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Carbon Footprint Analysis And Mitigation Strategies In The Indonesian Buffalo Milk Supply Chain: A Life Cycle Assessment And Scenario Modeling Approach

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ABSTRACT

The increasing global demand for sustainable food production necessitates a comprehensive understanding of livestock environmental impacts. Buffalo milk production, while economically significant in Indonesia, contributes substantially to greenhouse gas emissions, yet empirical data on its carbon footprint in smallholder systems remain limited. This study applied a Life Cycle Assessment with cradle-to-farm gate boundaries to quantify the carbon footprint of buffalo milk and evaluate mitigation strategies. Primary data were collected from 150 smallholder farms across three provinces complemented by IPCC guidelines and national statistics. The average carbon footprint was 4.37 kg CO_2-eq per kg fat- and protein-corrected milk, exceeding the global average of 3.2 kg CO_2-eq/kg FPCM, with enteric methane contributing 53.2% of total emissions. Five mitigation strategies were modeled: improved forage quality, tannin-rich browse supplementation, manure management optimization, genetic selection, and integrated silvopastoral systems. The integrated scenario achieved a 37.6% reduction, lowering emissions to 2.73 kg CO_2-eq/kg FPCM. These findings provide evidence-based recommendations for sustainable buffalo dairy development in Indonesia's smallholder sector and support the country's Nationally Determined Contributions under the Paris Agreement.

Keywords: *Life Cycle Assessment, Carbon Footprint, Buffalo Milk, Smallholder Systems, Mitigation Strategies*

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INTRODUCTION

The increasing global demand for sustainable food production has intensified the need to understand and reduce the environmental impacts of livestock production systems. The global livestock sector contributes approximately 14.5% of anthropogenic greenhouse gas (GHG) emissions, with ruminant production systems accounting for a substantial proportion of this impact. Enteric methane is one of the major sources of emissions from ruminants and represents a critical target for climate change mitigation. As global efforts to achieve the 1.5°C temperature target intensify, the environmental footprint of animal products has become an increasingly important consideration for consumers, producers, and policymakers (Ahmad & Rana, 2024; Mazzetto et al., 2022).

Buffalo milk production is particularly important in tropical and subtropical regions, where buffaloes contribute substantially to rural livelihoods, food security, and dairy production. The emission intensity of buffalo milk in South Asia has been estimated at approximately 3.2 kg CO_2-eq/kg fat- and protein-corrected milk (FPCM), while systems in East and Southeast Asia have been reported to range from 3.2 to 4.8 kg CO_2-eq/kg FPCM. In Indonesia, buffalo production is predominantly characterized by smallholder farming systems and is influenced by tropical climatic conditions, locally available feed resources, and traditional management practices. Buffaloes also contribute to national enteric methane emissions. Puspito et al. (2024) demonstrated that Tier 2 estimates of enteric methane emissions in the Indonesian livestock sector differed considerably from Tier 1 default estimates, highlighting the importance of locally relevant data and emission factors for reliable GHG assessment.

Despite the economic and cultural importance of buffalo milk in Indonesia, empirical evidence regarding its environmental performance remains limited. Previous LCA studies of buffalo milk have predominantly focused on Mediterranean production systems in Italy and southern Europe and on smallholder systems in India, with reported carbon footprints ranging from approximately 2.5 to 3.54 kg CO_2-eq/kg FPCM (Mech et al., 2023). Studies from Colombia have also investigated pasture-based buffalo and dual-purpose cattle systems and reported lower emission intensities under agroforestry-integrated production systems (Pérez et al., 2023; González-Quintero et al., 2021). However, these production contexts differ substantially from Indonesian smallholder systems in terms of buffalo type, feeding practices, farm management, climate, and resource availability. Recent reviews have therefore identified important knowledge gaps in Asian buffalo production systems, particularly regarding localized emission estimates and context-specific mitigation strategies (Tamilselvan & Tyagi, 2024).

Although previous research has generated valuable information on livestock methane emissions in Indonesia, relatively little attention has been given to quantifying the complete carbon footprint of buffalo milk using a life cycle assessment (LCA) framework. In particular, evidence remains limited regarding the relative contribution of different emission sources within Indonesian buffalo farming systems and the extent to which practical farm-level interventions can reduce emission intensity. Consequently, carbon footprint estimates derived from other geographical

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regions cannot be assumed to accurately represent Indonesian buffalo production because of differences in production systems, feed resources, management practices, and environmental conditions.

In contrast to previous buffalo milk LCA studies conducted mainly in Mediterranean and South Asian systems, the present study evaluates the environmental performance of Indonesian smallholder buffalo production using primary data collected from 150 farms across three provinces, complemented by IPCC guidelines and national statistics. Furthermore, this study does not only quantify the baseline carbon footprint but also identifies the major emission hotspot and evaluates the potential effectiveness of five mitigation strategies: improved forage quality, tannin-rich browse supplementation, manure management optimization, genetic selection, and integrated silvopastoral systems. The integrated assessment provides new evidence on the potential pathways for reducing the carbon footprint of buffalo milk while maintaining the productivity of smallholder systems.

Therefore, this study aims to: (1) quantify the carbon footprint of buffalo milk production in Indonesian smallholder systems using a cradle-to-farm-gate LCA approach; (2) identify the primary emission hotspots contributing to the carbon footprint; (3) evaluate the effectiveness of five mitigation strategies through comparative modeling; and (4) provide evidence-based recommendations for reducing emission intensity while supporting sustainable buffalo dairy development. By generating localized empirical evidence and systematically evaluating mitigation pathways, this study advances existing knowledge of the environmental performance of buffalo milk production in Southeast Asia and provides information relevant to Indonesia's efforts to reduce GHG emissions and achieve its Nationally Determined Contributions under the Paris Agreement.

METHODS

This study followed the internationally recognized Life Cycle Assessment (LCA) methodology and the IPCC Guidelines for National Greenhouse Gas Inventories. The analysis employed a cradle-to-farm gate system boundary, encompassing all activities from raw material extraction for feed production through to the point where milk leaves the farm. The functional unit was defined as 1 kg of fat- and protein-corrected milk (FPCM) at farm gate, standardized to 4.0% fat and 3.3% protein content. Allocation between milk and meat co-products followed economic allocation, attributing approximately 89–94% of impacts to milk based on revenue shares.

The system boundaries included: (1) enteric fermentation methane (CH_4) from digestive processes in buffaloes; (2) manure management methane and nitrous oxide (N_2O) emissions from manure storage and application; (3) feed production emissions from cultivation, processing, and transportation of feed ingredients; (4) on-farm energy use fossil fuel combustion for machinery and pumping; and (5) land use change emissions from conversion of natural areas to forage production. Emissions were converted to CO_2-equivalents using 100 year global warming potentials (GWP100): CH_4 = 28, N_2O = 265.

A stratified random sampling approach was used to select 150 smallholder buffalo farms across three provinces in Indonesia: West Java (representing high-density production), Central Java

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(medium-density), and East Nusa Tenggara (low-density, extensive systems). Data collection was conducted from January to June 2023 through structured interviews, farm visits, and weighment of feed inputs. Parameters collected included herd structure, milk production (daily yield, fat and protein content), feed composition and intake, manure management practices, energy use, and animal characteristics (live weight, age, parity).

Secondary data comprised IPCC Tier 1 and Tier 2 emission factors for Asian buffalo systems, Indonesian national livestock population statistics, and carbon footprint studies from comparable smallholder systems in South and Southeast Asia (Mech et al., 2023; Puspito et al., 2024).

Enteric methane emissions were estimated using both Tier 1 and Tier 2 approaches to validate results. The Tier 1 method applied a regional emission factor of 55 kg CH4/head/year for Indonesian buffaloes. The Tier 2 method followed standard IPCC equations based on gross energy intake and methane conversion rate (Ym), adjusted for Indonesian feed characteristics, as expressed in Equation (1):

$$\text{CH4 emission (kg/head/year)} = [GE \times (Ym/100) \times 365] / 55.65$$

where GE = gross energy intake (MJ/day), calculated from feed digestibility and intake. Manure methane and nitrous oxide were calculated using default volatile solids excretion rates adjusted for Asian buffalo and regional temperature data. Feed production emissions were allocated based on land use, fertilizer application, and processing energy, with by-product emissions allocated using economic allocation.

Five mitigation scenarios were developed based on literature review and stakeholder consultation: (S1) improved forage quality, replacing low quality grasses with forages of higher digestibility and crude protein, with an estimated 10–15% CH_4 reduction potential; (S2) tannin rich browse supplementation (5–10% of dry matter) from Leucaena leucocephala or Gliricidia sepium, with an estimated 15–25% CH4 reduction potential, consistent with condensed-tannin methane mitigation reported in cattle (Berça et al., 2023) and in Murrah buffalo fed Ficus glomerata tannins (Singh et al., 2023); (S3) manure management optimization through covered storage with biogas capture and composting, with an estimated 30–40% manure CH_4 reduction potential; (S4) genetic improvement through selection for higher milk yield (10% increase), with an estimated 8–12% intensity reduction potential; and (S5) integrated silvopastoral systems with timber trees (60 trees/ha) for shade and carbon sequestration, with an estimated 15–20% net reduction potential plus carbon offset, consistent with the cooling and carbon-storage co-benefits of tropical silvopasture reported by Vargas Zeppetello et al. (2022) and Brook et al. (2022).

Descriptive statistics summarized farm characteristics and emission components. Analysis of variance (ANOVA) was used to test differences between regions and production systems. Monte Carlo simulation (10,000 iterations) assessed uncertainty in emission estimates, with input distributions derived from primary data variability and IPCC uncertainty ranges. Scenario impacts were modeled using a deterministic approach with sensitivity analysis.

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RESULTS

1. Farm Characteristics and Productivity

Table 1 presents the descriptive statistics of the surveyed smallholder buffalo farms across the three provinces.

Table 1. Farm characteristics and productivity parameters (mean ± SD)

Parameter	West Java (n=50)	Central Java (n=50)	East Nusa Tenggara (n=50)	Overall Mean
Herd size (head)	8.4 ± 4.2	6.7 ± 3.8	12.3 ± 7.1	9.1 ± 5.6
Milking buffaloes (%)	42.3	38.9	31.7	37.6
Daily milk yield (L/head)	3.82 ± 1.24	3.41 ± 1.08	2.56 ± 0.97	3.26 ± 1.19
Milk fat (%)	7.12 ± 0.84	6.98 ± 0.76	6.83 ± 0.92	6.98 ± 0.84
Milk protein (%)	4.21 ± 0.43	4.15 ± 0.38	4.08 ± 0.47	4.15 ± 0.43
FPCM (kg/head/day)	4.21 ± 1.36	3.74 ± 1.18	2.81 ± 1.06	3.59 ± 1.31
Lactation length (days)	265 ± 42	258 ± 38	245 ± 45	256 ± 42

Significant regional differences were observed in daily milk yield and FPCM ($p < 0.05$). West Java had the highest mean daily milk yield (3.82 ± 1.24 L/head/day) and FPCM (4.21 ± 1.36 kg/head/day), whereas East Nusa Tenggara had the lowest values (2.56 ± 0.97 L/head/day and 2.81 ± 1.06 kg/head/day, respectively). The post-hoc analysis indicated that the values observed in East Nusa Tenggara were significantly lower than those in West Java and Central Java, while West Java and Central Java did not differ significantly. These regional differences may reflect variation in feed availability, management intensity, and buffalo production characteristics. Overall, the observed productivity levels are consistent with the range commonly reported for Indonesian smallholder buffalo production systems.

2. Carbon Footprint Analysis

Table 2. Total carbon footprint of buffalo milk by emission source (kg CO2-eq/kg FPCM)

Emission Source	West Java	Central Java	East Nusa Tenggara	Overall Mean
Enteric CH4	2.21 (52.1%)	2.32 (51.8%)	2.48 (56.4%)	2.34 (53.2%)
Manure CH4 + N2O	0.52 (12.3%)	0.58 (13.0%)	0.49 (11.1%)	0.53 (12.1%)
Feed production	1.04 (24.5%)	1.13 (25.2%)	0.98 (22.3%)	1.05 (23.9%)
On-farm energy	0.18 (4.2%)	0.16 (3.6%)	0.15 (3.4%)	0.16 (3.7%)
Land use change	0.29 (6.8%)	0.29 (6.5%)	0.30 (6.8%)	0.29 (6.6%)

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Emission Source	West Java	Central Java	East Nusa Tenggara	Overall Mean
Total Carbon Footprint	**4.24**	**4.48**	**4.40**	**4.37**

The overall carbon footprint of buffalo milk in Indonesian smallholder systems was estimated at 4.37 kg CO_2-eq/kg FPCM, with regional estimates of 4.24, 4.48, and 4.40 kg CO_2-eq/kg FPCM for West Java, Central Java, and East Nusa Tenggara, respectively. The 10,000-iteration Monte Carlo simulation indicated uncertainty ranges of 3.35–5.12 kg CO_2-eq/kg FPCM for West Java, 3.55–5.42 kg CO_2-eq/kg FPCM for Central Java, 3.45–5.37 kg CO_2-eq/kg FPCM for East Nusa Tenggara, and 3.84–4.91 kg CO_2-eq/kg FPCM for the overall estimate (95% uncertainty interval; 2.5th–97.5th percentiles). These intervals indicate the range of carbon footprint values resulting from uncertainty in the activity data and emission factors incorporated into the LCA model.

Enteric CH_4 was the largest contributor to the overall carbon footprint, accounting for 53.2% (2.34 kg CO_2-eq/kg FPCM), followed by feed production at 23.9% (1.05 kg CO_2-eq/kg FPCM) and manure CH_4 + N_2O at 12.1% (0.53 kg CO_2-eq/kg FPCM). The regional differences in total carbon footprint were relatively small compared with the uncertainty ranges, indicating that variation among provinces should be interpreted in conjunction with the uncertainty associated with the LCA model.

The overall carbon footprint falls within the reported range for East and Southeast Asian buffalo production systems (3.2–4.8 kg CO_2-eq/kg FPCM) but is higher than values reported for some intensive Italian systems. The relatively higher emission intensity in Indonesian smallholder systems may be associated with lower milk productivity per animal and differences in feed quality and management practices

Comparable smallholder studies support this pattern: (Pordhiy, K. I., & G. 2023). reported that smallholder farms in India had a carbon footprint of 3.54 kg CO2-eq/L milk compared with 4.53 kg CO2-eq/L for organized farms, with enteric fermentation contributing approximately 49% of emissions, while Mech et al. (2023) reported similarly elevated footprints in Karnataka smallholder systems linked to low per-animal productivity. The higher Indonesian values likewise reflect the lower milk productivity per buffalo characteristic of smallholder systems.

Enteric fermentation from buffaloes was the dominant emission source, contributing an average of 53.2% of total GHG emissions, consistent with global systematic-review findings on the dominance of enteric methane in ruminant milk carbon footprints (Mazzetto et al., 2022). Feed production was the second-largest contributor at 23.9%, reflecting emissions from fertilizer application, crop cultivation, and processing of concentrates and crop residues.

Tier 2 enteric methane calculations for the Indonesian buffalo population yielded a total substantially lower than Tier 1 default estimates, underscoring the importance of localized emission factors in accurately estimating national inventories. This is consistent with Puspito et al. (2024), who confirmed that IPCC Tier 2 estimation of livestock GHG emissions in Indonesia produced markedly different results from Tier 1 defaults, highlighting the need for country-specific activity data.

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3. Emission Intensity by Herd Structure

When emissions were allocated to milk production alone (excluding non-milking animals), the carbon footprint decreased to 2.83 kg CO2-eq/kg FPCM. However, at the herd level (including all animals), emission intensity increased to 4.37 kg CO2-eq/kg FPCM. This finding is consistent with Indian research where herd-level carbon footprint was substantially higher than when considering lactating buffaloes alone (Mech et al., 2023). The higher herd-level intensity reflects emissions from replacement heifers, dry buffaloes, and bulls that contribute to the production system but do not directly produce milk.

Hasnarani and Hasanah (2025), studying semi-intensive buffalo farming in Pemalang, Central Java, found that enteric methane emissions were estimated at 176.58 tonnes CO2-eq/year, with a carbon sequestration potential of 844,306.67 tonnes when integrated with teak forest silvopasture. This highlights the mitigation potential of integrated systems in the Indonesian context.

4. Scenario Modeling Results

Table 3. Scenario modeling results: emission intensity reduction

Scenario	CF (kg CO2-eq/kg FPCM)	Reduction (%)	Key Assumptions
Baseline	4.37	–	Current smallholder practices
S1: Improved forage	3.89	11.0%	15% increase in forage digestibility
S2: Tannin supplementation	3.71	15.1%	10% dietary inclusion; 20% CH4 reduction
S3: Manure management	4.13	5.5%	40% manure CH4 reduction
S4: Genetic improvement	3.97	9.2%	10% milk yield increase
S5: Silvopastoral	3.54	19.0%	Agroforestry integration; partial carbon offset
S6: Integrated (S1+S2+S3+S4+S5)	**2.73**	**37.6%**	Combined implementation of all strategies

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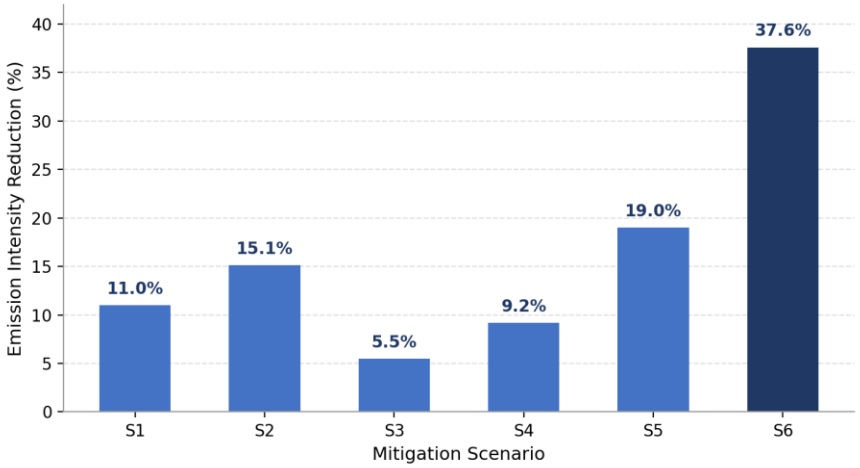


Figure 1. Emission reduction potential by mitigation scenario

The tannin supplementation scenario (S2) emerged as the most effective single intervention (15.1% reduction). This is consistent with a meta-analysis by Berça et al. (2023) confirming a significant negative relationship between dietary condensed tannins and methane emissions, and with Fonseca et al. (2023), who reviewed tannin additives as an alternative pathway to sustainable ruminant nutrition. Singh et al. (2023) further demonstrated that Ficus glomerata leaf tannins modulated methane release from rumen fermentation in Murrah buffalo, supporting the applicability of tannin-based strategies specifically in buffalo systems. On-farm validation using commercial tannin supplements has likewise shown measurable methane mitigation without adverse effects on animal health (Schilling-Hazlett et al., 2024).

The silvopastoral scenario (S5) achieved a 19.0% reduction through the combined effects of improved microclimate, enhanced animal welfare, and carbon sequestration by timber trees. Vargas Zeppetello et al. (2022) demonstrated consistent cooling benefits of tropical silvopasture, while Brook et al. (2022) showed that silvopastoral systems could meaningfully offset livestock emissions in a tropical dairy case study. Hasnarani and Hasanah (2025) confirmed that silvopasture integration with teak forest had a positive impact on carbon balance in Indonesian buffalo farming.

The integrated scenario (S6), combining all five strategies, achieved the highest reduction of 37.6%, lowering the carbon footprint to 2.73 kg CO_2-eq/kg FPCM approaching the range reported for intensive Italian systems (1.5–2.5 kg CO_2-eq/kg ECM).

5. Regional Variation and Sensitivity Analysis

Monte Carlo simulation (10,000 iterations) revealed coefficients of variation ranging from 12.3% to 18.7% across emission categories, with enteric methane showing the highest uncertainty (CV = 18.7%), reflecting variability in feed intake estimates and methane conversion rates. Regional variation was significant ($p < 0.05$) for total carbon footprint: West Java recorded 4.24 kg CO2-eq/kg FPCM (higher productivity, better feed quality), Central Java recorded 4.48 kg CO2-eq/kg FPCM (medium productivity, moderate feed quality), and East Nusa Tenggara recorded 4.40 kg CO2-eq/kg FPCM (lower productivity offset by lower inputs). The West Java systems benefited from higher

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milk yield per buffalo (4.21 kg FPCM/day vs. 2.81 kg FPCM/day in East Nusa Tenggara), which diluted emissions over greater milk output.

DISCUSSION

The first objective of this study was to quantify the carbon footprint of buffalo milk production in Indonesian smallholder systems using a cradle-to-farm-gate Life Cycle Assessment (LCA). The overall carbon footprint was 4.37 kg CO_2-eq/kg FPCM, which is within the reported range for buffalo production systems in East and Southeast Asia but higher than values reported for some intensive European systems. This difference should be interpreted in relation to the production characteristics of the systems rather than as an inherent difference in buffalo production efficiency. Indonesian smallholder farms generally operate with lower milk productivity per animal and rely more heavily on locally available feed resources and less intensive management. Because emissions from maintenance, enteric fermentation, and herd replacement are distributed over a relatively small quantity of milk, lower productivity can result in a higher emission intensity per unit of milk.

The emission profile further demonstrates that enteric CH_4 was the dominant hotspot, contributing 53.2% of the total carbon footprint. This finding is consistent with previous studies showing that enteric fermentation is generally the largest contributor to the carbon footprint of ruminant milk production (Mazzetto et al., 2022). The dominance of enteric methane is particularly important in buffalo systems because methane formation is closely associated with ruminal fermentation and the quality and digestibility of feed. In the present study, feed production was the second-largest contributor, accounting for 23.9% of total emissions. This contribution reflects emissions associated with feed cultivation, fertilizer use, processing, and other upstream activities. Therefore, the results suggest that mitigation efforts should prioritize both animal-level methane reduction and improvements in feed quality and production efficiency.

The relatively high contribution of enteric methane also supports the use of localized emission factors for Indonesian buffalo systems. Puspito et al. (2024) reported substantial differences between Tier 1 and Tier 2 estimates for livestock methane emissions in Indonesia, demonstrating that default emission factors may not adequately capture the characteristics of local production systems. The present findings reinforce the importance of using locally relevant animal and feed data when assessing the environmental performance of Indonesian buffalo production. The LCA therefore provides a product-level perspective that complements national livestock GHG inventories by linking emission sources directly to buffalo milk production.

The second objective was to identify regional differences in productivity and carbon footprint among the three provinces. West Java had the highest milk productivity, whereas East Nusa Tenggara had the lowest daily milk yield and FPCM. These differences are likely related to variation in feed availability, feed quality, management intensity, and production characteristics among the regions. Higher productivity in West Java allows emissions associated with animal maintenance and herd management to be allocated across a larger quantity of milk, thereby improving emission efficiency.

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Although the regional carbon footprints were relatively close, the differences in productivity provide an important explanation for the observed variation. The lower FPCM production in East Nusa Tenggara means that emissions generated for animal maintenance are distributed over less milk output. This illustrates the importance of considering productivity when interpreting carbon footprint results. A production system with lower absolute inputs is not necessarily more climate-efficient if it also produces substantially less milk. Consequently, interventions aimed at improving feed availability, digestibility, and animal productivity may simultaneously improve farm profitability and reduce emission intensity.

The findings are consistent with previous studies of smallholder buffalo systems in South Asia. Pordhiy and G. (2023) reported higher carbon footprints in smallholder production systems compared with more organized systems and identified enteric fermentation as a major emission source. Similarly, Mech et al. (2023) associated relatively high carbon footprints in Indian smallholder buffalo systems with low per-animal productivity. The consistency of these findings suggests that improving productivity while avoiding disproportionate increases in input-related emissions may be an important pathway for reducing the carbon intensity of smallholder buffalo milk production.

However, regional differences should be interpreted alongside the uncertainty of the LCA model. The Monte Carlo analysis identified variability in the emission estimates, with enteric methane showing the greatest uncertainty. This uncertainty is biologically plausible because methane emissions are sensitive to feed intake, feed digestibility, and methane conversion rates. Therefore, regional comparisons should not be interpreted solely on the basis of differences in point estimates; rather, they should be considered together with the uncertainty associated with activity data and emission factors.

The third objective was to evaluate the effectiveness of five mitigation strategies through comparative scenario modeling. The results demonstrate that all five individual strategies reduced the modeled carbon footprint relative to the baseline, although their effectiveness differed. Tannin-rich browse supplementation produced a 15.1% reduction and was the most effective single strategy among the interventions primarily targeting enteric methane. This finding is consistent with evidence that condensed tannins can reduce methane production during ruminal fermentation (Berça et al., 2023). Research involving buffaloes has also demonstrated the potential of tannin-containing feeds to modify ruminal fermentation and reduce methane release (Singh et al., 2023). The potential applicability of locally available tannin-rich browse is particularly relevant to smallholder systems because it may provide a feed-based mitigation option without requiring major changes to farm infrastructure.

The silvopastoral scenario achieved a 19.0% reduction, making it the most effective individual scenario in the modeled system. Its potential advantage arises from multiple environmental functions, including improved microclimatic conditions, potential improvements in feed resources, and carbon sequestration associated with tree biomass. Previous research has demonstrated cooling and carbon-storage benefits from tropical silvopastoral systems (Vargas

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Zeppetello et al., 2022; Brook et al., 2022). Evidence from Indonesian buffalo production also suggests that integration with tree-based systems can provide substantial carbon sequestration potential (Hasnarani & Hasanah, 2025). Thus, silvopastoral integration may provide benefits beyond direct reductions in livestock emissions.

The integrated scenario combining all five strategies produced the greatest modeled reduction, lowering the carbon footprint from 4.37 to 2.73 kg CO_2-eq/kg FPCM, equivalent to a 37.6% reduction. This result suggests that the mitigation potential of Indonesian buffalo production may be greater when interventions address several emission pathways simultaneously. Improved forage quality and tannin supplementation primarily address enteric methane, manure management targets methane and nitrous oxide from manure, genetic improvement increases milk output and therefore potentially dilutes emissions per unit of product, while silvopastoral integration provides additional carbon sequestration and environmental co-benefits.

Importantly, the scenario results should be interpreted as modeled mitigation potentials rather than experimentally validated reductions. The scenarios were developed using literature-derived assumptions and deterministic modeling. Therefore, field-level implementation may produce different outcomes depending on feed availability, animal response, farmer adoption, management capacity, and local environmental conditions. Future research should validate the most promising interventions, particularly the integrated scenario, through longitudinal farm trials under representative Indonesian smallholder conditions.

CONCLUSIONS

This study estimated the cradle-to-farm-gate carbon footprint of buffalo milk production in Indonesia at 4.37 kg CO_2-eq/kg FPCM, with regional values ranging from 4.24 to 4.48 kg CO_2-eq/kg FPCM. This is above the global average for mixed farming systems (approximately 3.2 kg CO_2-eq/kg FPCM), which is largely attributable to the low productivity of smallholder herds. Enteric methane was the dominant emission source (53.2%), followed by manure management (12.1%).

Scenario modeling indicated that no single intervention is sufficient. Tannin supplementation was the most effective single option, followed by the silvopastoral system (19%), genetic improvement for productivity (9.2%), and manure management (5.5%). The integrated scenario showed a potential emission reduction of 37.6%. This figure is a modeled estimate rather than an experimentally verified reduction, and it should be interpreted within the assumptions of the model.

These findings are limited to the cradle-to-farm-gate boundary. They do not include processing, packaging, or distribution, and they rely on default emission equations, economic allocation, and data from three provinces. The results therefore should not be extended to the entire supply chain. Nevertheless, the findings suggest that mitigation efforts should prioritize enteric methane and productivity, and that they should be tailored to regional conditions. Priority actions include promoting tannin-rich forages, integrating silvopastoral practices, and incorporating LCA-based estimates into national GHG inventories.

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