

Environmental sustainability evaluation of dairy manure bedding regeneration system based on emergy analysis and life cycle assessment method

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Abstract

Dairy farm bedding can be produced by composting technology using dairy manure, which offers advantages in terms of cost, availability and economic value. However, few information is available on the environmental sustainability and impacts for manure recycling systems for based on different composting methods. The resource-environmental impact and eco-economic sustainability of two manure bedding regeneration systems: forced-ventilation static-stack aerobic fermentation (FVSSAF) system (Scenario A) and bedding recovery unit (BRU) system (Scenario B) were evaluated in this study. The life cycle assessment yielded a combined environmental impact potential of 0.0170 for scenario B, much lower than the 0.1970 for scenario A. The emergy analysis showed that scenario B has a higher emergy input of about $1.34E + 18$ sej/a than scenario A with $6.34E + 17$ sej/a. This was due to the fact that scenario B can handle more dairy manure. Form the emergy indices of the two systems, scenario B had lighter environmental pressure and higher sustainability. In contrast, the BRU system had economic advantages and ecological sustainability, which was more suitable for large dairy farms. The trade-offs between environmental consequences, resource efficiency and economic benefits were analyzed from several perspectives in this study, and would help stakeholders to have a new understanding when choosing a bedding recycling treatment option.

1. Introduction

In recent years, in order to meet the rapid growth of milk production demand, many traditional dairy farm systems in China have been transformed into collective and intensive systems, and the corresponding increase in manure and sewage production has brought great challenges (Cui et al., 2021). There is a significant amount of manure produced in China, reaching 3.8 billion tons in 2020 (Li et al., 2021), leading to raised concerns about the environmental impact and resource utilization related to the dairy industry (Bai et al., 2018a; Thomassen et al., 2008). Manure and sewage are generally considered valuable biomass resources with high nutritional potential to improve soil quality to achieve sustainable productivity (Cortez-Arriola et al., 2015; Li et al., 2018; Qian et al., 2020). The conventional practices of manure and sewage management are mainly limited to land application and stockpiling. Untreated dairy manure waste leads to a range of environmental degradation, climate change and resource depletion issues (Adghim et al., 2020; Zhuang et al., 2020), as well as other impacts, including acidification and eutrophication potential (Wang et al., 2018). Therefore, it is important to find a way to treat the manure produced by dairy cows in a way that balances cost effectiveness and environmental impacts.

Preparation of bedding from manure was considered a clean production technology and introduced in the United States in the 1970s, which was also known as 'recycled manure solids' (RMS) (Keys-Jr et al., 1976; Timms, 2008a). Several studies have been reported on the use of dairy manure as a mattress. Husfeldt et al. (2012) concluded that recycled manure solids have significant advantages in terms of cost, availability, and economic value compared to conventional sources of organic bedding, but only for the mode of mechanical drum-composting. Leach et al. (2015) evaluated the economics and risks of manure mattresses on UK dairy farms and found that pathogens in manure were a major source of risk and different composting methods could reduce the number of pathogens. Most studies focused on the quality of products obtained from different composting methods, rather than comparing different processes; on the other hand, the environmental benefits evaluation of mattress production with different composting technologies is less considered.

Recently, many studies have focused on evaluating farm waste treatment systems through emergy analysis (EME) and life cycle assessment (LCA) (Li et al., 2020; Wang et al., 2021). EME emphasizes the input of environmental resources in the production process, reflecting "upstream sustainability", while LCA focuses on the environmental emissions generated during the system process, reflecting "downstream sustainability" (Santagata et al., 2020). The combined application of EME and LCA methods can provide a more complete and comprehensive evaluation of the integrated environmental, economic, and ecological performance of the system (Wang et al., 2016). However, research on the life-cycle environmental performance of dairy manure regeneration mattress systems is still limited and not well quantified, especially for different composting patterns.

In order to further understand the differences of environmental impacts and resource efficiency in different systems, in this study, we used the method of LCA and EME to evaluate the effects of material utilization and waste discharge on Eco-economic sustainability, energy efficiency, and environment impacts in the process of recycling bedding materials in different composting schemes of dairy manure under the same system boundary, which included the forced ventilation static stack aerobic fermentation (FVSSAF) system (Scenario A) and the bedding recovery unit (BRU) system (Scenario B). It covered the whole process from the transportation of cow dung to the treatment area where recycled cow dung into a usable cow mattress. Furthermore, the advantages and disadvantages of the two kinds of bedding material regeneration treatment schemes were evaluated to provide a theoretical reference for the selection of bedding material regeneration treatment scheme in the actual production process of large-scale dairy farms.

2. Methods And Materials

2.1 Study area and system description

This study was carried out in the third Yinxiang weiye international ranch, which located in Cao County, Heze City, Shandong Province ($115^{\circ} 32' E$, $34^{\circ} 35' N$), which had the typical characteristics of large-scale dairy farm. In 2018, there were 5,037 cows in the pasture, and 36 barns were built, all of which were fully open free lying barns with playground. Large scale dairy cows caused a lot of fecal pollution. The total daily fecal pollution of dairy farm was about 200 t, including 125 t fresh feces, 60 t urine and 15 t production sewage. To deal with the daily fecal pollution, the farm had two sets of solid-liquid separation equipment, two sets of silo aerobic fermentation unit and eight forced ventilation static stacks. These deviced provided two scenarios for fecal regeneration systems.

Scenario A: Forced ventilation static stack aerobic fermentation (FVSSAF) system, the cow dung solid treated by aeration for a period was composted by ventilated static pile for about 12 days. Then it was turned and dried in the drying field of the pasture for 2 days and used as bedding for the cow bed.

Scenario B: Bedding recovery unit (BRU) system was developed by Austrian fan company, which equipped with solid-liquid separation host and fermentation bin. The separated fecal solids can be subjected to aerobic fermentation for 10–12 hours. At the same time, the high temperature in the fermentation bin can eliminate the bacteria that may cause cow mastitis and obtain clean cow bedding.

2.2 LCA analysis

The ISO 14040 guideline was followed to carry out the study (ISO, 2006). The LCA analysis of two fecal regeneration bedding systems produced by the two methods was divided into four parts: determination of target and scope, inventory analysis, impact evaluation and result interpretation.

2.2.1 Goal and scope

The system boundary of both systems was: starting from the transportation of dairy manure to the manure treatment area, and the ending with the treatment of dairy manure into bedding that can be discharged (Fig. 1). The functional unit (FU) for the evaluation was one of fresh dairy manure, and other auxiliary inputs (wood chips etc.), energy inputs (i.e. electricity and diesel), product output, and pollutant emissions were all based on the corresponding values per functional unit.

2.2.2 Life cycle inventory analysis

Life cycle inventory is a quantitative analysis of all material, energy and emissions within the system boundaries of its research system for products, processes or activities, usually in the form of a data inventory table (Hélias et al., 2020). The basic data of daily operation consumption of two kinds of cushion material regeneration scenarios in this study are mainly through field investigation. GHGs emission data are from experimental detection, and the remaining data such as public system reference data are from public literature.

Scenario A:

There are eight forced ventilation static stacks in the pasture, each static stack can deal with 19 m³ cow dung. The static stack is equipped with 4 roots fans of 5kW power, and the fan ventilation time is set to 8 minutes on and 10 minutes off. After 12 days of forced aerobic fermentation, the dairy manure was piled up and dried for 2 days, and the ranch was equipped with a 10,000 cubic meter drying site. The drying is done by turning with a rake three times a day, consuming 13 liters of diesel fuel each time. At this point, the moisture of cow manure can be reduced to less than 50% and can be used as bedding for cows. The environmental emissions of forced ventilation static stack regeneration bedding system mainly include greenhouse gas emissions during composting, fan energy consumption, solid-liquid separator energy consumption and greenhouse gas emissions during drying.

The emission rates of CO₂, CH₄ and N₂O in the composting process of the system were 441.25 mg·kg⁻¹·h⁻¹, 1.35 mg·kg⁻¹·h⁻¹ and 94.41 μg·kg⁻¹·h⁻¹, respectively. The emission coefficients of greenhouse gases in the drying process were shown in the research results (Ba et al., 2020). Four different stages were selected for the experiment. After weighted average, the emission rates of greenhouse gases CO₂, CH₄ and NO₂ in the fermentation process were determined as 29.88 mg·kg⁻¹·h⁻¹, 0.77 mg·kg⁻¹·h⁻¹ and 37.47 μg·kg⁻¹·h⁻¹, respectively. The emission coefficient of NH₃ in the composting process was determined as the method of Ba et al. (2020).

The total energy consumption of solid-liquid separation process in one day was 620 kWh, and 40 m³ solid cow dung was obtained, namely 15.5 kWh·FU⁻¹. The total energy consumption of the fan during composting was 2560 kWh, that is, 20 kWh·FU⁻¹, and the energy consumption of the treatment process was mainly electric power consumption.

Given the boundary of the evaluation system, that is, the manure is transported to the treatment area until the cow manure is fermented and dried to become the cow bed bedding product, the treatment stage is only considered.

Scenario B:

The rated feed flow rate of the silo fermentation system was 45 m³/d. The emission rates of CO₂, CH₄ and N₂O during the operation of BRU were 3574.4 ± 337.2 mg·s⁻¹, 3.88 ± 0.93 mg·s⁻¹ and 0.052 ± 0.012 mg·s⁻¹, respectively. CO₂ emission was 3.30 ± 0.32 kg·FU⁻¹, CH₄ emission was 3.60 ± 1.77 g·FU⁻¹, N₂O emission was 47.53 ± 89.66 mg·FU⁻¹.

The total power of BRU was 29 kW, and 40 m³ cushion can be produced in 20 hours. The energy consumption of aerobic fermentation process was 580 kWh, that is, the unit energy consumption of functional evaluation was 12.89 kWh·FU⁻¹.

The pollutant emissions of the two treatment scenarios of FVSSAF system and BRU system were summarized, and the list of main pollutant emissions in the product life cycle after manure treatment was obtained as shown in Table S1 (Appendix).

2.2.3 Life cycle impact assessment

LCA is a quantitative and qualitative characterization of the potential impact load on the environment based on pollutant emissions, resources and energy consumption obtained in the inventory analysis stage.

1) Classification

Classification is to classify the input and output data in the process of system life cycle into different environmental impact categories. Since CO₂, CH₄, NO_x, N₂O, NH₃ and SO₂ were the main gases often produced in the process of fecal composting, four closely related impact types are selected in this study:

including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone synthesis potential (POSP).

2) Characterization

This study mainly considered four types of environmental impacts, including GWP, AP, EP and POSP. In this study, the equivalent factor method was used. The principle is that the contribution value of different pollutants (in the case of the same quality) to the same environmental impact type is different. Taking one of the pollutants as the benchmark, and its impact potential was regarded as 1, then the equivalent size of the reference material quality was obtained by comparing with the other pollutants. The calculation formula of product environmental impact potential was as follows:

$$EP(j) = \sum EP(j)_i = \sum [Q(j)_i \times EF(j)_i]$$

$EP(j)$ –Impact potential for type j of environmental impact;

$EP(j)_i$ –Contribution of environmental impact factor i to environmental impact potential j ;

$Q(j)_i$ –Emissions or consumption of environmental interference factor i ;

$EF(j)_i$ –Equivalent factor of type i environmental impact factor to type j environmental impact.

3) Standardization

This paper used the world per capita environmental impact potential released by Stranddorf as the environmental impact benchmark (Lindley et al., 2019).

4) Weighted evaluation

The weight coefficients of global warming, environmental acidification, eutrophication, photochemical ozone synthesis and inhalable particles were 0.15, 0.32, 0.36, 0.32 and 0.11, respectively. Comprehensive environmental impact calculation formula was as follows:

$$WP(j) = \sum WF(j) \cdot NP(j)$$

$WP(j)$ –Integrated environmental impact potential.

$WF(j)$ –Weight factor for type j environmental impacts.

$NP(j)$ –Standardized impact potential.

2.3 Energy analysis

The methodology of energy analysis and its steps has been explained at (Odum, 1996; Odum, 2000). Energy analysis consists of several successive steps:

1) drawing the process diagram and input and output flows;

2) using the system diagram to create an evaluation table for energy, materials, environmental services, money and labor flows. In this table, all input and output flows are estimated in their common units, and each item is multiplied by its solar conversion rate (the ratio of the total energy used to the energy or mass of the product, in units sej/J or sej/g) in order to convert into emergy unit;

3)calculating a set of emergy indicators.

The energy system diagram was shown in Fig. 2 and the system boundaries were consistent with the LCA, both starting at fresh and ending at dairy manure production as a mattress. In the diagram, the energy input of the two fecal regeneration bedding systems was mainly divided into two categories: one was "free energy": sun, wind, rain and cow dung were the renewable environmental resource (R), which were used in the process; non-renewable environmental resource (N) included land use. Another one was "purchase energy": flows of labor were Renewable industrial auxiliary energy (F_R), meanwhile flows of repair and maintenance, asset depreciation and electricity were non-renewable industrial auxiliary energy (F_N). Last but not least, the cow bedding and biogas slurry were the yield of process (Y). And the emergy conversion rates for the two systems which included all input and output flows under study were described in Table S2(Appendix A).

Moreover, the emergy indices were employed to analyze the operating efficiency, ecological characteristics and sustainability of different fecal regeneration bedding systems, namely emergy yield ratio (EYR), emergy investment ratio (EIR), emergy self-sufficiency ratio (ESR), renewable emergy ratio (RER), emergy sustainability index (ESI), environmental loading ratio (ELR) and emergy wastement ratio (EWR). The emergy indices were described in detail in Table S3(Appendix A).

3. Results And Discussion

3.1 Life cycle environmental impacts

The results of impact assessment of dairy manure on four different environmental impact including global warming, acidification, eutrophication and photochemical ozone synthesis under the two scenarios were shown in Fig. 3. The comprehensive environmental impact potentials of scenario A and scenario

B were 0.1970 and 0.0170, respectively (Table 1). Indicated that scenario B is more environmentally friendly.

Table 1
Environmental impact assessment results.

Projects	Parameter type	Discharge amount(kg/per.a)	Characterization factors	Equivalent factor	Environmental impact potential(kgCO ₂ /per.a)	Fiducial value	Standardized value	Weight	Total environm impact potential
GWP	A	CO ₂	CO ₂	1	3340	8700	3.84×10 ⁻¹	0.32	1.23×10 ⁻
		CH ₄		25					
		N ₂ O		320					
	B	CO ₂	CO ₂	1	57.2	8700	6.57×10 ⁻³	0.32	2.10×10 ⁻
		CH ₄		25					
		N ₂ O		320					
AP	A	SO ₂	SO ₂	1	2.31	35	6.60×10 ⁻²	0.36	2.38×10 ⁻
		NO _x		0.7					
		NH ₃		1.89					
	B	SO ₂	SO ₂	1	0.68	35	1.94×10 ⁻²	0.36	6.99×10 ⁻
		NO _x		0.7					
		NH ₃		1.89					
EP	A	NH ₃	NO ₃ ⁻	0.35	0.35	59	5.93×10 ⁻³	0.32	1.90×10 ⁻
		NO _x		0.1					
	B	NH ₃	NO ₃ ⁻	0.35	0.031	59	5.19×10 ⁻⁴	0.32	1.66×10 ⁻
		NO _x		0.1					
POSP	A	CH ₄	C ₂ H ₄	0.003	0.07	0.76	9.2×10 ⁻²	0.53	0.048
		CO		0.03					
		NO _x		0.03					
	B	CH ₄	C ₂ H ₄	0.003	0.0112	0.76	1.47×10 ⁻²	0.53	7.81×10 ⁻
		CO		0.03					
		NO _x		0.03					

3.1.1 Global warming potential

Contribution was a dominant process contributing to the GWP in scenario A, which accounting for 62.3%. However, the contributions of contribution of scenario B to GWP was only 12.3%. This was mainly because the static pile composting system will produce a large amount of CO₂, CH₄, N₂O, these gases were the main factors causing global warming, especially N₂O gas, its global warming potential was greater, about 320 times that of CO₂. Although the amount of CO₂ is large, it was not as big as the impact of N₂O. First, CO₂ production was unavoidable in composting. More N₂O in scenario A was mainly due to the better ventilation conditions and higher oxygen content of scenario A, resulting in more intense microbial denitrification and increased final emissions. In addition, some studies had shown that the emissions increased significantly in the post-rot maturity period, mainly dued to the reactor temperature is higher than the high temperature period, which was not conducive to the production. This was because the activity of nitrifying bacteria is inhibited in the high temperature period, which reduced the emission flux. After the decrease of reactor temperature in the post-rot maturity period, the activity of nitrifying bacteria increases, which leading to the increase of emission flux (Hao et al., 2005). Therefore, to reduce the environmental impact of global warming, as far as possible to use CH₄ and N₂O emission reduction technology. Hao et al. (2005) added phosphogypsum to cow manure compost, reducing the total CH₄ emission by 80%. In addition, Hao et al. (2005) also believed that there was a significant negative correlation between pH value and N₂O emission, so a moderately acidic composting environment was created to reduce the production of N₂O.

3.1.2 Acidification potential

In scenario B, acidification contributed more to the potential environmental impact, accounting for 40.96%, while in scenario A, it accounted for only 12.06%. In this study, the NH₃ emission generated during composting contributed greatly to the acidification effect of scenario A, which was similar to the results of Lopez-Ridaura et al. (2009) and Martínez-Blanco et al. (2010). However, NH₃ was not detected in scenario B, and its nitrogen oxides and hydrogen chloride had

little effect on the acidification of composting process (Luo et al., 2013). Therefore, in general, the acidification effect of scenario B was far less than that of scenario A. In order to reduce the acidification effect, NH_3 production should be reduced as much as possible. When the reactor had strong NH_4^+ -N retention capacity due to additives, material structure, pH value or upturn frequency, a large amount of NH_4^+ -N generated at high temperature was relatively difficult to be converted into ammonia volatilization loss (Beck-Friis et al., 2001; Jeong et al., 2005).

3.1.3 Eutrophication potential

Eutrophication had the lowest potential environmental impact in scenarios A and B, accounting for only 0.96% and 0.97. Among them, ammonia volatilization from compost contributed a lot, which was the emission of nitrous oxide. Since leachate was not collected during composting in this study, the contribution of leachate factors during composting was not included in the eutrophication effect. The study showed that the generation and emission of leachate and anaerobic fermentation wastewater from livestock and poultry manure treatment process would double the eutrophication effect. The leachate problem caused by livestock manure treatment in the actual production cannot be ignored. When leachate is generated during composting, the overall eutrophication effect may increase significantly.

3.1.4 Photochemical ozone synthesis potential

In scenario B, photochemical ozone synthesis had the greatest potential impact on the environment, accounting for 45.76%, and the proportion in scenario A was second only to GWP, accounting for 24.67%. CH_4 was the largest contributor, mainly because the composting process and power consumption process will produce a large amount of CH_4 .

Compared with the two scenarios, although the proportion of each environmental impact potential was quite different, the environmental impact potential of scenario A was larger than that of scenario B, even with an order of magnitude gap. Therefore, in conclusion, scenario B was recommended to choose pasture.

3.2 Energy analysis

Higher energy input was found in Scenario B, which was 68% higher than that in Scenario A (Table 2 and Fig. 4). This result mainly because of the electricity consumption by BRU system was high (1070 kWh/day). On contrast, the electricity consumption of 210 kWh/day was enough for intermittent forced ventilation during the aerobic composting process. Scenario B will bear higher equipment repair and maintenance costs, $2.37\text{E} + 16$ sej/a higher than Scenario A, but its proportion in the total energy input of Scenario B was lower than that of Scenario A. We also founded that the energy input ratio of dairy manure in Scenario B is 12.4% higher than that of Scenario A ($3.41\text{E} + 17$ sej/a), which means that Scenario B could handle a large amount of pasture manure and was more suitable for today's intensive farms. At the same time, the shelf life of maintenance was longer, this study was limited by time to obtain only static values, and future studies should take the values within the dynamic time change for comparison.

Table 2
Emergy analysis of two fecal regeneration bedding systems in this study.

Project	Solar transformity (sej/unit)	Scenario A		Scenario B	
		Raw data	Solar emery (sej/a)	Raw data	Solar emery (sej/a)
Inputs (U)					
Renewable natural resources (R)					
solar radiation	1.00E + 00	1.29E + 14	1.29E + 14	0.00E + 00	0.00E + 00
Rainwater chemical potential energy	3.05E + 04	1.12E + 09	3.42E + 13	0.00E + 00	0.00E + 00
Wind	2.45E + 03	9.75E + 09	2.39E + 13	0.00E + 00	0.00E + 00
Cow dung	2.70E + 04	5.79E + 12	1.56E + 17	1.84E + 13	4.97E + 17
Subtotal			1.57E + 17		4.97E + 17
Nonrenewable natural resources (N)					
Loss of soil topsoil	1.24E + 05	0.00E + 00	0.00E + 00	0.00E + 00	0.00E + 00
Renewable industrial auxiliary energy (F_R)					
Labor	1.07E + 06	4.38E + 09	4.69E + 15	6.57E + 09	7.03E + 15
Nonrenewable industrial auxiliary energy (F_N)					
Electric	2.67E + 05	1.12E + 12	2.99E + 17	2.08E + 12	5.55E + 17
Diesel oil	1.11E + 05	4.14E + 09	4.60E + 14	0.00E + 00	0.00E + 00
Depreciation of assets	4.94E + 12	1.57E + 04	7.76E + 16	3.33E + 04	1.65E + 17
Repair and maintenance	4.94E + 12	1.93E + 04	9.53E + 16	2.42E + 04	1.20E + 17
Subtotal			4.72E + 17		8.39E + 17
Total			6.34E + 17		1.34E + 18
Outputs (Y)					
Padding	4.94E + 12	1.94E + 05	9.58E + 17	6.38E + 05	3.15E + 18
Biogas slurry	1.24E + 05	1.15E + 12	1.43E + 17	2.61E + 12	3.24E + 17
Subtotal			1.10E + 18		3.48E + 18

However, the proportion of electric energy input in scenario B was 5.9% lower than that in scenario A, which indicated the input of non-renewable industrial auxiliary energy in Scenario B was smaller than that of Scenario A, which was more environmentally positive.

As can be seen from Fig. 4, the emery input in scenario A and scenario B were mainly non-renewable industrial auxiliary energy, but the renewable resource input in scenario B accounted for a large proportion. The scenario A need more nonrenewable resources to support the system compared with the scenario B, which means scenario B is more sustainable.

Different emery indexes are selected to evaluate and analyze from the aspects of ecological economy, sustainable development and environmental load. Figure 5 shows that under different operation modes, the EYR of scenario A and B were greater than 1, but their values were lower than the EYR of China's agricultural system of 2.18, which proved that both systems have a certain ability to output emery. Scenario B was 1.81 (79.04%) higher than scenario A, mainly because the emery output (bedding and biogas slurry) of scenario B was much higher than that of scenario A.

The EYR of scenario B was higher than that of scenario A, and its ELR was lower than that of scenario A. Therefore, the ESI of scenario B was greater than that of scenario A, indicating that scenario B had good sustainability compared with the scenario A. The renewable natural resources and renewable industrial auxiliary emery of scenario B were higher than that of scenario A, so that the ELR and EIR of scenario B were lower than that of scenario A, which proved that the investment cost of scenario B was lower than that of scenario A and had less pressure on the environment.

Therefore, it can be seen from the above analysis that BRU had strong sustainability and investment. In this sense, the emery analysis was useful, because it had the ability to demonstrate the different qualities of the resources that feed a system, starting from the evaluation of their different positions in the energetic hierarchy.

4. Conclusions

The environmental benefits of two scenarios (FVSSAF system and BRU system) based on two composting methods were compared in this study. The environmental impact potential of both scenarios was evaluated with LCA, yielding a relative value of 0.0170 for the combined environmental impact of the BRU system compared to that of the FVSSAF system (0.1970), which was 7.5 times higher than former, indicating that the BRU system had a better

comprehensive environmental friendliness. In the EME method, the electric energy of the BRU system accounted for 41.29% of the total investment, which was 47.19% lower than that of the FVSSAF system. In addition, the EYR and ESI of BRU system were approximately twice as high as those of the FVSSAF system, indicating its stronger sustainability. The comprehensive analysis showed that BRU system was more environmentally friendly than the FVSSAF system.

Declarations

Competing Interests

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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Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Availability of data and materials

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Author contributions

All authors participated in conceiving the study. Xinran Sun: Methodology, Data curation, Conceptualization, Writing – original draft. Yu Liu: Data curation, Visualization, Methodology. Yangyang Li: Data curation, Visualization, Software. Shengyang Chai: Methodology, Visualization. Hao Zhang: Data curation, Formal analysis. Yongdi Liu: Validation, Data curation. Guishen Zhao: Data curation, Writing – original draft. Ji Li: Conceptualization, Formal analysis, Validation, Funding acquisition, Writing - review & editing. Ting Xu: Conceptualization, Funding acquisition, Resources. Yuquan Wei: Conceptualization, Funding acquisition, Resources, Project administration.

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Figures

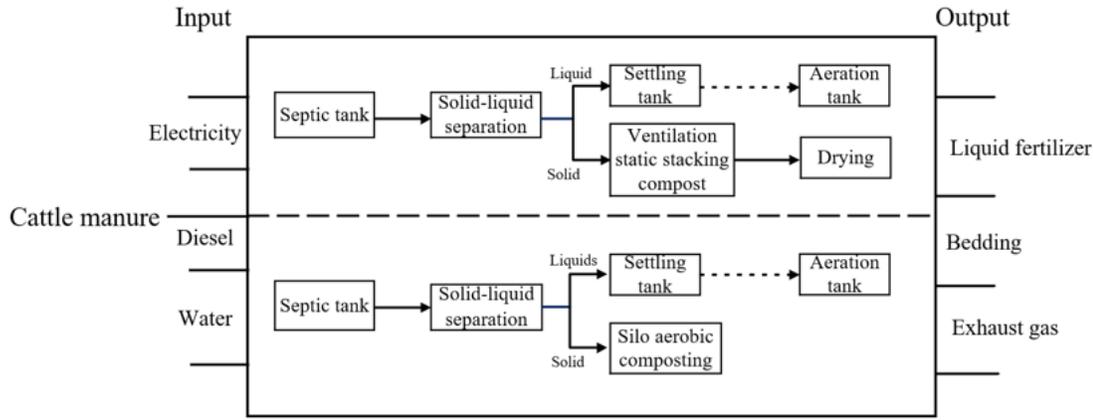


Figure 1
System boundary for life cycle assessment of two fecal regeneration bedding systems.

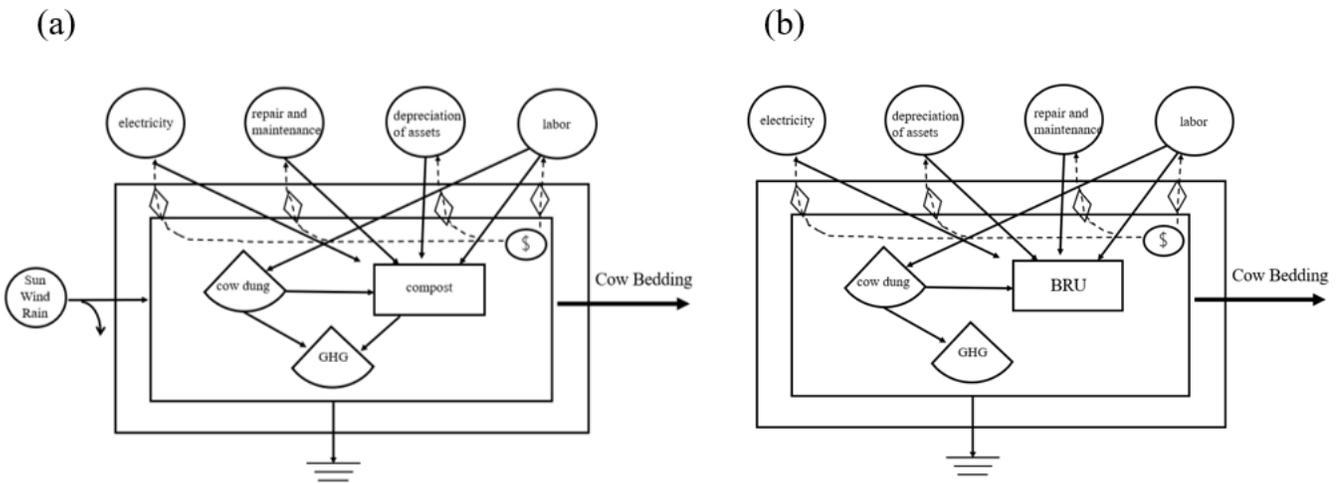


Figure 2
Aggregated energy flow diagrams of the two fecal regeneration bedding systems. (a) Forced ventilation static stack regeneration bedding system, (b) Bedding recovery unit system.

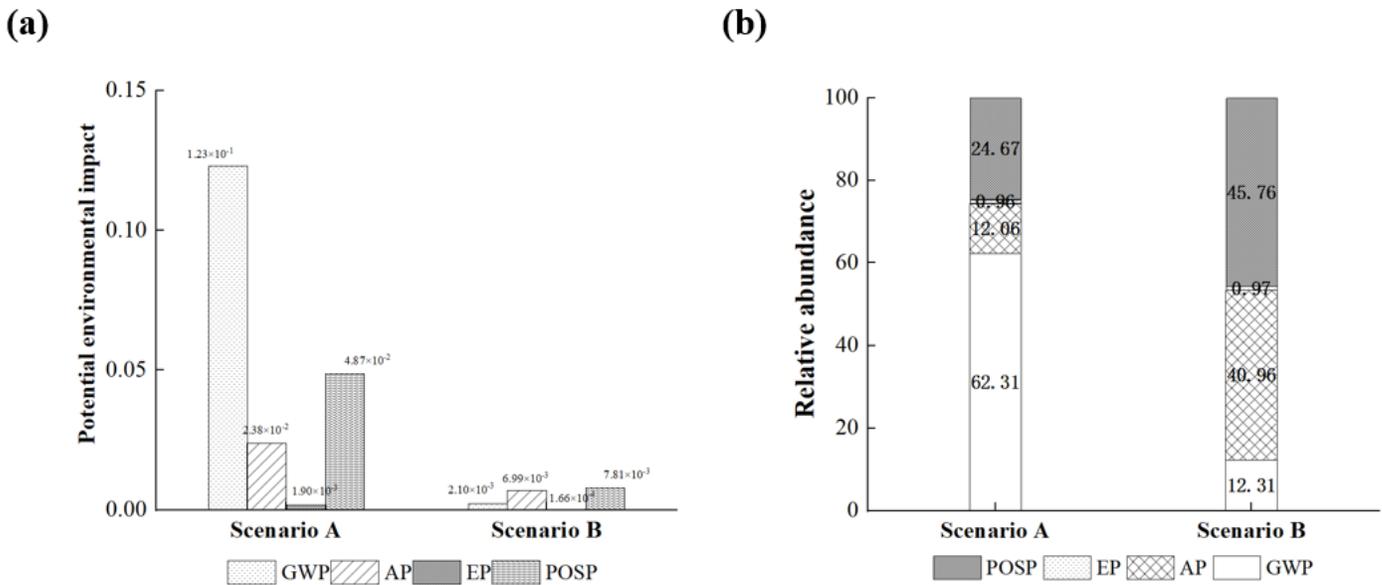
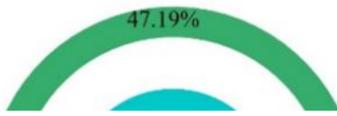


Figure 3

Potential results of environmental impact of the two scenarios. (a) potential distribution of environmental impact of the two scenarios, (b) relative richness of environmental impact potential of the two scenarios.

(a)



(b)

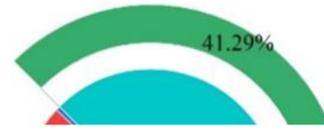


Figure 4

Energy flow diagrams of the two fecal regeneration bedding systems (%). (a) Energy flow for the forced ventilation static stack regeneration bedding system, and (b) Energy flow for the bedding recovery unit system.

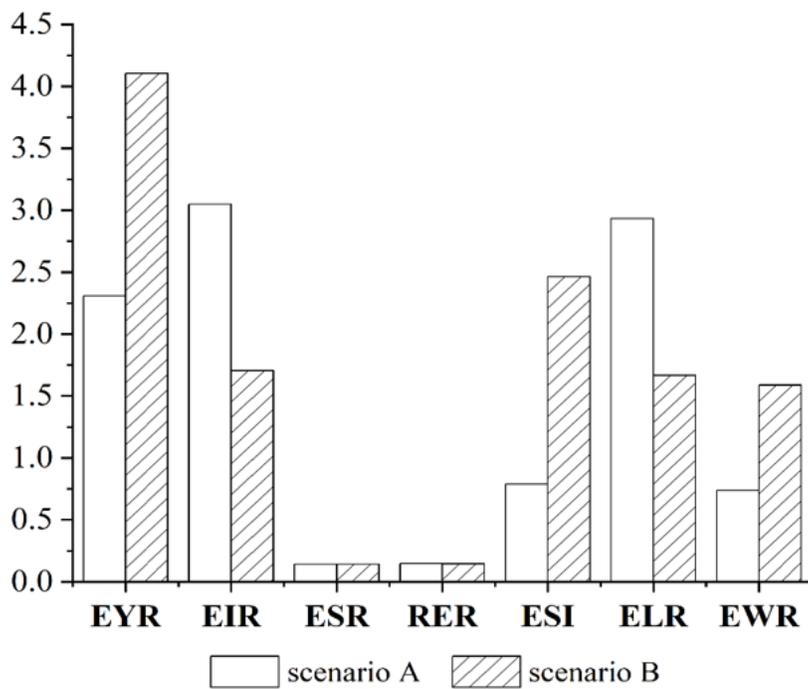


Figure 5

Comparative analysis of the energy indices of the two fecal regeneration bedding systems

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