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Exploring Continuous Cattle Slurry Acidification as a Strategy for Reducing Greenhouse Gas Emissions

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Abstract: *Cattle feedlot farming typically relies on multiple lagoons for slurry storage, which significantly contributes to greenhouse gas emissions. Slurry acidification is a promising approach for reducing greenhouse gas (GHG) and ammonia (NH_3) emissions from livestock manure management. A study was conducted to evaluate an alternative method of reducing NH_3 and CH_4 emissions during slurry storage by maintaining a lower pH through continuous acidification with concentrated hydrochloric acid (HCl), concentrated sulfuric acid (H_2SO_4), lactic acid ($C_3H_6O_3$), and nitric acid (HNO_3). Cattle slurry was collected from commercial farms, stored with different acids to maintain a pH of 5.0, and re-acidified every three weeks. The results showed that reducing slurry pH with HCl and H_2SO_4 significantly decreased NH_3 volatilization by 86.8% and 82.9%, respectively. Both HNO_3 and $C_3H_6O_3$ reduced NH_3 emissions by 63%. In terms of CH_4 emissions, HCl and H_2SO_4 inhibited emissions by 17.7% and 19.3%, respectively, while HNO_3 was more effective, reducing CH_4 by 57%. Interestingly, the use of $C_3H_6O_3$ did not reduce CH_4 emissions but instead led to a 151% increase in CH_4 release into the atmosphere. These findings emphasize the potential of acidification for mitigating emissions while highlighting the need to optimize acid selection and dosage to balance environmental and economic considerations. Further research should assess its long-term impacts, microbial interactions, and feasibility on-farm implementation.*

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

INTRODUCTION

The agricultural sector plays a significant role in contributing to global greenhouse gas (GHG) emissions, particularly through livestock-related activities such as enteric fermentation and manure management. These processes release methane (CH_4), a potent greenhouse gas with a global warming potential many times greater than carbon dioxide, and ammonia (NH_3), which contributes to atmospheric pollution, soil acidification, and water quality degradation. In Malaysia, livestock activities are responsible for a substantial portion of the country's GHG emissions, with 1,247.65 Gg CO_2-equivalent CH_4 emissions from enteric fermentation and 287.84 Gg CO_2-equivalent CH_4 from manure management reported in 2022. Additionally, livestock manures release 108.7 Gg CO_2-equivalent nitrous oxide (N_2O), further exacerbating the environmental burden (Ministry of Natural Resources and Environmental Sustainability, (NRES), 2024). As the impacts of climate change intensify, managing and reducing these emissions has become an urgent priority in Malaysia's agricultural sector.

Despite the importance of addressing GHG emissions from livestock, the adoption of mitigation technologies in Malaysia has lagged behind compared to developed countries. One major barrier is the cost and technical expertise required for implementing GHG reduction methods in livestock operations. The traditional profit-driven approach in the Malaysian livestock sector often limits the adoption of advanced, sustainable practices. While various GHG mitigation strategies have been explored globally—including changes in animal diets, the use of feed additives, improved manure management, and advanced technologies (Anderson et al., 2006; Chen et al., 2008; Božic et al., 2009; Petersen et al., 2013), many of these approaches remain unfeasible, unaffordable or difficult to implement for small- and medium-scale farms in Malaysia.

Among the promising approaches to mitigate GHG emissions from manure, slurry acidification has gained attention due to its cost-effectiveness and practicality. Slurry acidification involves lowering the pH of livestock slurry using either chemical or biological acids, which inhibits the microbial processes responsible for methane and ammonia production. This method has been shown to effectively reduce CH_4 emissions by 67-87% and NH_3 emissions by 50-88% during slurry storage and soil application (Petersen et al., 2012a; Fangueiro et al., 2015; Kupper et al., 2020). Additionally, acidification can help control odors and minimize the overall environmental impact of manure. However, while slurry acidification has been extensively studied and applied in temperate regions, its effectiveness in tropical climates like Malaysia remains largely unexplored. The unique environmental conditions in Malaysia, including high ambient temperatures and greater organic matter content in manure, present challenges that may affect the success of acidification techniques.

To address this gap, this study aims to evaluate the potential of slurry acidification in reducing GHG emissions, specifically CH_4 and NH_3 from dairy cattle slurry under tropical conditions. The research focuses on the continuous acidification of slurry using different types of acids, including concentrated hydrochloric acid (HCl), sulfuric acid (H_2SO_4), nitric acid (HNO_3), and lactic acid. By examining the effectiveness of these acids in a controlled lab-scale setting, this study seeks to provide an initial evaluation of how slurry acidification can mitigate GHG

emissions in Malaysia's tropical climate. The findings of this study will contribute to the development of more sustainable manure management practices in Malaysia, aligning with global climate change mitigation strategies. By assessing the potential of acidification to reduce GHG emissions, this research aims to provide valuable insights into cost-effective techniques that can be adopted by local farmers, supporting the transition toward more environmentally responsible livestock production systems. Ultimately, the goal is to provide evidence-based recommendations for policymakers and agricultural stakeholders to encourage the adoption of sustainable practices that contribute to both environmental sustainability and the long-term viability of the livestock sector.

MATERIALS AND METHODS

Fresh cattle slurry (FS) was collected from a holding pit and slurry pond at a private farm located near MARDI headquarters. The slurry originated from various breeds of dairy cattle that were fed a total mixed ration (TMR) formulated for dairy cattle. The feed was provided at 3% of their body weight on a dry matter (DM) basis and consisted of 60% concentrates and 40% fresh grass or pasture (DM basis). The concentrate feed primarily included palm kernel expeller (PKE), ground corn, soybean meal, soybean hulls, ground rice hulls, crude palm oil (CPO), molasses, and limestone, along with less than 0.002% minerals and trace elements to meet the nutritional requirements for optimal growth.

The slurry obtained were kept in a 1200 L HDPE polytank and stored for 48-92 hr prior to use. The slurry physicochemical composition (pH; oxidation redox potential, ORP; dry matter, DM; volatile solid, VS; carbon and nitrogen was characterized before the experimental design was carried out. Initial slurry characteristics were 2.4 ±0.21% dry matter Kg^{-1} slurry (DM), 69.9 ±5.31% volatile solid Kg^{-1} DM (VS), total carbon (C) 333.9 ±46.90 mg Kg^{-1} slurry, total nitrogen (N) 25.7 ±4.7 mg Kg^{-1} slurry, C:N ratio 13:1, and pH 7.7±0.09. Approximately 60kg of cattle slurry was transferred into 130 L *high-density polyethylene* (HDPE) and the slurries then is acidified to pH 5.0 using concentrate hydrochloride acid (HCl), concentrated sulphuric acid (H_2SO_4), lactic acid ($C_3H_6O_3$) and nitric acid (HNO_3). The acidification took couples of hours until slurry pH stabilized. The slurries pH is monitored periodically and reacidification to pH 5 is carried out every 3 weeks. The experiment was carried out for a period of 3 months.

Table 1: Summary of treatments used in the study

No.	*Abbreviations*	*Treatments*
1	Ctrl	Control, no acidification
2	HCl	Acidified using HCl
3	$C_3H_6O_3$	Acidified using lactic acid
4	HNO_3	Acidified using nitric acid
5	H_2SO_4	Acidified using sulfuric acid

Moisture loss, temperature and slurry pH and oxidation redox potential

The moisture loss of the slurry was measured using a digital weighing scale (FX5000i, AND Company Limited, Japan). Slurry temperature and pH/ORP monitored using a Hanna pH electrode probe (model HI 991003; Hanna Instrument, USA), with measurements taken only for the Ctrl treatment slurry to prevent any disturbance to the slurry surface. Additionally,

ambient temperature and humidity were recorded using an EasyLog EL-USB-2-LCD device (Lascar Electronics, United Kingdom).

Slurry dry matter (DM) and volatile solids (VS) content

Slurry dry matter (DM) and volatile solids (VS) were determined by drying 10 g slurry samples at 80°-105°C for 16 hours until a constant weight was achieved. The loss on ignition was then calculated by heating the samples at 450°C for 16 hours in a Carbolite CWF 1200 muffle furnace (Carbolite Ltd, UK).

Total carbon (C) and nitrogen (N)

The total C and N of fresh slurry were measured by Elementar Analyzer (CHNOS) model Vario Macro Cube (Elementar, Germany).

Total Phosphorus (P) and available Phosphorus (P)

Determination of Total Phosphorus (P):

Phosphorus concentration in slurry samples was determined using a standardized ashing and colorimetric method. A five (5) g of slurry sample was dried in oven at 100^{o}C for 3 hours and burned in a muffle furnace at 550^{o}C for 3 hours. The ashes were dissolved with 20 mL distilled water and 2 mL 2.88N sulphuric acid (H_2SO_4). The mixed solution was filtered using ashless filter paper and mixed. An approximately 0.2 mL of the mixture were mixed with 3.9 mL dH_2O and 1 mL ascorbic acid-molybdenum blue reagent (known as Murphy-Riley reagent). The solution absorbance was read at 880 nm after 10-20 mins reaction using UV-spectrophotometer (Thermo Scientific, US).

Determination of Available Phosphorus (P):

Approximately 0.3 g air dried slurry samples were extracted in 30 mL 0.5M sodium bicarbonate ($NaHCO_3$) for 16 hours, centrifuged at ~13,000 RPM for 10 min and filtered through Whatman 42 filter paper. A 0.2 mL supernatant sample was diluted to 4.0 mL dH_2O and 1 mL reducing agent [5.28 mg/ml ascorbic acid ($C_6H_8O_6$)]. Following a reaction between 10-20 minutes, the phosphorus content was analysed spectrophotometrically at 880nm spectrophotometer (Thermo Scientific, US).

Relative ammonia volatilization

Ammonia (NH_3) was sampled concurrently with the gas sampling period. The relative NH_3 volatilization was measured using a 0.02 M orthophosphoric acid (H_3PO_4) passive trap, which was placed in a sealed, non-ventilated environment (Misselbrook and Powell, 2005). The acid trap was carefully suspended within the headspace, positioned 3 cm from the vessel's edge. After one hour of incubation with the lid closed, the traps were removed, and the ammonium-N (NH_4^+N) concentration in the H_3PO_4 solution was determined following the method described by (Mulvaney, 1996). Before the incubation at 30°C, 15 µL of 6% Na_2EDTA, 60 µL of Na-Salicylate-nitroprusside, and 30 µL of hypochlorite solution were added. The Na-Salicylate-nitroprusside solution contained 7.8% (w/v) Na-Salicylate and 0.125% (w/v) Na-nitroprusside, while the hypochlorite solution (pH 13) included 2.96% (w/v) NaOH, 9.96% (w/v) K_2HPO_4, and 10% (v/v) Na-hypochlorite. Absorbance was measured after 30 minutes of incubation

using a SpectraMax ABS microplate reader at 667 nm, and the results were analysed with SoftMax Pro 7 (Molecular Devices, USA).

Methane emission

Greenhouse gas fluxes were sampled from the *ca.* 2 litres vessel headspace above drum through a butyl rubber septum during closed system. Headspace gas samples were taken immediately (T0) securing the lid in place, after 30 (T30) and 60 minutes (T60). Gas samples were placed in 20 mL pre-evacuated gas vials and analysed using Agilent 7890B gas chromatogram (GC). The GC was equipped with J &W Scientific CS- Gaspro 45 m X 0.320 µm capillary columns, and equipped with a flame ionized detector (FID). Gas fluxes were calculated based on the linear increase in gas concentration between the T0 and T60 samples over the one-hour period, headspace volume and slurry weight. Cumulative gas emissions for the storage period were calculated by interpolating the measurements between adjacent sampling points using the trapezoidal rule (Cardenas et al., 2010).

RESULTS

General physiochemical observation

The slurry collected from the reception pit in this study exhibited characteristics at the lower end of the spectrum (Table 2) (Agriculture and Horticulture Development Board, 2023). The results showed that the Ctrl slurry used had 2.44% Fwt DM with 72.9% VS DM^{-1} content, and insignificant change after over 91 days storage period (Table 2). The low dry matter content can be attributed to the use of solid-liquid separators at the slurry collection point. There were no significant changes between treatments on DM and VS content. Thus, other perimeters were subjected to the effect of the low dry matter content available. The slurry pH was at neutral pH 7.4 and increased to pH 7.7 on the end of storage period. Moderate C:N ratio at 13:1 led to balanced mineralization and release of nitrogen, which makes available for a plant uptake. The slurry temperature recorded is following the ambient temperature. After over 91 days of storage, the decrease in total C and the increase in ammonium (NH_4^+) content indicated mineralization or biodegradation of organic matter in the slurry. In addition, acidification resulted in higher NH_4^+ content (Table 3). However, lower NH_4^+ content in Ctrl and HNO_3 is unclear, probably may due to loss in a gas form as NH_3. This NH_4^+ content is represented as available N for plant or grass root uptake.

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Table 2: Slurry characteristic after 91 days storage.

Treatment	End Observation			
	pH	ORP (mV)	Dry Matter Kg^{-1} Fresh Slurry % DM (±SEM)	Volatile solid Kg^{-1} DM % VS (±SEM)
Ctrl	7.7 ±0.09	-30.0 ±79.10	2.42 ±0.21	69.88 ±5.31
HCl	5.5 ±0.45	-86.6 ±34.96	3.24 ±0.06	76.02 ±1.17
$C_3H_6O_3$	7.0 ±0.09	-200.2 ±3.40	3.65 ±0.23	72.63 ±0.53
HNO_3	6.1 ±0.04	174.6 ±39.76	3.27 ±0.14	80.11 ±4.10
H_2SO_4	4.7 ±0.56	-55.4 ±94.92	3.15 ±0.18	74.39 ±1.50

Values represent mean ± SEM (n = 5).

Table 3: Slurry ammonium, carbon and nitrogen content during storage period. n=5

Treatments	Ammonium (NH_4^+) Content (mg/kg slurry, ±SEM)		Total Carbon Nitrogen (C/N) Day 0		Total Carbon Nitrogen (C/N) Day 91	
	Day 0	Day 91	Total N (g/kg FM)	Total C (g/kg FM)	Total N (g/kg FM)	Total C (g/kg FM)
Ctrl	98.61 ±17.70	36.58 ±17.60	25.7 ±4.7	333.9 ±46.90	27.9 ±3.5	349.5 ±57.60
HCl	104.41 ±42.40	207.71 ±46.95	24.9 ±7.4	273.8 ±55.70	26.2 ±5.0	373.6 ±91.20
$C_3H_6O_3$	102.20 ±31.77	64.99 ±45.67	19.0 ±2.3	250.5 ±45.00	21.3 ±4.6	348.8 ±69.10
HNO_3	101.18 ±16.26	28.56 ±17.51	16.3 ±5.4	263.5 ±110.30	27.2 ±4.5	427.1 ±102.30
H_2SO_4	105.93 ±32.17	241.83 ±2.97	25.8 ±4.8	287.7 ±71.90	23.2 ±4.7	497.2 ±99.00

Values represent mean ± SEM (n = 5).

Slurry temperature, ambient temperature and moisture loss

Throughout the storage period, slurry temperature remained relatively stable, closely mirroring ambient temperature fluctuations (Figure 1 and Figure 2). Variations in ambient temperature and humidity levels were recorded, potentially impacting evaporation rates and microbial activity within the slurry (Figure 3). Moisture loss are constant among treatments were observed over time, likely influenced by environmental conditions and storage parameters (Figure 3).

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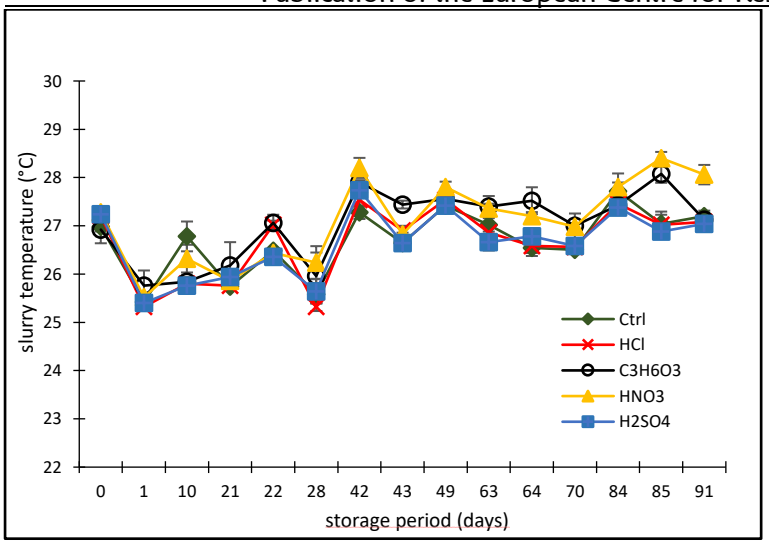

Figure 1: Slurries temperature during storage period.

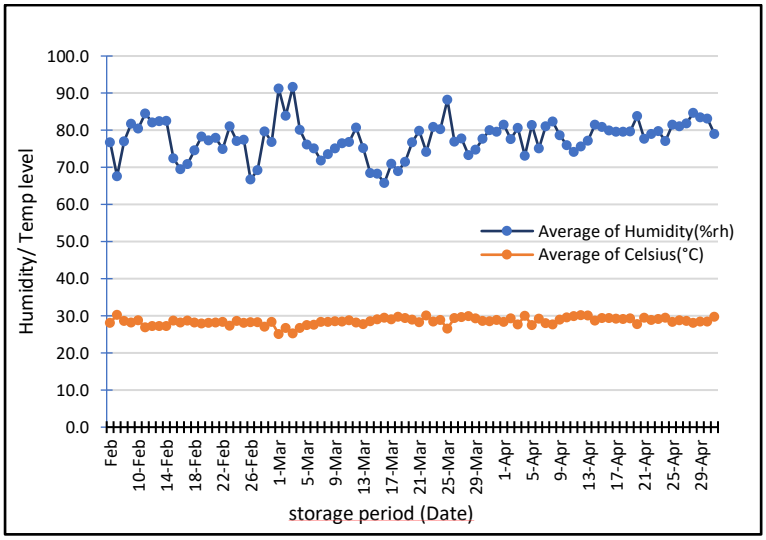

Figure 2: Ambient temperature and humidity level during storage period.

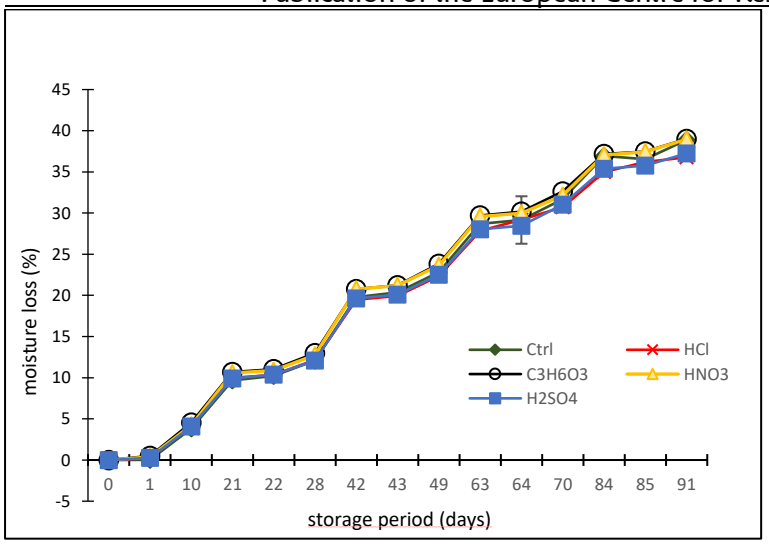

Figure 3: The amount of moisture loss during storage period.

The slurry pH dynamics

All slurries with organic acids addition showed an increased in their pH, rise to neutral pH at day 14 (pH 6.7-7.6; Figure 4). The reacidification every 3 weeks needed to remain the slurry on acidic environment for all treatments with higher volume acids needed mainly for the HNO_3 and $C_3H_6O_3$ while HCl and H_2SO_4 constantly remain below pH 6.0 during the observation periods. The Ctrl pH dynamics remain above pH 7.4 and periodically rose above pH 8.0 during similar periods.

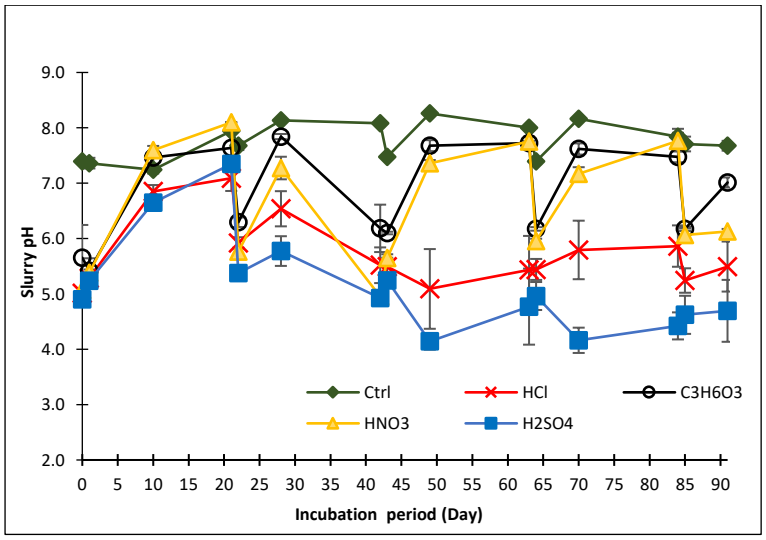

Figure 4: Slurries pH dynamics during storage period. Reacidification to pH 5.0 was carried every 3 weeks

Total Phosphorus (P) and available Phosphorus (P)

Table 3 below presents the total phosphorus (Total P) and available phosphorus (Available P) concentrations in slurry samples at Day 0 and Day 91 across different acidification treatments. At Day 0, total phosphorus concentrations ranged from 8.35 mg kg^{-1} FS (H_2SO_4 treatment) to 11.22 mg kg^{-1} FS (HNO_3 treatment), while available phosphorus was below detection limits (*bdl*) for most treatments, except for HNO_3 (0.39 mg kg^{-1} FS). Following storage and slurry anaerobic fermentation, the digestion (Day 91) all treatments showed an increase in total phosphorus content, with values ranging from 16.76 mg kg^{-1} FS ($C_3H_6O_3$ treatment) to 18.72 mg kg^{-1} FS (H_2SO_4 treatment) and the available phosphorus increased in some treatments, with the highest concentration observed in H_2SO_4 (1.77 mg kg^{-1} FS), followed by HCl (1.37 mg kg^{-1} FS). In contrast, available phosphorus remained below detection limits in the $C_3H_6O_3$ treatment, indicating a lack of solubilization over time.

Table 3: Slurry Phosphorus content during storage period.

Treatments	Day 0		Day 91	
	Total P (mg kg^{-1} FS)	Available P (mg kg^{-1} FS)	Total P (mg kg^{-1} FS)	Available P (mg kg^{-1} FS)
Ctrl	9.52	*bdl*	17.06	0.76
HCl	9.75	*bdl*	17.78	1.37
$C_3H_6O_3$	10.62	*bdl*	16.76	*bdl*
HNO_3	11.22	0.39	17.63	0.73
H_2SO_4	8.35	*bdl*	18.72	1.77

Values represent mean ± SEM (n = 5). *bdl* ; below detection limits

GHG emissions: Relative ammonia volatilization and methane emission

The acidification of cattle slurry using four different acids resulted in varying effects on NH_3 and CH_4 emissions. The process occasionally caused foaming on the slurry surface (Figure 5), which may have acted as a barrier, reducing NH_3 volatilization. As shown in Figure 6 (i) and (ii), cumulative NH_3 emissions were recorded as 82.42, 30.27, 30.01, 14.11, and 10.87 mg m^{-2} for the control (Ctrl), HNO_3, $C_3H_6O_3$, H_2SO_4, and HCl treatments, respectively. Acidification by the use of concentrated HCl and H_2SO_4 demonstrated the highest effectiveness, reducing NH_3 emissions by 86.8% and 82.9% compared to the untreated control. For CH_4 emissions, as shown in Figure 7 (i) and (ii), the use of concentrated HCl and H_2SO_4 resulted in reductions of 17.7% and 19.3%, respectively, relative to the control. HNO_3 showed the highest CH_4 inhibition rate at 57.0%. Conversely, the use of $C_3H_6O_3$ led to a significant increase in CH_4 emissions, with a 151% rise compared to the untreated slurry.

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Figure 5: Foaming observed on slurry surface following reacidification processes

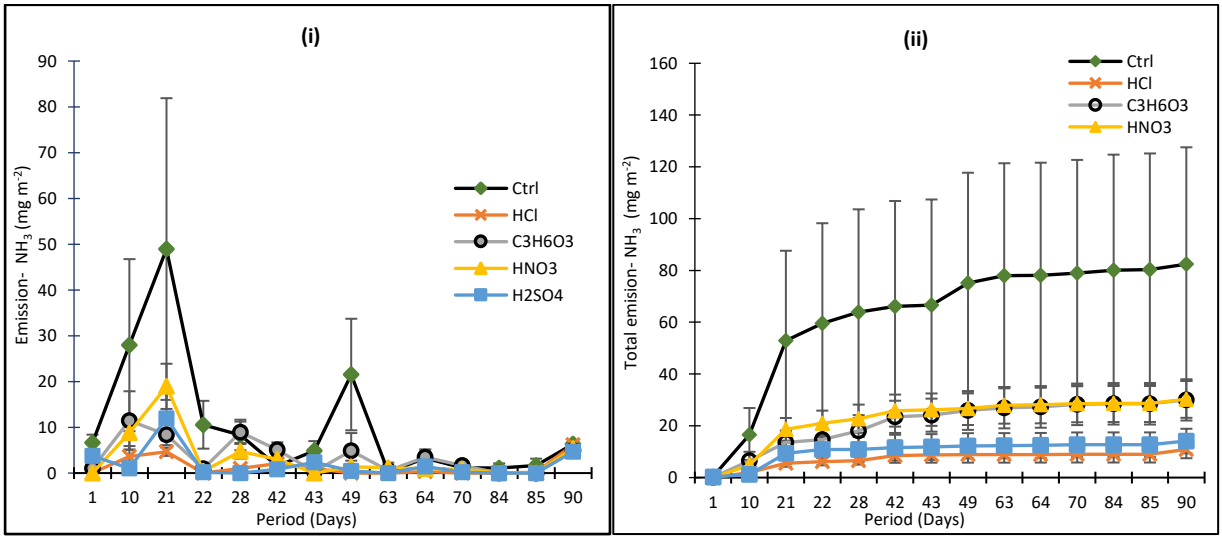

Figure 6: Effect of continuous acidification (i) ammonia volatilization fluxes; (ii) cumulative ammonia volatilization from cattle slurry during 3 months storage.

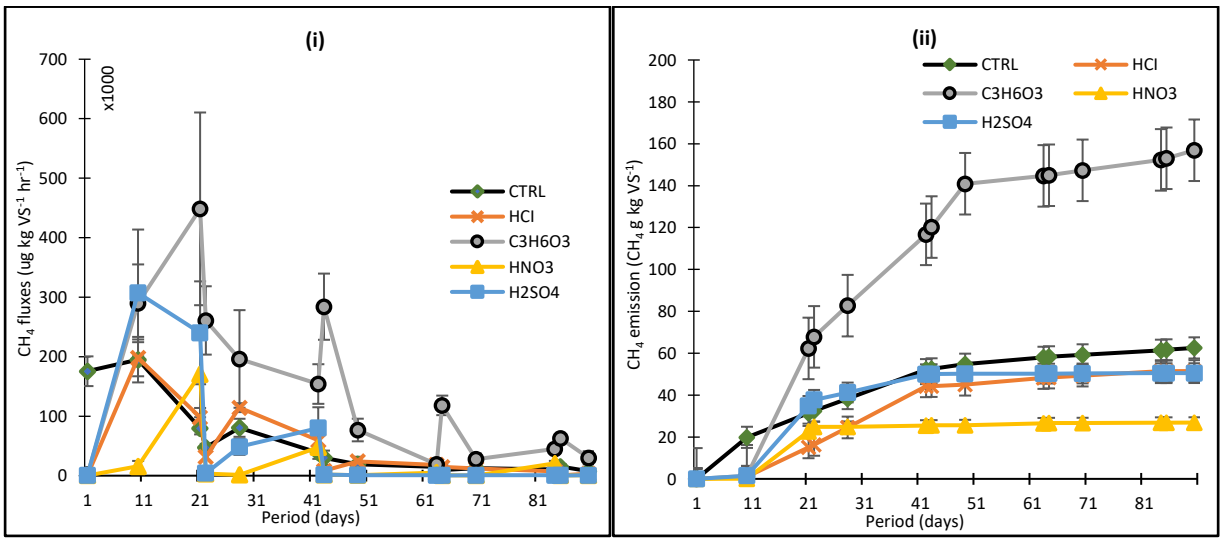

Figure 7: Effect of continuous acidification on (i) methane fluxes from cattle slurry; (ii) cumulative methane emission from cattle slurry during 3 months storage.

DISCUSSION

Slurry acidification at different stages of the manure handling chain is an effective strategy for reducing ammonia (NH_3) and methane (CH_4) emissions, improving air quality, and enhancing nutrient retention. Acidification at the initial stage, particularly in animal housing, slurry storage, and post-field application, significantly reduces gaseous emissions. This study evaluates the inhibition potential of both strong and weak acids in slurry acidification, considering their impact on emissions and nutrient dynamics. Weak acids, such as nitric acid (HNO_3) and lactic acid, have been studied for their effectiveness in reducing NH_3 losses (Berg et al., 2006). However, the choice of acid is crucial; for example, sulfuric acid (H_2SO_4) can lead to increased hydrogen sulphide (H_2S) emissions and elevate sulphur content in slurry (Berg et al., 2006; Sørensen and Eriksen, 2009a; Dai and Blanes-Vidal, 2013; Wang et al., 2014; Overmeyer et al., 2023), while nitric acid may contribute to significant nitrous oxide (N_2O) production (Berg et al., 2006). Additionally, weak acids such as lactic acid (pKa 3.86) require larger volumes to achieve comparable pH reductions (Berg et al., 2006).

Beyond emission reduction, slurry acidification plays a crucial role in improving phosphorus (P) retention, enhancing its availability for crops while minimizing environmental losses (Fangueiro et al., 2018; Kleinman et al., 2022). Acidification and anaerobic digestion influenced P distribution in slurry differently; anaerobic digestion enhances both labile inorganic and moderately labile P fractions, while acidification increased labile inorganic P and reduced stable P fractions (Yuhong-Li, 2017). Acidification stabilizes nitrogen within the slurry, thereby reducing NH_3 volatilization and limiting CH_4 and N_2O production (Garder et al., 2023; Schreiber et al., 2023). Moreover, by preventing phosphorus runoff, acidification supports water quality protection and contributes to sustainable agricultural practices (Withers et al., 2017).

The results of this study align with previous findings that slurry acidification can reduce NH_3 emissions by 50–70% (Zhang et al., 2006; Kai et al., 2008; Sommer et al., 2017) However, lower inhibition rates have been observed in slurries stored beneath slatted floors in pig barns, though acidification still offers benefits by reducing harmful gas exposure for animals and workers (Overmeyer et al., 2023). NH_3 reduction in livestock facilities is particularly significant, as a major fraction of NH_3 emissions originates from urea degradation on slats and other urine-wetted surfaces (Sommer et al., 2007). Additionally, Sepperer et al., (2020) demonstrated that tannin-based substances, such as flavonoids, can achieve NH_3 reductions exceeding 75%. Achieving substantial NH_3 mitigation is critical for meeting European Union environmental targets, which aim to reduce NH_3 emissions by 30% by 2030 compared to 2005 levels, presenting both a challenge and an opportunity for sustainable manure management.

Meanwhile, the CH_4 emission inhibition observed in this finding showed much lower than (Petersen et al., 2012b; Sommer et al., 2017; Habtewold et al., 2018a), where inhibition rate was higher at 67-87%. This difference is due to lower organic and volatile matter content in the slurry used. The lower pH suggests in resulted reduction in *Methanosarcina species*, a

methanogenic communities which contributed to high CH_4 emissions in slurries (Habtewold et al., 2018b; Shin et al., 2019) rather than other types of methanogenic archaea (Bastami et al., 2020). The continuous acidification on cattle slurries was initiated due to significant increases in slurry pH following the microbial and organic matter breakdown. There is a concern in methanogenesis and regeneration of CH_4 emission when the slurry pHs return to normal range unless the slurry acidification can be prolong or extended. This gradual increase was similar to Petersen (2012), thus suggesting it might require periodic addition of acid or re-acidification until complete slurry removal from storage (Haeussermann et al., 2006). In some countries, such as Denmark, farmers practice slurry acidification using HCl or H_2SO_4. Although this method incurs additional costs, but it returns the benefits to farm in terms of higher N availability (NH_3 emissions are reduced during slurry storage and during slurry spreading) for crop uptake (Sørensen and Eriksen, 2009b). It also promotes an improved in-house climate if used in slurry stores under buildings. Yet, due to lower pH, organic matter retention might be higher compared to non-acidified slurry as acidification causes lower biodegradation activity (Sørensen and Eriksen, 2009a). Furthermore, according to Donham (1977), as reviewed by (Petersen et al., 2012b), acidified slurry could pose risks to animals and human health in closed buildings or barns. Similar to this study, slurry acidification technique is a practical approach to reduce NH_3 loss and inhibit CH_4 emission (Sørensen and Eriksen, 2009b; Petersen et al., 2012b).

Perhaps that 'self-acidification' or 'bio-acidification' through anaerobic fermentation using fermentable carbohydrate could replacing the chemical-acidification on slurries (Bastami, 2016; Prado et al., 2020). Slurry acidification should ideally begin as early as possible, as the slurry is excreted to maximise the inhibition emission (Petersen et al., 2012b). This study may help the current move to reduce the global GHG emission as advocated by the Kyoto Protocol (1997) under the United Nations Framework Convention on Climate Change (UNFCCC) (Nations, 1998).

Slurry acidification during storage is a promising strategy for reducing greenhouse gas emissions; however, a comprehensive economic assessment is essential to ensure its cost-effectiveness within the ruminant industry. The financial viability of acidification depends on whether the additional costs incurred outweigh the economic benefits derived from emission reductions, including lower environmental impact and potential financial returns. A thorough economic analysis facilitates a precise evaluation of costs and benefits, enabling evidence-based decision-making and optimal resource allocation. According to the U.S. Environmental Protection Agency (EPA, 2023), high-quality economic assessments enhance the effectiveness of environmental policy by systematically evaluating alternative mitigation strategies. Similarly, the Food and Agriculture Organization (FAO, 2023) underscores the importance of economic analysis in assessing the feasibility of agricultural and environmental initiatives to ensure resource efficiency and long-term sustainability. Integrating economic considerations into applied science projects not only optimizes resource use but also minimizes waste and supports the broader sustainability of livestock waste management practices.

CONCLUSIONS

This study demonstrates the effectiveness of continuous acidification of cattle slurry with low organic matter content using concentrated acids, such as hydrochloric acid (HCl) and sulfuric acid (H_2SO_4), as an effective approach to mitigating greenhouse gas (GHG) emissions and combating climate change. The results demonstrated substantial reductions in ammonia (NH_3) volatilization, with inhibition rates of 86.8% for HCl and 82.9% for H_2SO_4 compared to untreated slurry, while methane (CH_4) emissions were reduced by 17.7% and 19.3%, respectively. These findings underscore the dual benefits of slurry acidification in curbing NH_3 and CH_4 emissions while enhancing nutrient retention for improved soil fertility. However, optimizing acid application strategies is crucial to balance emission reductions, nutrient availability, and environmental safety. Future research should focus on refining acidification protocols and assessing long-term sustainability to support widespread adoption in agricultural systems.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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