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Environmental performance of smallholder dairy farming systems under different levels of technology adoption

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ABSTRACT

Smallholder dairy farming is essential to milk production and rural livelihoods in Indonesia; however, its environmental performance under different levels of technology adoption remains insufficiently quantified. This study aimed to quantify the global warming potential (GWP), acidification, and eutrophication of smallholder dairy farms in Central Java, compare these impacts among technology-adoption categories, and identify production inputs associated with environmental hotspots. A cradle-to-farm-gate life cycle assessment (LCA) was conducted using 1 kg of fresh milk at the farm gate as the functional unit. Primary data were collected from 40 Friesian Holstein dairy farms through field observations, farmer interviews, farm records, and measurements of daily farm activities. Farms were classified into five categories: no selected technology (Category I); using forage chopper (Category II); forage chopper and milking machine (Category III); using biogas (Category IV); and an integrated system combining a forage chopper, milking machine, and biogas (Category V). Environmental impacts were assessed using OpenLCA 2.5, the CML-IA baseline method, and the Ecoinvent 3.10 background database. Data were analyzed using one-way ANOVA, Games-Howell post hoc tests, and multiple linear regression. The mean impacts were 1.94 ± 0.82 kg CO_2-eq, 0.0073 ± 0.003 kg SO_2-eq, and 0.0160 ± 0.008 kg PO_4^{3-}-eq per kg milk for GWP, acidification, and eutrophication, respectively. The category V produced the lowest impacts, at 1.16 ± 0.25 kg CO_2-eq, 0.0042 ± 0.0010 kg SO_2-eq, and 0.0095 ± 0.0023 kg PO_4^{3-}-eq per kg milk. Biogas adoption alone did not provide the lowest environmental burdens. Concentrate, direct emissions, and detergent use were significantly associated with all three impact categories. In conclusion, integrated technology adoption improves environmental performance more effectively than stand-alone interventions. Policymakers and dairy cooperatives should promote integrated technology packages alongside combines feed efficiency, improved manure management, biogas utilization, and use of environmentally preferable detergents, technical support for smallholders' dairy farmers.

Keywords: milk; global warming potential; acidification; eutrophication; life cycle assessment.

INTRODUCTION

Dairy farming plays an important role in supplying animal protein and supporting rural livelihoods in developing countries (Duncan et al., 2013). As a developing country, in Indonesian around 98% dairy cows' population are concentrated in Java Island, namely West Java, East Java, Central Java and Yogyakarta province (Asmarasari et al., 2023). Smallholder dairy farms are dominants type of dairy farming, an important component of the regional milk production system, particularly through the rearing of Friesian Holstein cattle under diverse management

conditions. In Central Java, the farmers average 51 years old and dominantly with low education, they owned 4-7 cows per farm and land 0.5 to 1 hectare, and milk production 9-15 liters cow/day (Kusumastuti et al., 2024). With the limited availability of land, dairy farmers rely heavily on input of concentrates and by-products to supplement the limited home-grown forage, beside that the farmers usually discharge manure directly into the environment, losing valuable nutrients and polluting water resources (Apdini et al., 2024).

Farming activity to produce milk can generate environmental burdens using feed, water, energy, fuel, fertilizer, and sanitation materials, as well as through emissions from animals and manure. Smallholder dairy farm in Indonesia vary in herd size, feeding practices, technology adoption, manure handling, and milk productivity, which may influence both production efficiency and environmental performance. Methane (CH_4) is mainly produced from enteric fermentation and manure management, while nitrous oxide (N_2O) may originate from manure and nitrogen fertilizer use (FAO, 2023). Poor manure and wastewater management may also increase pollutant. Manure from dairy farms is a significant source of pollution of the Citarum river in West Java, Indonesia (Djuwita et al., 2021). The nitrogen and phosphorus losses to soil and water, thereby contributing to eutrophication, while ammonia volatilization and other acidifying emissions may contribute to acidification potential (de Vries and de Boer, 2010; Hristov et al., 2019). The smallholder dairy farmer in West Java resulted in emission of global warming potential, acidification, and eutrophication were 1.61 kg CO_2eq, 0.03 kg SO_2eq, and 0.03 kg $PO4^{3-}$eq (Brilianty et al., 2016).

Life cycle assessment (LCA) is widely used to evaluate environmental impacts of livestock products across defined system boundaries. In dairy systems, LCA enables the integration of upstream and on-farm processes, including feed production, energy use, fertilizer use, enteric fermentation, manure management, and direct farm emissions (de Vries and de Boer, 2010). Among the most frequently assessed environmental impact categories in milk production LCA studies are global warming potential (GWP), acidification, and eutrophication (Cruz-Rivero et al., 2025). Environmental impacts of dairy production are strongly influenced by productivity, feed efficiency, fossil energy use, and manure management (Veltman et al., 2021). In smallholder systems, these factors are highly heterogeneous because farmers differ in capital availability, access to technology, knowledge, and local resource conditions. The cow feeding forage using small-scale technologies, such as a chopper for chopping the forage, could increase milk production and change the quantity and characteristics of manure compared with the cow feeding forage without chopping (Fischer et al. 2018). Using a milking machine could improve milking efficiency and biogas digesters could facilitate manure utilization (Romanuik et al. 2020). However, their environmental benefits may depend on whether they are adopted individually or integrated within the whole production system (FAO, 2023; Lei et al., 2024).

Research regarding LCA of dairy farming in Indonesia has been conducted by Taufiq et al. (2016) however, their study only compared smallholder farms with large-scale (modern) farms. Their findings indicated that the Global warming potential (GWP), acidification, and eutrophication of smallholder farms were higher than those of modern farms. Another study by Apdini et al. (2021) examined greenhouse gas emissions (GHG) from smallholder dairy farms in Indonesia, focused solely on seasonal effects by comparing the dry and rainy seasons. Globally, the study related to LCA on smallholder dairy farm has also been widely carried out, Bartl et al. (2011) who studying LCA to comparing smallholder dairy farming system in highland and coastal area in Peru. Garg et al. (2016) who studying to explore the carbon footprint of milk production under the multi-functional smallholder dairy system in western India. Rogers-Montoya et al. (2026) who studying LCA to comparing two system feeding management in smallholder dairy farming in Mexico. Although LCA has been widely applied to dairy production, evidence from developing countries in smallholder dairy systems remains limited, particularly regarding how different levels of technology practices affect GWP, acidification, and eutrophication per unit of fresh milk. The effect of using mechanization technology in smallholder dairy farm has been reported by Hadiana et al (2019), however only focused on herd size and labor efficiency. Information on how technology used in smallholder farming methods affects the environment is still lacking worldwide. The present study addresses this applied evidence gap by comparing farms with no selected technology, forage chopping, forage chopping plus machine milking, biogas, and an integrated package of all three technologies. Its

novelty lies in the side-by-side assessment of these configurations under one functional unit and modelling framework, particularly the comparison between stand-alone biogas adoption and integrated technology use. The study does not propose a new LCA method or a new scientific theory; rather, it provides context-specific empirical evidence that may support technology targeting and hypothesis generation for larger confirmatory studies.

Therefore, the objectives of this study were to quantify the GWP, acidification, and eutrophication potential of smallholder dairy farms in Central Java and compare environmental impacts among technology adoption categories and identify production inputs associated with environmental hot spots. The findings are expected to provide scientific evidence for improving environmental management in smallholder dairy farms and supporting mitigation strategies for more sustainable dairy production systems in Indonesia.

METHODOLOGY

Study area and research design

This study evaluated the environmental performance of smallholder dairy farm with different technology adoption in Central Java, Indonesia, with specific focus on global warming potential, acidification, and eutrophication. Field data were collected from October to December 2025 from smallholder dairy farms located in several districts and municipalities in Central Java Province, Indonesia. The surveyed farms were classified into five technology adoption categories as shown in Figure 1: Category I, farms without selected technologies (without mechanization and the discharge of manure directly into the environment); Category II, farms using forage choppers (mechanization for feeding preparation, however without mechanization for milking activity and discharge of manure directly into the environment); Category III, farms using forage choppers and milking machines (mechanization for feeding preparation and milking activity, however discharge of manure directly into the environment); Category IV, farms using biogas technology (without mechanization for feeding preparation and milking activity, however the farm has a tank digester was used to produce biogas from manure) ; and Category V, farms integrating forage choppers, milking machines, and biogas technology (a farm has mechanization for feeding preparation and milking activity and has a tank digester that was used to produce biogas from manure).

A quantitative survey approach was combined with direct field observation and LCA. The

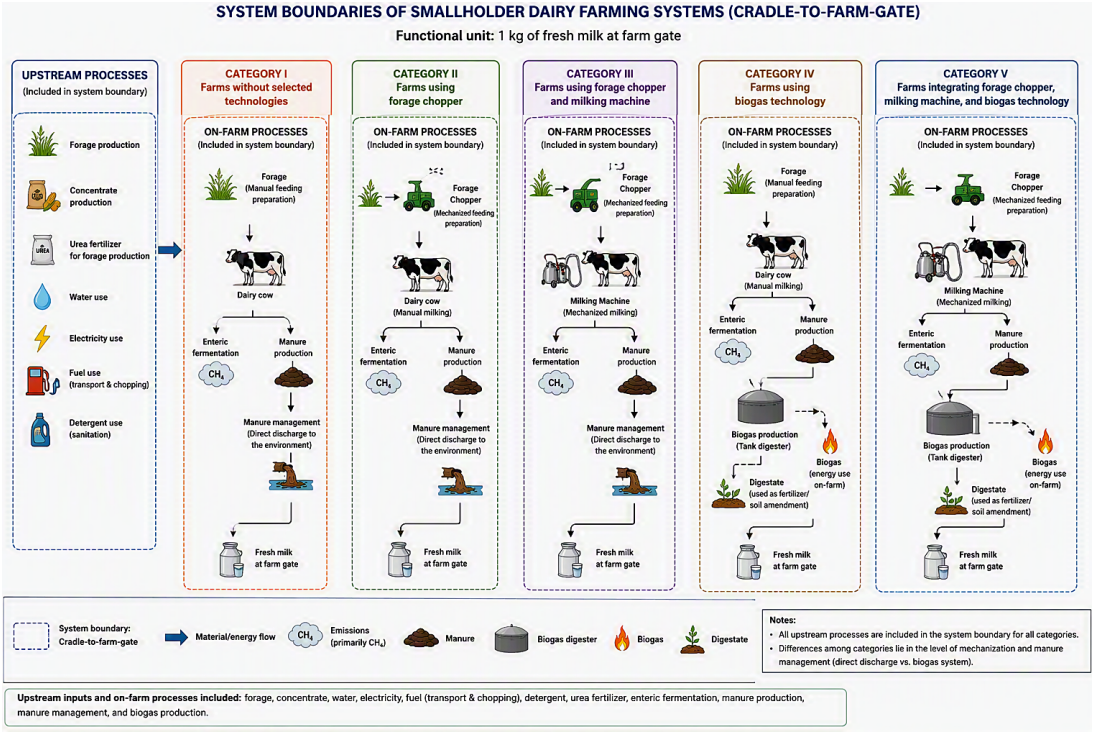


Figure 1. Designer system boundaries

assessment was conducted using a cradle-to-farm gate system boundary and 1 kg of fresh milk at farm gate as the functional unit. Life cycle impact assessment was performed using OpenLCA 2.5 with the CML-IA baseline method and the Ecoinvent 3.10 background database. The ecoinvent database provides broad life cycle inventory datasets across multiple sectors and is available for LCA modelling in OpenLCA (Ecoinvent, 2023). All input flows, output flows, emissions, and environmental impact values were normalized to this functional unit, except herd size and daily milk production, which were reported as farm-level characteristics.

Farm selection and classification

The study involved 40 smallholder dairy farms raising Friesian Holstein dairy cow in Central Java. Farm selection was conducted using a combination of cluster sampling and purposive sampling (Table 1). First, districts and municipalities were grouped into three clusters based on the Friesian Holstein dairy cattle population reported by Badan Pusat Statistik (2023): high population, more than 10,000 heads; medium population, 1,000 to 10,000 heads; and low population, fewer than 1,000 heads.

Within the selected districts or municipalities, farms were selected purposively based on three criteria: the farm had been operating for at least three years, the cattle raised were Friesian Holstein dairy cow, and the farm had at least three lactating cows in the second or later lactation. The farms surveyed were in Boyolali, Semarang Regency, Salatiga City, Klaten, Semarang City, Magelang, and Wonosobo, with a total of 515 cattle across 40 farms.

System boundary and functional unit

The system boundary was defined as cradle-to-farm-gate. The boundary included upstream and on-farm processes associated with fresh milk production, including forage production, concentrate use, water use, electricity use, fuel use for forage transport and chopping, detergent use for sanitation, urea fertilizer use for forage production, enteric fermentation, manure production, manure management, and biogas production.

Post-farm gate processes were excluded, including milk collection, transportation to processing facilities, milk processing, packaging, retail, consumption, and post-consumption waste treatment. Capital goods, such as buildings, machinery manufacture, long-term equipment, and road infrastructure, were also excluded because of limited farm-level data availability and their relatively small contribution per kg of milk in smallholder dairy systems.

The functional unit was defined as 1 kg of fresh milk at farm gate. Milk production was recorded as daily fresh milk output. When milk volume was recorded in litres, it was converted into kilograms using milk density data. All inventory flows and environmental impacts were expressed per 1 kg fresh milk at the farm gate.

Data collection and life cycle inventory

Primary data were collected through direct field observation, farmer interviews, farm records, and measurement of daily farm activities. Data collection included feed use, water use, electricity consumption, fuel consumption, detergent use, forage land area, urea fertilizer use, milk production, manure production, technology adoption, and

Table 1. Distribution of surveyed smallholder dairy farms in Central Java

Cluster	District or municipality	Number of farms	Number of cattle	Category				
				I	II	III	IV	V
High population, >10,000 heads	Boyolali	19	263	5	4	3	2	5
High population, >10,000 heads	Semarang Regency	6	50	4	1	0	1	0
Medium population, 1000 to 10,000 heads	Salatiga City	2	13	1	1	0	0	0
Medium population, 1000 to 10,000 heads	Klaten	6	61	3	3	0	0	0
Low population, <1000 heads	Semarang City	3	34	1	1	0	1	0
Low population, <1000 heads	Magelang	1	12	1	0	0	0	0
Low population, <1000 heads	Wonosobo	3	82	0	2	1	0	0
Total		40	515	15	12	4	4	5

waste management practices. Daily variables, including feed use, water use, electricity use, milk production, and manure production, were observed for one week on each farm and averaged to obtain representative daily values. Annual variables, including fuel use, detergent use, forage land area, and urea fertilizer use, were obtained from farmer interviews and farm records, then converted into daily values and normalized to milk production.

Forage and concentrate use were determined by weighing the total amount of feed offered per day during the observation period. The average daily feed use was divided by total daily milk production to obtain feed use per kg of milk. Water use included drinking water and sanitation water and was expressed as L/kg milk. Electricity use was calculated from the electricity consumption of farm equipment and expressed as kWh per kg of milk. Fuel use included fuel used for forage transport and forage chopping and was expressed as L/kg milk. Detergent use was calculated from annual detergent consumption, converted into daily use, and divided by daily milk production. Urea fertilizer use was expressed as kg/kg milk throughout the analysis. Milk production was measured daily during the observation period. Manure production was measured from total manure collected during morning and afternoon cleaning activities and expressed per kg milk. The data collected and the inventory data are presented in Supplementary 1.

Emission estimation and biogas potential

Direct greenhouse gas emissions were estimated using IPCC Tier 1 approaches (IPCC, 2026). Methane emissions from enteric fermentation were calculated using an emission factor of 68 kg CH_4/head/year. Methane emissions from manure management were calculated using an emission factor of 31 kg CH_4/head/year. Both enteric and manure CH_4 emissions were divided by annual milk production to obtain kg CH_4/kg milk. Nitrous oxide emissions from manure management were estimated based on nitrogen excretion, body weight, and the IPCC emission factor of 0.002 kg N_2O-N/kg N excreted. The resulting N_2O-N value was converted into N_2O using the molecular weight ratio of 44/28 and then normalized to milk production.

Emissions from fuel use were estimated from fuel consumption, net calorific value, fuel density, and IPCC emission factors. The emission factors used were 74,100 kg CO_2/TJ, 3.0 kg CH_4/TJ, and 0.6 kg N_2O/TJ. Fuel-derived emissions were expressed per kg fresh milk. Emissions from urea fertilizer use included CO_2 from urea hydrolysis and direct and indirect N_2O emissions from nitrogen application. CO_2 emissions were estimated using the carbon content of urea and the molecular conversion factor from carbon to CO_2. N_2O emissions were estimated based on nitrogen content, direct emission factors, volatilization fraction, and molecular conversion from N_2O-N to N_2O. The emissions measurements protocol is presented in Supplementary 2.

Biogas production was estimated from manure production, dry matter content, volatile solid content, and biogas yield coefficient. Manure dry matter was assumed to be 20%, while volatile solids were calculated as 75 to 85% of dry matter. Biogas potential was estimated using a coefficient of 0.25 m^3/kg volatile solids. LPG substitution potential was estimated using an equivalence factor of 0.46 kg LPG/m^3 biogas according to Purnomo and Yusriadi (2023). In this study, LPG substitution from biogas was treated as a potential energy recovery indicator. The LPG substitution value was reported separately to indicate the potential contribution of biogas to renewable energy use at the farm level.

Life cycle impact assessment

Life cycle impact assessment was performed using OpenLCA 2.5 with the CML-IA baseline method. The background inventory database used in OpenLCA was Ecoinvent 3.10 background database, while foreground data were obtained from farm-level measurements, direct observations, farmer interviews, and farm records. The selected impact categories were: global warming potential, expressed as kg CO_2-eq/kg fresh milk; acidification potential, expressed as kg SO_2-eq/kg fresh milk; and eutrophication potential, expressed as kg PO_4^{3-}-eq/kg fresh milk. All impact values were calculated per 1 kg fresh milk at farm gate.

The GWP category incorporated greenhouse gas emissions from enteric fermentation, manure management, fuel use, electricity use, and urea fertilizer use. Acidification and eutrophication were characterized by using the CML-IA baseline method based on the relevant elementary flows available in the LCA inventory. Because direct measurements of NH_3, NOx, SO_2, nutrient runoff, and leaching were not conducted, acidification

and eutrophication results were interpreted as modelled impact potentials based on the inventory structure and characterization factors used in the LCA model. The workflow of OpenLCA Calculation Process is presented Supplementary 2.

Statistical and sensitivity analysis

Statistical analyses were performed at SPSS 27. Separate one-way ANOVA compared the five technology categories for GWP, acidification, and eutrophication. Normality was assessed from residual diagnostics and homogeneity using an appropriate equal-variance test. Because group sizes differed and equal variances could not always be assumed, Games-Howell pairwise comparisons were used. The result statistical analysis is presented in Supplementary 3.

The sensitivity analysis was conducted to evaluate the robustness and reliability of the LCA results. A one-factor-at-a-time sensitivity analysis was performed to assess the influence of inventory input uncertainties on environmental impact estimates. Each input parameter was individually varied by −40%, −20%, +20%, and +40% from the baseline value, while all remaining parameters were maintained at their original levels. The evaluated parameters comprised forage, concentrate feed, water, electricity, fuel, detergent, and fertilizer use. For each scenario, environmental impacts were recalculated using the same system boundary and impact assessment methodology as the baseline analysis. Changes in global warming potential (GWP), acidification potential, and eutrophication potential were subsequently compared with baseline values to identify the most influential parameters affecting the LCA results. The result sensitivity analysis is presented in Supplementary 4.

RESULTS AND DISCUSSION

Smallholder dairy farms characteristics and life cycle inventory

The smallholder dairy farms evaluated in this study differed considerably in herd size, milk production, input use, manure generation, emission intensity, and level of technology adoption (Table 2). The number of lactating cows ranged from 4.20 to 15.25 heads, while daily milk production ranged from 57.03 to 205.40 kg per farm. Our findings in this study were like the study reported by Ariningsih et al. (2022) who reported in West Java, Indonesia, the farmer have 6-10 dairy cows with the milk production per farm 40 – 60 kg fresh milk per day.

Forage was the dominant feed input, ranging from 2.73 to 3.23 kg/kg milk, while concentrate use ranged from 0.36 to 1.17 kg/kg milk.

Table 2. Smallholder dairy farm characteristics and life cycle inventory among categories

Variable	Cat. I	Cat. II	Cat. III	Cat. IV	Cat. V
Number of farms, unit	15	12	4	4	5
Lactating cows, head	4.20 ±1.8	7.17 ±2.59	15.25 ±10.34	8.00 ±5.42	8.60 ±5.37
Milk production, kg/day	57.03 ±38.15	89.18 ±44.27	205.40 ±144.51	97.57 ±72.38	129.40 ±66.89
Forage, kg/kg milk	2.82 ±1.17	3.00 ±1.75	3.10 ±1.11	3.23 ±0.92	2.73 ±1.17
Concentrate, kg/kg milk	0.85 ±0.47	0.62 ±0.22	0.73 ±0.27	1.17 ±0.37	0.36 ±0.13
Water, L/kg milk	6.47 ±5.75	8.82 ±5.14	11.83 ±8.97	8.20 ±4.07	9.88 ±3.90
Fuel for transport, L/kg milk	0.013 ±0.0092	0.011 ±0.0071	0.0087 ±0.0057	0.0080±0.0029	0.0080 ±0.0013
Fuel for chopper machine, L/kg milk	-	0.0054 ±0.0034	0.0048 ±0.0039	-	0.0071 ±0.0031
Electricity, kWh/kg milk	0.113	0.132	0.117	0.077	0.060
Manure, kg/kg milk	2.39	2.41	1.86	1.24	1.48
CO_2, kg/kg milk	0.0373	0.0540	0.0414	0.0229	0.0435
CH_4, kg/kg milk	0.0064	0.0040	0.0027	0.0038	0.0026
N_2O, kg/kg milk	0.000040	0.000096	0.000066	0.000024	0.000017
Biogas, m^3/kg milk	-	-	-	0.0897	0.0591
LPG substitution potential, kg/kg milk	-	-	-	0.0413	0.0272

Note: Herd size and milk production are presented as farm-level averages, while other flows are expressed per 1 kg fresh milk at farm gate.

This study was similar to the study reported by Al-Zahra et al (2020) who reported on farm-level feed compositions and nutrient utilization in Indonesian smallholders, forage forms the main bulk of dry matter intake, while supplemental concentrate efficiency varies greatly across management tiers each farm. Category V had the lowest concentrate use, at 0.36 kg/kg milk, indicating a more efficient feed-use pattern than the other categories. The lower concentrate use in Category V may reflect better ration management, improved forage processing, or higher efficiency in converting feed into milk. This is important because concentrate use was later identified as a significant predictor of GWP, acidification, and eutrophication (Salvador et al., 2016).

Water use ranged from 6.47 to 11.83 L/kg milk. This finding was similar with the study reported by Murphy et al. (2017) who evaluated global water footprints in dairy farming and noted that on-farm water use in small-to-medium systems generally ranges from 5 to 15 L/kg milk, largely dictated by sanitation routines rather than herd size alone. while electricity consumption ranged from 0.060 to 0.132 kWh/kg milk. Category V showed the lowest electricity use, whereas Category II had the highest electricity consumption per kg milk. These differences indicate that technology adoption does not automatically increase energy demand per unit of milk. Instead, the effect of technology depends on how efficiently equipment is used and how well it is integrated into the overall production system. Shine et al. (2020) analyzed energy efficiency across different levels of technology adoption in dairy farms. They concluded that higher technology adoption only leads to higher energy efficiency per liter of milk when utilization rates are high (e.g., milking machines operating at full animal capacity), whereas underutilized machinery increases electricity consumption per kg of milk.

Manure production ranged from 1.24 to 2.41 kg/kg milk. The lowest manure output was observed in Category IV, whereas the highest value was recorded in Category II. Manure excretion was related to the dry matter intake of the cow and the composition of the feed, the highest forage intake the highest manure excretion (Weiss et al., 2007). The result from this study was lower compared than the study reported by Leip et al. (2019) who reported in dairy cow in Brazil resulted 2.89 kg manure/kg milk. Category I had the highest value of CH_4, CO_2, and N_2O per milk production, while Category V had the lowest value. This pattern suggests that integrated technology adoption may reduce emission intensity per kg milk through combined improvements in feed management, productivity, and manure utilization. This interpretation is consistent with the concept that productivity gains can reduce emission intensity per unit of dairy products (Gerber et al., 2011).

Effects of technology adoption and waste management on environmental impacts

The results of one-way ANOVA followed by Games-Howell post hoc tests showed significant differences in GWP, acidification, and eutrophication among technology categories (Table 3). The lowest environmental impact is Category V compared to Category I and IV, then Category II and III was similar with Category I, IV and V (P>0,05).

This finding indicates that integrated technology adoption can improve environmental performance more effectively than partial technology adoption. The better performance of Category V may be attributed to the combined effects of improved feed processing, more efficient milking management, lower electricity use, lower concentrate use, reduced CH_4 and N_2O intensity, and energy recovery from manure through biogas. Thus, substantive reductions in environmental footprints

Table 3. Environmental impacts of smallholder dairy systems by technology adoption level

Farm system category	GWP, kg CO_2-eq/kg milk	Acidification, kg SO_2-eq/kg milk	Eutrophication, kg PO_4^{3-}-eq/kg milk
Category I	2.38 ± 0.96^{a}	0.0089 ± 0.0037^{a}	0.0201 ± 0.0094^{a}
Category II	1.69 ± 0.60^{ab}	0.0064 ± 0.0021^{ab}	0.0139 ± 0.0047^{ab}
Category III	1.60 ± 0.69^{ab}	0.0062 ± 0.0024^{ab}	0.0119 ± 0.0054^{ab}
Category IV	2.33 ± 0.34^{a}	0.0092 ± 0.0015^{a}	0.0174 ± 0.0032^{a}
Category V	1.16 ± 0.25^{b}	0.0042 ± 0.0010^{b}	0.0095 ± 0.0023^{b}
Average	1.94 ± 0.82	0.0073 ± 0.003	0.0160 ± 0.008

Note: Different superscript letters within the same column indicate significant differences among farm categories at $P < 0.05$.

in small dairy farms require the adoption of full integration of technology (Liu et al., 2023).

Category I, without technology, had the highest GWP and eutrophication potential. This can be attributed to lower productivity, higher CH_4 intensity, and less efficient resource use. Without improved feed processing or manure valorization, emissions and nutrient losses become more concentrated per kg of milk. This confirms that conventional smallholder systems may have higher environmental intensity when productivity and input efficiency remain low. This high environmental intensity stems from low animal productivity combined with unmitigated enteric and manure emissions, confirming that unmechanized smallholder farms are constrained by resource inefficiency per unit of output (Knapp et al., 2014; Poore & Nemecek, 2018).

Category IV, which adopted biogas technology alone, did not show the lowest environmental impacts and was not significantly different from Category I based on environmental impact. This is an important finding because it indicates that manure-based biogas should not be treated as a stand-alone solution. Although biogas can capture part of manure-derived methane and support renewable energy use, its overall life-cycle benefits are frequently undermined by low feedstock quality, poor digester efficiency, fugitive CH_4 leakage, or improper slurry management (Vu., 2014). Without concurrent improvements in feed efficiency and milk yield, single-component waste treatment delivers minor net benefits (Chuenchart et al., 2024).

Categories II and III showed intermediate impact values. The use of forage chopper and milking machines may improve operational efficiency, but these technologies alone may not fully address manure-derived emissions and nutrient losses. This explains why partial technology adoption did not always produce significant reductions compared with the conventional system (Kumar and Doan, 2025).

Our study demonstrates that environmental mitigation in smallholder dairy farming requires a systems approach. Improving a single component, such as feed processing or manure treatment, may produce limited benefits if other components remain inefficient. The lowest environmental impacts were achieved when feed management, milking efficiency, and manure valorization were combined in one integrated production system.

Effects of production inputs on environmental impacts

Sensitivity analysis was conducted to evaluate the robustness and reliability of the LCA results. The sensitivity analysis demonstrated that input of concentrate feed, detergent use, and direct emissions were the principal contributors driving variations in environmental impacts across all assessed impact categories. Concentrate feed exerted a stronger influence in Categories III and IV, whereas detergent use and direct emissions showed comparable contributions in Categories I, II, and V. The observed sensitivity patterns indicate that changes in these dominant contributors resulted in substantially greater variations in GWP than those associated with electricity consumption, or water use (Figure 2).

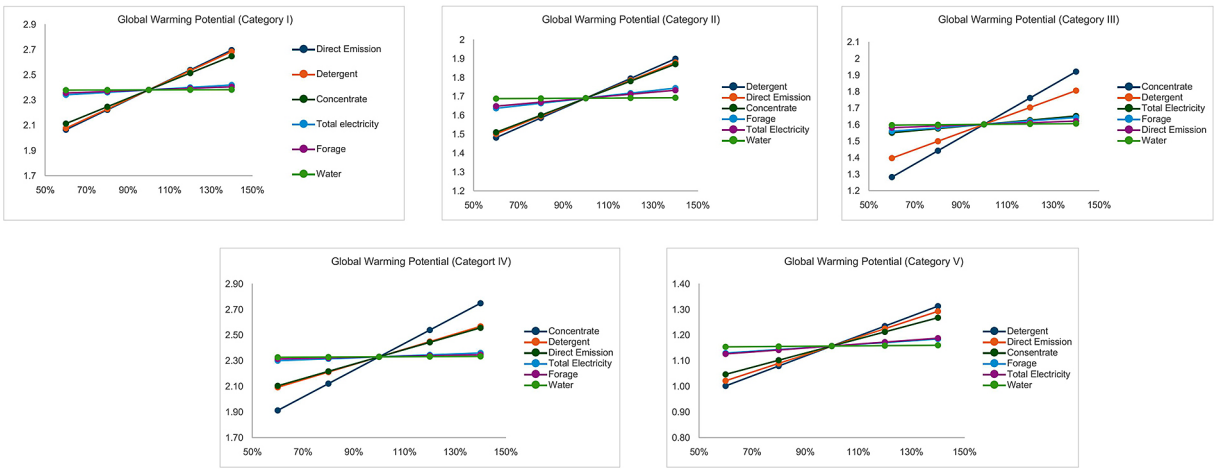


Figure 2. Global warming potential sensitivity analysis

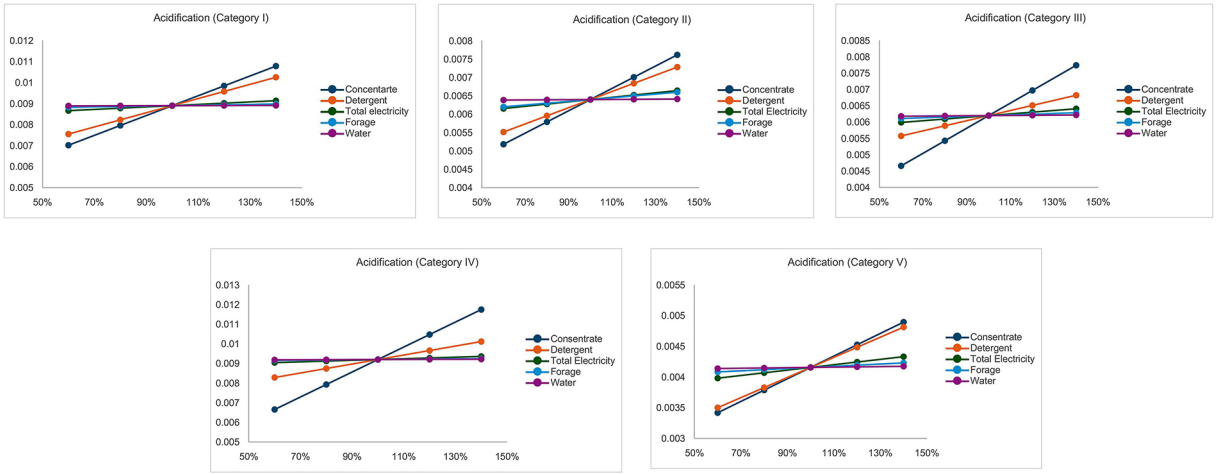


Figure 3. Acidification sensitivity analysis

In the acidification impact (Figure 3), concentrate feed was consistently identified as the dominant hotspot, accounting for the largest proportion of total impacts across all categories. Detergent use represented the second most influential contributor, while the contributions of electricity, water, and forage remained comparatively limited. In contrast, eutrophication impact (Figure 4) was largely driven by detergent use in all categories and consistently emerged as the most sensitive inventory flow. This dominance underscores the importance of cleaning practices and wastewater-related emissions in shaping eutrophication outcomes.

Concentrate, direct emissions, and detergent were significantly associated with all three environmental impact categories. Concentrate showed tended to increase GWP, acidification and eutrophication. This may be explained by upstream burdens associated with concentrate production, including crop cultivation, fertilizer application, processing, and transport. In addition, excessive nutrient intake from concentrate may increase nitrogen and phosphorus excretion through feces and urine, thereby increasing eutrophication and acidification potential (Sabia et al., 2020).

Direct emissions were among the major contributors to the Global Warming Potential (GWP) is expected because direct emissions from livestock systems specifically ruminant's animal are primarily composed of methane (CH_4) and nitrous oxide (N_2O), two greenhouse gases with substantially higher global warming potentials than carbon dioxide on a mass basis. Methane is mainly generated through enteric fermentation in ruminants, whereas nitrous oxide is released from manure management and nitrogen transformation

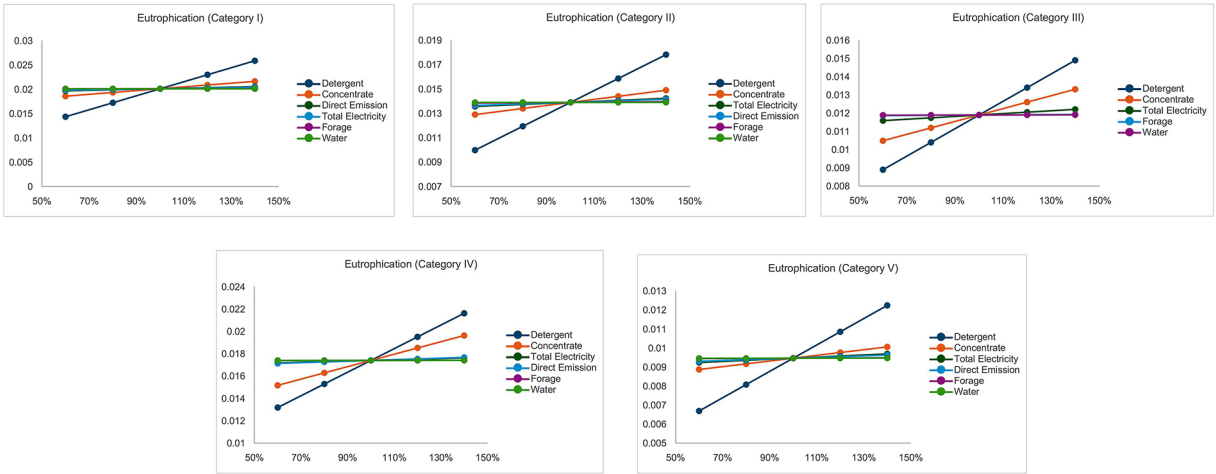


Figure 4. Eutrophication sensitivity analysis

processes within the production system (Beachemin et al., 2022)

Detergent may contribute directly to environmental burdens through production, transport, and wastewater discharge (Rattanaphra, 2025). Detergent use may also be a stand-in for the farm, how often cows are milked, how often sanitation is done, or how often milking equipment is used. Therefore, further inventory refinement is needed to distinguish the direct environmental contribution of detergent from its correlation with overall production intensity.

Overall, the sensitivity analysis identified concentrate feed, detergent use, and direct emissions as the main environmental hot spots within the production system. Therefore, mitigation strategies targeting concentrate feed optimization, direct emission reduction, and the use of environmentally preferable cleaning agents are likely to yield the greatest improvements in overall environmental performance.

Mitigation implications

The findings indicate that mitigation strategies for smallholder dairy production should prioritize integrated improvements in feed management, direct-emission control, manure utilization, and farm sanitation rather than relying on stand-alone technologies. Farms integrating forage chopping, machine milking, and biogas utilization (Category V) could reduce 50% of environmental impacts per kg of milk compared to a dairy farm with biogas adoption alone (Category IV) did not consistently provide the lowest impacts. The sensitivity analysis further identified impact-specific environmental hotspots, with concentrate feed being particularly influential for GWP and acidification, direct emissions contributing substantially to GWP, and detergent use strongly influencing eutrophication. Accordingly, mitigation measures should focus on improving feed-use efficiency and concentrate utilization, reducing enteric and manure-derived emissions, strengthening manure recovery and nutrient recycling, and improving sanitation and wastewater management. These findings emphasize that environmental improvements are more likely to be achieved when technological interventions are combined with improvements in overall farm-resource efficiency.

From a policy perspective, technology-support programs should shift from promoting individual technologies toward context-specific integrated mitigation packages. Government agencies, dairy cooperatives, and extension services should facilitate access to appropriate technologies, including forage choppers and anaerobic digesters, while simultaneously providing technical assistance for feed optimization, manure management, efficient sanitation, and proper operation and maintenance of the technologies. Financial instruments such as targeted subsidies, low-interest credit, or cooperative-based investment schemes could prioritize farms adopting combinations of practices that address the environmental hotspots identified in this study. Nevertheless, because the observed differences among farm categories represent associations rather than definitive causal effects of adoption of technology, policy implementation should be accompanied by farm-level monitoring of productivity, input efficiency, emissions, and nutrient losses. Such an approach would enable technology-support programs to be progressively refined based on their demonstrated environmental effectiveness under smallholder dairy farming conditions.

The empirical necessity of this dual strategy is well-supported by the previous study that was reported from other countries. In example study by Jiang et al (2018) who reported that decreasing mechanization for decreasing particle size of forage could increase digestibility of feed and milk yield. Physical processing such as chopping the forage could decrease the enteric methane emissions from dairy cow (Knapp et al., 2014). Furthermore, utilizing local agro-industrial by-products instead of imported concentrates significantly shortens supply chains, cutting transport-related fossil energy demand (Udo et al., 2011). The study by Ngeno (2024) reported in Kenya when the small-scale dairy farmers are encouraged to adopt technology intensively, it will have a positive impact on their income.

Given the capital constraints of smallholder operations, key stakeholders including government bodies, non-governmental organizations, and dairy farm cooperatives should provide targeted financial and technical assistance. Specifically, subsidizing forage choppers and anaerobic digesters would accelerate the transition toward low-emission, highly efficient smallholder dairy production.

CONCLUSIONS

Smallholder dairy systems in Indonesia play a significant role in both milk yields and rural socioeconomic well-being, but little is known about how technology adoption affects their environmental impact. This study demonstrated that the environmental performance of smallholder dairy farms in Central Java, Indonesia varied according to technology adoption. Integrated technology adoption, such as farming technology combining forage chopper, milking machine, and biogas technology, showed the lowest environmental impacts across all categories. In contrast, biogas adoption alone did not produce the lowest impact values, indicating that single-technology intervention is insufficient to improve environmental performance. Concentrate use, direct emissions, and detergent use were identified as key production inputs associated with environmental impact. Overall, improving the sustainability of smallholder dairy farms requires an integrated mitigation strategy that combines feed efficiency, improved manure management, biogas utilization, and use of environmentally preferable cleaning agents. Future studies should include larger and more balanced samples, and direct emission measurements.

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REFERENCES

1. Al-Zahra, W., van Middelaar, C. E., Oosting, S. J., & de Boer, I. J. (2024). Nutrient imbalances of smallholder dairy farming systems in Indonesia: The relevance of manure management. *Agricultural Systems*, *218*, 103961. https://doi-org.proxy.undip.ac.id/10.1016/j.agsy.2024.103961
2. Apdini, T., Al Zahra, W., Oosting, S. J., De Boer, I. J., De Vries, M., Engel, B., & Van Middelaar, C. E. (2021). Understanding variability in greenhouse gas emission estimates of smallholder dairy farms in Indonesia. *The International Journal of Life Cycle Assessment*, *26*(6), 1160-1176. https://doi.org/10.1007/s11367-021-01923-z
3. Apdini, T., van Middelaar, C. E., & Oosting, S. J. (2024). Developing sustainable dairy farms in the tropics: From policy to practice. *Agricultural Systems*, *220*, 104097. https://doi.org/10.1016/j.agsy.2024.104097
4. Ariningsih, E., Erwidodo, Riski Irawan, A., & Purwati Saliem, H. (2022). Dairy cattle manure utilization by smallholder dairy farmers in West Java, Indonesia. *E3S Web of Conferences*. https://doi.org/10.1051/e3sconf%2F202236103013
5. Asmarasari, S. A., Azizah, N., Sutikno, S., Puastuti, W., Amir, A., Praharani, L., Rusdiana, S., Hidayat, C., Hafid, A., Kusumaningrum, D.A., Saputra, F., Chalip, T., Herliantika, A., Shiddiieqy, M.I., & Hayanti, S. Y. (2023). A review of dairy cattle heat stress mitigation in Indonesia. *Veterinary World*, *16*(5), 1098. https://doi.org/10.14202/vetworld.2023.1098-1108
6. Bartl, K., Gómez, C. A., & Nemecek, T. (2011). Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru. *Journal of Cleaner Production*, *19*(13), 1494-1505. https://doi-org.proxy.undip.ac.id/10.1016/j.jclepro.2011.04.010
7. Beauchemin, K. A., Ungerfeld, E. M., Abdalla, A. L., Alvarez, C., Arndt, C., Becquet, P., Benchaar, C., Berndt, A., Mauricio, R.M., McAllister, T.A., Oyhantçabal, W., Salami, S.A., Shalloo, L., Sun, Y., Tricarico, J., Uwizeye, A., De Camillis, C., Bernoux, M., Robinson, T., & Kebreab, E. (2022). Invited review: Current enteric methane mitigation options. *Journal of Dairy Science*, *105*(12), 9297-9326.
8. Brilianty, S. L., Suprihatin, S., & Purwoko, P. (2022). Penilaian daur hidup produk susu sapi segar: studi kasus di KPBS Pangalengan. *Jurnal Teknologi Industri Pertanian*, *32*(3), 220-228. (In Indonesian).
9. Chuenchart, W., Timilsina, A. P., Ge, J., & Shah, A. (2024). Advances in biorefinery of cattle manure for value-added products. *Fermentation*, *10*(11), 568. https://doi.org/10.3390/fermentation10110568
10. Cruz-Rivero, L., Hernández, E. A., Lince-Olguín, E., Mar-Orozco, C. E., López-García, S. A., & Cruz-Martínez, P. Y. (2025). Life cycle assessment applied to milk production and processing: An integrative systematic literature review. *Sustainability, 17*(4), Article 1615. https://doi.org/10.3390/su17041615
11. de Vries, M., & de Boer, I. J. M. (2010). Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science, 128*(1–3), 1–11. http://dx.doi.org/10.1016/j.livsci.2009.11.007
12. Djuwita, M. R., Hartono, D. M., Mursidik, S. S., & Soesilo, T. E. B. (2021). Pollution load allocation on water pollution control in the Citarum River. *J. Eng. Technol. Sci*, *53*(1), 210112. https://doi.

org/10.5614/j.eng.technol.sci.2021.53.1.12

13. Duncan, A. J., Teufel, N., Mekonnen, K., Singh, V. K., Bitew, A., & Gebremedhin, B. (2013). Dairy intensification in developing countries: effects of market quality on farm-level feeding and breeding practices. *ANIMAL 7:* 2054–2062. https://doi.org/10.1017/S1751731113001602
14. Ecoinvent. (2023). *ecoinvent database version 3.10*. ecoinvent Association. https://ecoinvent.org/
15. FAO. (2023). *Pathways towards lower emissions – A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems*. Rome https://doi.org/10.4060/cc9029en
16. Fischer, G., Wittich, S., Malima, G., Sikumba, G., Lukuyu, B., Ngunga, D., & Rugalabam, J. (2018). Gender and mechanization: Exploring the sustainability of mechanized forage chopping in Tanzania. *Journal of Rural Studies*, *64*, 112-122. https://doi.org/10.1016/j.jrurstud.2018.09.012
17. Garg, M. R., Phondba, B. T., Sherasia, P. L., & Makkar, H. P. (2016). Carbon footprint of milk production under smallholder dairying in Anand district of Western India: a cradle-to-farm gate life cycle assessment. *Animal Production Science*, *56*(3), 423-436. https://doi.org/10.1071/AN15464
18. Gerber, P., Vellinga, T., Opio, C., & Steinfeld, H. (2011). Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science, 139*(1–2), 100–108. https://doi-org.proxy.undip.ac.id/10.1016/j.livsci.2011.03.012
19. Hadiana, M. H., Daud, A. R., & Supratman, R. H. (2019). Mechanizing the smallholder dairy farm: its impact on herd size and labor efficiency. *Livestock Research for Rural Development*, *31*(8), 1-9. http://www.lrrd.org/lrrd31/8/hadia31125.html
20. Hristov, A. N., Bannink, A., Crompton, L. A., Huhtanen, P., Kreuzer, M., McGee, M., Nozière, P., Reynolds, C. K., Bayat, A. R., Yáñez-Ruiz, D. R., Dijkstra, J., Kebreab, E., Schwarm, A., Shingfield, K. J., & Yu, Z. (2019). Invited review: Nitrogen in ruminant nutrition. *Journal of Dairy Science, 102*(6), 4714–4741. https://doi.org/10.3168/jds.2018-15829
21. Intergovernmental Panel on Climate Change. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies. https://www.ipcc-nggip.iges.or.jp/public/2006gl/
22. Jiang, F., Lin, X., Yan, Z., Hu, Z., Wang, Y., & Wang, Z. (2018). Effects of forage source and particle size on feed sorting, milk production and nutrient digestibility in lactating dairy cows. *Journal of animal physiology and animal nutrition*, *102*(6), 1472-1481. https://doi.org/10.1111/jpn.12984
23. Knapp, J. R., Laur, G. L., Vadas, P. A., Weiss, W. P., & Tricarico, J. M. (2014). Invited review: Enteric methane in dairy cattle production: Quantifying emissions and mitigation strategies. *Journal of Dairy Science*, *97*(6), 3231–3261. http://dx.doi.org/10.3168/jds.2013-7234
24. Kumar, D., & Doan, M. K. (2025). Adoption of agricultural technologies by smallholder farmers: a synthesis of empirical evidence. *World Bank Group: Washington, DC, USA*. https://documents1.worldbank.org/curated/en/099092925141086193/pdf/P500443-c5c1ae72-ed75-442e-885c-7ced9e0bb0ea.pdf
25. Kusumastuti, T. A., Abidin, M. Z., & Widiati, R. (2024). Total economic value of smallholder dairy farm in Java Island Indonesia. *International Journal of Dairy Science*, *19*(1), 8-17. https://doi.org/10.3923/ijds.2024.8.17
26. Lei, Y., Cheng, M., McCarl, B., & Cessna, J. (2024). A review of options and costs for mitigating GHG emissions from the U.S. dairy sector. *Atmosphere, 15*(8), Article 926. https://doi.org/10.3390/atmos15080926
27. Leip, A., Ledgard, S., Uwizeye, A., Palhares, J. C., Aller, M. F., Amon, B., Binder, M., Cordovil, CM.d.S., De Camillis, C., Dong, H., Fusi, A., Helin, J., Hörtenhubero, S., Hristov, A.N., Koelsch, R., Liu., C, Masso, C., Nkongolo, N.V., Patra, A.K., Redding, M.R., Rufino M.C., Sakrabani, R., Thoma, G., Vertès, F., & Wang, Y. (2019). The value of manure-Manure as co-product in life cycle assessment. *Journal of environmental management*, *241*, 293-304. https://doi.org/10.1016/j.jenvman.2019.03.059
28. Liu, C., Shi, X., & Li, C. (2023). Digital technology, factor allocation and environmental efficiency of dairy farms in China: Based on carbon emission constraint perspective. *Sustainability*, *15*(21), 15455. https://doi.org/10.3390/su152115455
29. Murphy, E., De Boer, I. J. M., Van Middelaar, C. E., Holden, N. M., Shalloo, L., Curran, T. P., & Upton, J. (2017). Water footprinting of dairy farming in Ireland. *Journal of Cleaner Production*, *140*, 547-555. https://doi.org/10.1016/j.jclepro.2016.07.199
30. Ngeno, V. (2024). Adoption of dairy feed technology and its impact on smallholder farmers' income and poverty in Kenya's south-western region. *Scientific African*, *23*, e02123. https://doi.org/10.1016/j.sciaf.2024.e02123
31. Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, *360*(6392), 987–992. https://doi.org/10.1016/j.landusepol.2026.108315
32. Purnomo, N., & Yusriadi, Y. (2023). Potensi Energi Terbarukan dari Biogas Limbah Ternak Ruminansia Di Kabupaten Sidrap. *Jurnal Sains Dan Teknologi Industri Peternakan*, *3*(1), 1-7. (in Indonesian)

https://doi.org/10.55678/jstip.v3i1.621

33. Rattanaphra, D., Tawkaew, S., Kingkam, W., Nuchdang, S., Kitpakornsanti, K., & Suwanmanee, U. (2025). Global Warming Assessment of Dairy Farms: A Case Study of Organic and Conventional Fluid Milk in Thailand. *Sustainability*, *17*(6), 2687. https://doi.org/10.3390/su17062687
34. Rogers-Montoya, N. A., Cruz-Olayo, A., Martínez-Castañeda, F. E., Sainz-Ramírez, A., Herrera-Haro, J. G., Domínguez-Olvera, D. A., Vásquez-Ibarra, L., & Arriaga-Jordán, C. M. (2026). Environmental Trade-Offs of Methane-Related Farm Typologies in Mexican Smallholder Dairy Systems: A Life Cycle Assessment. *Agriculture*, *16*(15), 1587. https://doi.org/10.3390/agriculture16151587
35. Romaniuk, W., Mazur, K., Borek, K., Borusiewicz, A., Wardal, W. J., Tabor, S., & Kuboń, M. (2021). Biomass energy technologies from innovative dairy farming systems. *Processes*, *9*(2), 335. https://doi.org/10.3390/pr9020335
36. Salvador, S., Corazzin, M., Piasentier, E., & Bovolenta, S. (2016). Environmental assessment of small-scale dairy farms with multifunctionality in mountain areas. *Journal of Cleaner Production*, *124*, 94-102. http://dx.doi.org/10.1016/j.jclepro.2016.03.001
37. Sabia, E., Kühl, S., Flach, L., Lambertz, C., & Gauly, M. (2020). Effect of feed concentrate intake on the environmental impact of dairy cows in an alpine mountain region including soil carbon sequestration and effect on biodiversity. *Sustainability*, *12*(5), 2128. https://doi.org/10.3390/su12052128
38. Shine, P., Upton, J., Sefeedpari, P., & Murphy, M. D. (2020). Energy consumption on dairy farms: A review of monitoring, prediction modelling, and analyses. *Energies*, *13*(5), 1288. https://doi.org/10.3390/en13051288
39. Taufiq, F. M., Padmi, T., & Rahardyan, D. B. (2016). Life cycle assessment of dairy farms. *Reviews on Environmental Health*, *31*(1), 187-190. https://doi.org/10.1515/reveh-2015-0037
40. Udo, H. M. J., Aklilu, H. A., Phong, L. T., Bosma, R. H., Budisatria, I. G. S., Patil, B. R., Samdup, T., & Bebe, B. O. (2011). Impact of intensification of different types of livestock production in smallholder crop-livestock systems. *Livestock science*, *139*(1-2), 22-29. http://dx.doi.org/10.1016/j.livsci.2011.03.020
41. Veltman, K., Rotz, C. A., Chase, L., Cooper, J., Forest, C. E., Ingraham, P. A., , R. C´esar Izaurralde, R.C., Jones, C.D., Nicholasi, R.E, Ruark, M.D., Salas, W., Thoma, G., and Jolliet, O. (2021). Assessing and reducing the environmental impact of dairy production systems in the northern US in a changing climate. *Agricultural Systems*, *192*, 103170. https://doi.org/10.1016/j.agsy.2021.103170
42. Vu, T. K. V., Vu, D. Q., Jensen, L. S., Sommer, S. G., & Bruun, S. (2015). Life cycle assessment of biogas production in small-scale household digesters in Vietnam. *Asian-Australasian Journal of Animal Sciences*, *28*(5), 716. https://doi.org/10.5713/ajas.14.0683
43. Weiss, W. P., St-Pierre, N. R., Willett, L. B., & Eastridge, M. L. (2007, July). Factors affecting manure output on dairy farms. In *Tri-State Dairy Nutrition Conference* (Vol. 2007, pp. 24-25).