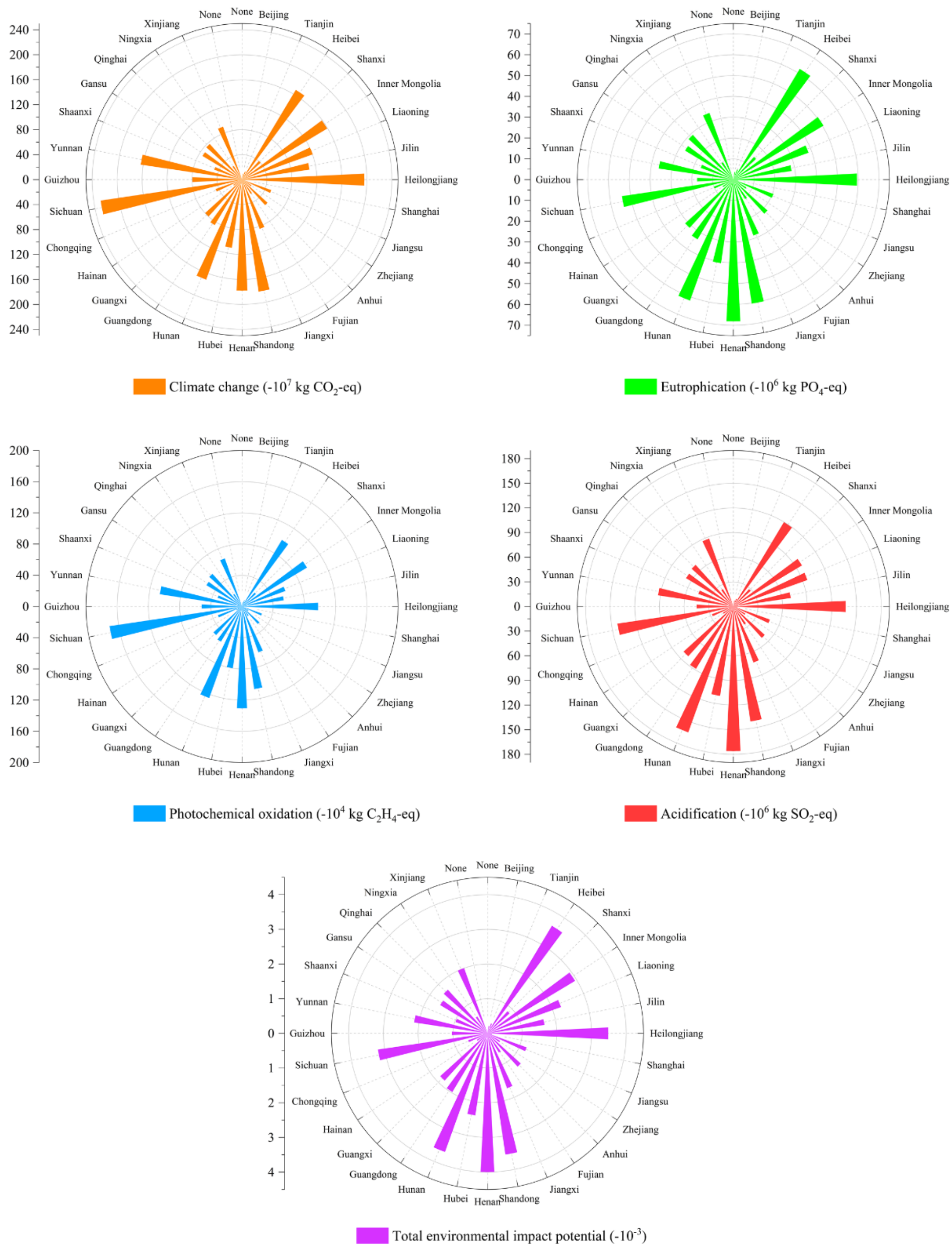


**Fig. 7.** Environmental benefits of LEs utilization in 30 regions.

### *4.4 Socioeconomic benefits of livestock excrements utilization*

The economic benefits of LEs utilization in 30 regions are presented in Fig. 8. The regions with larger energy benefits also have more considerable economic benefits. Total potential net profit in Sichuan reaches 0.163 billion USD, followed by that in Henan (0.126), Yunnan (0.126), Shandong (0.121), Hunan (0.120), Heilongjiang (0.115), Hebei (0.112) and Inner Mongolia (0.107). Total economic benefits in 30 regions amount to 1.88 billion USD. In addition, the income is composed of that from the sales of biogas power and bio-fertilizers, with roughly equal contribution. In the cost structure of LEs utilization, depreciation cost accounts for 28.79%, followed by tax (20.97%) and transportation (17.35%). For the social benefits, 73.06 thousand employments could be newly created, contributing to 373.55 million USD workers' income.

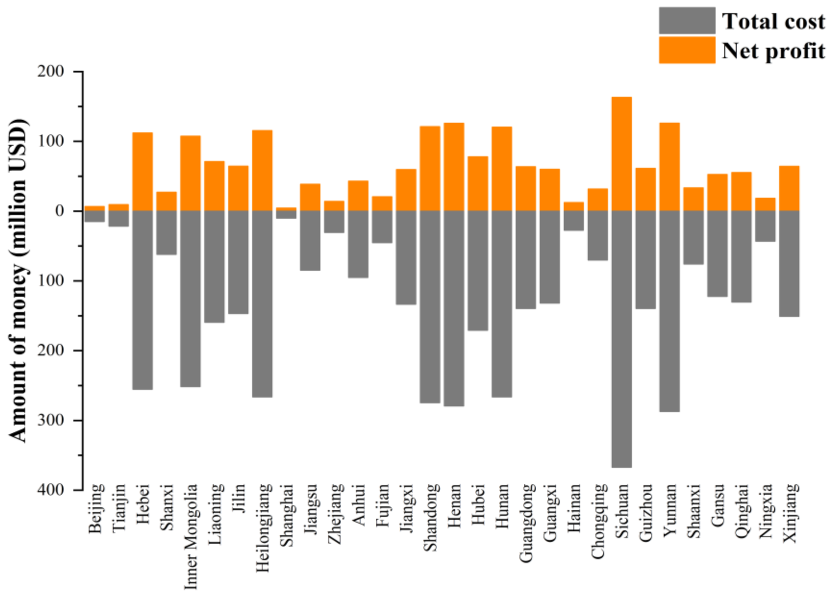


**Fig. 8.** Economic benefits of LEs utilization in 30 regions.

## 5. Discussion and policy implications

The life cycle integrated model constructed in this study is applied to assess the energy, environmental and socioeconomic benefits of livestock (swine, beef cattle and dairy cow) excrements utilization in 30 provincial regions that are divided into six large areas spatially. The excrement generation coefficients of livestock, discharge factors of water pollutants from husbandry feedlots and emission factors of power consumption for GHGs and atmospheric pollutants correspond to regional power grids in six areas (see Table 1) are adopted to precisely calculate the theoretical reserve and environmental benefits. The theoretical reserve of LEs in China shows the same trend as the gross product of husbandry industry from 2008 to 2017. Generally, the regions with more prosperous husbandry development have a larger quantity of livestock and thus a larger theoretical reserve of LEs. The collectible quantity of theoretical reserve of LEs can be collected is determined by the coefficient of commercial scale husbandry and collection coefficient collectively (see Table 3). The energy conversion coefficients (for biogas, electricity and standard coal-equivalent) (see Table 3) are also important factors when estimating the energy benefits. Sichuan, Yunnan, Shandong, Henan and Heilongjiang are the top five regions with the largest energy benefits. When biogas is converted into electricity, which regions benefit more from LEs utilization can be revealed through the proportion of biogas power in total local power consumption. Jilin, Heilongjiang, Hunan, Sichuan, Yunnan and Qinghai have larger benefits on this regard. According to the substitution assumption that the LEs generated by husbandry feedlots are not properly treated and discharged into water environment, discharges of COD, $NH_3$-N, and TP could be considerably avoided, thus contributing to significant mitigated eutrophication potential. The "$CO_2$-neutral" nature of LEs, power substitution and fertilizer substitution collectively contribute to mitigating climate change, photochemical oxidation and acidification. Compared with other environmental impact potentials, eutrophication potential is particularly large (accounting for 96.77% in total potential). Generally, the regions with larger energy benefits have larger environmental benefits, however with some exceptions. Sichuan and Yunnan rank top two with regard to the energy benefits, but do not have most remarkable environmental benefits, especially for eutrophication mitigation. This is because the discharge factors of water pollutants from LEs for the southwest are much smaller than those for other areas, resulting in loss of the avoided discharges of water pollutants and thus the mitigated eutrophication potential (see Table 2). Owing to the elaborative assessment of the mitigated environmental impact potentials, how much a region can benefit from LEs utilization from which environmental dimension is revealed, which is one of the key findings of this study. Besides the net profits, the economic benefits for regions are considerable in terms of the contribution to regional husbandry industry. For example, total income of LEs utilization is estimated to account for around 1.7% in total gross product of husbandry industry in Sichuan. Whilst, the industrial development of LEs utilization can promote the development of other industries related with LEs utilization. There overall forms a consistency for regions that, larger energy benefits imply larger environmental and economic benefits, as well as more necessity to promote LEs utilization.

The assumptions we set for LEs utilization process and the selection of some parameters may lead to uncertainties the results of the integrative benefits in this study. (1) As the (locations of) consumers of bio-fertilizers cannot be determined, transportation of fertilizers to consumers is not incorporated into the system boundary, which may lead to conservative results. (2) Due to different development level of husbandry industry in different regions, the coefficient of commercial scale husbandry should be diverse, which directly affects the estimation of the quantity of collectible LEs. (3) The biogas generation coefficient for the colder regions in the north such as Heilongjiang, Jilin, Inner Mongolia might be smaller since temperature plays a crucial role in affecting the stability and efficiency of anaerobic digestion (Lin et al., 2017). (4) The composition of biogas is assumed to be constant, as well as the power generation coefficient during CHP process. Considering the stability of biogas composition and CHP process, power generation from unit quantity of biogas ranges within 1.6-2.0 kWh/$m^3$, according to which power generation from unit quantity of LEs ranges within 556.4-695.5 kWh/t-LEs. (5) The subsidization policies of government for LEs utilization in different regions may be diverse, leading to disparities in the prices of biogas power and bio-fertilizer. The above aspects may affect the accuracy of the results for the integrative benefits and should be amended in future work once relevant data are available.

Based on the above results and discussions, some policy implications on LEs utilization can be inspired. Compared with Europe and other developed countries, China has the advantage of abundant biomass resources, while the disadvantage of the failure to realize large scale industrialization. For LEs utilization, we find that the coefficient of commercial scale husbandry, which represents the development level of husbandry industry, is most influential on the quantity of collectible LEs, as well as the energy, environmental and socioeconomic benefits. For example, the coefficient of commercial scale husbandry for beef cattle is only 28.1%, with nearly 70% of LEs from beef cattle wasted. Therefore, regions with larger proportion of commercial scale husbandry feedlots are more suitable to develop LEs utilization. The quantity of biogas that could be generated from unit quantity of LEs is also a key factor affecting LEs utilization. LEs from beef cattle and dairy cow are better feedstock for biogas plant with larger energy conversion coefficient. Furthermore, for the selection of feedstock, the reviewed studies have disclosed that biogas generation efficiency could be promoted by mixing LEs with other kinds of biomass such as straw, a factor worth considering by regions with more developed farming and husbandry industry (Matuszewska et al., 2016). For the enterprises, the motivation of operating biogas plant is the income determined by the prices of biogas power and fertilizers. Government should formulate locally pertinent subsidization policies to promote enterprise development and industrialization of LEs utilization, especially when taking into account the potential environmental benefits that can be created by LEs utilization. In terms of the results for the current, Sichuan, Yunnan, Shandong, Henan, Heilongjiang, Inner Mongolia, Hunan and Hebei are more advantageous in promoting energy-oriented LEs utilization.

## 6. Conclusion

In this study, an integrated assessment model is constructed based on the life cycle of LEs utilization for energy conversion. The integrative energy, environmental and socioeconomic benefits of LEs utilization in 30 provincial regions in China are assessed by applying the model and the spatial features of the benefits are elaborately revealed. Some conclusions can be drawn as follows:

(1) The theoretical reserve of LEs shows an overall increasing trend from 2008-2017, reaching 200.36 Mt (on a dry mass basis) in 2017. Spatially, Sichuan has the most reserve of LEs, amounting to 16.15 Mt, followed by Yunnan, Inner Mongolia, Heilongjiang and Shandong.

(2) Total collectible quantity of LEs from commercial scale husbandry feedlots reaches 51.12 Mt. LEs from swine account for around a half. Total quantity of biogas produced amounts to 16.92 billion $m^3$, and the net energy benefits are 11.30 Mtce.

(3) The eutrophication potential is most significant, amounting to -9.08E+08 kg $PO_4$-eq and accounting for 96.77% in total potential followed by the potentials of climate change,

photochemical oxidation and acidification. Sichuan has the largest mitigated potentials of climate change and photochemical oxidation, and Henan has the largest mitigated potentials of eutrophication and acidification.

(4) In total, the sales of biogas power and fertilizers could contribute to 1.88 billion USD net profits and 73.06 thousand employments and 373.55 million USD workers' income could be created.

(5) Regions with greater integrative benefits are Sichuan, Yunnan, Shandong, Henan, Heilongjiang, Inner Mongolia, Hunan and Hebei.

Besides the uncertainties relevant to the life cycle boundary and parameter setting, the results of this study could be more accurate if taking geographical differences (temperature, technology, etc.) in different regions into account, to involve region-specific parameters such as the coefficient of commercial scale husbandry, biogas generation efficiency, etc. The above aspects direct the focus of our future work once sufficient data are available. Also, we will conduct the prediction of the trend in the quantity of LEs considering multiple affecting factors (such as the demand for meat and milk, increase in the proportion of commercial scale husbandry, etc.) The constructed integrated model has the applicability in assessing the comprehensive benefits of the utilization of other types of biomass resources. The energy, environmental and socioeconomic benefits of LEs utilization, as well as the spatial features of the benefits are expected to provide government with references regarding better planning of national and regional LEs utilization.


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## Appendix

**Table A-1.** Supplementary data on parameters.

**(1) Emission factors of diesel consumed during LEs transportation**

| Energy (MJ/(kg*km)) | $CO_2$ (g/MJ) | CO (g/MJ) | $CH_4$ (g/MJ) | $NO_x$ (g/MJ) | $SO_2$ (g/MJ) | $N_2O$ (g/MJ) |
|---|---|---|---|---|---|---|
| 6.78E-04 | 74.04 | 0.47 | 0.0042 | 0.28 | 0.016 | 0.0019 |

**(2) Discharge factors of wastewater treatment unit during diagestate utilization**

| COD (g/kg-biogas slurry) | $NH_3$-N (g/kg-biogas slurry) | TP (g/kg-biogas slurry) |
|---|---|---|
| 0.4 | 0.08 | 0.008 |

**(3) Nutrient elements in digestate (g/kg)**

| Total nitrogen | Total phosphorus | Total potassium |
|---|---|---|

| Biogas residue | Biogas slurry | Biogas residue | Biogas slurry | Biogas residue | Biogas slurry |
|---|---|---|---|---|---|
| 17.01 | 1.15 | 12.86 | 0.19 | 8.86 | 0.48 |
| **(4) Emission factors of bio-fertilizer consumption** | | | | | |
| $NH_3$ | | | $N_2O$ | | |
| 5% of nitrogen in bio-fertilizer | | | 0.39% of nitrogen in bio-fertilizer | | |
| **(5) Proportions of nutrient in synthetic fertilizer** | | | | | |
| Nitrogen fertilizer | | Phosphorus fertilizer | | Potash fertilizer | |
| 46% | | 44% | | 83% | |
| **(6) Emission factors of synthetic fertilizer production (g/kg)** | | | | | |
| | $CO_2$ | $NH_3$ | $CH_4$ | $NO_x$ | $SO_2$ |
| Nitrogen fertilizer | 6513.2 | 6.7 | 16.13 | 27.93 | 21.14 |
| Phosphorus fertilizer | 1117.5 | 0.01 | 1.86 | 8.54 | / |
| Potash fertilizer | 625.14 | / | 1.56 | 1.27 | 0.46 |

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