

Field-Scale Pilot Observation of Continuous Cattle Slurry Acidification on Methane and Ammonia Emission Mitigation

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Abstract: *Livestock activities are a major source of anthropogenic greenhouse gas emissions, particularly in tropical regions where high ambient temperatures accelerate manure degradation. This study evaluated the efficacy of field-scale continuous cattle slurry acidification using concentrated sulfuric acid (H₂SO₄) to mitigate methane (CH₄) and ammonia (NH₃) emissions under Malaysian conditions. Pilot observations in 600-liter high-density polyethylene tanks demonstrated that maintaining a slurry pH of 5.0 through periodic re-acidification reduced cumulative CH₄ emissions by 62.3% and total NH₃ volatilization by 35.3% over a 120-day storage period. A parallel field pond trial confirmed a 90% immediate reduction in CH₄ flux following acidification to pH 5.0, though emissions gradually rebounded as the slurry's natural buffering capacity returned the pH toward neutral. Economic analysis indicated the technology is viable with a Benefit-Cost Ratio (BCR) of 1.30, primarily driven by carbon (C) credit potential from CH₄ mitigation, which accounted for over 80% of total benefits. However, the relatively modest net benefit indicates that the economic performance of the system remains sensitive to fluctuations in key market parameters, particularly carbon pricing and chemical input costs. These findings suggest that decentralized acidification is a practical tool for SME farmers to align with Net Zero 2050 targets, provided that policy interventions stabilize the economic returns against market volatility.*

Keywords: cattle slurry, continuous acidification, methane, ammonia, greenhouse gas

INTRODUCTION

The global livestock sector is currently at a crossroads, serving as a vital food source while simultaneously acting as a major contributor to climate change. It is responsible for approximately 16.5% of anthropogenic greenhouse gas (GHG) emissions worldwide (Twine, 2021). The heart of this environmental challenge lies in enteric fermentation and the way we manage manure produced by livestock activities. These processes result in substantial emissions of methane (CH₄), a potent greenhouse gas with a 100-year global warming potential approximately 28 times greater than that of carbon dioxide (CO₂) based on the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) (Myhre et al., 2013), as well as ammonia (NH₃), a major driver of soil acidification and degradation of surface and groundwater quality. In Malaysia, the scale of this issue has become increasingly clear through recent national inventories. According to the Ministry of Natural Resources and Environmental Sustainability (NRES, 2024), livestock activities in 2022 generated 1,247.65 Gg CO₂-equivalent (eq) of CH₄ from enteric fermentation, while manure management alone contributed 287.84 Gg CO₂ eq. When the 108.7 Gg of nitrous oxide (N₂O) emissions from livestock waste are taken into account, it is evident that Malaysia's agricultural sector is under significant pressure to meet its commitments under the Global Methane Pledge and the broader Net Zero 2050 targets.

Despite the growing urgency for environmental reform, Malaysia's transition toward sustainable livestock management is significantly hampered by the high capital costs of industrial manure processing and a localized shortage of technical expertise (Tiraieyari et al., 2014). While global research often highlights advanced anaerobic digesters or sophisticated feed additives, these solutions remain largely inaccessible to Malaysian small and medium enterprise (SME) farmers due to extreme financial constraints (Aziz et al., 2024). This has led to a widening gap between the technical requirements for mitigating greenhouse gas emissions and the economic reality of manure management, stalling the adoption of greener practices (Nagy et al., 2025). To bridge this divide, focus must shift toward practical and low-cost alternatives such as slurry acidification or the use of floating biological covers made from agricultural waste such as rice husks or wood chips, which can effectively suppress CH₄ and NH₃ emissions without the need for prohibitive industrial investment (Guarino et al., 2006; Petersen et al., 2012).

Slurry acidification represents a promising practical intervention to mitigate agricultural emissions by lowering pH levels, typically between 5.0 and 6.0; to shift the chemical equilibrium from volatile NH₃ to stable ammonium (NH₄⁺) ions. Beyond nitrogen (N) retention, this drop in pH effectively inhibits the methanogenic Archaea activities for CH₄ production. In temperate climates, this method has successfully inhibited CH₄ emissions by up to 87% (Petersen et al., 2012). However, these results cannot be directly extrapolated to a

tropical context like Malaysia, where high ambient temperatures and unique manure compositions present unexplored biochemical challenges. Furthermore, most existing literature remains confined focusing primarily on controlled laboratories studies or large-scale industrial digesters, leaving a critical gap in accessible, field-ready applications for smaller producers. To address the gap between laboratory findings and practical application, this study transitions to a field-scale pilot observation. By utilizing 600-liter high-density polyethylene (HDPE) tanks, the research replicates the durable, corrosion-resistant storage systems typical of modern farm infrastructure. This study evaluates the continuous acidification of beef cattle slurry using concentrated sulfuric acid to evaluate on-farm observation and provide a scalable solution that aligns with the farm management practices while balancing environmental stewardship with economic viability under Malaysia's specific tropical conditions.

MATERIALS AND METHODS

The study was conducted at the manure pond of the Feedlot Complex, MARDI Kluang Station, Johor. Fresh cattle slurry (FS) was obtained from the complex's manure collection pond. The fresh slurry was pumped and homogenized in a 2,000-liter high-density polyethylene (HDPE) tank before being distributed in 700-liter experimental polytanks. This process was repeated until eight polytanks were filled for the study. The slurry was derived from Brakmas and crossbreed beef cattle maintained on a total mixed ration (TMR) formulated to meet growth requirements. The diet consisted of 60% concentrates (palm kernel expeller, ground corn, soybean meal, and crude palm oil) and 40% fresh pasture on a dry matter (DM) basis. Baseline physicochemical analysis characterized the slurry with a pH of 6.5 ± 0.04 , DM content of $3.5 \pm 0.21\%$, and volatile solids (VS) at $59.8 \pm 2.70\%$. The total carbon (C) and nitrogen (N) concentrations were 58.05 ± 9.10 g/kg and 3.79 ± 0.46 g/kg, respectively, yielding a C:N ratio of 15.32 :3.04.

Pilot Observation

Experimental Design and Acidification Protocol

The study was conducted over three months using a pilot-scale framework. Approximately 560–600 L of slurry were transferred into 700 L high-density polyethylene (HDPE) tanks, with four replicates assigned to each treatment ($n=4$). The experimental groups consisted of a non-acidified control (Ctrl) and an acidified treatment (H_2SO_4). For the latter, concentrated sulfuric acid (H_2SO_4) was added to the slurry incrementally with continuous mixing until a pH of 5.0 was achieved. To account for the buffering capacity of the organic matter, pH levels were monitored periodically, and re-acidification was carried out multiple times until the pH stabilized at 5.0. Throughout 4 months observation period, re-acidification was performed every three weeks following the removal and replacement of 1/3 of the tank volume with new fresh slurry.

Physicochemical and Nutrient Analysis

Dry matter (DM) and volatile solids (VS) were determined gravimetrically by oven-drying at 105°C and subsequent combustion at 450°C in a muffle furnace (Carbolite CWF 1200, UK). Elemental Carbon (C) and Nitrogen (N) were quantified using a Vario Macro Cube CHNOS Analyzer (Elementar, Germany). Slurry temperature and pH/ORP (oxidation redox potential) were monitored using a Hanna pH electrode probe (model HI 991003; Hanna Instrument, USA). Additionally, ambient temperature and humidity were recorded using an EasyLog EL-USB-2-LCD device (Lascar Electronics, United Kingdom).

Greenhouse Gas and Ammonia Quantification

Methane emissions were measured from the headspace of HDPE polytanks utilizing a method analogous to the static chamber approach. During sampling intervals, the tanks were hermetically sealed with lids and reinforced with five layers of wrapping film to ensure a gas-tight environment. Headspace gas was then extracted through butyl rubber septa using a 25 mL syringe at 0, 30, and 60 minutes, with 22 mL of the sample transferred into pre-evacuated 20 mL vials. The gas composition was subsequently analyzed using a customized Agilent 8890B Gas Chromatograph with Agilent 8697 Headspace autosampler equipped with Electron Capture (ECD) and Flame Ionization (FID) detectors alongside two HayeSep Q 2 mm columns of 12 feet and 6 feet in length.

Ammonia (NH₃) volatilization was quantified using a closed-loop recirculating blowing method. Headspace gas was continuously pumped and circulated through an external trap containing 0.02 M orthophosphoric acid (H₃PO₄) before being returned to the tank. The resulting ammonium-N (NH₄⁺-N) concentration in the acid trap was determined using the salicylate-hypochlorite method (Mulvaney, 1996) and measured at 667 nm using a SpectraMax ABS microplate reader. Cumulative emissions were calculated by integrating flux data over the storage duration using the trapezoidal rule (Cardenas et al., 2010).

Cost Benefit and Economy study

i. Cost-Benefit Analysis (CBA) Framework

A Cost-Benefit Analysis (CBA) is employed to evaluate the economic viability of livestock slurry acidification using H₂SO₄. The functional unit is defined as 1,000 liters of slurry, providing a standardized scale for comparing treated and untreated scenarios. The system boundary encompasses the entire process from chemical treatment to the resulting changes in greenhouse gas (GHG) emissions and nutrient recovery. Greenhouse gas reductions, specifically CH₄ and indirect N₂O, are calculated following the IPCC Tier 1 methodology (IPCC, 2019) and converted into CO₂ equivalents (CO₂ eq) using Global Warming Potential (GWP100) factors. Indirect N₂O mitigation is estimated based on the reduction of NH₃ volatilization, utilizing the IPCC emission factor (EF4) to quantify the avoided transformation of N into N₂O after deposition.

ii. Economic Valuation and Indicators

Economic viability is determined by aggregating total costs and benefits into monetary units to derive the Net Benefit and the Benefit-Cost Ratio (BCR). Total costs include chemical inputs (H_2SO_4) and operational expenses such as labor and logistics. Benefits are categorized into three streams: carbon credits from CH_4 mitigation, the market value of retained N as fertilizer, and the economic gains from avoided indirect N_2O emissions. Within this analytical framework, the C price was held constant at a premium of RM1,003.50/ CO_2 eq to reflect current high-value carbon scenarios. The carbon price applied in this analysis reflects a premium or policy-driven valuation scenario, which may differ from baseline voluntary carbon market prices, and therefore should be interpreted within this contextual assumption. Chemical expenditures were indexed to prevailing market rates to ensure contemporary economic relevance. A BCR exceeding 1.0 is used as the primary indicator of economic feasibility and investment efficiency under the defined analytical assumptions. This framework integrates environmental dimensions with economic performance to provide a comprehensive assessment of the technology's sustainability (Fangueiro et al., 2015; Boardman et al., 2018).

Field Pond Trial*Slurry Pond Acidification*

Localized acidification was facilitated within a 30 ft x 90 ft manure pond, which was partitioned using a PVC membrane from both ends to isolate a controlled experimental area of 12 ft x 30 ft. Acidification was executed by applying a concentrated H_2SO_4 at multiple strategic locations. To ensure chemical homogeneity, the slurry was agitated using a suction and circulation pump system until a stabilized target pH of 5.0 was attained. Slurry pH was monitored in situ near the sampling site using a Hanna Instrument HI 991003 (USA). These measurements were synchronized with each gas sampling event to establish a direct correlation between the acidification-induced chemical stability of the slurry and the resulting NH_3 volatilization and CH_4 emission rates.

Floating Chamber Deployment for Ammonia and Methane Sampling

To quantify NH_3 and CH_4 emissions from the slurry surface, a dual floating chamber system was deployed at the manure collection pond. Each unit comprised a transparent headspace chamber measuring 30 x 30 x 30 cm, which was mounted onto a rigid support frame (Figure 1(i)). To maintain a gas-tight seal against the slurry while adapting to fluctuating liquid levels, the chambers were equipped with buoyancy floaters and an integrated air-water lock mechanism between the frame and the chamber headspace. The headspace of each unit was connected to a pond-side sampling station via silicone tubing. A closed-loop circulation pump was utilized to continuously draw gas through the sampling line for the precise analysis of NH_3 and CH_4 concentrations.

Gas Sampling and Monitoring

Gas sampling was performed twice at different spots on the same day to provide replicates (two replicates across two chambers; n=4). This was repeated over multiple intervals to capture temporal variations in emissions. The sampling schedule was divided into two distinct phases:

- i. Baseline phase: Sampling was conducted multiple times at different daily intervals before the acidification treatment.
- ii. Post-treatment phase: Sampling conducted at intervals following the acidification of the slurry.

Methane gas was sampled from the sampling port at the sampling station. Gas samples were extracted from the headspace through butyl rubber septa using a 25 mL syringe at 0, 30, and 60 minutes post-sealing. Each sample was immediately transferred to a pre-evacuated 20 mL glass vial. Similarly, the CH₄ concentration was determined using the customised GC mentioned above. While, NH₃ volatilization was measured using a closed-loop recirculating blowing method, an acid trap system was located at the sampling station. Headspace gas was continuously pumped from the tank, circulated and bubbled through an external trap containing 100 mL of 0.02 M orthophosphoric acid (H₃PO₄) before being returned to the floating chamber on the pond. Each sampling session consisted of a one-hour circulation period, after which the acid trap was collected for analysis. The accumulated ammonium-N (NH₄⁺-N) concentration within the trap was quantified via the salicylate-hypochlorite method (Mulvaney, 1996), with absorbance measured at 667 nm using a SpectraMax ABS microplate reader.



(i)



(ii)



(iii)

Figure 1: Field deployment of the recirculating gas sampling system (i), highlighting the battery-operated pumps (ii) and the manual extraction of headspace gas via syringe (iii).

RESULTS AND DISCUSSION

General physicochemical observation

The slurry collected from the reception pit in this study exhibited characteristics at the lower end of the spectrum (Table 1) (Agriculture and Horticulture Development Board, 2023). The results showed that the Ctrl slurry used had 3.50% Fwt DM with 59.78% VS DM⁻¹ content, and a significant change after over 119 days of storage period (Table 1). The low dry matter content can be attributed by the pond deep cleaning maintenance prior to the experimental study. There were no significant changes between treatments in DM and VS content. Thus, other perimeters were subjected to the effect of the low dry matter content available. The Ctrl

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slurry pH was at neutral pH 6.48 with an average at pH 6.51 during the entire storage period. The C/N ratios of the analysed slurry samples ranged from 12.56 ± 2.84 to 17.43 ± 1.22 . These values fall well below the critical threshold of 20:1, which is traditionally recognized as the pivot point between N immobilization and mineralization. Consequently, these results suggest that the organic matter in the slurry is likely to undergo net mineralization, ensuring that N is readily converted into inorganic forms (NH_4^+) available for plant uptake.

Table 1: Comparative physicochemical analysis of untreated (Ctrl) and treated (H_2SO_4) livestock slurry at Day 0 and the final day of the experimental period. Data are expressed as mean \pm SEM (n = 4).

Slurry Characteristics	Ctrl		Acidified (H_2SO_4)	
	Start (Day 0)	End (day 119)	Start (Day 0)	End (day 119)
Dry Matter (% Fwt)	3.50 ± 0.49	8.97 ± 1.73	2.44 ± 0.21	10.23 ± 0.88
Volatile solid (% VS /DM)	59.78 ± 2.70	60.19 ± 1.67	51.63 ± 4.11	61.86 ± 1.01
Ammonium (NH_4^+N) Content (mg/kg slurry)	5.34 ± 0.26	67.69 ± 2.10	5.62 ± 0.77	76.98 ± 2.09
pH	6.5 ± 0.04	6.38 ± 0.07	4.9 ± 0.02	6.11 ± 0.04
ORP (mV)	-135 ± 1.44	-192.0 ± 4.78	-123.2 ± 1.65	-146.8 ± 5.24
Total C (g/kg slurry)	58.05 ± 9.10	33.76 ± 3.82	26.62 ± 4.36	45.67 ± 3.12
Total N (g/kg slurry)	3.79 ± 0.46	2.12 ± 0.23	2.12 ± 0.33	2.62 ± 0.04
Slurry temperature ($^\circ\text{C}$)	33.65 ± 0.10	27.8 ± 0.21	33.9 ± 0.42	27.8 ± 0.21

Slurry Dry Matter and Volatile Solid Content

The dynamics of DM and VS content per 1,000 kg of slurry over the incubation period are illustrated in Figure 2. Both the acidified (H_2SO_4) and Ctrl groups exhibited an upward trend in solids content during the first half of the incubation. Initially, DM content for the H_2SO_4 group was lower at 24.5 kg compared to 34.9 kg in the control. However, by mid-June, the H_2SO_4 group showed a sharper increase, reaching a peak of 102.3 kg, while the control reached 89.5 kg. Following this peak, both groups showed fluctuations, with the control group experiencing a more pronounced dip in late July before recovering toward the end of the observation period. A similar trend was observed for VS, which represents the organic fraction of the slurry. The VS content in the H_2SO_4 group rose from an initial 12.5 kg to a stabilized range between 58.0 kg and 63.4 kg after June. The control group followed a similar trajectory but generally maintained lower VS values compared to the acidified treatment from June onwards, peaking at 61.4 kg in early July. The higher retention of DM and VS in the acidified group suggests that the addition of H_2SO_4 may have influenced the degradation rate or the preservation of organic matter within the slurry compared to the untreated control.

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The dynamic progression of dry matter (DM) and volatile solids (VS) is influenced by the accumulation of organic matter in the pond following daily manure input into the pond. The result also suggests that H₂SO₄ acidification acts as a stabilizing agent, potentially inhibiting the rapid microbial decomposition of organic fractions compared to untreated slurry. While both treatments exhibited an initial accumulation phase peaking in mid-June, likely influenced by the net mineralization indicated by the low C/N ratios (12.56 to 17.43), the acidified group maintained higher retention of DM (102.3 kg/1000kg) and VS throughout the latter half of the incubation period. This preservation of solids aligns with the observation that C/N ratios below the 20:1 threshold favor the conversion of organic matter into plant-available inorganic N, yet the lower pH (initial 4.9) in the H₂SO₄ treatment appears to have moderated the degradation rate (Agriculture and Horticulture Development Board, 2023). The pronounced fluctuations in the control group's DM and VS levels relative to the more stabilized acidified profile further suggest that H₂SO₄ addition mitigates the volatility of organic matter breakdown, thereby enhancing the nutrient density and structural integrity of the slurry over extended storage durations.

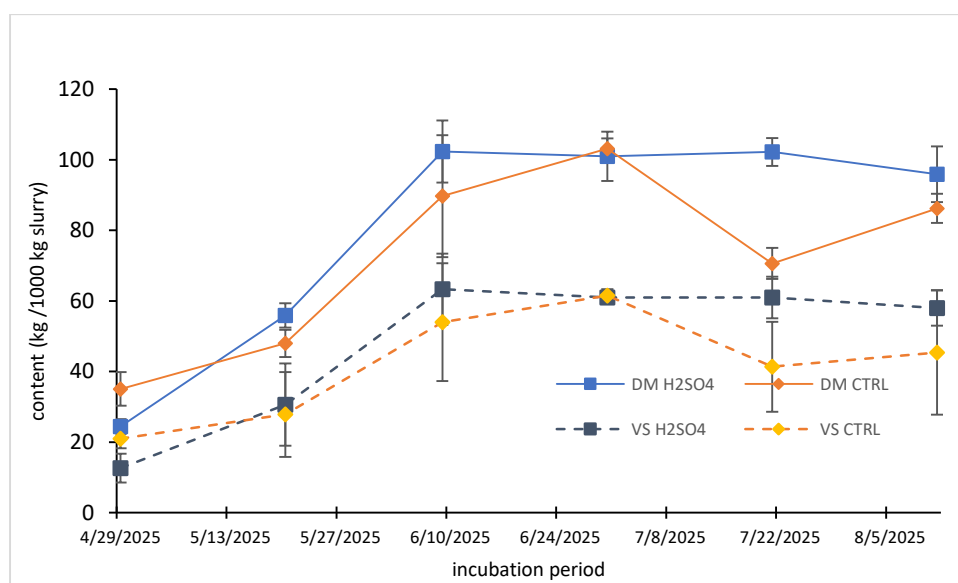


Figure 2: Dry Matter and Volatile Solid Content (per 1000kg slurry) Dynamic Over Incubation Period

Slurry pH and ORP

The acidified slurry with H₂SO₄ addition showed a gradual increase in its pH, rose to nearly neutral pH at day 16 (pH 6.5; Figure 3). The reacidification every 3 weeks is needed to return the slurry to an acidic environment below pH 6.0 during the observation periods. The immediate drop in slurry pH indicates reacidification to pH 5.0 followed by an increase to pH 5.3 to 5.3 in the following day. These occurrences repeated during the reacidification processes. In contrast, the Ctrl pH dynamics remain above pH 6.0 at between pH 6.3 and 6.8 during similar

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periods. This observation indicates the Ctrl slurry did not reach pH 7.0 and above during pilot observation. Meanwhile, the ORP of the slurry remained consistently negative throughout the incubation (Figure 4), indicating predominantly reducing conditions in both treatments. However, the H₂SO₄-treated samples showed greater variability, with ORP values fluctuating widely (approximately -320 to -100 mV) and several transient increases followed by sharp declines to more reduced states, which was reflected by the reacidification processes. Overall, acidification led to more dynamic ORP changes and generally more reducing conditions compared to the control. Overall, the H₂SO₄ treatment consistently maintained lower (more negative) ORP values than the control, particularly during the mid-incubation phase.

The rapid pH "rebound" following H₂SO₄ addition highlights the strong buffering capacity of the slurry, likely driven by the release of ammonium (NH₄⁺) and bicarbonate (HCO₃⁻) during organic matter degradation (Hjorth et al., 2010). The recurring reacidification indicates that the slurry's chemical equilibrium naturally shifts toward neutral pH during anaerobic storage, counteracting mineral acid inputs (Fangueiro et al., 2015). The intensified reducing conditions (lower ORP) in the acidified treatment suggest a shift in microbial metabolism. By introducing sulfate (SO₄²⁻), H₂SO₄ provides a terminal electron acceptor that favors the activity of sulfate-reducing bacteria (SRB). These organisms typically outcompete methanogens and drive the redox potential to more negative values (Sokolov et al., 2020). The wide ORP fluctuations further suggest that periodic reacidification creates a dynamic environment, forcing the microbial community to repeatedly adjust its metabolic pathways in response to chemical perturbations.

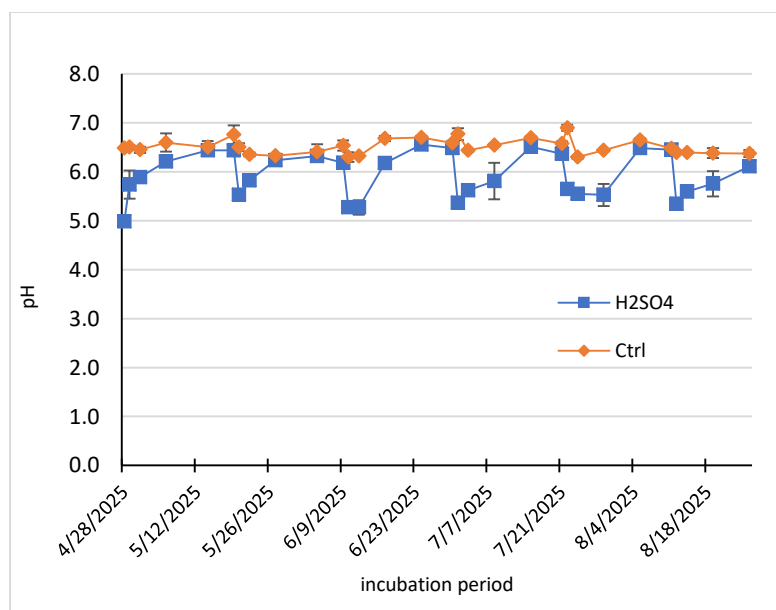


Figure 3: Slurry pH dynamic over incubation period

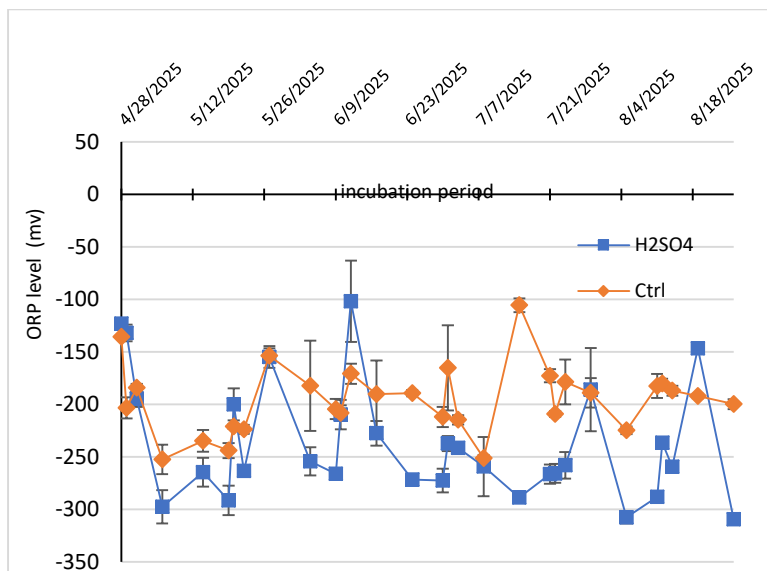


Figure 4: Slurries oxidation redox potential (ORP) dynamics during storage period.

Slurry Temperature, Ambient Temperature and Rainfall

The dynamic of slurry temperature throughout the incubation period for both the H₂SO₄ treated and control groups is shown in Figure 5. Both groups followed a consistent and closely linked trend, with temperatures remaining stable between approximately 26.0°C and 34.0°C. Initial temperatures were highest, at 32.7°C for the H₂SO₄ group and 33.6°C for the control. Over the course of the incubation, both treatments exhibited periodic fluctuations, often reflecting the ambient air temperature patterns. A notable peak occurred around July 1st, where the H₂SO₄ slurry reached 32.7°C, contrasting with a slight decrease observed on July 24th, when the control slurry dipped to 27.4°C. The standard deviations for both groups remained small, suggesting high reproducibility between the measurement replicates. Ultimately, no statistical difference was observed between the temperatures of the H₂SO₄ treated slurry and the control group, indicating that the acid treatment did not influence the internal temperature profile.

Meteorological data (Figure 6) showed steady ambient temperatures (avg. 27°C) but substantial volatility in relative humidity (78%–99%). Peak humidity levels coincided with intermittent precipitation events between May and August, with the most significant rainfall (>1.20 mm) recorded on June 16th and August 12th. This thermal synchrony between the slurry and the atmosphere aligns with Hafner et al. (2020), who established that thermal inertia in uninsulated liquid manure storage is governed by external meteorological forcing rather than internal biogenic heat production. Furthermore, the strong congruence between rainfall patterns and humidity spikes underscores the sensitivity of the storage environment to regional climatic

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shifts. These conditions create a diminished vapor pressure gradient at the slurry-air interface, which may hinder the convective mass transfer of volatile compounds independently of the acidification treatment.

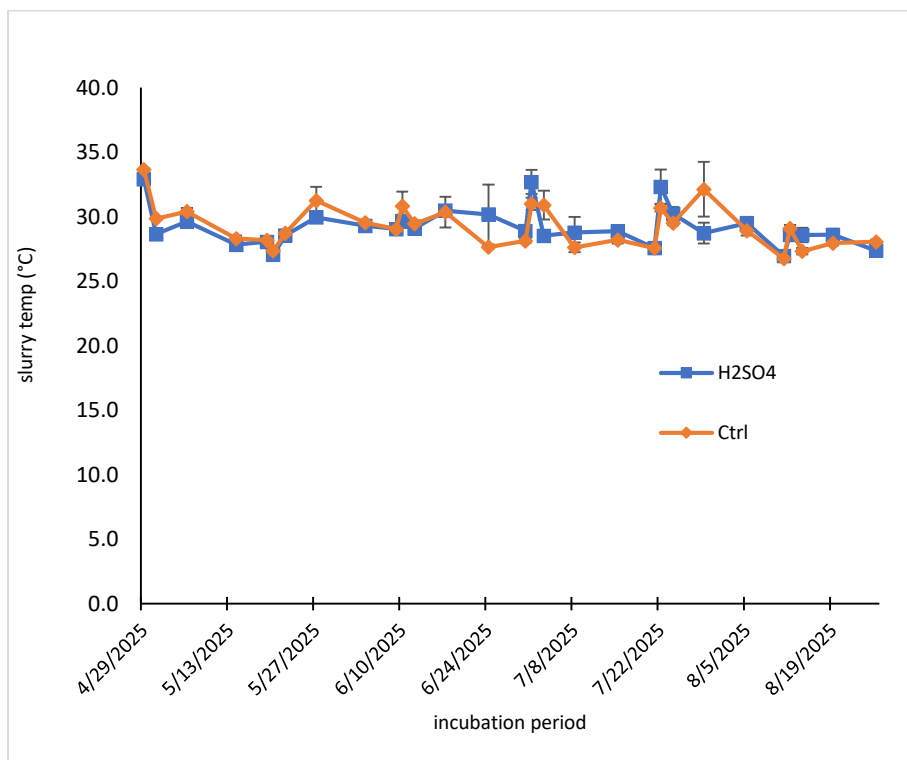


Figure 5: Slurries temperature during storage period.

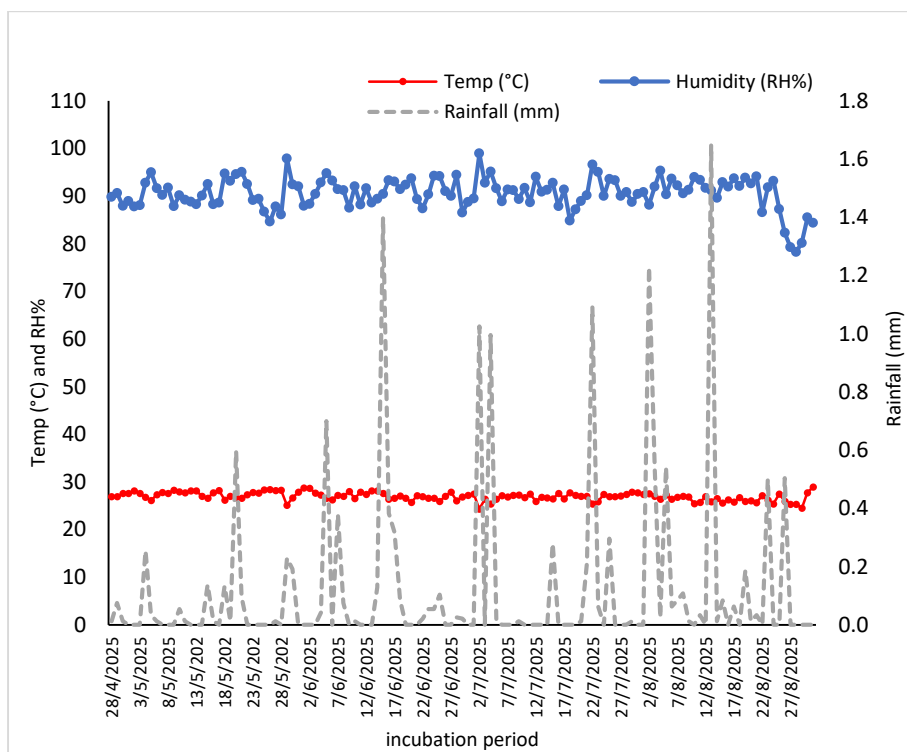


Figure 6: Ambient temperature, humidity and rainfall level during storage period.

Methane and Ammonia Emissions

Methane Emission

The temporal and cumulative dynamics of CH₄ emissions reveal a striking contrast between the acidified and untreated cattle slurries. In the Ctrl group, daily CH₄ fluxes were characterized by sporadic and intense bursts of activity, reaching a maximum peak of approximately 54×10^6 mg/kg VS/day around day 108. Conversely, the H₂SO₄ treatment effectively "flattened the curve," suppressing these spikes and maintaining flux levels generally below 20×10^6 mg/kg VS/day throughout the 120-day period. This suppression is even more evident in the cumulative data. The cumulative emission by the end of the incubation, the Ctrl slurry released roughly 115 g/kg VS of CH₄, more than double the 43 g/kg VS emitted by the acidified by H₂SO₄. A notable divergence occurred after day 22, where the Ctrl group entered a phase of rapid, stepped increases, while the acidified treatment successfully delayed and attenuated the onset of major methanogenesis. Overall, the use of H₂SO₄ resulted in a 62.3% reduction in cumulative methane emissions compared to the control.

The substantial reduction in both daily flux and cumulative CH₄ emissions underscores the potency of H₂SO₄ acidification as a mitigation tool for livestock waste management. This sharp decline is attributed to the fact that acidification effectively inhibits the majority of the

methanogenic population. However, certain acid-tolerant methane producers within the phylogenetic Orders *Methanobacteriales*, *Methanomicrobiales*, and *Methanosarcinales* are known to persist despite the low-pH environment (Bastami et al., 2020). By lowering the slurry pH, the treatment disrupts the primary enzymatic pathways of most microbes, stalling the final stage of anaerobic digestion. Nevertheless, the eventual resurgence in emissions suggests that the resilient members of these specific orders are responsible for the renewed CH₄ production as they overcome the initial acid stress. These findings align with previous research, such as the study by Misselbrook et al., (2016), which reported that slurry acidification to a pH of 5.5 can reduce methane emissions by 67–90% during storage. Similarly, the delayed onset of methanogenesis observed after day 22 mirrors results from Kavanagh et al., (2019) suggesting that acid treatment extends the lag phase of methanogenic archaea development.

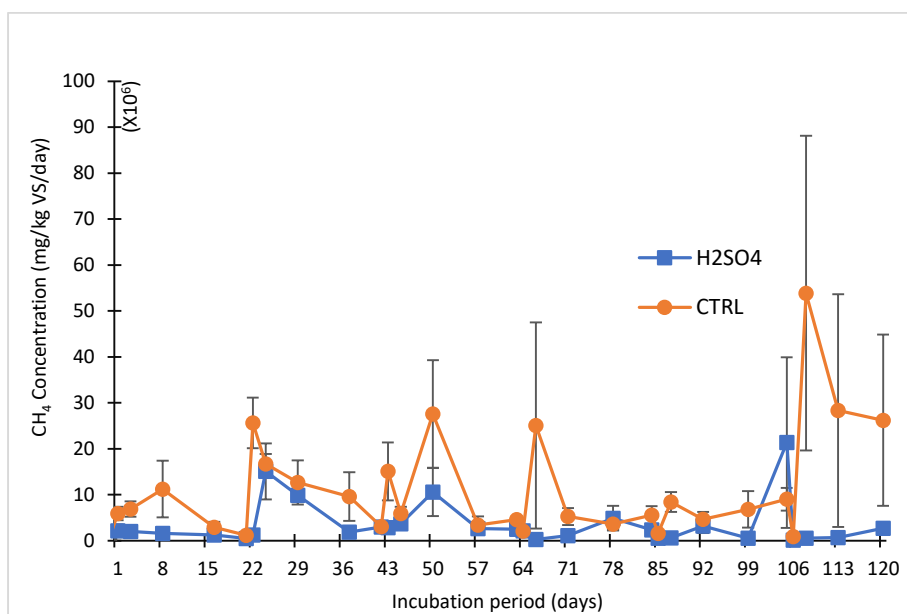


Figure 7: Comparative methane fluxes from sulfuric acid treated and untreated (Ctrl) slurry over a 120-Day storage incubation.

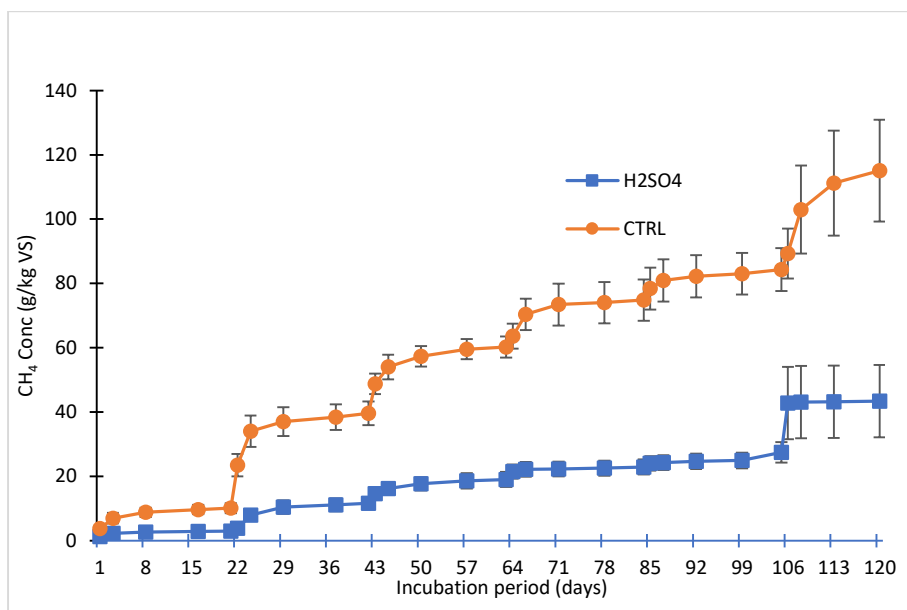


Figure 8: Cumulative methane emissions from Sulfuric Acidified and untreated (Ctrl) cattle Slurries during a 120-Day Incubation Period.

Ammonia Volatilization

The dynamics of NH₃ volatilization over a 120-day incubation period revealed a distinct suppressing effect of H₂SO₄ acid treatment compared to the Ctrl. While both groups maintained low emissions for the first 36 days, several high-magnitude pulses occurred thereafter. Despite a sharp transient peak in the H₂SO₄ group on day 64 reaching 23,000 mg/m², the acidified treatment generally maintained lower flux rates throughout the study. Cumulative data highlights this divergence after day 43, with final N losses for the control reaching 102 x 10⁶ g/m² compared to only 66 x 10⁶ g/m² in the H₂SO₄ treatment, representing a significant reduction in total N escape. This represents a substantial 35.3% reduction in total ammonia volatilization, demonstrating the high efficacy of acidification in mitigating N escape during storage.

The dy

namics of NH₃ volatilization observed in this study are primarily driven by the chemical equilibrium at the surface interface, where the addition of H₂SO₄ effectively shifts the NH₄⁺/NH₃ balance toward the non-volatile ionic form. The rapid loss of NH₃ seen in the control suggests a high rate of conversion from ammonium, a process typically exacerbated by elevated pH levels and temperature (Sanz-Cobena et al., 2017). This volatilization represents a substantial loss of N, which directly impairs the nutrient use efficiency of the system. The sharp, episodic flux peaks observed in both treatments likely correspond to fluctuations in surface moisture or ambient temperature, yet the cumulative data confirm that acidification provides a consistent buffer against these environmental drivers. To mitigate these losses,

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intervention strategies should focus on pH stabilization or the use of inhibitors to prevent the gaseous escape of N, ensuring better retention of nutrients for their intended agricultural or biological functions (Fangueiro et al., 2015). By lowering the slurry pH, H₂SO₄ treatment serves as a critical intervention to minimize the concentration of free NH₃ available for transport across the liquid-gas interface.

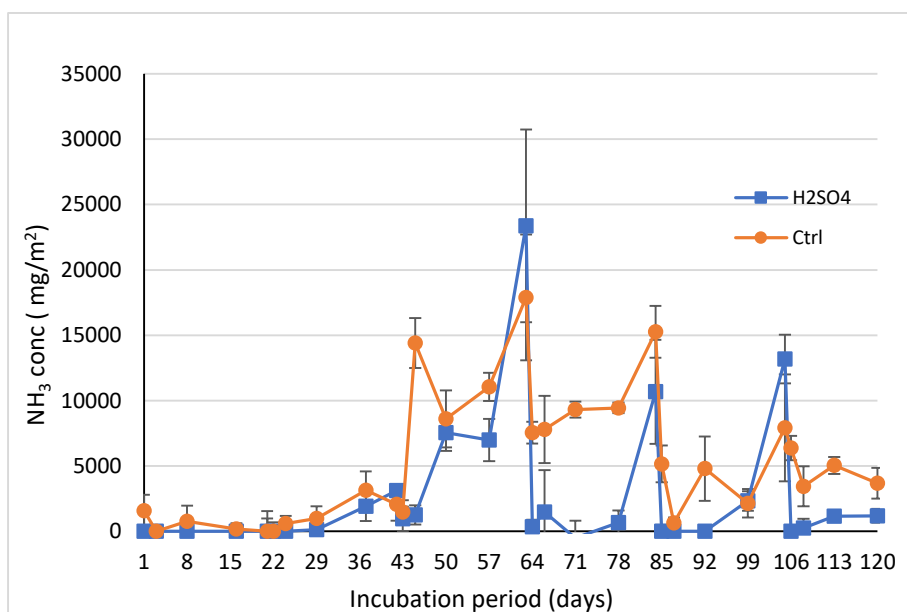


Figure 9: Comparative ammonia fluxes from sulfuric acid-treated and untreated (Ctrl slurries during a 120-day incubation period)

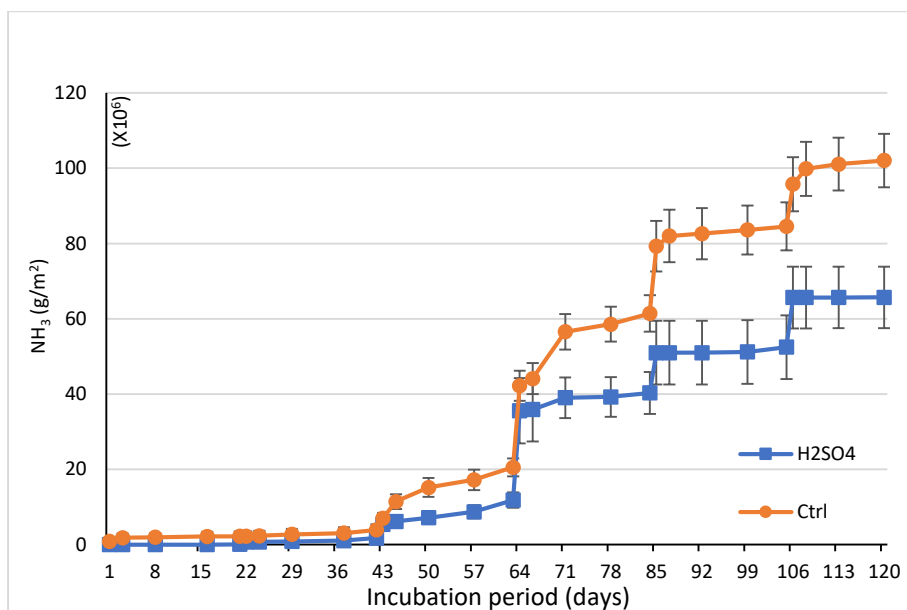


Figure 10: Cumulative ammonia emissions from Sulfuric Acidified and untreated (Ctrl) cattle slurries during a 120-day incubation period

Cost Benefit and Economy Study

The cost-benefit analysis (CBA) indicates that slurry acidification using H₂SO₄ is economically viable, yielding a positive return of RM26.84 per 1,000 liters of treated slurry. With an estimated treatment cost of RM88.95 and total benefits of RM115.79, the technology achieves a Benefit-Cost Ratio (BCR) of 1.30 (Table 2). While a BCR > 1.0 justifies investment, the moderate net benefit suggests that profitability remains sensitive to market fluctuations, particularly regarding input costs and C pricing.

Table 2: Summary of Costs and Benefits per 1,000 Liters of Slurry

Component	Value (RM)
Treatment Cost	88.95
Methane (CH ₄) Mitigation	95.51
Fertilizer Value (Nitrogen)	19.02
Indirect N ₂ O Mitigation	1.25
Gross Benefits	115.79
Net Benefit	26.84
Benefit-Cost Ratio (BCR)	1.30

Benefit Composition and Nutrient Recovery

Methane mitigation is the primary economic driver, accounting for over 80% of total benefits. This concentration of benefits highlights a structural dependency on carbon-based revenue streams, suggesting that the long-term sustainability of the system may require complementary value generation from nutrient recovery or policy support mechanisms. Although N retention and indirect N₂O reduction contribute less to the total monetary value, they provide critical agronomic advantages. By preserving N, the approach enhances the fertilizer quality of the slurry, reducing the producer's dependence on synthetic inputs and aligning with "carbon and nutrient recovery" frameworks in sustainable agriculture (Fangueiro et al., 2015).

Sensitivity Analysis and Socio-Environmental Implications

The economic viability of acidification is highly contingent upon market fluctuations, specifically C pricing and chemical expenditures. Sensitivity analysis reveals that H₂SO₄ procurement constitutes approximately 87% (RM77.35) of total treatment costs, making the project's BCR vulnerable to price shocks in the chemical sector; for instance, a 20% increase in acid costs would nearly neutralize the net benefit. Furthermore, the technology's profitability relies heavily on premium C valuation (RM1,003.50/tCO₂ eq). A shift toward standard market rates would see CH₄ benefits drop drastically, potentially driving the BCR below the 1.0 feasibility threshold. This indicates that the economic feasibility of the technology is condition-dependent, where viability is sustained primarily under favourable carbon pricing scenarios and controlled input costs. Despite these identified market sensitivities, significant environmental and systemic advantages are offered by this technology through the simultaneous mitigation of CH₄, NH₃, and indirect N₂O pathways. Circular economy principles are further supported as slurry management is transitioned from a waste disposal challenge to a strategic resource optimization. However, for the viability of this multi-dimensional mitigation tool to be maintained at the farm level, policy interventions such as stable C incentives or chemical subsidies are considered essential to buffer producers against market volatility and ensure the consistency of economic returns.

Slurry pond acidification and GHG emissions

Following the acidification on 17 June 2025, a sharp drop in the pond's pH was observed, falling from a baseline of 7.1 to a target of 5.0 (Figure 7). This sudden shift in the chemical environment had a profound impact on CH₄ production. Prior to treatment, high methanogenic activity was exhibited by the untreated slurry, with baseline emissions peaking near 80,000 mg/m² (Figure 8). Once the slurry pH was reduced to 5.0, CH₄ emissions were recorded to have plummeted to 8,000 mg/m² by the following day. This change represented an effective reduction in methane output of 90%. Over the subsequent weeks, a gradual increase in pH was caused by the slurry's natural buffering capacity, reaching 6.6 by mid-July. This recovery was closely mirrored by the CH₄ flux; as the acidity weakened, emissions were seen to rise steadily before eventually leveling off at approximately 40,000 mg/m². A direct link between slurry pH

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and gas suppression is highlighted by these findings, suggesting that while CH₄ emissions can be powerfully curbed by acidification, long-term success is dependent on the duration for which the lowered pH can be maintained.

The observed suppression of methanogenesis at a pH of 5.0 is consistent with the physiological constraints of methanogenic archaea, which typically thrive in circumneutral conditions. The 90% reduction in CH₄ flux immediately following acidification suggests that the enzymatic pathways responsible for methanogenesis were effectively inhibited. As stated by Kavanagh et al., (2019), the maintenance of a slurry pH below 6.0 is essential for the sustained inhibition of methanogenic archaea, as higher pH levels facilitate a rapid recovery of microbial activity. The subsequent resurgence in emissions alongside the recovery of pH to 6.6 underscores the resilience of the slurry's microbial population and the limitations of isolated acidification events. As the pH returned toward the neutral range, the thermodynamic favorability of methanogenic pathways was restored, allowing emissions to stabilize at 50% of the original baseline. This phenomenon highlights the "buffering challenge" inherent in waste management; without repeated dosing or the application of strong mineral acids to permanently alter alkalinity, the environmental benefits of acidification remain transient. As noted by (Sokolov et al., 2020), the natural buffering capacity of organic slurries often necessitates continuous monitoring and re-acidification to maintain gas suppression targets over extended periods.

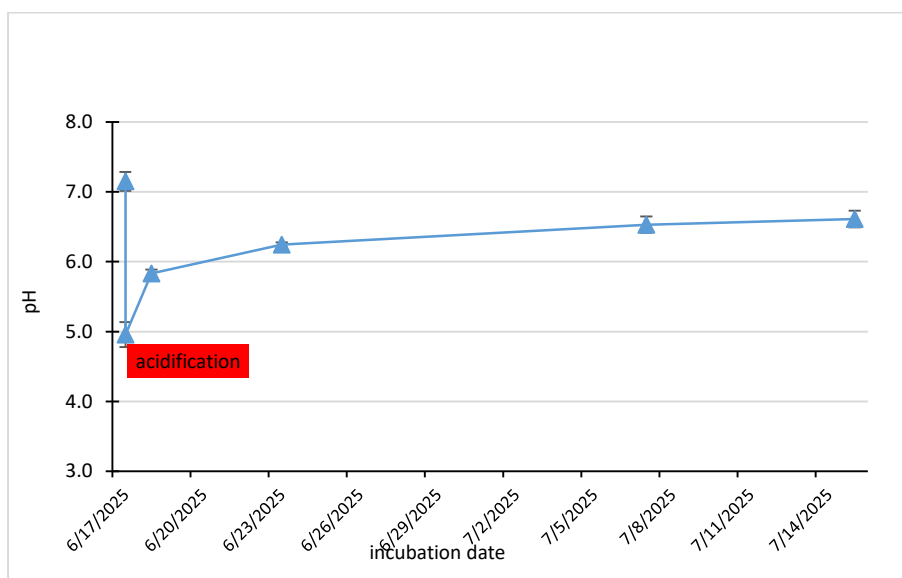


Figure 11: Slurry pond pH levels over time following acidification

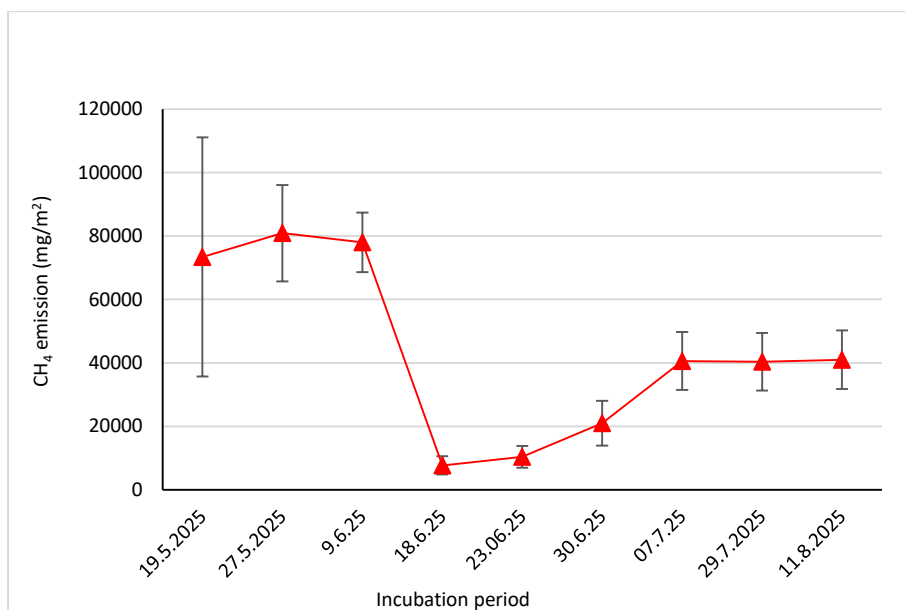


Figure 12: Methane (CH₄) emission flux during the storage observation period

General Discussion

The transition of cattle slurry acidification from controlled laboratory environments to field-scale pilot observations reveals critical insights into its potential as a cornerstone for sustainable livestock management in Malaysia. While traditional mitigation strategies like large-scale anaerobic digestion for biogas, offer high energy recovery, they are often hindered by prohibitive capital costs and a lack of specialized technical expertise among local small-to-medium enterprise (SME) farmers. By maintaining a slurry pH of 5.0, the treatment effectively shifts the chemical equilibrium to stabilize N as ammonium ions and inhibits methanogenic Archaea, providing a dual benefit of nutrient retention and greenhouse gas suppression. Furthermore, this approach has already been successfully standardized; for instance, in Denmark, in-house and storage acidification systems have become a benchmark technology for reducing ammonia emissions and improving N use efficiency (Fangueiro et al., 2015; Geels et al., 2023).

From a broader perspective, the practicality of acidification in Malaysia is bolstered by its economic viability, evidenced by a Benefit-Cost Ratio (BCR) of 1.30. Although the analysis demonstrates positive economic returns, the relatively small net benefit per functional unit may influence adoption decisions among small and medium enterprise farmers (SME farmers), particularly in the absence of financial incentives or risk-sharing mechanisms. This figure serves as an initial indication in the analysis; notably, adopting a strategy of recycling slurry

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pond effluent as a barn flushing liquid is expected to reduce the consumption of acidifying chemicals and consequently increase the BCR. This technology is significantly more accessible than high-tech manure processing, though its profitability remains sensitive to the market price of sulfuric acid, which constitutes approximately 87% of total treatment costs. To enhance farmer acceptance, the strategy must be framed as a resource optimization tool rather than a mere waste disposal requirement. The retention of N provides a tangible economic gain by increasing the market value of the slurry as a bio-fertilizer, potentially reducing a farmer's reliance on expensive synthetic inputs (Kavanagh et al., 2019). Furthermore, the immediate 90% reduction in methane flux observed at the pond scale demonstrates that even isolated or intermittent interventions can yield profound environmental results, though long-term success requires managing the "buffering challenge" where natural alkalinity tends to return the pH toward neutral. To ensure widespread adoption across the Malaysian agricultural landscape, the technology must be supported by policy interventions such as C incentives or chemical subsidies to protect producers from market volatility. Integrating acidification into current farm management practices can bridge the gap between scientific research and practical application, providing farmers with manageable tools that fit into their daily routines without intensive training. As the industry faces increasing pressure to meet commitments under the Global Methane Pledge and Net Zero 2050 targets, slurry acidification offers a scalable pathway to transform livestock waste into a strategic management in the C storage and market. Future efforts should focus on simplifying the re-acidification process and establishing stable C credit frameworks to ensure that environmental stewardship remains aligned with the economic survival of local producers, mirroring the regulatory successes seen in European livestock sectors (Sokolov et al., 2020).

CONCLUSIONS

This study concludes that continuous acidification of cattle slurry to a target pH of 5.0 is an effective strategy for mitigating CH₄ and NH₃ emissions in tropical climates. The field-scale pilot successfully demonstrated that decentralized, low-tech acidification can significantly reduce the environmental footprint of livestock management, achieving a 62.3% reduction in cumulative methane and a 35.3% reduction in ammonia loss. While the slurry's natural buffering capacity presents a technical challenge requiring regular monitoring and re-dosing, the immediate 90% drop in methane flux at the pond scale confirms the high reactivity of the treatment. Economically, the Benefit-Cost Ratio of 1.30 supports feasibility of the system under the current assumptions; however, sustained viability will depend on stable carbon pricing frameworks and effective cost management.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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