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Carbon footprint assessment of a whole dairy farming system with a biogas plant and the use of solid fraction of digestate as a recycled bedding material

Akira Setoguchi [a,*], Kazato Oishi [a], Yoshiaki Kimura [b], Akifumi Ogino [c], Hajime Kumagai [a], Hiroyuki Hirooka [a]

[a] *Laboratory of Animal Husbandry Resources, Division of Applied Biosciences, Graduate School of Agriculture, Kyoto University, Kyoto 606-8502, Japan*
[b] *Hokkaido Research Organization, Hokkaido 060-0619, Japan*
[c] *Institute of Livestock and Grassland Science, National Agriculture and Food Research Organization, Ibaraki 305-0901, Japan*

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ABSTRACT

Biogas generated from livestock manure is a renewable energy source and the digestate is used as a fertilizer. Moreover, dewatered biogas digestate can be used as a bedding material (recycled bedding material). The aims of the present study were to model a whole dairy system with a biogas plant using recycled bedding material and to assess the life cycle greenhouse gas (GHG) emissions. Emissions from the material flow of dairy cattle production, manure treatment and organic fertilizer application to on-farm crops were evaluated. In the emissions from organic fertilizer storage and recycled bedding material production, CH_4 emission was decreased by 43.0%, and consequently the system with a biogas plant reduced total GHG emissions by 6.8% compared with conventional slurry storage and straw bedding. The use of recycled bedding material from a biogas plant has the potential to create a resource cycle and to be beneficial as a GHG mitigation strategy.

1. Introduction

As global climate change has become an increasingly serious threat in recent years, industries worldwide are required to develop climate change mitigation technologies. The Paris Agreement (United Nations Framework Convention on Climate Change (UNFCCC) 2015) signed at the Conference of the Parties (COP21) set the goal "to hold the increase in global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C." Gerber et al. (2013) reported that livestock production accounted for 14.5% of human-induced greenhouse gas (GHG) emissions, and Springmann et al. (2018) estimated that GHG emissions from food production systems would increase by 87% between 2010 and 2050 in the absence of mitigation measures, with most of the increase being attributed to animal production. Therefore, the introduction of mitigation strategies in livestock production systems plays an important role in climate change policies.

It has been suggested that the introduction of biogas plants is one of the most promising strategies for climate change mitigation. Utilizing a biogas plant for livestock manure treatment reduces GHG emissions by recovering the methane (CH_4) gas emitted from the waste and using it as a source for renewable energy production (Holm-Nielsen et al., 2009; Burg et al., 2018). Moreover, the digestate produced from the anaerobic biogas process has several benefits: it emits less nitrous oxide (N_2O) than raw slurry after field application (Amon et al., 2006; Chantigny et al., 2007) and helps reduce odor, pathogens, and weed seed germination in animal manure (Yiridoe et al., 2009; Massé et al., 2011). The digestate serves not only as a nutrient-rich organic fertilizer, but can also be reused as a bedding material after dewatering and composting (termed "recycled bedding material") (Kimura et al., 2020). The use of dairy waste solids (or manure solids) as a bedding material for cattle has been examined since the 1970s (Leach et al., 2015). Risk of mastitis due to the use of recycled bedding material from a biogas plant is considered to be very low because mastitis-causing pathogens are significantly reduced in the process of composting (Okamoto et al., 2018).

Life cycle assessment (LCA) is a standard method for evaluating environmental impacts from all processes in a production system, including material exploitation, transport, and disposal (International Organization for Standardization 2006). Numerous studies have assessed the environmental impacts of livestock production systems

* Corresponding author.
E-mail address: setoguchi.akira.i33@kyoto-u.jp (A. Setoguchi).

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(Ogino et al., 2008; Pelletier 2008; Veysset et al., 2010; Oishi et al., 2013; Turner et al., 2022) and several mitigation strategies, such as low-protein diet feeding in swine (Ogino et al., 2013; Garcia-Launay et al., 2014) and the use of additives during manure composting (Cao et al., 2019). While some studies have evaluated the environmental impacts of biogas plants themselves through LCA (Esteves et al., 2019), to our knowledge, there have been no studies evaluating the environmental impacts of the use of recycled bedding material in dairy production systems. Therefore, the objectives of the present study were to model a whole dairy farming system with a biogas plant producing recycled bedding material and to conduct a cradle to farm gate assessment comparing the GHG emissions of this alternative system to those of a conventional system with slurry storage and straw bedding.

2. Methods

2.1. Description of the dairy production system in the present study

The first step in LCA is to define the goal and scope of the analysis and the system boundaries. The goal was to evaluate the GHG emissions of a whole dairy farming system including a biogas plant and recycled manure solids for bedding (recycled bedding material). Conducting a cradle to farm gate assessment with an attributional approach, two scenarios for manure treatment were designed. The system analyzed in the present study is outlined in Fig. 1. The production system was modeled based on a representative dairy farm with 250 lactating cows in northern Japan. The system boundary encompassed the whole dairy production system integrating all processes from upstream of farm production until the products leaving the farm gate. The products in the dairy system were milk, surplus calves, culled cows and electricity generated in the biogas plant. The production processes included feed production, feed transportation, animal housing, manure treatment, and enteric fermentation. As upstream resources, emissions from intermediate consumption of production of purchased feed and straw bedding material were also considered. Manure excreted by the dairy cattle was processed and applied to on-farm crop fields as organic fertilizers. The emissions derived from manure processing were calculated based on the material flow through three sections: dairy cattle production, manure treatment, and organic fertilizer application to on-farm crops. These sections are described in detail below.

2.1.1. Dairy cattle production

Considering the dairy herd structure shown in Fig. 2, we evaluated outputs from the dairy cattle production system on a herd basis. All calves and culled cows were assumed to be shipped out from the system, except for female calves to be reared as replacement heifers. Production parameters of dairy cows in the present study are shown in Table 1. Heifers were assumed to deliver calves at 27 months of age and continue calving up to six times with a calving interval of 425 days and a culling rate of 19.6% at the end of every lactation. The weight change was set to be linear before weaning and follow Richards growth curve (Richards 1959) after weaning, as reported in the Japanese Feeding Standard for Dairy Cattle (National Agriculture and Food Research Organization (NARO) 2017). Daily milk yields were calculated according to Wood's lactation curve (Wood 1967). Annual milk yield was set to 9,967 kg/head based on an interview with a representative local farmer, and other lactation curve parameters were set based on a previous study in Japanese dairy cows (Choumei et al., 2006). Daily feed intake of the dairy cattle was estimated based on dry matter intake (DMI) or the total digestible nutrient (TDN) requirement according to the Japanese Feeding Standard for Dairy Cattle (NARO 2017) with the change in feed compositions taken into account. Detailed calculations of growth,

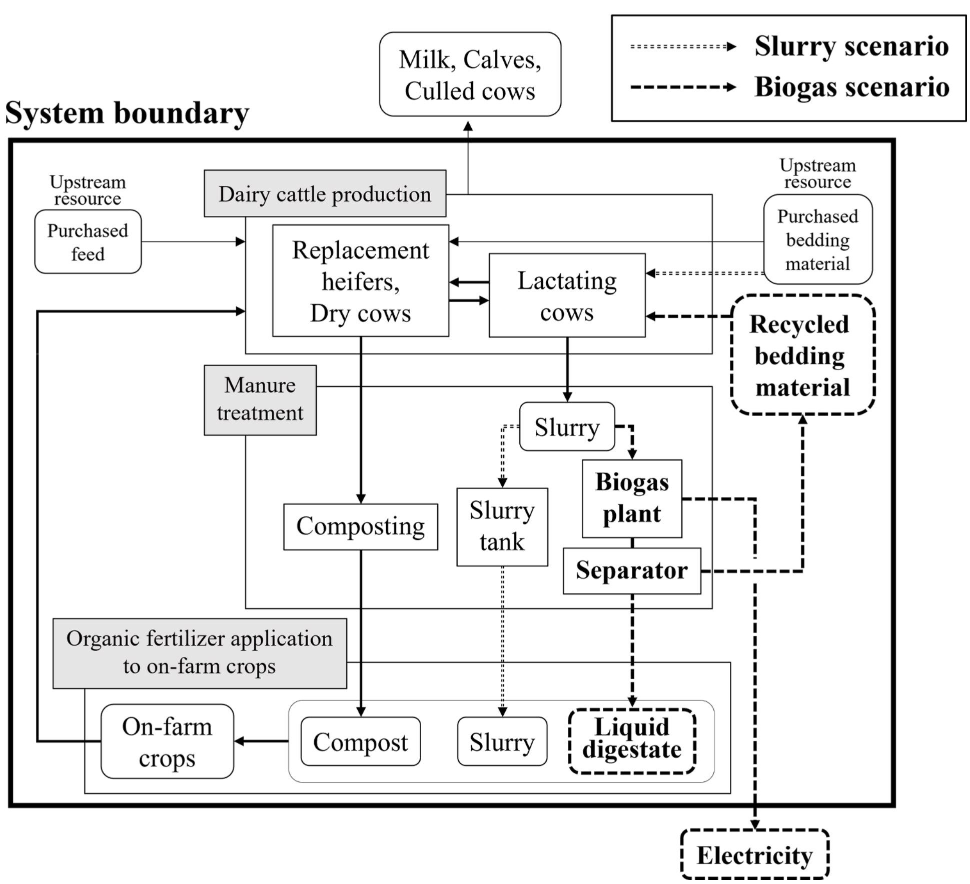

Fig. 1. Outline of the dairy farming system in the present study. The thin and bold arrows indicate unidirectional flows and the recycling flow of the system, respectively. The dotted arrows indicate the flow in case of the implementation of a biogas plant (Biogas scenario).

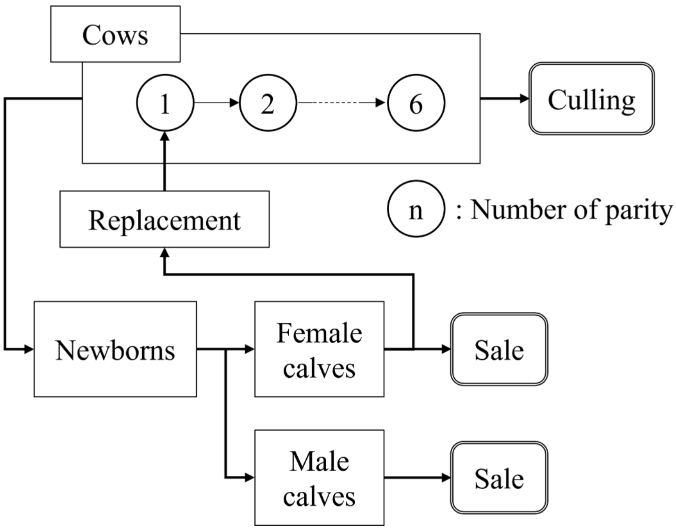

Fig. 2. Outline of the herd structure of the dairy system in the present study.

Table 1
Production parameters of dairy cows in the present study.

Parameters	Values
Birth weight	43 kg
Mature weight	700 kg
Total annual milk yield	9967 kg
Parameters for Wood's lactation curve	
B	0.147
C	0.028
Fat content of milk	3.92%
Protein content of milk	3.25%
Gestation length	280 days
Weaning age	45 days
Age at first mating	486 days
Culling rate	19.60%
Maximum number of parities	6

lactation, and nutrient requirements are presented in Appendix A of the Supplementary Materials.

Diet composition is presented in Table 2. Nutrient contents were determined referring to the Standard Tables of Feed Composition in Japan (NARO 2010). The crude protein (CP) content of the conventional diet (Cont) for lactating cows was set to 17% on a dry matter basis. As Lee et al. (2012) reported that feeding a low-protein diet with amino acids reduced the level of nitrogen excreted and GHG emissions from lactating cows, the scenario of feeding a low-protein diet containing a rumen-protected amino acid was additionally considered in the present study. The CP content of the low-protein diet (LowCP) was set to 14% and rumen-protected methionine (RPMet) was added as a limiting amino acid. As Lee et al. (2015) reported that milk yield and quality could be maintained by feeding rumen-protected amino acid even with the setting of CP content of 13.7 DM%, cows fed the LowCP diet were assumed to maintain the productivity level of cows fed Cont diet; i.e., it was assumed that growth, milk production, and reproductive performance of dairy cows were equivalent between the two diets' scenarios. Both diets were designed to supply equal amounts of digestible methionine to the small intestine as calculated based on the Nutrient Requirements of Dairy Cattle (National Research Council 2001). The methionine content, rumen bypass rate, and digestibility of RPMet were set to 85%, 80%, and 90%, respectively (Evonik Industries AG 2021). Assuming that the emission from production of RPMet with coating materials was equal to that of methionine itself, emission from the production of RPMet was set to 5.35 kg-CO_2eq/kg as the level of emission from crystalline amino acids reported by Ogino et al. (2013).

Table 2
Composition and nutrient contents of the diets assumed for cows and heifers in the present study.

	Calves	Heifers	Dry cows	Lactating cows	
				Cont	LowCP
Ingredient (%)					
Timothy hay	9.1	57.3	40.2		
Timothy silage				19.2	19.2
Corn silage		26.1	28.5	34.8	34.8
Wheat straw		2.1	20.4		
Oats hay		5.2	1.5		
Alfalfa hay cube	27.3			11.5	12.1
Maize	41.8			14.8	18.7
Nonenzymatically browned soybean meal	5.5	4.2	5.8	4.2	1.9
Soybean meal	16.4			4.0	1.8
Beet pulp				7.4	7.4
Concentrated pellet		4.7	2.9	3.9	3.9
Calcium carbonate		0.5	0.7	0.1	0.1
Salt				0.1	0.1
Chemical composition					
DM (%)	87.5	70.7	69.2	55.1	55.0
CP (%DM)	16.9	12.0	11.7	17.0	14.0
TDN (%DM)	67.7	64.5	60.6	75.5	75.5
RUP (g/kg)	–	–	–	25.2	21.1
EAA (%CP)	–	–	–	38.4	36.6
Met (%EAA)	–	–	–	3.9	4.1

Cont: conventional diet, LowCP: low-protein diet containing a rumen-protected amino acid, DM: dry matter, CP: crude protein, TDN: total digestible nutrients, RUP: ruminally undegradable protein, EAA: essential amino acids, Met: methionine.

2.1.2. *Manure treatment*

Two treatment scenarios for manure from the lactating cows were compared: slurry storage as a conventional treatment (Slurry) and treatment in a biogas plant (Biogas). Fig. 3 outlines the manure treatment processes. In the Slurry scenario, manure mixed with barley straw bedding was placed in an open slurry tank and stored for 140 days on average for spreading on-farm crop fields as slurry. In the Biogas scenario, dewatered digested manure was used as recycled bedding material in the barn. Excreted manure mixed with recycled bedding material in the barn was treated in the fermenter and the biogas produced was collected and used for power generation. After 30 days of anaerobic fermentation, the digested manure was separated into solid and liquid

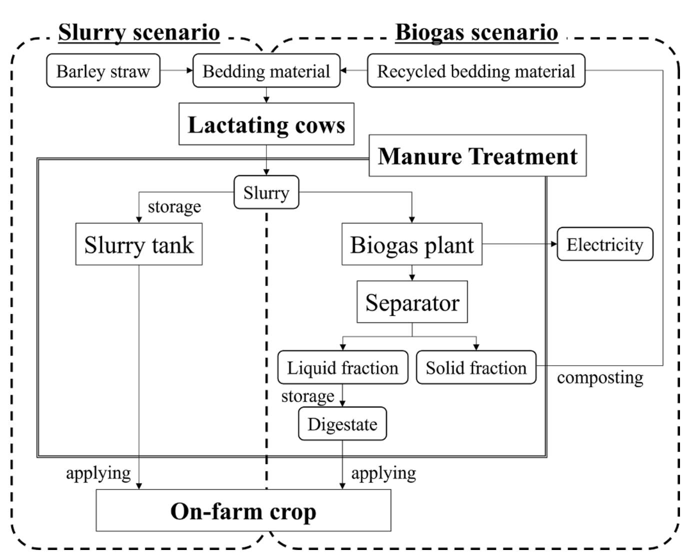

Fig. 3. Outline of the model structure of manure treatment for lactating cows using conventional slurry treatment (Slurry scenario) and with the implementation of a biogas plant (Biogas scenario).

components using a screw press separator. The solid component was piled up and composted for 9 days and then used as recycled bedding material. The liquid component was stored for 140 days on average in an open storage tank for spreading on-farm crop fields as liquid digestate. In both scenarios, manure from the replacement heifers and dry cows was composted together with their bedding barley straw introduced from outside the dairy farm. In this section, CH_4 and direct N_2O emissions and indirect N_2O emission through volatilization of ammonia (NH_3) and nitrate oxide (NO_X) were considered as organic matter and nitrogen losses. These emission factors are shown in Table 3. Since it was assumed that flowing wastewater was prevented in manure management in Japan (Ministry of the Environment, Japan (MOE) 2020), nitrogen leaching and runoff from manure facilities and indirect N_2O emission related to the leaching and run-off were not considered in this section.

2.1.3. Organic fertilizer application to on-farm crops

Timothy and corn fed to animals were produced on the farm. All organic fertilizer obtained from manure treatment was applied to on-farm crops, and chemical fertilizers were additionally applied to compensate for deficient nitrogen and phosphate. On-farm crops were applied slurry in Slurry scenario and applied liquid digestate in Biogas scenario. Table 4 shows the inputs of fertilizer for the on-farm corn production. For timothy hay and timothy silage, 29.8 kg-N/kg and 4.0 kg-P_2O_5/kg of slurry or liquid digestate were applied to the production of timothy hay and 10.4 kg-N/kg and 1.4 kg-P_2O_5/kg of slurry or liquid digestate were applied to the production of timothy silage. All remaining slurry or liquid digestate were applied to the production of corn silage as well as produced compost. The amount of chemical fertilizer application to the production of corn silage was adjusted so that the effective nitrogen and phosphate levels applied were equal to those in conventional application. The surplus slurry used to meet the amount of application was included in the calculation of emissions as it was assumed to be spread on-field. Assuming that crop yields were the same in all scenarios, yields of timothy hay, timothy silage and corn silage were set to be 14, 60, 60 tonne/ha, respectively. On-farm crop production was inventoried based on a face-to-face interview with the representative local farmer. Considering the effectiveness of the fertilizers based on Hokkaido Fertilizer Recommendations 2020 (Department of Agriculture, Hokkaido Government 2020), relative uptake ratios of both nitrogen and phosphate were calculated to be 1.0, 0.2, and 0.4 for chemical fertilizers, compost, and slurry and liquid digestate, respectively. In this section, indirect N_2O emission through volatilization of NH_3 and NO_X by fertilizer applications as well as direct N_2O emission was accounted for nitrogen losses. In addition, we evaluated indirect N_2O from nitrogen leaching and run-off, considering that 30% of nitrogen in applied fertilizer leaches and runs off (MOE 2020). The emission factors and volatilization rates mentioned above are shown in Table 3.

Table 3
Emission factors and volatilization rates associated with the dairy farming system in the present study.

Source	Coefficient	Reference
Emission factors of direct emission		
Feed production		
N_2O (kg-N_2O-N/kg-N)	0.62%[2,3]	MOE (2020)
Manure treatment		
CH_4 (kg/kg-OM)	2.36%[4], 3.03%[5], 3.80%[6]	MOE (2020)
N_2O (kg-N_2O-N/kg-N)	0.02%[4], 0.15%[5], 2.40%[6]	MOE (2020)
Emission factors of indirect emission		
N_2O (kg-N_2O-N/kg-NH_3-N+NO_X-N volatilized)[1]	1.0%	IPCC (2006)
Feed production		
N_2O (kg-N_2O-N/kg-N leaching and run-off)	0.75%	IPCC (2006)
Volatilization rates		
Feed production		
NH_3+NO_X (kg-$NH_3\_N+NO_X-N$/kg-N)[1]	10%[2], 20%[3]	IPCC (2006)
Animal housing		
NH_3+NO_X (kg-$NH_3\_N+NO_X-N$/kg-N)[1]	10.3%[7], 4.5%[8]	MOE (2020)
Manure treatment		
NH_3+NO_X (kg-$NH_3\_N+NO_X-N$/kg-N)[1]	10.8%[4,5], 13.7%[6]	MOE (2020)

[1] Volatilized ammonia and nitrate oxide were counted due to calculation of indirect N_2O emission.
[2] Chemical fertilizer.
[3] Organic fertilizer.
[4] Slurry storage.
[5] Liquid digestate storage.
[6] Compost and production of recycled bedding material.
[7] Dairy cows.
[8] Heifers and dry cows.

Table 4
Input of fertilizer applied to on-farm crop fields of corn silage (per tonne of yield).

	Chemical fertilizer		Compost		Slurry / Liquid digestate*	
	kg-N	kg-P_2O_5	kg-N	kg-P_2O_5	kg-N	kg-P_2O_5
Slurry with Cont	0.0	1.8	5.0	2.0	10.0	1.3
Slurry with LowCP	1.3	1.8	5.0	2.0	6.8	1.3
Biogas with Cont	0.5	2.0	5.0	2.0	8.6	1.2
Biogas with LowCP	2.6	2.0	5.0	2.0	3.4	1.2

For timothy hay and timothy silage, 29.8 kg-N/kg and 4.0 kg-P_2O_5/kg of slurry or liquid digestate were applied to the production of timothy hay and 10.4 kg-N/kg and 1.4 kg-P_2O_5/kg of slurry or liquid digestate were applied to the production of timothy silage. Yields of timothy hay, timothy silage and corn silage were assumed to be 14, 60, 60 tonne/ha, respectively.
Slurry scenario: the use of slurry storage in manure treatment, Biogas scenario: the implementation of a biogas plant producing recycled bedding material in manure treatment, Cont: conventional diet, LowCP: low-protein diet containing a rumen-protected amino acid.
* Values are inputs of slurry for the Slurry scenario and inputs of liquid digestate for the Biogas scenario.

2.2. Life cycle inventory

The second step in LCA is to draw an inventory of all resources and emissions related to all activities within the system boundaries of the dairy farming system.

Emissions of environmental substances from crop production and transportation processes were calculated according to the methodology practiced by Ogino et al. (2012). Emissions from production of feeds and bedding straw were determined from the inputs of materials and energy and relevant emissions (Table S1 in Supplementary Materials). Emissions from feed transportation were calculated from the percentages of major exporting countries to Japan and the transportation distances (Table S2 in Supplementary Materials). The input fertilizers for on-farm crop production were described in the previous section.

The enteric CH_4 emission from dairy cattle was calculated from daily DMI (kg/day) using the following quadratic regression equation reported by Shibata et al. (1993):

$$CH_4\ (L/day) = -17.766 + 42.793\ \times DMI - 0.849\ \times DMI^2. \quad (1)$$

The CH_4 emissions from calves were calculated as a function of weeks of age, as follows (Sekine et al., 1986):

$$CH_4\ (g/day) = 3.4\ \times (weeks\ of\ age) - 1.2. \quad (2)$$

The nitrogen content in the manure was calculated by subtracting the protein retained for growth, pregnancy, and lactation from CP intake. The organic matter content in the manure was calculated by subtracting the contents of crude ash and digestible nutrients from the dry matter content in the diets based on the Standard Tables of Feed Composition in Japan (NARO 2010).

Emissions from manure treatment were calculated by multiplying the amounts of organic matter and nitrogen in the manure by the emission factors reported in the National Greenhouse Gas Inventory Report of Japan (MOE 2020). In the Biogas scenario, power generation, recycled bedding material production, and liquid digestate storage were considered. The amount of electricity generated in the biogas plant was calculated using the following equation:

$$Electricity\ (kWh) = OM_{excrete}/1000 \times y_{biogas} \times frac_{methane} \times util_{methane} \times cal_{methane}/cal_{elec} \quad (3)$$

where $OM_{excrete}$ is the organic matter in the manure (kg), y_{biogas} is the biogas yield from the organic matter (393 m^3/t-OM) determined based on a face-to-face interview with the representative local farmer, $frac_{methane}$ is the fraction of methane gas in the biogas (60%), $util_{methane}$ is the efficiency of electricity utilization (0.25 MJ/MJ-CH_4) (New Energy and Industrial Technology Development Organization (NEDO) 2015), and $cal_{methane}$ and cal_{elec} are the calorific values of CH_4 (39.8 MJ/m^3) and electricity (3.6 MJ/kWh), respectively. The electricity generated by the biogas plant could be a substitute resource for the electricity generated by conventional power generation in Japan. Therefore, a part of the emissions from the conventional power generation was assumed to be offset by the generated electricity at the biogas plant. In the process of dewatering after fermentation in the biogas plant, the ratios of separation of the organic matter and nitrogen from the digested manure into the solid component were set to 41.7% and 25.1%, respectively. The solid component was composted to produce recycled bedding material, and the liquid component was stored and applied on-farm crop fields. Therefore, the solid component of the manure from the lactating cows was thought to be continuously circulated as a recycled bedding material and gradually decomposed and transformed into the liquid component. The emission from recycled bedding material production was calculated by multiplying the amounts of organic matter and nitrogen in the digested manure by the separation ratios into the solid component and the emission factors for composting. The contents of organic matter and nitrogen in the recycled bedding material and liquid digestate were calculated using the following equations:

$$OM_{RBM} = OM_{solid} \times \left(1 - ef_{solid_{CH_4}}\right) \quad (4)$$

$$OM_{applied} = OM_{liquid} \times \left(1 - ef_{liquid\_CH_4}\right) + OM_{RBM} \quad (5)$$

$$N_{RBM} = N_{solid} \times \left(1 - ef_{solid\_N_2O-N} - vr_{solid\_NH_3-N+NO_X-N}\right) \quad (6)$$

$$N_{applied} = N_{liquid} \times \left(1 - ef_{liquid\_N_2O-N} - vr_{liquid\_NH_3-N+NO_X-N}\right) + N_{RBM} \quad (7)$$

where OM_{RBM} is the amount of organic matter in the recycled bedding material (kg), $OM_{applied}$ is the amount of organic matter in the liquid digestate applied on-farm crop fields (kg), OM_{solid} and OM_{liquid} are the amounts of organic matter in the solid and liquid components (kg), $ef_{solid\_CH_4}$ and $ef_{liquid\_CH_4}$ are the emission factors of CH_4 from the solid and liquid components of the digested manure (kg-CH_4/kg-OM), N_{RBM} and $N_{applied}$ are the nitrogen contents in the recycled bedding material and liquid digestate (kg), N_{solid} and N_{liquid} are the nitrogen contents in the solid and liquid components (kg), $ef_{solid\_N_2O-N}$ and $ef_{liquid\_N_2O-N}$ are the emission factors of N_2O from the solid and liquid components of the digested manure (kg-N_2O−N/kg-N), and $vr_{solid\_NH_3-N+NO_X-N}$ and $vr_{liquid\_NH_3-N+NO_X-N}$ are the volatilization rates of NH_3+NO_X from the solid and liquid components of the digested manure (kg-NH_3−N+NO_X−N/kg-N), respectively. Values for these emission factors and volatilization rates are shown in Table 3.

Energy consumption of the facilities for housing the cattle and manure treatment was considered as the energy required for housing, and the environmental loads were calculated from the quantities of fuel and electricity used (Agriculture, Forestry and Fisheries Technology Information Society 2000; Hishinuma et al., 2002). The amount of the consumption of fuel and electricity is shown in Table S3 in Supplementary Materials. It was assumed that lactating cows were managed in free-stall barns with manure scraper and that the biogas plant processed 29 m^3/day with 1,160 m^3 of digester and 5,400 m^3 of storage tank.

Emissions of CO_2 from respiration and excreted manure were not accounted as GHG emissions because they were assumed to be offset by carbon fixation through photosynthesis as described by Pirlo et al. (2014) and Uddin et al. (2021). As well, emissions of CO_2 from combustion of methane at power generation was considered as carbon neutral (Paolini et al., 2018). Environmental loads associated with the production of capital goods, such as cattle barns, front loaders, the biogas plant, and the slurry tank, were not taken into account.

2.3. Life cycle impact assessment

The contribution of the dairy production system to climate change was expressed as CO_2-equivalent factors according to the Intergovernmental Panel on Climate Change (IPCC 2007): CO_2: 1, CH_4: 25, N_2O: 298, based on a time horizon of 100 years. The functional unit was defined as 1 kg of fat and protein corrected milk (FPCM) (International Dairy Federation (IDF) 2010). The amount of FPCM production was calculated using the following equation based on a milk fat percentage of 3.92% and a protein percentage of 3.25% according to the annual average value of the farm:

$$FPCM\ (kg) = (amount\ of\ milk\ (kg)) \times (0.1226 \times (milk\ fat\ percentage) + 0.0776 \times (milk\ protein\ percentage) + 0.2534) \quad (8)$$

Multiple products, including milk, surplus calves, and culled cows, were produced in the dairy farming system. Therefore, whole GHG emissions were biophysically allocated to milk production using the following allocation factor (IDF 2010):

$$Biophysical\ allocation\ factor = 1 - 6.04 \times M_{meat}/M_{milk} \quad (9)$$

where M_{meat} is the sum of live weight of all animals sold and M_{milk} is the sum of FPCM sold. The sum of live weight of surplus calves and culled cows were 6,396 kg/year and 52,500 kg/year, respectively. The total of sold FPCM was calculated to be 2,650,000 kg/year. Therefore, the percentage of environmental loads allocated to milk was calculated to be 86.6% of the total. Here, we also calculated economic allocation factor as a reference; considering the sale price of milk was determined as 100 yen/kg (about 0.83 US$/kg (120 yen/US$)) and the sale prices of male and female calves and culled cows were 128,660, 298,660, and 169,695 yen/head, respectively, the economic allocation factor was calculated to be 87.6%. Due to the similarity of the allocation factors for the dairy cattle production system, only the biophysical allocation was conducted for evaluation of GHG emissions in the present study.

2.4. Economic data of the biogas plant

In addition to the assessment of GHG emissions, a simple economic evaluation for the use of the biogas plant was conducted. Table 5 shows the parameters for the economic evaluation in the present study. All electricity generated in the biogas plant was assumed to be sold at the price of 39 yen/kWh. Assuming that the cost for the construction of a biogas plant for 250 cows was 200 million yen and its depreciation was 20 years, the annual cost was calculated to be 40,000 yen/head. The annual running cost of purchased fuels and electricity used in the biogas plant was calculated to be 10,000 yen/head. Annual cost of facility construction for slurry treatment was 28,294 yen/head (Hishinuma et al., 2008) and that of the use of fuels and electricity was 10,000

Table 5
Parameters for economic evaluation in the present study.

Items	Price	Unit
Sales price		
Milk	100	yen/kg
Electricity generated in biogas plant	39	yen/kWh
Male calf	128,660	yen/head
Female calf	298,660	yen/head
Culled cow	169,695	yen/head
Cost		
Bedding straw	14	yen/kg
Facility construction for biogas plant	40,000	yen/head/year
Facility construction for slurry treatment	28,294	yen/head/year
Purchased fuels and electricity used in biogas plant	10,000	yen/head/year
Purchased fuels and electricity used in slurry treatment	10,000	yen/head/year

(120 yen/US$).

yen/head (Hishinuma et al., 2002). In order to calculate the cost of conventional bedding materials, a price of barley straw was assumed to be 14 yen/kg.

3. Results

3.1. GHG emissions from the dairy farming system

Fig. 4 shows the GHG emissions in the two scenarios with or without the use of low-protein diet. For the dairy production systems using the Cont diet, GHG emissions were estimated to be 894 and 833 g-CO_2eq/kg-FPCM for the Slurry and Biogas scenarios, respectively. The Biogas scenario showed a 6.8% reduction in GHG emission when compared with the Slurry scenario. As for the systems using the LowCP diet, GHG emissions were 887 and 817 g-CO_2eq/kg-FPCM for the Slurry and Biogas scenarios, respectively. The LowCP diet for lactating cows reduced GHG emissions by 1.0% and 8.6% in the Slurry and Biogas scenarios when compared with the Cont diet in the Slurry scenario, respectively. Enteric fermentation, feed production, and manure treatment were large sources of GHG emission, accounting for 35.5%, 28.3%, and 21.9% of the total, respectively, on average for the four systems.

Details of the GHG emission sources are presented in Table 6.

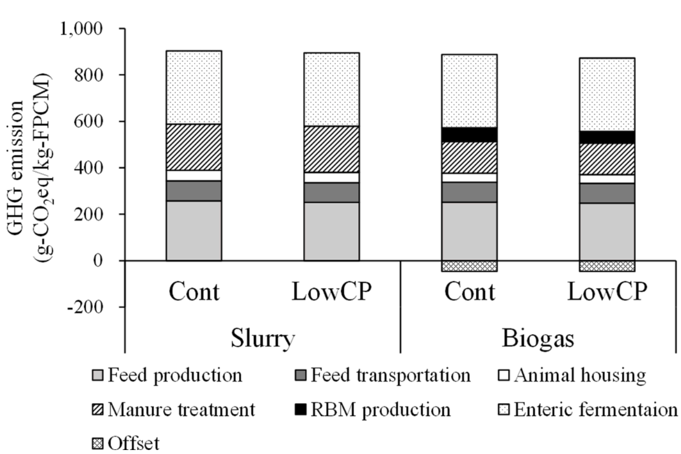

Fig. 4. GHG emissions from the dairy production system in each scenario (g-CO_2eq/kg-fat and protein corrected milk (FPCM)). Slurry: the use of slurry storage in manure treatment, Biogas: the implementation of a biogas plant producing recycled bedding material in manure treatment, Cont: conventional diet, LowCP: low-protein diet containing a rumen-protected amino acid, RBM: recycled bedding material, Offset: it is assumed that the electricity generated by the biogas plant can be a substitute resource for the electricity generated by conventional power generation, resulting in reduced emissions from the conventional power generation.

Emissions of CH_4 and CO_2 accounted for 50.9% and 28.8% of the total GHG emissions, respectively, on average for the four systems. Compared with the Slurry scenario, the Biogas scenario decreased CH_4 emission by 42.2 g-CO_2eq/kg-FPCM, but increased N_2O emission by 21.3 g-CO_2eq/kg-FPCM on average. The Biogas scenario reduced CH_4 emission from manure treatment by 28.3% on average when compared with the Slurry scenario. The Biogas scenario with the Cont and LowCP diets increased N_2O emission from manure treatment by 88.2% and 68.7% when compared with Slurry scenario with the Cont and LowCP diets, respectively. With regards to the high emission of CO_2, the dairy system in the present study consumed a large amount of imported feed, which resulted in a large CO_2 impact during feed transportation. It is one of the characteristics of countries having high dependence on imported feeds.

3.2. Nitrogen flows in the manure treatment

The annual nitrogen flows in the dairy system with 250 lactating cows are presented in Fig. 5. Dairy cows fed the Cont diet excreted 33.3 tonnes of nitrogen as slurry per year. In the Slurry scenario, slurry was stored together with straw bedding and applied to on-farm crop fields. In the processes of storage and application, 4.1 and 19.3 tonnes of nitrogen were lost as the nitrogen source for N_2O emissions, mostly indirect emissions, respectively. Because there were 3.0 tonnes of surplus nitrogen in the slurry from the cows fed a Cont diet, no chemical fertilizer was required for field application in this scenario. In the Biogas scenario with cows fed the Cont diet, nitrogen from the digestated manure in the biogas plant was separately channeled into recycled bedding material and liquid digestate at 8.4 and 24.9 tonnes, respectively. In the processes of recycled bedding material production, storage, and application, 1.3, 2.7, and 16.9 tonnes of nitrogen were lost as the nitrogen source for N_2O emissions, respectively. Feeding the LowCP diet reduced the annual nitrogen excretion by 24.6% and consequently, the nitrogen source for N_2O emissions from the on-farm crop fields were reduced by 16.9% on average. The amount of chemical fertilizer used was estimated to increase to compensate for the nitrogen deficiency in the organic fertilizer in the scenarios with the LowCP diet; the amounts of chemical fertilizer applied to the on-farm crop fields were 1.7 and 3.6 tonnes of nitrogen for the Slurry and Biogas scenarios with the LowCP diet, respectively.

3.3. Economic evaluation of the use of recycled bedding material from a biogas plant

In the present study, the annual sales of generated electricity was estimated to be 39,150 yen/head, the reduction in bedding cost was 7,730 yen/head and the increase cost of facility construction and management was 11,706 yen/head. Thus, the implementation of a biogas plant was expected to improve annual profits by 35,174 yen/head (293 US$/head).

4. Discussion

4.1. Environmental impacts of the implementation of a biogas plant

In the total emissions from organic fertilizer storage and recycled bedding material production through solid-liquid separation, CH_4 emission was decreased by 43.0% in the Biogas scenario despite the fact that only manure from lactating cows was processed into biogas whereas manure from heifers and dry cows was composted. Anaerobic fermentation and liquid-solid separation are notable features of a biogas plant producing recycled bedding material. In a biogas plant, part of the organic matter in the manure is converted to biogas, leading to a reduction in CH_4 emission during storage of digestate. Battini et al. (2014) reported a 67% reduction in CH_4 emission from stored biogas digestate compared to stored raw slurry. Moreover, solid-liquid separation reduces the amount of organic matter that enters storage, reducing CH_4 emission during storage (Fillingham et al., 2017). Guest

Table 6
Environmental impact of GHG emissions from dairy production systems (g-CO_2eq/kg-FPCM).

	Slurry						Biogas					
	Cont			LowCP			Cont			LowCP		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Feed production												
Purchased feed	105.71	2.44	54.69	101.23	2.44	58.87	105.71	2.44	54.69	101.23	2.44	58.87
On-farm crop	25.83	0.66	65.42	27.24	0.71	56.54	26.49	0.68	58.93	28.84	0.75	52.10
Amino acid				1.28						1.28		
Feed transportation	81.15	2.20	1.30	80.42	2.18	1.29	81.15	2.20	1.30	80.42	2.18	1.29
Animal housing												
Electricity and fuels	28.85	0.62	0.26	28.85	0.62	0.27	28.85	0.62	0.26	28.85	0.62	0.27
Ammonia			7.50			6.05			7.50			6.05
Straw production	3.00	0.07	4.74	3.00	0.07	4.74	0.65	0.02	0.82	0.65	0.02	0.82
Manure treatment												
Electricity and fuels	11.17	0.13	0.26	11.17	0.13	0.26	14.41	0.25	0.25	14.41	0.25	0.25
Composting		49.65	31.75		49.65	31.75		49.65	31.75		49.65	31.75
Storage		96.71	7.47		97.82	5.88		29.04	9.84		29.47	7.42
RBM production								26.02	32.47		26.40	24.51
Enteric fermentation		311.98			311.98			311.98			311.98	
Offset							−43.95	−0.40	−1.12	−44.60	−0.41	−1.14
Total	255.70	464.47	173.38	253.18	465.60	165.64	213.31	422.51	196.68	211.07	423.36	182.19

FPCM: fat and protein corrected milk, Slurry scenario: the use of slurry storage in manure treatment, Biogas scenario: the implementation of a biogas plant producing recycled bedding material in manure treatment, Cont: conventional diet, LowCP: low-protein diet containing a rumen-protected amino acid, RBM: recycled bedding material, Offset: it is assumed that the electricity generated by the biogas plant can be a substitute resource for the electricity generated by conventional power generation, resulting in reduced emissions from the conventional power generation.

et al. (2017) evaluated a dairy production system with solid-liquid separation of raw slurry for bedding use of the solid and showed that bedding use reduced CH_4 emission from manure treatment by 63% compared to storing raw slurry because of a large reduction in CH_4 emission from the liquid storage. Therefore, the implementation of a biogas plant producing recycled bedding material significantly reduces CH_4 emission due to a reduction in organic matter in the digestate through fermentation in the plant and solid-liquid separation after the fermentation. Furthermore, the use of sealed tanks for storage can prevent gas emissions into the atmosphere. For example, Battini et al. (2014) reported a further GHG reduction using a closed tank. Thus, in addition to the reduction in GHG emissions by the measures presented in this study, the use of sealed tanks has the potential to further reduce CH_4 emissions from storage.

The substitution of fossil fuels by power generation in a biogas plant is one approach to reduce GHG emissions, and further GHG emission reduction can be indirectly achieved by increasing the amount of power generated. However, compared to other agricultural residues, animal manure has a low carbon content, and biogas production from livestock manure alone is generally inefficient (Esteves et al., 2019). Therefore, changes in the quality and quantity of the recycled bedding material by using external carbon resources should be considered to enhance power generation in dairy production systems with a biogas plant. By mixing manure with industrial food waste at a 73:27 wt ratio, Ebner et al. (2015) found that GHG emission from manure treatment was reduced by 71%, including a reduction in GHG emission from disposal of the food waste. Using a mixture of livestock manure and wheat straw to maximize the production of CH_4 for a biogas plant, Wang et al. (2012) reported that the optimal carbon-nitrogen ratio in biogas production was in the range of 25:1 to 30:1 and the optimal mixture yielded an 59.2% increase in CH_4 production compared to the emissions from the individual materials. These studies pointed out that the input of external carbon resources could contribute to further GHG reduction by increasing the amount of electricity generated in a biogas plant.

Considering the material flow from feed to organic fertilizer application in the present study, the CP content of the diets influenced GHG emissions during manure treatment and on-farm crop production. Although the production of recycled bedding material is associated with high N_2O emission due to the aerobic condition, the LowCP diet reduced N_2O emission by 24.5% in manure treatment. This synergistic effect led to a 9% reduction in the total GHG emission. Thus, the flow model for the dairy farming system used in this study suggested that N_2O emission from the production of recycled bedding material can be effectively reduced when combined with a low-protein diet containing RPMet. Until now, reports on LCA analysis for livestock fed low-protein diets supplemented with amino acids have been limited. Ogino et al. (2013), evaluating the environmental impacts of fattening pigs fed low-protein diets supplemented with amino acids, showed a 20% reduction in GHG emissions during manure treatment when compared with the use of conventional diets by a reduction in excreted nitrogen and N_2O emission during manure treatment.

Although the implementation of the biogas plant showed reduction in GHG emissions in the present study, the biogas plant may increase impacts on other environmental impact categories. Bacenetti et al. (2016) assessed environmental impacts of dairy production using a biogas plant with sealed tank and reported that the use of biogas plant strongly reduced impacts on global warming, acidification and eutrophication. For the use of biogas plants producing recycled bedding materials, however, it is expected to increase impacts on acidification and eutrophication due to a large impact of nitrogen oxides emitted from production of recycled bedding material. Zilio et al. (2020) reported that liquid digestate after solid-liquid separation showed decreased organic matter as well as increased pH, indicating increase of NH_3 emission. On the other hand, Finzi et al. (2020) indicated that solid-liquid separation could prevent accumulation of nitrogen sources on the farm by the export of the surplus solid component to other farms. Considering the new resource cycling is currently under investigation, the relevant emission factors should be refined since the emission characteristics of the liquid digestate may not be similar to those of conventional digestate. To evaluate environmental impacts of biogas plant producing recycled bedding material, more comprehensive studies including investigation of the characteristics will be needed.

4.2. *Economics of the implementation of a biogas plant producing recycled bedding material in dairy farming systems*

The results of the economic analysis showed that the introduction of a biogas plant improved annual profits by 35,174 yen/head. This is equivalent to 3.2% of the average profit of Japanese dairy farmers of 1,085,852 yen/head (9,049 US$/head) (Ministry of Agriculture, Forestry and Fisheries 2022). In addition, digestate from a biogas plant produces less odor and is associated with lower levels of pathogens and

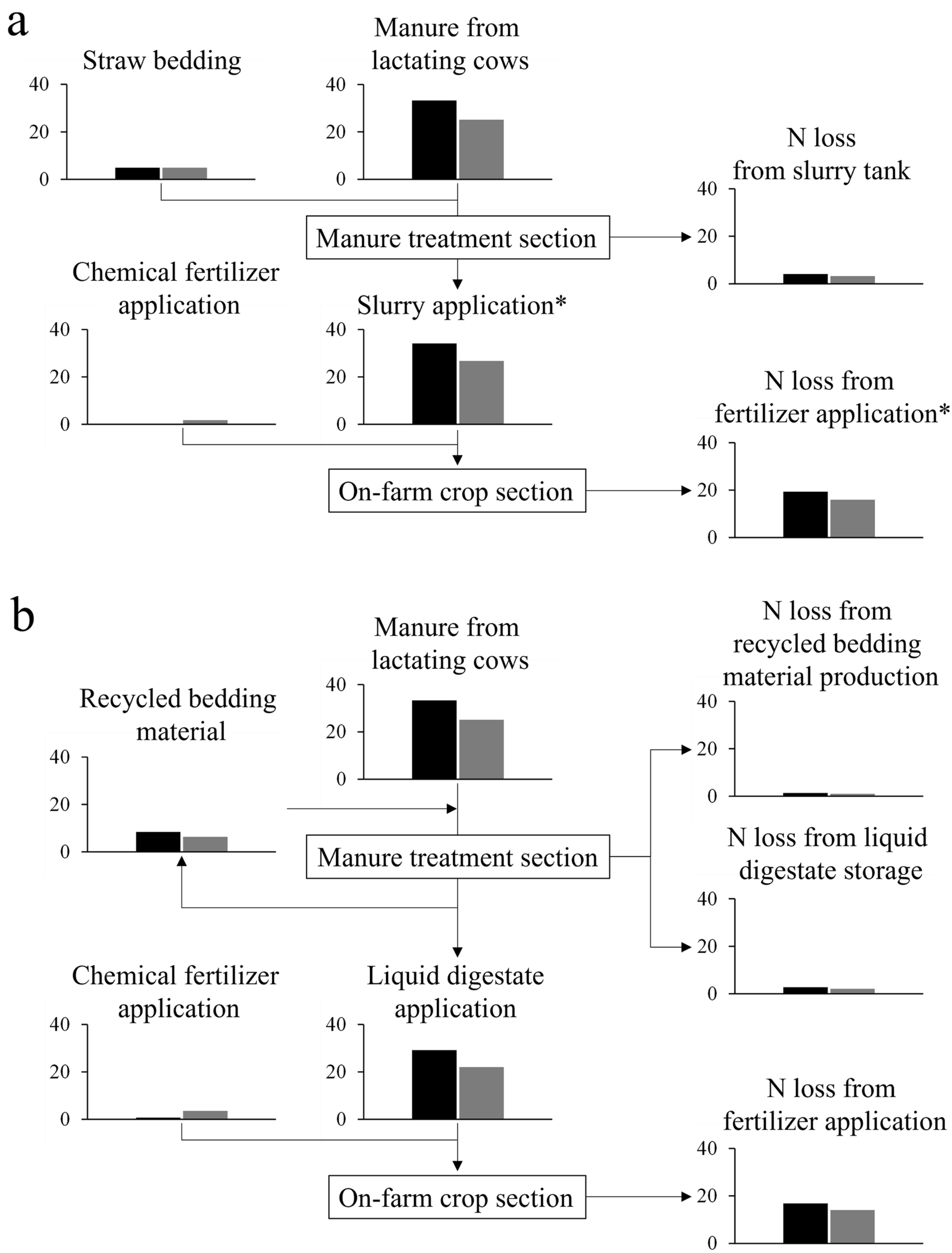

Fig. 5. Annual nitrogen flow of the dairy system with 250 lactating cows in the Slurry scenario (a) and Biogas scenario (b). Black bar: Cont (conventional diet), Gray bar: LowCP (low-protein diet containing a rumen-protected amino acid), *including 3.0 t-N/year of surplus slurry with Cont diet. The Y axis in each bar chart indicates the amount of nitrogen (t-N).

weed seed germination (Yiridoe et al., 2009), which may imply a potential to further indirectly improve the profitability of a farm.

At present, recycled bedding materials generated from biogas plants are not widely used. Farmers may wrongly assume that the characteristics of recycled bedding materials are similar to those of bedding materials from raw manure: a possibility to increase bacterial counts (Leach et al., 2015; Rowbotham and Ruegg 2015). In contrast to bedding materials from raw manure, recycled bedding materials may have lower levels of pathogens due to the composting process (Okamoto et al., 2018). To encourage farmers to use recycled bedding materials generated from biogas plant, it is essential to further inform farmers of the characteristics of recycled bedding materials.

Table 7
Annual costs related to the manure treatment with 250 lactating cows in the dairy systems (million yen).

	Slurry	Biogas	Biogas*
Facility construction of manure treatment	7.1	10.0	10.0
Fuels and electricity used in manure treatment	2.5	2.5	2.5
Bedding straw for lactating cows	1.9		
Electricity generated in biogas plant (Sales)		−9.8	−5.0
Total	11.5	2.7	7.5

(120 yen/US$).
Slurry scenario: the use of slurry storage in manure treatment, Biogas scenario: the implementation of a biogas plant producing recycled bedding material in manure treatment, *: the price of electricity generated in biogas plant assumed to be 20 yen/kWh.

In Japan, there are only about 100 biogas plants for livestock manure (NEDO 2015). Thus, there is room to increase the number of biogas plants at farms by promoting their introduction. However, the implementation of biogas plants at individual farms is generally considered to be not economically profitable, especially for small-scale farms, because of the high cost of biogas plants. Namuli et al. (2013) reported that in Quebec Province in Canada, the net present value of dairy farming systems using a biogas plant became negative when the herd size was below 80 cows. Thus, for small-scale farmers, sharing a biogas plant with neighboring farmers may be beneficial (Pukšec and Duić 2012). Moreover, Kimura et al. (2020) reported a dry type methane fermentation system that can be used in small-scale farms with tie-stall housing where conventional methane fermentation systems are not suitable. Thus, sharing biogas plants among farmers or the use of alternative fermentation systems may promote the implementation of biogas plants at farms.

It should be noted that the economic advantage of the implementation of a biogas plant largely depends on the price at which farmers can sell the electricity produced. At present, the electricity generated from biogas plants can be sold at a higher price than the purchase price of electricity in Japan due to the policy to promote the introduction of renewable energy. Table 7 shows the annual costs for 250 lactating cows in the dairy system in the present study, considering the case where the price of electricity generated in the biogas plant drops to the purchase price of conventional electricity generated from power station (20 yen/kWh). Although the use of a biogas plant is still more economically advantageous than the conventional slurry scenario even at the price of generated electricity being the same with conventional electricity, the incentive to implement a biogas plant might be reduced. Furthermore, it is considered that farmers be reluctant to investing in a biogas plant that costs several hundred million yen. Therefore, in order to incentivize dairy farmers to implement biogas plants to reduce GHG emissions, sufficient added value for the renewable energy and/or a subsidy for construction of the plant would be essential. In addition, it may be necessary to implement policies that promote on-farm consumption of the electricity to achieve sustainable production.

5. Conclusions

In the present study, recourse cycling of dairy farming system including a biogas plant producing recycled bedding material was firstly modeled to assess the GHG emissions. Implementation of a biogas plant producing recycled bedding material reduced GHG emissions by 6.8% when compared with conventional slurry treatment, which was attributed to a reduction in organic matter in the digestate through fermentation and solid-liquid separation, and the offset by the electricity generated. The emissions were further reduced when a low-protein diet containing a rumen-protected amino acid was used for feeding. The material flow showed that the low-protein diet containing a rumen-protected amino acid reduced nitrogen excretion and N_2O emission from the production of recycled bedding material by 24.5% in manure treatment. Finally, our results suggested that the biogas plant producing recycled bedding material not only reduced GHG emission, but also generated economic profits through electricity sales and saving bedding cost. To assess the environmental impacts of the use of recycled bedding materials more precisely, further studies including investigation of the emission characteristics and evaluation of other environmental impact categories will be required.

CRediT authorship contribution statement

Akira Setoguchi: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Kazato Oishi:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Yoshiaki Kimura:** Conceptualization, Investigation. **Akifumi Ogino:** Conceptualization. **Hajime Kumagai:** Writing – review & editing. **Hiroyuki Hirooka:** Writing – review & editing.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcradv.2022.200115.

References

Agriculture, Forestry and Fisheries Technology Information Society (AFFTIS), 2000. Investigation of Energy-Managing Agricultural Production System Development (in Japanese). AFFTIS, Tokyo.
Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric. Ecosyst. Environ. 112, 153–162. https://doi.org/10.1016/j.agee.2005.08.030.
Bacenetti, J., Bava, L., Zucali, M., Lovarelli, D., Sandrucci, A., Tamburini, A., Fiala, M., 2016. Anaerobic digestion and milking frequency as mitigation strategies of the environmental burden in the milk production system. Sci. Total Environ. 539, 450–459. https://doi.org/10.1016/j.scitotenv.2015.09.015.
Battini, F., Agostini, A., Boulamanti, A.K., Giuntoli, J., Amaducci, S., 2014. Mitigating the environmental impacts of milk production via anaerobic digestion of manure: case study of a dairy farm in the Po Valley. Sci. Total Environ. 481, 196–208. https://doi.org/10.1016/j.scitotenv.2014.02.038.
Burg, V., Bowman, G., Haubensak, M., Baier, U., Thees, O., 2018. Valorization of an untapped resource: energy and greenhouse gas emissions benefits of converting manure to biogas through anaerobic digestion. Resour. Conserv. Recycl. 136, 53–62. https://doi.org/10.1016/j.resconrec.2018.04.004.
Cao, Y., Wang, X., Bai, Z., Chadwick, D., Misselbrook, T., Sommer, S.G., Qin, W., Ma, L., 2019. Mitigation of ammonia, nitrous oxide and methane emissions during solid waste composting with different additives: a meta-analysis. J. Clean. Prod. 235, 626–635. https://doi.org/10.1016/j.jclepro.2019.06.288.
Chantigny, M.H., Angers, D.A., Rochette, P., Bélanger, G., Massé, D., Côté, D., 2007. Gaseous nitrogen emissions and forage nitrogen uptake on soils fertilized with raw and treated swine manure. J. Environ. Qual. 36, 1864–1872. https://doi.org/10.2134/jeq2007.0083.
Choumei, Y., Kahi, A.K., Hirooka, H., 2006. Fit of Wood's function to weekly records of milk yield, total digestible nutrient intake and body weight changes in early lactation of multiparous Holstein cows in Japan. Livest. Sci. 104, 156–164. https://doi.org/10.1016/j.livsci.2006.04.015.

Department of Agriculture, Hokkaido Government, 2020. Hokkaido Fertilizer Recommendations 2020 (In Japanese). https://www.pref.hokkaido.lg.jp/fs/5/4/4/7/0/6/9/_/V%E7%89%A7%E8%8D%89%E3%83%BB%E9%A3%BC%E6%96%99%E4%BD%9C%E7%89%A9.pdf. (accessed 18 April 2022).

Ebner, J.H., Labatut, R.A., Rankin, M.J., Pronto, J.L., Gooch, C.A., Williamson, A.A., Trabold, T.A., 2015. Lifecycle greenhouse gas analysis of an anaerobic codigestion facility processing dairy manure and industrial food waste. Environ. Sci. Technol. 49, 11199–11208. https://doi.org/10.1021/acs.est.5b01331.

Esteves, E.M.M., Herrera, A.M.N., Esteves, V.P.P., Morgado, C.do R.V., 2019. Life cycle assessment of manure biogas production: a review. J. Clean. Prod. 219, 411–423. https://doi.org/10.1016/j.jclepro.2019.02.091.

Evonik Industries AG, 2021. Rumen-protected DL-Methionine Mepron® https://animal-nutrition.evonik.com/en/products/methionine-and-derivatives/mepron (accessed 16 October 2021).

Fillingham, M.A., VanderZaag, A.C., Burtt, S., Baldé, H., Ngwabie, N.M., Smith, W., Hakami, A., Wagner-Riddle, C., Bittman, S., MacDonald, D., 2017. Greenhouse gas and ammonia emissions from production of compost bedding on a dairy farm. Waste Manag. 70, 45–52. https://doi.org/10.1016/j.wasman.2017.09.013.

Finzi, A., Mattachini, G., Lovarelli, D., Riva, E., Provolo, G., 2020. Technical, economic, and environmental assessment of a collective integrated treatment system for energy recovery and nutrient removal from livestock manure. Sustain 12, 2756. https://doi.org/10.3390/su12072756.

Garcia-Launay, F., van der Werf, H.M.G., Nguyen, T.T.H., le Tutour, L., Dourmad, J.Y., 2014. Evaluation of the environmental implications of the incorporation of feed-use amino acids in pig production using life cycle assessment. Livest. Sci. 161, 158–175. https://doi.org/10.1016/j.livsci.2013.11.027.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling Climate Change Through livestock: a Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations (FAO). https://www.fao.org/3/i3437e/i3437e00.htm (accessed 16 October 2021).

Guest, G., Smith, W., Grant, B., VanderZaag, A., Desjardins, R., McConkey, B., 2017. A comparative life cycle assessment highlighting the trade-offs of a liquid manure separator-composter in a Canadian dairy farm system. J. Clean. Prod. 143, 824–835. https://doi.org/10.1016/j.jclepro.2016.12.041.

Hishinuma, T., Hohiba, S., Morita, S., Tshukada, Y., Amano, T., 2002. Evaluation of a biogas plant on farm from the energetic point of view (in Japanese). Nogyo Shisetsu (J. Society of Agricultural Structures, Japan) 33, 45–52. https://doi.org/10.11449/sasj1971.33.45.

Hishinuma, T., Kurishima, H., Yang, C., Genchi, Y., 2008. Environmental impact of manure treatment and utilization system with biogas plant by life cycle assessment method : comparison with other systems (in Japanese). Anim. Behav. Manag. 44, 7–20. https://doi.org/10.20652/abm.44.1_7.

Holm-Nielsen, J.B., AI Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresour. Technol. 100, 5478–5484. https://doi.org/10.1016/j.biortech.2008.12.046.

Intergovernmental Panel on Climate Change (IPCC), 2006. IPCC Guidelines For National Greenhouse Gas Inventories. IPCC/IGES, Hayama, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (accessed 16 October 2021).

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate change 2007: the physical science basis. https://www.ipcc.ch/report/ar4/wg1/ (accessed 16 October 2021).

International Dairy Federation (IDF), 2010. Bulletin of the IDF No 445/2010. A common Carbon Footprint Approach For dairy. The IDF Guide to Standard Lifecycle Assessment Methodology For the Dairy Sector. International Dairy Federation, Brussels, Belgium.

International Organization for Standardization (ISO), 2006. Environmental Management – Life cycle assessment: Principles and Framework. International Organization for Standardization (ISO), Switzerland.

Kimura, Y., Suzuki, T., Yasui, S., Ishii, K., Kaziyama, T., Oishi, K., Ogino, A., Hinata, T., Hirooka, H., Osada, T., Fujita, H., 2020. Simulation of livestock biomass resource recycling and energy utilization model based on dry type methane fermentation system. IOP Conference Series: Earth Environ. Sci. 460, 012020 https://doi.org/10.1088/1755-1315/460/1/012020.

Leach, K.A., Archer, S.C., Breen, J.E., Green, M.J., Ohnstad, I.C., Tuer, S., Bradley, A.J., 2015. Recycling manure as cow bedding: potential benefits and risks for UK dairy farms. Vet. J. 206, 123–130. https://doi.org/10.1016/j.tvjl.2015.08.013.

Lee, C., Hristov, A.N., Cassidy, T.W., Heyler, K.S., Lapierre, H., Varga, G.A., de Veth, M.J., Patton, R.A., Parys, C., 2012. Rumen-protected lysine, methionine, and histidine increase milk protein yield in dairy cows fed a metabolizable protein-deficient diet. J. Dairy Sci. 95, 6042–6056. https://doi.org/10.3168/jds.2012-5581.

Lee, C., Giallongo, F., Hristov, A.N., Lapierre, H., Cassidy, T.W., Heyler, K.S., Varga, G.A., Parys, C., 2015. Effect of dietary protein level and rumen-protected amino acid supplementation on amino acid utilization for milk protein in lactating dairy cows. J. Dairy Sci. 98, 1885–1902. https://doi.org/10.3168/jds.2014-8496.

Massé, D.I., Talbot, G., Gilbert, Y., 2011. On farm biogas production: a method to reduce GHG emissions and develop more sustainable livestock operations. Anim. Feed Sci. Technol. 166–167, 436–445. https://doi.org/10.1016/j.anifeedsci.2011.04.075.

Ministry of Agriculture, Forestry and Fisheries (MAFF), 2022. Livestock production costs, survey of agricultural management statistics (in Japanese). https://www.e-stat.go.jp/stat-search/file-download?statInfId=000032183840&fileKind=0 (accessed 15 April 2022).

Ministry of the Environment (MOE), 2020. National greenhouse gas inventory report of Japan. https://www.nies.go.jp/gio/archive/nir/jqjm1000000pcibe-att/NIR-JPN-2020-v3.0_GIOweb.pdf (accessed 16 October 2021).

Namuli, R., Pillay, P., Jaumard, B., Laflamme, C.B., 2013. Threshold herd size for commercial viability of biomass waste to energy conversion systems on rural farms. Appl. Energy 108, 308–322. https://doi.org/10.1016/j.apenergy.2013.03.037.

National Agriculture and Food Research Organization (NARO), 2010. Standard Tables of Feed Composition in Japan, 2009 (in Japanese). Japan Livestock Industry Association, Tokyo.

National Agriculture and Food Research Organization (NARO), 2017. Japanese Feeding Standard For Dairy Cattle (in Japanese). Japan Livestock Industry Association, Tokyo.

National Research Council (NRC), 2001. Nutrient Requirements of Dairy cattle: 2001. National Academies Press, Washington, DC. https://doi.org/10.17226/9825.

New Energy and Industrial Technology Development Organization (NEDO), 2015. Guidebook For the Introduction of Biomass Energy (in Japanese). https://www.nedo.go.jp/library/biomass_guidebook.html (accessed 16 October 2021).

Ogino, A., Ishida, M., Ishikawa, T., Ikeguchi, A., Waki, M., Yokoyama, H., Tanaka, Y., Hirooka, H., 2008. Environmental impacts of a Japanese dairy farming system using whole-crop rice silage as evaluated by life cycle assessment. Anim. Sci. J. 79, 727–736. https://doi.org/10.1111/j.1740-0929.2008.00587.x.

Ogino, A., Ishida, M., Ohmori, H., Tanaka, Y., Yamashita, T., Yokoyama, H., Tatsugawa, K., Ijiri, S., Kawashima, T., 2012. Life cycle assessment of animal feeds prepared from liquid food residues: a case study of rice-washing water. J. Environ. Qual. 41, 1982–1988. https://doi.org/10.2134/jeq2011.0442.

Ogino, A., Osada, T., Takada, R., Takagi, T., Tsujimoto, S., Tonoue, T., Matsui, D., Katsumata, M., Yamashita, T., Tanaka, Y., 2013. Life cycle assessment of Japanese pig farming using low-protein diet supplemented with amino acids. Soil Sci. Plant Nutr. 59, 107–118. https://doi.org/10.1080/00380768.2012.730476.

Oishi, K., Kato, Y., Ogino, A., Hirooka, H., 2013. Economic and environmental impacts of changes in culling parity of cows and diet composition in Japanese beef cow–calf production systems. Agric. Syst. 115, 95–103. https://doi.org/10.1016/j.agsy.2012.09.007.

Okamoto, E., Miyanishi, H., Nakamura, A., Kobayashi, T., Kobayashi, N., Terawaki, Y., Nagahata, H., 2018. Bacteriological evaluation of composted manure solids prepared from anaerobic digested slurry for hygienic recycled bedding materials for dairy cows. Anim. Sci. J. 89, 727–732. https://doi.org/10.1111/asj.12962.

Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., Cecinato, A., 2018. Environmental impact of biogas: a short review of current knowledge. J. Environ. Sci. Health, Part A 53, 899–906. https://doi.org/10.1080/10934529.2018.1459076.

Pelletier, N., 2008. Environmental performance in the US broiler poultry sector: life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. Agric. Syst. 98, 67–73. https://doi.org/10.1016/j.agsy.2008.03.007.

Pirlo, G., Carè, S., Fantin, V., Falconi, F., Buttol, P., Terzano, G.M., Masoni, P., Pacelli, C., 2014. Factors affecting life cycle assessment of milk produced on 6 Mediterranean buffalo farms. J. Dairy Sci. 97, 6583–6593. https://doi.org/10.3168/jds.2014-8007.

Pukšec, T., Duić, N., 2012. Economic viability and geographic distribution of centralized biogas plants: case study Croatia. Clean Technol. Environ. Policy 14, 427–433. https://doi.org/10.1007/s10098-012-0460-y.

Richards, F.J., 1959. A Flexible growth function for empirical use. J. Exp. Bot. 10, 290–301. https://doi.org/10.1093/jxb/10.2.290.

Rowbotham, R.F., Ruegg, P.L., 2015. Association of bedding types with management practices and indicators of milk quality on larger Wisconsin dairy farms. J. Dairy Sci. 98, 7865–7885. https://doi.org/10.3168/jds.2015-9866.

Sekine, J., Kondo, S., Okubo, M., Asahida, Y., 1986. Estimation of methane production in 6-week-weaned calves up to 25 weeks of age (in Japanese). Jpn. J. Zootech. Sci. 57, 300–304. https://doi.org/10.2508/chikusan.57.300.

Shibata, M., Terada, F., Kurihara, M., Nishida, T., Iwasaki, K., 1993. Estimation of methane production in ruminants. Anim. Sci. Technol. 64, 790–796. https://doi.org/10.2508/chikusan.64.790.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0.

Turner, I., Heidari, D., Pelletier, N., 2022. Life cycle assessment of contemporary Canadian egg production systems during the transition from conventional cage to alternative housing systems: update and analysis of trends and conditions. Resour. Conserv. Recycl. 176, 105907 https://doi.org/10.1016/j.resconrec.2021.105907.

Uddin, M.E., Aguirre-Villegas, H.A., Larson, R.A., Wattiaux, M.A., 2021. Carbon footprint of milk from Holstein and Jersey cows fed low or high forage diet with alfalfa silage or corn silage as the main forage source. J. Clean. Prod. 298, 126720 https://doi.org/10.1016/j.jclepro.2021.126720.

United Nations Framework Convention on Climate Change (UNFCCC), 2015. Adoption of the Paris Agreement. Report No. FCCC/CP/2015/L.9/Rev.1 https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf (accessed 16 October 2021).

Veysset, P., Lherm, M., Bébin, D., 2010. Energy consumption, greenhouse gas emissions and economic performance assessments in French Charolais suckler cattle farms: model-based analysis and forecasts. Agric. Syst. 103, 41–50. https://doi.org/10.1016/j.agsy.2009.08.005.

Wang, X., Yang, G., Feng, Y., Ren, G., Han, X., 2012. Optimizing feeding composition and carbon–nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw. Bioresour. Technol. 120, 78–83. https://doi.org/10.1016/j.biortech.2012.06.058.

Wood, P.D.P., 1967. Algebraic model of the lactation curve in cattle. Nature 216, 164–165. https://doi.org/10.1038/216164a0.

Yiridoe, E.K., Gordon, R., Brown, B.B., 2009. Nonmarket cobenefits and economic feasibility of on-farm biogas energy production. Energy Policy 37, 1170–1179. https://doi.org/10.1016/j.enpol.2008.11.018.

Zilio, M., Orzi, V., Chiodini, M.E., Riva, C., Acutis, M., Boccasile, G., Adani, F., 2020. Evaluation of ammonia and odour emissions from animal slurry and digestate storage in the Po Valley (Italy). Waste Manag 103, 296–304. https://doi.org/10.1016/j.wasman.2019.12.038.