International Journal of Applied Research
Journal HP: www.intjar.com; ISSN: 2411-6610

Comparative assessment of greenhouse gas emissions from cattle manure storage and management systems in the haor wetlands ecosystem of Bangladesh

Mahmudul Hasan[1], Shamme Akther Jui[1], Tahrima Tabassum Chapa[1], Mohammad Sohan[1], Md. Mohsin Taluckder[2], Md. Dedarul Hasan[2], Md. Shahiduzzaman[1]*

[1]Department of Parasitology, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh
[2]One Health and Climate Smart Research Center, International Institute of Applied Science and Technology, Rangpur-5400, Bangladesh

ARTICLE INFO

Article history

Received: 03 July 2026
Accepted: 07 September 2026
Published: 10 September 2026

Keywords

Greenhouse Gas (GHG) Emissions, Cattle Manure storage, manure treatment strategy, Haor Wetland Ecosystem

Corresponding Author

Md. Shahiduzzaman
Email: szaman@bau.edu.bd

ABSTRACT

The global livestock sector is a major contributor to greenhouse gas (GHG) emissions, with manure management being a critical source of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). This study conducted a comparative assessment of GHG emissions from cattle manure under pit and heap storage methods in three representative locations within Bangladesh's ecologically sensitive wetland ecosystem: Mitamoin, Itna, and Austagram. Using the closed chamber technique and gas chromatography, gas fluxes were monitored alongside environmental parameters. Results revealed that pit storage consistently produced significantly higher emissions across all measured gases compared to heap storage. Specifically, CH_4 emissions from pit storage (409.89 ± 27.54 mg m^{-2} d^{-1}) were approximately 2.4 times higher than from heap storage (167.56 ± 25.88 mg m^{-2} d^{-1}), while N_2O (3.14 ± 0.80 mg m^{-2} d^{-1} vs. 1.53 ± 0.83 mg m^{-2} d^{-1}) and CO_2 (4489.33 ± 566.38 mg m^{-2} d^{-1} vs. 1790.67 ± 347.92 mg m^{-2} d^{-1}) emissions were also markedly elevated. Regression and correlation analyses identified the storage method as the primary driver of emission dynamics, with temperature and pH as secondary regulators. While CO_2 dominated the total emission profile, CH_4 contributed a substantial secondary share, particularly in pit systems. Furthermore, Austagram exhibited the highest overall emissions, indicating significant site-specific variability. These findings underscore that traditional pit storage is large source of GHGs. The study highlights the urgent need for climate-smart manure management strategies, such as improved aeration or location-specific heap management, to mitigate the environmental footprint of livestock production in Bangladesh's haor ecosystems.

1. Introduction

The global livestock sector is a significant contributor to anthropogenic greenhouse gas (GHG) emissions, accounting for approximately 14.5% of total global emissions (Gerber et al., 2013). Within this sector, manure management represents a critical yet complex source of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), which are the primary drivers of climate change (IPCC, 2006; Steinfeld et al., 2006). In developing nations like Bangladesh, where agriculture is the backbone of the economy, the livestock subsector plays a pivotal role in rural livelihoods and food security (BBS, 2023; DLS, 2023). However, the rapid expansion of the livestock population has led to a substantial increase in manure production, posing severe environmental challenges, particularly in sensitive ecosystems such as the haor wetlands (Mahal et al., 2024; Joy et al., 2026).

The haor basin, located in the northeastern part of Bangladesh, is a unique wetland ecosystem characterized by seasonal flooding and high biodiversity (Jakariya & Islam, 2017). This region is home to a large population of cattle, which are essential for draft power and milk production. Despite their importance, the management of cattle manure in these areas remains largely traditional, with storage methods often dictated by local customs and environmental constraints (Mahal & Yabar, 2025). Common practices include heap storage, where manure is piled in open areas, and pit storage, where it is collected in excavated depressions (Venier & Yabar, 2017; Sun & Wu, 2013). These storage environments significantly influence the biochemical processes that govern gas emissions.

Methane is primarily produced under anaerobic conditions through methanogenesis, a process that is highly active in compacted or liquid manure storage systems like pits (Higarashi et al., 2013; Moeletsi & Moeletsi, 2015). Conversely, nitrous oxide is generated through nitrification and denitrification processes, which are sensitive to moisture content, aeration, and nitrogen availability (van der Weerden et al., 2023; Sapkota et al., 2019). Carbon dioxide emissions from manure storage are often considered a byproduct of microbial respiration and the decomposition of organic matter (Azevedo et al., 2013; Savic et al., 2022). The

Cite this article: *Hasan, M., Jui, S. A., Chapa, T. T., Sohan, M., Taluckder, M. M., Hasan, M. D., & Shahiduzzaman, M. (2026). Comparative assessment of greenhouse gas emissions from cattle manure storage and management systems in the haor wetlands ecosystem of Bangladesh. International Journal of Applied Research, 12(1), 93–105. DOI: 10.5281/zenodo.23684449*

magnitude of these emissions is further modulated by environmental factors such as temperature, pH, and moisture, which regulate microbial activity and gas solubility (Hu et al., 2023; Junk, 2002). In Bangladesh, livestock manure contributes approximately 11.32% of the total agricultural GHG emissions (Mahal et al., 2024). While several studies have estimated national-level emissions (Das et al., 2020; FAO, 2014), there is a dearth of site-specific research focusing on the haor ecosystem, where the interaction between manure management and wetland dynamics is particularly pronounced. Understanding the comparative impact of different storage methods is essential for developing climate-smart manure management strategies that can mitigate emissions without compromising agricultural productivity (Smith et al., 2008; Searchinger et al., 2019).

This study aims to fill this knowledge gap by conducting a comparative assessment of GHG emissions (CH_4, N_2O, and CO_2) from cattle manure under pit and heap storage conditions in three representative haor locations: Mitamoin, Itna, and Austagram. By analyzing the influence of environmental factors and storage methodologies, this research provides critical insights into the emission dynamics of the haor ecosystem. Such findings are vital for informing policy decisions and promoting sustainable livestock practices in one of Bangladesh's most ecologically vulnerable regions (Conley et al., 2009; Elser et al., 2007).

2. Materials and methods

2.1. Study area

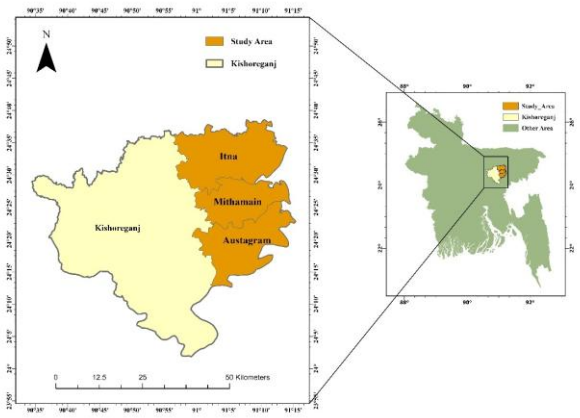

Fig.1. Study area of hoar (Itna, Mitamoin, Austagram upazilas of Kishoregonj)

This study was conducted within the haor wetland ecosystem of Bangladesh, specifically focusing on three distinct geographical locations: Mitamoin, Itna, and Austagram (Fig. 1). The overarching objective was to conduct a comparative assessment of greenhouse gas (GHG) emissions originating from cattle manure, evaluating two prevalent storage methodologies: Pit storage and Heap storage. These methods were selected for their widespread application in regional manure management practices.

2.2. Gas sampling

Sample was collected from different sites of three different upazilas of haor region of Bangladesh. Collection of key greenhouse gas emissions, namely nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2), was performed using static air tied chambers with dimensions of 0.4 m (length) x 0.4 m (width) x 0.4 m (height) (Fig 2). Gas samples were collected gradually at 0, 30, and 60minute intervals using a three-way connector and syringe.

Fig. 2. A: Gas collection chamber, B: Three-way stopcock; C: Collection syringe; D: 10ml collection vial; E: Gas collection; F: Digital tester; G: Gas Chromatography machine

The collected gas was then preserved in 10 ml vacuum thermo-scientific approved vials (Fig 2.C) and subsequently analyzed using a Gas Chromatography (GC) (Fig 2.G) machine for quantification and further calculation. Concurrently, critical environmental parameters recognized for their influence on these emissions specifically pH, temperature, and moisture content of the manure were systematically monitored and measured by a digital soil tester (Fig 2.F).

2.3. Gas chromatography analysis & calculation of gas

Gas chromatography analysis: To investigate the sources and emissions of major GHG (N2O, CO_2,

CH4), accurate concentration analysis was made after sample collection. Gas concentration analysis was performed using a gas chromatograph device to simultaneously analyze N2O, CO_2 and CH4.

Gas Sampling and Measurement: Gas samples were collected using the closed chamber technique at three-time intervals (0, 30, and 60 minutes). Gas concentrations of methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) were measured using a gas chromatograph (GC) and expressed in parts per million (ppm).

Standard gas: TDL31_.5L (Tunable Diode Laser) 500ppm for CH4, TDL31_.5L 50ppm for N2O, TDL31_.5L 1000ppm for CO2.

Conversion of Concentration Units

ppb = ppm × 1000

Estimation of Gas Concentration Change (Slope)

dC/dt = slope of concentration vs time

Gas Flux Calculation ($\mu g\ m^{-2}\ h^{-1}$)

$$F = \frac{(dC/dt) \times (V/A) \times (M \times P)}{R \times T}$$

Where:

F = gas flux ($\mu g\ m^{-2}\ h^{-1}$)

dC/dt = rate of change of gas concentration (ppm min^{-1})

V = chamber volume (m^3)

A = chamber area (m^2)

M = molar mass ($g\ mol^{-1}$)

P = atmospheric pressure (atm)

R = 0.0821

T = temperature (K)

Chamber Volume: V = A × H

Where length of chamber L=0.4m; Height =0.4m; width =0.4m;

Gas Molar Mass:

CH_4 = 16.04 $g\ mol^{-1}$, CO_2 = 44.01 $g\ mol^{-1}$, N_2O = 44.01$g\ mol^{-1}$

Temperature and Pressure Conversion:

T(K) = T(°C) + 273

P(atm) = P(hPa) / 1013.25

Flux Conversion: $mg\ m^{-2}\ d^{-1} = (\mu g\ m^{-2}\ h^{-1} \times 24) / 1000$

Area Conversion: $g\ ha^{-1}\ d^{-1} = mg\ m^{-2}\ d^{-1} \times 10$

Quality Control: Only datasets with $R^2 \geq 0.90$ were considered reliable. Non-linear data were excluded.

2.4. Data analysis

The calculated data were subjected to comprehensive statistical analysis to examine greenhouse gas (GHG) emission patterns and their relationships with environmental factors. All data were initially entered and organized using Microsoft Excel. Subsequently, the data were transferred to IBM SPSS statistical software for comprehensive statistical analysis. Descriptive statistics (minimum, maximum, mean, standard deviation) were employed to characterize the distribution and variability of environmental parameters (pH, temperature, moisture) and GHG emissions (N_2O, CH_4, CO_2). Subsequently, comparative analyses were conducted to assess significant differences in GHG emissions and environmental parameters between the Pit and Heap storage methods, utilizing appropriate statistical tests (e.g., t-tests, as inferred from reported t-statistics and p-values). Site-specific variations in N_2O, CH_4, and CO_2 emissions were also examined. To explore the interdependencies among environmental parameters and GHG emissions, a correlation analysis was performed, visualized through a heatmap, to identify significant positive or negative associations. Further, linear regression models were developed to quantify the direct influence of environmental factors (pH, temperature, moisture) on N_2O, CH_4, and CO_2 emissions, yielding coefficients, p-values, and R-squared values to delineate explanatory power. A two-way Analysis of Variance (ANOVA) was executed to ascertain the individual and interactive effects of Site and Storage method, treated as categorical factors, on N_2O, CH_4, and CO_2 emissions. The reliability and reproducibility of GHG emission measurements were evaluated through a replication consistency analysis, involving the calculation of mean values, standard deviations (SD), and coefficients of variation (CV%) across various sites and storage methods. Finally, emission ratios analysis (CH_4:CO_2 and N_2O:CO_2) was conducted to provide insights into the relative contributions of methane and nitrous oxide within the overall emission profile across different sites and storage methodologies.

3. Results

3.1. Environmental factors and GHG emission from cattle manure storage systems

As shown in (Table 1), environmental conditions were relatively stable, with narrow ranges for pH and temperature, but wider variability in moisture. In contrast, greenhouse gas emissions exhibited considerable dispersion, particularly CH_4 and CO_2, which showed broad ranges and high standard deviations. These descriptive results emphasize the

heterogeneity of emission profiles and provide the foundation for subsequent regression and ratio analyses. pH values ranged from 6.8 to 8.4, with a mean of 7.78 (SD = 0.46), indicating slightly alkaline conditions. Temperature varied between 20-28 °C, averaging 23.94 °C (SD = 2.01), while moisture content spanned 46-85% with a mean of 66% (SD = 9.80). For emissions, N_2O fluxes ranged from 0.57 to 4.63 mg m^{-2} d^{-1} (mean = 2.34, SD = 1.14), CH_4 from 127 to 442 mg m^{-2} d^{-1} (mean = 288.72, SD = 127.35), and CO_2 from 1165 to 4876 mg m^{-2} d^{-1} (mean = 3140, SD = 1461.41). The large standard deviations for CH_4 and CO_2 highlight substantial heterogeneity in emission profiles across sites and storage methods.

Table 1: Environmental factors and GHG emission from cattle manure storage systems.

Variable	Minimum	Maximum	Mean	Std. Error	Std. Deviation
pH	6.8	8.4	7.78	0.108	0.457
Temperature (°C)	20.0	28.0	23.94	0.475	2.014
Moisture (%)	46.0	85.0	66.00	2.309	9.798
N_2O (mg m^{-2} d^{-1})	0.57	4.63	2.34	0.270	1.145
CH_4 (mg m^{-2} d^{-1})	127.0	442.0	288.72	30.016	127.35
CO_2 (mg m^{-2} d^{-1})	1165.0	4876.0	3140.00	344.458	1461.41

Mean = average; Std. error = standard error, Std. Deviation = standard Deviation.

3.2. Comparative analysis of GHG emissions from livestock waste management

This study investigated the differences in greenhouse gas (GHG) emissions, specifically nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2), between two common cattle manure storage methods: Pit and Heap. Additionally, key environmental parameters such as pH, temperature, and moisture content were analyzed to assess their potential influence. The comparison between heap and pit storage methods revealed striking differences in greenhouse gas emissions, with pit systems consistently producing higher fluxes across all measured gases. Table 2 summarizes the differences in greenhouse gas emissions (N_2O, CH_4, and CO_2) and associated environmental parameters (pH, temperature, and moisture) between heap and pit storage systems.

Table 2: Comparative analysis of GHG emissions from livestock waste management.

Parameter	Storage Method	Mean ± SD	t-statistic	p-value
N_2O (mg m^{-2} d^{-1})	Heap	1.53 ± 0.83	-4.1815	0.0007
	Pit	3.14 ± 0.80		
CH_4 (mg m^{-2} d^{-1})	Heap	167.56 ± 25.88	-19.2342	< 0.0001
	Pit	409.89 ± 27.54		
CO_2 (mg m^{-2} d^{-1})	Heap	1790.67 ± 347.92	-12.1799	< 0.0001
	Pit	4489.33 ± 566.38		
pH	Heap	7.93 ± 0.27	1.4366	0.1701
	Pit	7.63 ± 0.56		
Temperature (°C)	Heap	23.22 ± 2.11	-1.5882	0.1318
	Pit	24.67 ± 1.73		
Moisture (%)	Heap	65.89 ± 9.28	-0.0467	0.9633
	Pit	66.11 ± 10.86		

Note: p-values less than 0.0001 are reported as < 0.0001 for clarity. Units for N_2O, CH_4, and CO_2 are mg m^{-2} d^{-1}.

The results indicate that pit storage consistently produced significantly higher emissions of N_2O, CH_4, and CO_2 compared to heap storage. Specifically, N_2O emissions from pit storage (3.14 ± 0.80 mg m^{-2} d^{-1}) were more than double those from heap storage (1.53 ± 0.83 mg m^{-2} d^{-1}; $p = 0.0007$). Methane emissions showed the most pronounced difference, with pit storage (409.89 ± 27.54 mg m^{-2} d^{-1}) releasing approximately 2.4 times more CH_4 than heap storage (167.56 ± 25.88 mg m^{-2} d^{-1}; $p < 0.0001$). Similarly, CO_2 emissions were markedly elevated in pit storage (4489.33 ± 566.38 mg m^{-2} d^{-1}) compared to heap storage (1790.67 ± 347.92 mg m^{-2} d^{-1}; $p < 0.0001$). In contrast,

environmental parameters such as pH, temperature, and moisture content did not differ significantly between the two storage methods. The pH values remained within a neutral range (heap: 7.93 ± 0.27; pit: 7.63 ± 0.56; p = 0.1701), while temperature (heap: 23.22 ± 2.11 °C; pit: 24.67 ± 1.73 °C; p = 0.1318) and moisture content (heap: 65.89 ± 9.28%; pit: 66.11 ± 10.86%; p = 0.9633) were statistically comparable. These findings underscore the critical influence of storage method on emission dynamics and highlight pit storage as a disproportionately large source of greenhouse gases compared to heap storage, with important implications for climate-smart manure management strategies.

3.3. Site wise comparison of N2O, CH4 & CO2 emission from manure treatment strategy

Fig. 3 depicts the mean fluxes of methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) measured at three representative haor locations: Mitamoin, Itna, and Austagram. CH_4 and CO_2 emissions are expressed on the left y-axis (mg m^{-2} d^{-1}), while N_2O emissions are plotted on the right y-axis (mg m^{-2} d^{-1}). Error bars represent standard deviations, reflecting variability among replicates. Across all sites, CO_2 emissions were dominant, exceeding both CH_4 and N_2O fluxes by several orders of magnitude. CH_4 emissions were consistently higher than N_2O, but the relative magnitude varied by site. Austagram exhibited the highest overall emissions for all three gases, suggesting site-specific conditions such as substrate availability, microbial activity, and moisture content may have amplified greenhouse gas release. Mitamoin and Itna showed comparatively lower fluxes, though the same emission hierarchy (CO_2 > CH_4 > N_2O) was maintained. The error bars highlight the heterogeneity of emissions within sites, indicating that micro-environmental factors strongly influence flux variability. The comparatively small N_2O fluxes, despite their lower magnitude, remain important due to the high global warming potential of N_2O. These site-specific differences reinforce the statistical findings presented in Table 2, where pit storage consistently produced higher emissions than heap storage. Taken together, the figure demonstrates that both storage method and geographic location significantly affect greenhouse gas dynamics. The dominance of CO_2 and CH_4 emissions underscores the importance of targeted mitigation strategies, while the variability across sites highlights the need for location-specific management practices in haor ecosystems.

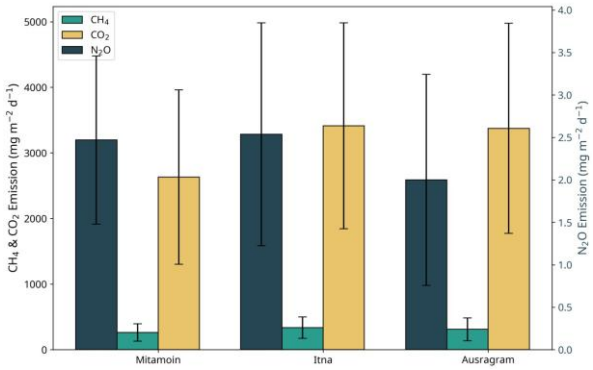

Fig. 3. Site wise comparison of N2O, CH4 & CO2 emission from manure treatment strategy

3.4. Correlation analysis of environmental factors and cattle manure-derived greenhouse gas emissions

The correlation heatmap (Fig. 4) reveals several significant relationships among the measured environmental parameters. A highly significant positive correlation was observed between methane (CH_4) and carbon dioxide (CO_2) (r = 0.98), indicating that factors influencing CH_4 emissions are likely to similarly affect CO_2. Nitrous oxide (N_2O) also showed substantial positive correlations with both CH_4 (r = 0.73) and CO_2 (r = 0.67), suggesting co-occurrence or shared underlying drivers of these greenhouse gas emissions. In contrast, soil pH demonstrated moderate negative correlations with CH_4 (r = -0.37) and CO_2 (r = -0.41), implying that lower pH values may enhance gas release, potentially through biogeochemical processes sensitive to acidity.

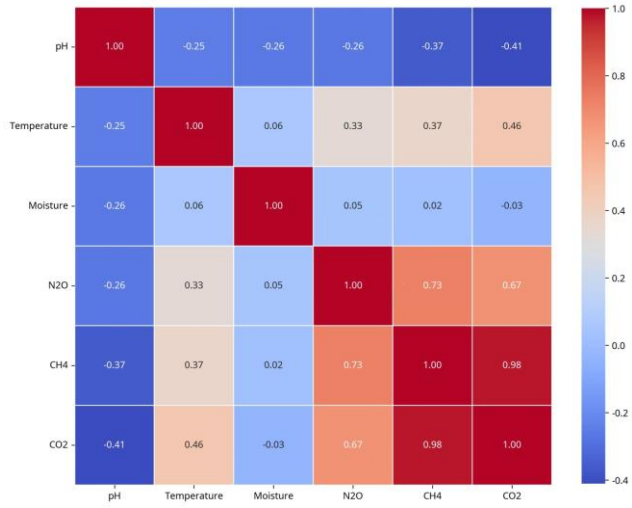

Fig.4. Correlation matrix of environmental factors (pH, temperature, moisture) and cattle manure gas emissions (N_2O, CH_4, CO_2).

Temperature exhibited positive associations with gas emissions, showing a weak correlation with N_2O ($r = 0.33$) and moderate correlations with CH_4 ($r = 0.37$) and CO_2 ($r = 0.46$), highlighting the role of warmer conditions in favoring microbial activity. Moisture content, however, displayed negligible correlations with all three gases, such as CH_4 ($r = 0.02$) and CO_2 ($r = -0.03$), indicating limited direct influence within the observed dataset. Collectively, these findings underscore the strong interdependencies among greenhouse gases, particularly the near-perfect linkage between CH_4 and CO_2, while also pointing to pH and temperature as key environmental regulators of emission dynamics.

3.5. Regression results for greenhouse gas emissions from cattle manure

The regression analysis revealed varying degrees of influence of the tested predictors on the emissions of N_2O, CH_4, and CO_2 from cattle manure. The detailed results, including estimates, standard errors (SE), t-values, and p-values for each predictor, are presented in Table 3. Nitrous Oxide (N_2O) Emissions: For N_2O emissions, the Storage method emerged as a statistically significant predictor (Estimate = -1.283, SE = 0.492, t = -2.61, p = 0.023). This indicates that the method of manure storage significantly influences N_2O release. Other continuous predictors, including pH ($p = 0.366$), Temperature ($p = 0.432$), and Moisture (%) ($p = 0.545$), did not show a statistically significant effect on N_2O emissions in this model. The 'Site' variable also did not significantly influence N_2O emissions ($p = 0.174$). Methane (CH_4) Emissions: The Storage method was a highly significant predictor for CH_4 emissions (Estimate = -241.174, SE = 17.154, t = -14.06, $p < 0.001$). This strong negative association suggests that different storage methods have a profound impact on methane production. Conversely, pH ($p = 0.843$), Temperature ($p = 0.962$), Moisture (%) ($p = 0.834$), and Site ($p = 0.691$) did not exhibit statistically significant relationships with CH_4 emissions. Carbon Dioxide (CO_2) Emissions: Similar to CH_4, the Storage method was a highly significant factor influencing CO_2 emissions (Estimate = -2679.593, SE = 217.539, t = -12.32, $p < 0.001$). Furthermore, the Site variable also showed a statistically significant effect on CO_2 emissions (Estimate = 392.703, SE = 158.971, t = 2.47, p = 0.029). This indicates that both the storage method and the geographical location play crucial roles in determining CO_2 release. pH ($p = 0.679$), Temperature ($p = 0.479$), and Moisture (%) ($p = 0.726$) were not found to be statistically significant predictors for CO_2 emissions.

Table 3: Regression results for greenhouse gas emissions from cattle manure.

Predictor	N_2O				CH_4				CO_2			
	Estimate	SE	t	p	Estimate	SE	t	p	Estimate	SE	t	p
Intercept	7.657	6.85	1.12	0.286	427.62	238.99	1.79	0.099	1519.24	3030.78	0.50	0.625
pH	-0.627	0.68	-0.94	0.366	-4.70	23.30	-0.20	0.843	125.29	295.49	0.42	0.679
Temperature	0.097	0.11	0.81	0.432	-0.20	4.16	-0.05	0.962	38.58	52.856	0.73	0.479
Moisture (%)	-0.016	0.03	-0.62	0.545	0.19	0.91	0.21	0.834	4.184	11.659	0.36	0.726
Storage method	-1.283	0.49	-2.61	0.023	-241.17	17.15	-14.06	<0.001	-2679.59	217.53	-12.32	<0.001
Site	-0.519	0.36	-1.45	0.174	5.10	12.53	0.41	0.691	392.70	158.97	2.47	0.029

Note: SE: Standard Error; t: t-statistic; p: significance level. Storage method was coded as a categorical variable (Heap = 1, Pit = 0). Site includes Mitamoin, Itna, and Austagram. Negative estimates for the storage method indicate that emissions were significantly higher in the pit storage system compared to the heap system. Significant effects ($p < 0.05$) are shown in bold or indicated by the p-value

3.6. Effects of site and storage method on N_2O, CH_4, and CO_2 emissions

A two-way ANOVA was performed treating Site and Storage method as categorical factors, and the results revealed distinct patterns across greenhouse gas emissions (Fig. 5). For N_2O, the Site factor did not show a statistically significant effect ($p = 0.516$), whereas Storage method had a highly significant effect ($p = 0.002$), indicating that different storage practices led to markedly different emission levels. The Site × Storage interaction was not significant ($p = 0.580$), suggesting that the influence of storage method was consistent across sites. Similarly, CH_4 emissions were strongly affected by Storage method ($p < 0.001$), while Site ($p = 0.137$) and the interaction term ($p = 0.284$) were not significant, confirming that pit storage consistently produced

higher emissions than heap storage across all sites. In contrast, CO_2 emissions were significantly influenced by both Site ($p < 0.001$) and Storage method ($p < 0.001$), while the interaction effect remained non-significant ($p = 0.166$). Collectively, these findings highlight storage method as the dominant driver of greenhouse gas emissions, with site-specific differences contributing notably to CO_2 variability.

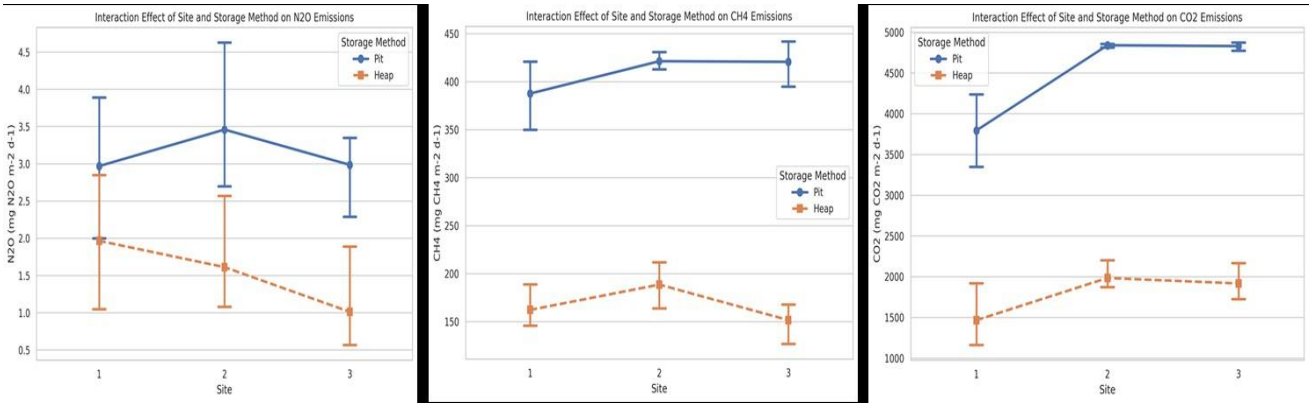

Fig.5. Effects of site and storage method on greenhouse gas emissions

3.7. Replication consistency check report for greenhouse gas emissions

Replication consistency analysis was undertaken to evaluate the reliability of greenhouse gas emission measurements across sites and storage methods, with mean values, standard deviations (SD), and coefficients of variation (CV%) presented in Table 4. The results revealed clear differences in variability among gases and treatments. N_2O emissions exhibited the greatest variability, with CV% values ranging from approximately 20% to 75%. This high variability suggests that N_2O fluxes are more sensitive to micro-environmental heterogeneity and measurement uncertainty compared to CH_4 and CO_2. The most pronounced inconsistency was observed in Site 3 under heap storage (CV = 74.92%), highlighting the unstable nature of N_2O emissions in this condition.

Table 4: Consistency of replicated measurements by site and storage method

Emission	Site	Storage	Mean	Std. Dev.	CV%
N_2O	1	Heap	1.97	0.90	45.79
		Pit	2.97	0.95	31.85
	2	Heap	1.61	0.83	51.47
		Pit	3.46	1.03	29.72
	3	Heap	1.01	0.76	74.92
		Pit	2.99	0.60	20.21
CH_4	1	Heap	162.33	23.29	14.35
		Pit	387.67	35.70	9.21
	2	Heap	188.67	24.03	12.74
		Pit	421.33	9.07	2.15
	3	Heap	151.67	21.73	14.33
		Pit	420.67	23.80	5.66
CO_2	1	Heap	1468.00	399.70	27.23
		Pit	3795.67	444.00	11.70
	2	Heap	1985.67	188.66	9.50
		Pit	4841.33	25.42	0.53
	3	Heap	1918.33	226.21	11.79
		Pit	4831.00	51.39	1.06

Mean = average; SD = standard deviation; CV% = coefficient of variation (%).

In contrast, CH_4 emissions demonstrated moderate to low variability, with CV% values generally below 15%. The lowest variability was recorded at Site 2 under pit storage (CV = 2.15%), indicating highly consistent measurements and suggesting that pit storage may provide more stable conditions for

CH_4 release. CO_2 emissions also showed relatively low variability, with most CV% values below 30%. Particularly noteworthy were Site 2 and Site 3 under pit storage, where CV% values were exceptionally low (0.53% and 1.06%, respectively), reflecting highly reproducible measurements and stable emission dynamics. Taken together, these findings underscore that replication consistency varied substantially across gases and treatments. N_2O emissions were characterized by high variability, reflecting their complex dependence on site-specific and micro-scale factors such as soil chemistry and microbial activity. In contrast, CH_4 and CO_2 emissions were generally more stable, especially under pit storage conditions, which yielded highly consistent results across replications. This pattern suggests that while N_2O emissions may require more intensive replication and careful methodological control to ensure reliability, CH_4 and CO_2 emissions can be measured with greater confidence in their reproducibility. The consistency observed in pit storage treatments further emphasizes the role of management practices in shaping not only emission magnitudes but also the reliability of experimental outcomes.

3.8. Emission ratios analysis report

The analysis of greenhouse gas emission ratios (CH_4:CO_2 and N_2O:CO_2) across sites and storage methods provides insights into the relative contributions of methane and nitrous oxide compared to carbon dioxide (Fig. 6). CH_4:CO_2 ratios varied among sites, with Site 1 generally exhibiting higher values than Sites 2 and 3. In Sites 1 and 2, heap storage resulted in comparatively higher methane-to-carbon dioxide ratios than pit storage, whereas in Site 3 the pit method produced slightly higher ratios. In contrast, N_2O:CO_2 ratios were consistently much lower than methane ratios across all sites, reflecting the minor relative contribution of nitrous oxide to overall emissions. The highest N_2O:CO_2 ratio was observed in Site 1 under heap storage (0.0013), indicating localized variability in nitrous oxide release. When comparing sites, Site 1 demonstrated the greatest relative contribution of non-CO_2 greenhouse gases, underscoring site-specific differences in emission dynamics. Collectively, these findings highlight that while CO_2 dominates total emissions, methane contributes a notable secondary share, particularly under heap storage, whereas nitrous oxide remains a minor but variable component of the emission profile.

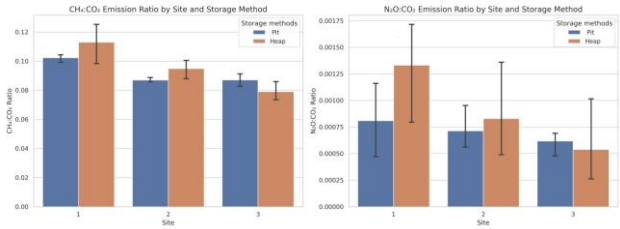

Fig.6. Emission ratio of GHG in different site and storage methods

3.9. Linear regression analysis

The findings from the linear and logistic regression analyses, examining the influence of environmental factors (pH, temperature, and moisture) on manure gas emissions (N_2O, CH_4, and CO_2). Linear regression models were developed to assess the direct impact of environmental factors on the magnitude of N_2O, CH_4, and CO_2 emissions. The results, including coefficients, p-values, and R-squared values, are summarized in Table 5. For N_2O emissions, the model explained approximately 14.6% of the variance (R-squared = 0.146). Temperature showed a positive coefficient (0.161), suggesting that higher temperatures are associated with increased N_2O emissions, though this was not statistically significant ($p = 0.286$). pH exhibited a negative coefficient (-0.498), indicating that higher pH might lead to lower N_2O emissions, but also lacked statistical significance ($p = 0.464$). Moisture had a negligible and non-significant effect. For CH_4 emissions, the model accounted for 22.3% of the variance (R-squared = 0.223). Temperature again showed a positive coefficient (18.807, $p = 0.242$), while pH had a negative coefficient (-86.875, $p = 0.236$). Both factors approached statistical significance, suggesting a trend where higher temperatures increase CH_4 emissions and higher pH decreases them. Moisture's effect was minimal and non-significant. For CO_2 emissions, the model explained 32.2% of the variance (R-squared = 0.322), indicating a stronger fit compared to N_2O and CH_4. Temperature had a positive coefficient (272.658, $p = 0.121$), and pH had a negative coefficient (-1135.734, $p = 0.153$). These results suggest that both higher temperatures and lower pH levels are associated with increased CO_2 emissions, with these relationships being closer to statistical significance than for the other gases. Moisture's impact remained non-significant.

Table 5: Summary of linear regression models for gas emissions

Dependent Variable	Independent Variable	Coefficient	P-value	R-squared
N_2O	pH	-0.498	0.464	0.146
	Temperature (°C)	0.161	0.286	
	Moisture (%)	-0.002	0.937	
CH_4	pH	-86.875	0.236	0.223
	Temperature (°C)	18.807	0.242	
	Moisture (%)	-1.008	0.755	
CO_2	pH	-1135.734	0.153	0.322
	Temperature (°C)	272.658	0.121	
	Moisture (%)	-21.727	0.533	

Coefficient = regression coefficient; P-value = significance level; R^2 = coefficient of determination.

4. Discussion

The comparative assessment of greenhouse gas (GHG) emissions from cattle manure in the haor wetland ecosystem of Bangladesh reveals significant differences between storage methods and locations. Our results demonstrate that pit storage consistently produces higher fluxes of methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) compared to heap storage. This finding is consistent with previous research indicating that anaerobic conditions in pit systems favor methanogenesis and microbial respiration (Higarashi et al., 2013; Moeletsi & Moeletsi, 2015). The higher CH_4 emissions from pit storage (409.89 ± 27.54 mg m^{-2} d^{-1}) compared to heap storage (167.56 ± 25.88 mg m^{-2} d^{-1}) highlight the critical role of storage environment in methane production (Mahal et al., 2024; Joy et al., 2026).

4.1. Storage method as a primary driver of GHG fluxes: biogeochemical mechanisms

The pronounced disparity in CH_4 emissions between pit and heap storage ($p < 0.0001$) unequivocally underscores the profound influence of oxygen availability on microbial metabolic pathways. Methane production, or methanogenesis, is an obligately anaerobic process primarily driven by methanogenic archaea, which convert organic substrates into CH_4 (IPCC, 2006; Steinfeld et al., 2006). In pit storage systems, the inherent design, often characterized by deep, compacted manure layers and limited exposure to the atmosphere, creates and maintains highly anaerobic conditions. This environment, coupled with high moisture content, provides an ideal ecological niche for these microorganisms to thrive and actively decompose organic matter (Hu et al., 2023; Junk, 2002). The physical structure of the pit effectively limits gas diffusion, establishing a stable anaerobic core that facilitates sustained and elevated rates of methanogenesis.

Conversely, heap storage allows for greater aeration and gas exchange with the surrounding atmosphere. This increased oxygen penetration significantly inhibits methanogenesis, as methanogens are highly sensitive to oxygen toxicity. Instead, aerobic decomposition processes are promoted, where facultative and obligate aerobic microorganisms utilize oxygen to break down organic matter, primarily releasing CO_2 and water (Sun & Wu, 2013; & Yabar, 2017). Furthermore, the increased surface-area-to-volume ratio in heaps facilitates the activity of methanotrophic bacteria, which can oxidize a portion of the produced methane into CO_2 before it escapes into the atmosphere, thereby reducing net CH_4 emissions. The near-perfect correlation between CH_4 and CO_2 ($r = 0.98$) observed in our study is a critical indicator of shared underlying biogeochemical processes. This strong linkage suggests that factors influencing methane production also similarly affect carbon dioxide release, likely through shared microbial pathways and substrate availability (Azevedo et al., 2013; Savic et al., 2022). Both gases are end-products of organic matter decomposition, albeit under different redox conditions. The high correlation implies that the overall metabolic activity within the manure mass whether predominantly aerobic or anaerobic is governed by a common set of environmental and management constraints.

4.2. Nitrous oxide dynamics and variability: micro-environmental heterogeneity

Nitrous oxide emissions also showed a significant increase in pit storage (3.14 ± 0.80 mg m^{-2} d^{-1}) compared to heap storage (1.53 ± 0.83 mg m^{-2} d^{-1}). N_2O is a potent GHG primarily produced through two microbial processes: nitrification and

denitrification (van der Weerden et al., 2023; Sapkota et al., 2019). The higher N_2O emissions in pit storage, despite its generally anaerobic nature, can be attributed to the formation of spatially and temporally dynamic aerobic and anaerobic micro-environments within the manure mass. These heterogeneous conditions facilitate coupled nitrification-denitrification, where nitrification occurs in oxygenated zones and the resulting nitrate diffuses into adjacent anaerobic zones to be denitrified to N_2O (Gerber et al., 2011; Ioannou-Ttofa et al., 2021).

However, N_2O emissions exhibited the greatest variability (CV% up to 75%), reflecting their complex dependence on micro-scale factors such as soil chemistry and microbial activity (Huang et al., 2017; Conley et al., 2009). This "hot-spot" and "hot-moment" behavior is characteristic of N_2O fluxes, where small, localized changes in environmental parameters or substrate availability can trigger disproportionately large emission events. The high CV% values, particularly in heap storage at Site 3 (74.92%), suggest that heap systems may be more susceptible to environmental fluctuations, such as wind-driven aeration or localized drying, which disrupt the stability of N_2O-producing microbial communities.

4.3. Environmental regulators: pH and temperature as key modulators

Environmental factors such as pH and temperature were found to be key regulators of emission dynamics. Our correlation analysis revealed moderate negative correlations between pH and CH_4 ($r = -0.37$) and CO_2 ($r = -0.41$), implying that lower pH values may enhance gas release (Elser et al., 2007; Sigua et al., 2009). While methanogens typically exhibit optimal activity in neutral to slightly alkaline conditions, the observed negative correlation could be attributed to the influence of pH on the solubility of gases or the activity of competing microbial groups. Temperature exhibited positive associations with gas emissions, showing moderate correlations with CH_4 ($r = 0.37$) and CO_2 ($r = 0.46$), highlighting the role of warmer conditions in favoring microbial activity (Smith et al., 2008; Searchinger et al., 2019). Microbial metabolic rates are highly temperature-dependent, generally increasing with rising temperatures within their optimal range. The regression analysis further supported this, with temperature showing positive coefficients across all gases, although not always reaching statistical significance within the narrow-observed range (20-28 °C). This suggests that even minor seasonal or diurnal temperature shifts in the haor region could significantly modulate the annual GHG budget of livestock operations. These findings underscore the importance of considering environmental conditions when developing mitigation strategies (Das et al., 2020; FAO, 2014).

4.4. Site-specific influences and the unique wetland context

Site-specific differences were evident, with Austagram exhibiting the highest overall emissions for all three gases. This suggests that localized conditions such as substrate availability, microbial activity, and moisture content may amplify greenhouse gas release (Jakariya & Islam, 2017; Mahal & Yabar, 2025). The haor ecosystem, characterized by seasonal flooding and high-water tables, presents a unique biogeochemical environment. The periodic inundation can influence the baseline moisture levels and nutrient cycling in the surrounding soil, indirectly affecting manure decomposition and gas emissions.

The dominance of CO_2 emissions across all sites, exceeding both CH_4 and N_2O fluxes by several orders of magnitude, emphasizes the importance of targeted mitigation strategies for carbon dioxide (BBS, 2023; DLS, 2023). While N_2O fluxes were lower in magnitude, their high global warming potential (GWP) remains a significant concern for climate change (IPCC, 2013; IPCC, 2007). The emission ratio analysis (CH_4:CO_2 and N_2O:CO_2) further highlighted that Site 1 had the greatest relative contribution of non-CO_2 GHGs, underscoring that management strategies must be tailored not just to the storage method, but also to the specific geographic and ecological context (Mahal et al., 2024). This site-specificity necessitates localized assessments and the development of region-appropriate mitigation measures (Tittonell et al., 2010; Laubach et al., 2015).

4.5. Implications for climate-smart manure management and future directions

This study underscores the critical influence of storage method and geographic location on greenhouse gas dynamics in the haor wetland ecosystem. Pit storage was identified as a disproportionately large source of greenhouse gases compared to heap storage, with important implications for climate-smart manure management

strategies (Cattaneo et al., 2023; Prusty et al., 2014). Transitioning from traditional pit storage to improved heap storage designs, or implementing aeration and covering techniques, could serve as viable and cost-effective mitigation pathways for smallholder farmers in Bangladesh.

The variability across sites and the strong interdependencies among greenhouse gases point to the need for integrated and location-specific approaches to mitigate emissions from cattle manure in Bangladesh (Leitner et al., 2021; Cheng et al., 2007). Future research should focus on long-term monitoring across different seasons to capture the full temporal variability of emissions and to evaluate the cost-effectiveness and socio-economic feasibility of various mitigation interventions in the unique socio-ecological landscape of the haor wetlands. Furthermore, the development of localized emission factors, tailored to the specific conditions of the haor region, is crucial for accurate national GHG inventories and effective policy formulation.

5. Conclusion

This research offers a critical evaluation of greenhouse gas (GHG) emission dynamics associated with cattle manure management within the ecologically fragile haor wetland systems of Bangladesh. The empirical evidence underscores that the configuration of manure storage serves as the predominant driver of gas flux magnitudes. Specifically, pit storage systems emerged as disproportionately high sources of methanogenesis e, carbon dioxide, and nitrous oxide relative to traditional heap storage. This divergence is fundamentally linked to the distinct biochemical environments created by each method; the anaerobic, moisture-rich conditions inherent in pit storage facilitate robust methanogenesis and microbial respiration, whereas the increased aeration characteristic of heap storage appears to mitigate these processes by disrupting anaerobic microbial pathways. Beyond the primary influence of storage methodology, the study reveals a sophisticated interdependence among the measured GHGs, suggesting synchronized microbial activity and shared substrate utilization. Although environmental variables such as temperature and pH modulate these emission profiles, the storage technique remains the most reliable predictor of gas release across diverse geographical sites. Furthermore, the observed spatial variations in emissions suggest that localized environmental conditions and substrate heterogeneity significantly refine the regional GHG footprint. The pronounced variability in nitrous oxide fluxes further highlights their sensitivity to micro-scale biogeochemical fluctuations, necessitating more granular management approaches. These findings provide a vital scientific foundation for the implementation of climate-smart agricultural policies in wetland regions. Transitioning from unmanaged pit storage to optimized, aerated heap systems present a technically feasible strategy for reducing the carbon footprint of the livestock subsector without compromising rural food security. Consequently, it is imperative for policymakers to integrate these insights into broader environmental conservation frameworks, prioritizing the adoption of sustainable manure handling practices. Future research should prioritize long-term monitoring and the development of scalable, low-cost mitigation technologies that are culturally and economically compatible with the unique requirements of the haor ecosystem.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

This study adhered to ethical standards and received approval from the research ethics committee of the Animal Welfare and Experimentation Ethics Committee (AWEEC) of Bangladesh Agricultural University. The approval was granted on January 10, 2025, under approval number AWEEC/BAU/2025(2)/82(a). Informed consent was obtained from all participants, guaranteeing their voluntary participation, protection of their rights and confidentiality of their data. The ethical approval and consent procedures implemented in this study demonstrate our dedication to responsible and ethical research practices, ensuring the welfare and well-being of the participants.

Author's contribution

Mahmudul Hasan: Conceptualization, Data curation, Methodology, Software, Visualization, Formal analysis, Writing - original draft, Writing - review & editing. Shamme Akther Jui: Data curation, Methodology, Formal analysis, Writing original draft. Tahrima Tabassum Chapa: Formal

analysis, Software, Visualization, Writing - review & editing. Mohammad Sohan: Formal analysis, Software, Visualization, Writing - review & editing. Md. Mohsin Taluckder: Data curation, Methodology, Formal analysis, Writing - review & editing. Md. Dedarul Hasan: Formal analysis, Software, Visualization, Writing - review & editing. Md. Shahiduzzaman: Conceptualization, Investigation, Supervision, writing - original draft, Writing - review & editing.

Acknowledgement

The authors would like to express their sincere gratitude to the farmers of the haor areas for their cooperation and participation, and to the Upazila livestock offices of Itna, Mitamoin, Austagram of Kishoreganj district whose guidance and assistance were instrumental in data collection.

Data availability

Data will be made available on request.

References

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2018). Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria. Journal of Cleaner Production, 203, 718-735. https://doi.org/10.1016/j.jclepro.2018.08.282

Azevedo, L. B., van Zelm, R., Elshout, P. M., Hendriks, A. J., & Huijbregts, M. A. J. (2013). Modifying the life cycle impact assessment of freshwater eutrophication to include site-specific characteristics. Environmental Science & Technology, 47(19), 11113-11121. https://doi.org/10.1021/es401410v

Bangladesh Bureau of Statistics (BBS). (2023). Statistical Yearbook of Bangladesh. Bangladesh Bureau of Statistics.

Bangladesh Bureau of Statistics (BBS). (2023). Report on Agriculture and Labor Statistics. Bangladesh Bureau of Statistics.

Cattaneo, M., et al. (2023). Assessing Ammonia and Greenhouse Gas Emissions from Livestock Manure: A Comparative Study. Sustainability, 15(22), 15987. https://doi.org/10.3390/su152215987

Cheng, H., Ouyang, W., Hao, F., Ren, X., & Yang, S. (2007). Estimation of non-point source pollution in livestock-breeding areas of the Heihe River basin in Yellow River. Stochastic Environmental Research and Risk Assessment, 21, 213-221. https://doi.org/10.1007/s00477-006-0057-y

Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., Lancelot, C., & Likens, G. E. (2009). Controlling Eutrophication: Nitrogen and Phosphorus. Science, 323(5917), 1014-1015. https://doi.org/10.1126/science.1167755

Das, N. G., Sarker, N. R., & Haque, M. N. (2020). An estimation of greenhouse gas emission from livestock in Bangladesh. Journal of advanced veterinary and animal research, 7(1), 133. https://doi.org/10.5455/javar.2020.g402

Department of Livestock Services (DLS). (2023). Livestock Economy at a Glance. Department of Livestock Services.

Department of Livestock Services (DLS). (2023). Annual Report. Department of Livestock Services.

Elser, J. J., Bracken, M. E., Cleland, E. E., Gruner, D. S., Harpole, W. S., Hillebrand, H., Ngai, J. T., Seabloom, E. W., Shurin, J. B., & Smith, J. E. (2007). Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters, 10(12), 1135-1142. https://doi.org/10.1111/j.1461-0248.2007.01113.x

Food and Agriculture Organization (FAO). (2014). Greenhouse Gas Emissions from Agriculture, Forestry and Other Land Use. FAO.

Food and Agriculture Organization (FAO). (2024). FAOSTAT Database. FAO.

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., & Tempio, G. (2013). Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. FAO.

Gerber, P., Vellinga, T., Opio, C., & Steinfeld, H. (2011). Productivity gains and greenhouse gas emissions intensity in dairy systems. Livestock Science, 139(1-2), 100-108. https://doi.org/10.1016/j.livsci.2011.03.012

Higarashi, m., angnes, g., nicoloso, r. D. S., de oliveira, p. A. V., & mattei, r. (2013). Greenhouse gases emissions during open pit storage and composting of swine slurry in Brazil.https://doi.org/10.1590/S1415-43662013000600011

Hu, S., Zhu, H., Bañuelos, G., Shutes, B., Wang, X., Hou, S., & Yan, B. (2023). Factors influencing gaseous emissions in constructed wetlands: a meta-analysis and systematic review. International Journal of Environmental Research and Public Health, 20(5), 3876.https://doi.org/10.3390/ijerph20053876

Huang, J., Xu, C., Ridoutt, B. G., Wang, X., & Ren, P. (2017). Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China. Journal of Cleaner Production, 159, 171-179. https://doi.org/10.1016/j.jclepro.2017.05.008

Intergovernmental Panel on Climate Change (IPCC). (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES.

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate Change 2007: The Physical Science Basis. Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2013). Climate Change 2013: The Physical Science Basis. Cambridge University Press.

Ioannou-Ttofa, L., Foteinis, S., Seifelnasr Moustafa, A., Abdelsalam, E., Samer, M., & Fatta-Kassinos, D. (2021). Life cycle assessment of household biogas production in Egypt: Influence of digestate, methane leakages, and digestate valorization as biofertilizer. Journal of Cleaner Production, 286, 125468. https://doi.org/10.1016/j.jclepro.2020.125468

Jakariya, M., & Islam, M. N. (2017). Evaluation of climate change induced vulnerability and adaptation strategies at Haor areas in Bangladesh by integrating GIS and DIVA model. Modeling Earth Systems and Environment, 3, 1303-1321. https://doi.org/10.1007/s00477-017-0378-9

Joy, T. A., Amin, B., & Hossain, M. M. D. A. (2026). A comparative analysis of livestock methane emissions across Plain and Haor ecosystems in Bangladesh. Research Square. https://doi.org/10.21203/rs.3.rs-8505800/v1

Junk, W. J. (2002). Long-term environmental trends and the future of tropical wetlands. Environmental Conservation, 29(4), 414-435. https://doi.org/10.1017/S037689290200031X

Laubach, J., Heubeck, S., Pratt, C., Woodward, K. B., Guieysse, B., Van Der Weerden, T. J., ... & Craggs, R. J. (2015). Review of greenhouse gas emissions from the storage and land application of farm dairy effluent. New Zealand Journal of Agricultural Research, 58(2), 203-233.https://doi.org/10.1080/00288233.2015.1011284

Leitner, S., Ring, D., Wanyama, G. N., Korir, D., Pelster, D. E., Goopy, J. P., ... & Merbold, L. (2021). Effect of feeding practices and manure quality on CH4 and N2O emissions from uncovered cattle manure heaps in Kenya. Waste Management, 126, 209-220. https://doi.org/10.1016/j.wasman.2021.02.034

Mahal, Z., & Yabar, H. (2025). Spatial Estimation of Biogas and Compost Potential for Sustainable Livestock Manure Management in Bangladesh. Applied Sciences, 15(12), 6753. https://doi.org/10.3390/app15126753

Mahal, Z., Yabar, H., & Mizunoya, T. (2024). Spatial Assessment of Greenhouse Gas Emissions and Eutrophication Potential from Livestock Manure in Bangladesh. Sustainability, 16(13), 5479. https://doi.org/10.3390/su16135479

Moeletsi, M. E., & Moeletsi, M. E. (2015). Methane and Nitrous Oxide Emissions from Manure Management in South Africa. Animals, 5(2), 193-205. https://doi.org/10.3390/ani5020193

Prusty, S., Sontakke, U. B., & Kundu, S. S. (2014). Methane and nitrous oxide emission from livestock manure. African Journal of Biotechnology, 13(44). https://doi.org/10.5897/AJB2014.13827

Sapkota, T. B., Vetter, S. H., Jat, M. L., Sirohi, S., Shirsath, P. B., Singh, R., Jat, H. S., Smith, P., Hillier, J., & Stirling, C. M. (2019). Cost-effective opportunities for climate change mitigation in Indian agriculture. Science of The Total Environment, 655, 1342-1354. https://doi.org/10.1016/j.scitotenv.2018.11.225

Savic, R., Stajic, M., Blagojevic, B., Bezdan, A., Vranesevic, M., Nikolić Jokanović, V., Baumgertel, A., Bubalo Kovačić, M., Horvatinec, J., & Ondrasek, G. (2022). Nitrogen and Phosphorus Concentrations and Their Ratios as Indicators of Water Quality and Eutrophication of the Hydro-System Danube–Tisza–Danube. Agriculture, 12(7), 935. https://doi.org/10.3390/agriculture12070935

Searchinger, T., Waite, R., Hanson, C., & Ranganathan, J. (2019). Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 billion People by 2050. World Resources Institute.

Sigua, G. C., Coleman, S. W., & Albano, J. (2009). Beef cattle pasture to wetland reconversion: Impact on soil organic carbon and phosphorus dynamics. Ecological Engineering, 35(8), 1231-1236. https://doi.org/10.1016/j.ecoleng.2009.03.020

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., et al. (2008). Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1492), 789-813. https://doi.org/10.1098/rstb.2007.2184

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., & de Haan, C. (2006). Livestock's Long Shadow: Environmental Issues and Options. FAO.

Sun, C., & Wu, H. (2013). Assessment of pollution from livestock and poultry breeding in China. International Journal of Environmental Studies, 70(2), 232-240. https://doi.org/10.1080/00207233.2013.784504

Tittonell, P., Rufino, M. C., Janssen, B. H., & Giller, K. E. (2010). Carbon and nutrient losses during manure storage under traditional and improved practices in smallholder crop-livestock systems evidence from Kenya. Plant and soil, 328(1), 253-269. https://doi.org/10.1007/s11104-009-0107-x

Van Der Weerden, T. J., Noble, A. N., Beltrán, I., Hutchings, N. J., Thorman, R. E., De Klein, C. A. M., & Amon, B. (2023). Influence of key factors on ammonia and nitrous oxide emission factors for excreta deposited by livestock and land-applied manure. Science of the Total Environment, 889, 164066.https://doi.org/10.1016/j.scitotenv.2023.163410

Venier, F., & Yabar, H. (2017). Renewable energy recovery potential towards sustainable cattle manure management in Buenos Aires Province: Site selection based on GIS spatial analysis and statistics. Journal of Cleaner Production, 162, 1317-1333. https://doi.org/10.1016/j.jclepro.2017.06.118