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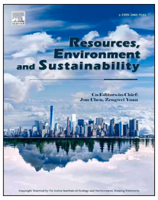

Research article

Manure management in African smallholder farms affects greenhouse gas emissions and leachate losses

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ABSTRACT

In sub-Saharan Africa, cattle manure is a critical yet undervalued bioresource, typically stored in uncovered heaps prior to land application, resulting in substantial greenhouse gas (GHG) emissions and nitrogen (N) losses. We quantified N losses and GHG emissions from six manure management treatments: uncovered and covered manure, interacted with or without straw or charcoal amendments. Covered manure treatments were sheltered with small roofs made of opaque polyethylene installed 10 cm above the container, while the uncovered treatments remained open. Aliquots of 200 kg solid cattle manure were incubated outdoors in open containers to simulate representative storage conditions. While charcoal addition reduced CH_4 emissions, it did not affect N_2O. Conversely, straw-amended treatments emitted approximately twice as much N_2O as unamended manure, with no significant effect of covering. Site-specific ^{15}N-N_2O analysis provided evidence that denitrification dominated N_2O production, with 85–95% of N_2O reduced to N_2. Emission factors ranged between 2.1 and 4.8% for N_2O and 18.6-68.0 g CH_4 kg^{-1} volatile solids, significantly exceeding IPCC default values, highlighting a critical gap in regional emission inventories. Overall, while straw amendment resulted in the greatest N losses, covering was an effective, low-cost and scalable option to preserve nutrients for sustainable crop production.

1. Introduction

Livestock production contributes approximately 12% of global anthropogenic greenhouse gas (GHG) emissions (FAO, 2023a) of which ~13% originate from manure management (Yan et al., 2024). Although sub-Saharan Africa (SSA) hosts approximately 25% of the global livestock population (Butterbach-Bahl et al., 2020), manure-related GHG emissions from the region are currently estimated to represent only 10% of global manure emissions. More specifically, SSA contributes 5% to global emissions from manure management, 4% to emissions from manure applied to soils, and 25% to emissions from manure left on pasture (Tubiello et al., 2014). This apparent discrepancy largely reflects the widespread reliance on default IPCC emission factors (EFs), which are rarely validated under SSA conditions (Dong et al., 2006) and fail to account for indigenous breeds, low-N feeds, climate conditions, or manure storage practices (Ndambi et al., 2019; Leitner et al., 2021; Zhu et al., 2021, 2024). Most studies on manure management have been conducted in temperate regions, while studies on low-quality manure, which is dominant in SSA livestock systems (Leitner et al., 2021), remain scarce. As a result, current national and regional GHG inventories systematically underestimate manure-related emissions (Butterbach-Bahl et al., 2020; Merbold et al., 2021; Graham et al., 2022). Given the rapid growth of the livestock sector in SSA (Lelieveld et al., 1998; Dangal et al., 2017), region-specific flux data and a mechanistic understanding of the processes driving those fluxes are urgently needed to develop accurate baselines and interventions.

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Regarding manure volume, cattle manure is the most important in SSA because cattle are the dominant livestock species in terms of biomass, which directly correlates to the volume of manure produced (FAO, 2023b). In addition, in many SSA smallholder systems, cattle are central to crop-livestock integration, and many farmers use cattle manure to fertilize their croplands. On smallholder farms in SSA, manure is typically stored in uncovered heaps, either with or without bedding material such as straw (Ndambi et al., 2019). This practice can generate substantial nitrous oxide (N_2O) and methane (CH_4) emissions when anaerobic conditions develop within moist heap cores (Petersen et al., 2013). Crucially, up to 75% manure-N may be lost during storage (Tittonell et al., 2010) exacerbating nutrient limitations in smallholder systems where crop yields are already far below attainable levels (i.e. actual yields are only 10-25% of attainable yields) (Mueller et al., 2012; Fraval et al., 2019; Yuan et al., 2025). Improving manure management through low-cost interventions is therefore critical to enhance nutrient circularity, increase crop productivity, and reduce GHG emissions and groundwater pollution (Li et al., 2024; Cheng et al., 2026).

Several manure management strategies have been proposed to reduce N losses and GHG emissions (Banik et al., 2023; Yan et al., 2024). Covering manure heaps can reduce N_2O emissions and nitrate (NO_3^-) leaching by retaining N in organic form and as ammonium (NH_4^+) (Chadwick, 2005). Biochar addition has also been shown to decrease GHG emissions by improving aeration, absorbing substrates, and altering microbial processes (Harrison et al., 2022; Yang X. et al. 2023). While engineered biochar use in SSA remains limited, charcoal production in traditional kilns is widely available and shares similar physiochemical properties (Zulu and Richardson, 2013; Mensah et al., 2022). However, its potential to mitigate GHG emissions and nutrient losses during manure storage remains largely unexplored. In contrast, the effects of adding straw – a common practice in SSA – are uncertain (Gwenzi et al., 2015; Fungo et al., 2019; Kätterer et al., 2019; Roobroeck et al., 2019). Straw alters the carbon to nitrogen (C:N) ratio and heap structure, with reported effects ranging from reduced to increased CH_4 and N_2O emissions (Chadwick et al., 2011; Wang et al., 2012; Ndambi et al., 2019; Leitner et al., 2021).

Despite the relevance of these promising interventions, empirical data on baseline GHG emissions, nutrient losses, and mitigation options for solid manure storage in SSA are scarce.

Therefore, this study aimed to (i) characterize changes in manure chemical composition and fertilizer quality during storage, (ii) quantify baseline GHG emissions and nutrient leaching from uncovered manure heaps with and without straw, and (iii) assess the effectiveness of manure covering and charcoal addition as mitigation strategies. We hypothesized that a) covering manure increases CH_4 emissions but reduces N_2O emissions and nutrient leaching, b) charcoal and straw additions reduce CH_4 but increase N_2O emissions by increasing heap aeration and C:N ratio, and c) IPCC default EFs underestimate actual N_2O and CH_4 from solid manure storage in SSA.

2. Materials and methods

2.1. Study site

The experiment was conducted at the Mazingira Centre for Environmental Research and Education, hosted by the International Livestock Research Institute (ILRI), Nairobi, Kenya (1.27°S, 36.72°E; 1809 m a.s.l., https://www.ilri.org/research/facilities/mazingira-centre). The site has a subtropical highland climate with a mean annual precipitation of 869 mm and air temperature of 19.0 °C (Pelster et al., 2016). Precipitation, air temperature and humidity were measured on-site with an all-in-one weather station (ATMOS 41, Meter Group, Germany).

2.2. Experimental design and treatments

Fresh cattle manure was incubated in 600 L cylindrical high-density black polyethylene containers (top diameter 88.0 cm × bottom diameter 83.5 cm × height 87 cm) equipped with a drainage outlet for leachate collection and an air-tight lid for GHG measurements (Fig. S1). Each container was initially filled with 200 kg fresh cattle manure collected from Boran cattle housed on concrete flooring without bedding at the ILRI research farm. Manure was collected over several mornings in June 2021 to obtain the required volume.

Six manure management treatments were tested with five replicates each: (i) manure only, (ii) manure + straw, and (iii) manure + charcoal, each under covered and uncovered conditions. Rice straw (89.8 ± 0.0% dry matter (DM), 0.28 ± 0.02% N, 43.8 ± 1.0% C) was added at a ratio of 3% manure fresh weight (FW), while charcoal <5 mm particle size (93.3 ± 0.0% DM, 0.69 ± 0.02% N, 39.8 ± 0.1% C) was added at a ratio of 9% manure FW. These amendment ratios were chosen based on previous studies who reported charcoal/biochar additions between 2.5 and 10% FW (e.g. Han et al., 2025; Pires et al., 2025; Vu et al., 2015) and straw additions between 5 and 10% (e.g., Jindo et al., 2012; Zhou et al., 2016). We chose amendment rates at the lower end of the range to account for the general low availability of residues in smallholder farms (Lukuyu et al., 2011). Amendments were thoroughly mixed into the manure prior to incubation. Charcoal was produced locally from Acacia shrubs (*Vachellia drepanolobium*) that were removed during shrub-clearing of a nearby pasture (Mensah et al., 2022). In total, 5.9 kg straw and 18.0 kg charcoal were added to the manure to reach 200 kg FW for + straw and +charcoal treatments, respectively. Covered manure treatments were sheltered with small roofs made of opaque polyethylene installed 10 cm above the container, while the uncovered treatments remained open.

Leachate was collected via PVC tubing into 20 L containers pre-filled with 200 ml of 5.0 M HCl to prevent ammonia volatilization.

Containers were randomly arranged on platforms connected to a hanging scale to monitor mass loss, and tubes for leachate collection were disconnected before weighing. Manure temperature and moisture were continuously measured at the heap center (using TEROS-11 sensors, METER Environment, Munich, Germany). Composite manure samples were collected from the containers using a corer (14 mm diameter) across the full heaps. Three randomly taken samples were then pooled into one sample of ca. 100 g per container. The small holes created by the auger sampling closed within 24-48 h due to manure settling and therefore only minimally affected manure-atmosphere gas exchange. Leachate volume was recorded for each container and subsamples were taken for chemical analysis.

2.3. CH_4 and N_2O flux measurements

Manure CH_4 and N_2O fluxes were measured using the static chamber method coupled with a cavity ring-down laser absorption spectrometer (Picarro G2508, Picarro Inc., CA, USA). Chamber lids were fitted with a fan for headspace mixing, temperature probes, and gas inlet and outlet ports connected via Teflon tubing to the laser absorption spectrometer. CH_4 and N_2O flux measurements lasted 5-10 min per container followed by 3-min flush period.

Flux measurements were conducted over 72 days between June and November 2021, with high frequency sampling during the first two months of storage (every weekday between 08:00-12:00 a.m.). Thereafter, measurement frequency was reduced to three times per week (16-Aug-2021 to 08-Oct-2021). Further reduction in measurement frequency occurred until the end of the experiment (twice a week, 09-Oct-2021 till 01-Nov-2021). CH_4 and N_2O fluxes were calculated from linear concentration changes over time and expressed per kg dry manure using equation (1):

$$F = (b \times M_W \times V_{Ch} \times 60) \ / \ (DW \times V_m) \qquad \text{(Eq. 1)}$$

where F is the flux rate (mg CH_4-C kg^{-1} DM h^{-1} or μg N_2O-N kg^{-1} DM h^{-1}), b is the slope of concentration change (ppm min^{-1} for CH_4, ppb

min^{-1} for N_2O) calculated using linear regression, M_W is the molecular weight (12 g CH_4-C mol^{-1} or 28 g N_2O-N mol^{-1}), V_{Ch} is the headspace volume of the cylinder (0.32 m^3), DW is the manure dry weight at the start of the experiment (ca. 29.8 kg), and V_m is the corrected standard gaseous molar volume (m^3 mol^{-1}) calculated using local air pressure and measured headspace temperature, relative to standard conditions (273.15 K and 1013.25 hPa) during GHG flux measurement.

Data quality control was based on the R^2 values of the linear regression with headspace CH_4 and N_2O concentration change during measurement. Flux values with an $R^2 < 0.7$ for both CH_4 and N_2O were excluded. Furthermore, all negative CH_4 and N_2O fluxes were also discarded. In total <10% of all the 2340 fluxes calculated were discarded. Cumulative emissions were derived by linear interpolation between individual CH_4 and N_2O flux observations over a period of 145 days. Emission factors (EF) for CH_4 and N_2O were calculated following the IPCC methodology (Eggleston et al., 2006; Eggleston et al., 2006).

2.4. Manure and leachate analysis

Manure dry matter content was determined by oven-drying at 105 °C. Total carbon (C) and N content were measured on samples (50 °C for 72h) with an elemental combustion analyzer (VarioMAX Cube CN analyzer, Elementar, Langenselbold, Germany). Volatile solid (VS) was quantified by grinding the oven-dried sample (50 °C, 60 µm particle size) and ashing it in a muffle furnace (550 °C, 4h). Structural components (hemicellulose, cellulose, and lignin), were estimated from neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) analysis using the filter bag technique (Zhu et al., 2020a). Ammonium (NH_4^+) and nitrate (NO_3^-) concentrations in manure and leachate were measured colorimetrically in 1M KCl extracts using a 1:5 manure: extractant ratio (Hood-Nowotny et al., 2010). To determine Dissolved Organic Carbon (DOC) and Total Dissolved Nitrogen (TDN) concentrations in leachate, the leachate was filtered with glass fibre filters (Whatman GC/F, <0.45 µm) and analyzed using a Total Organic Carbon/Total Nitrogen analyzer (TOC-L/TN analyzer, Shimadzu, Kyoto, Japan).

2.5. N_2O position-specific isotope analysis

Position-specific isotope analysis ($\delta^{15}N$ bulk, $\delta^{18}O$, $\delta^{15}N^{SP}$) to determine the main production pathways of N_2O was conducted on four treatments (manure only covered/uncovered, +straw uncovered, and +charcoal uncovered, each with four replicates) to identify whether these improved management options influenced N_2O production pathways. Due to budget limitations, not all treatments could be measured. Samples were taken after 8, 34, and 47 days of incubation. Gas samples were taken from the chamber headspace using a 60 ml syringe immediately after chamber closure and again when the N_2O concentrations reached 600 ppb. For each sample, 180 ml of headspace air was injected into pre-evacuated 110 ml serum crimp vials sealed with 20 mm butyl injection stoppers.

Isotopic composition was determined using an isotope ratio mass spectrometer (IRMS, IsoPrime100, Elementar, UK) coupled to a purge-and-trap preparation unit (Trace Gas, Elementar, UK) (Verhoeven et al., 2019; Gallarotti et al., 2021).

Isotope unmixing for $\delta^{15}N^{bulk}$, SP and $\delta^{18}O$ was done using the following equation:

$$\delta = (\delta_{end}\, C_{end} - \delta_{start}\, C_{start}) \,/\, (C_{end} - C_{start}) \qquad \text{(Eq. 2)}$$

with δ_{start} and δ_{end} denoting the different δ-values of N_2O at beginning and end of chamber closure, respectively. Similarly, C_{start} and C_{end} denote the concentrations of N_2O at beginning and end of chamber closure.

Partitioning contributions from different N_2O production pathways was done using a Markov-Chain Monte Carlo algorithm (Fractionation And Mixing Evaluation – FRAME) (Lewicki et al., 2022) which estimates the fractional contributions from individual sources (bD – bacterial denitrification, nD – nitrifier denitrification, fD – fungal denitrification, Ni - nitrification) based on the measured isotopic signatures of N_2O ($\delta^{15}N^{bulk}$, $\delta^{15}N^{SP}$, $\delta^{18}O$). Respective mean endmember signatures of N_2O isotope processes were taken from Yu et al. (2020) (Fig. S6). $\delta^{18}O$ endmember values of bD, nD, and fD were subsequently corrected for $\delta^{18}O$ of precipitation of the nearest location to our study area (Muguga, Nairobi; latitude: −1.22, longitude: 36.63) accessed via the GNIP database ($\delta^{18}O_{H2O} = -3.35‰$) whereas for Ni no correction was done due to the stable nature of atmospheric $\delta^{18}O$-O_2. For $\delta^{15}N$ source signature substrate correction, a δ-value of 0‰ was assumed for NH_4^+ and NO_3^- as recommended in Lewicki et al. (2022) for cases where this was not determined. FRAME was run with the default settings of 100′000 maximum iterations and 100 burn-out Monte Carlo entries. Model input was $\delta^{15}N^{bulk}$, $\delta^{15}N^{SP}$, and $\delta^{18}O$ averages per treatment per sampling day and their respective standard deviation. Note, bD and nD fractions were aggregated due to weak isotopic separation between them, which was evident from a strong correlation between bD and nD model output. Besides estimating the fractional contribution of processes leading to N_2O emissions, FRAME also estimates the residual unreduced N_2O pool which is not fully denitrified to N_2 (Yu et al., 2020).

2.6. Data analysis

Statistical analyses were performed in R (v4.4.3, R core team, 2025). Treatments effects on cumulative CH_4 and N_2O emissions, EFs, and C and N leaching losses were assessed using generalized linear mixed models (GLMM) with gaussian error distribution. Changes in manure chemical composition (DM, C, N, cellulose, hemicellulose, and lignin) were analyzed using models including treatment, time, and their interaction effect between fresh and final manure (after storage). Homogeneity of variance and normality were evaluated based on diagnostic plots of residuals. Treatment differences after analysis of variance were determined by post-hoc pairwise comparisons using the R package *emmeans* with p-values adjusted according to the Tukey method. Unless specifically stated otherwise, we only report statistically significant results.

3. Results

3.1. Manure chemical composition

Initial manure dry matter (DM) concentration was highest in the +charcoal treatments (21.6 to 42.4%), and lowest in manure only treatments, (14.7 to 27.4%) and the +straw uncovered and covered treatments (16.3 to 24.2%, Fig. 1a). Overall DM manure mass loss during storage was small and difficult to detect with the weighing setup (Fig. S3); the largest loss occurred in the +straw uncovered treatment, which lost approximately 20% DM after 144 days of storage (from 30.9 ± 0.3 kg $container^{-1}$ to 24.8 ± 1.0 kg $container^{-1}$).

Initial carbon (C) concentrations were 38.5 ± 0.2% for manure-only, slightly lower for + straw treatments (37.1 ± 0.1%), and higher for + charcoal treatments (41.1 ± 0.2%). Carbon concentrations declined similarly across treatments by 5–10% during storage (Fig. 1b). Initial N concentrations ranged from 1.80 ± 0.02% (manure-only) to 1.69 ± 0.02% (+straw) and 1.14 ± 0.01% (+charcoal) treatments. After 144 days, N concentrations increased in all treatments, with larger increases in covered and +charcoal covered treatments than in uncovered treatments (Fig. 1c). Consequently, the manure C:N ratio declined from 23.4 initially to 16.9 in covered and 18.3 in uncovered treatments (Fig. S3).

The initial NH_4^+ concentrations were highest in the uncovered and covered manure only treatment (3.5 ± 0.2 mg NH_4^+-N g^{-1} DW) and declined rapidly during the first three months of the experiment, to 0.1-0.6 mg NH_4^+-N g^{-1} DW across all treatments, after which concentrations

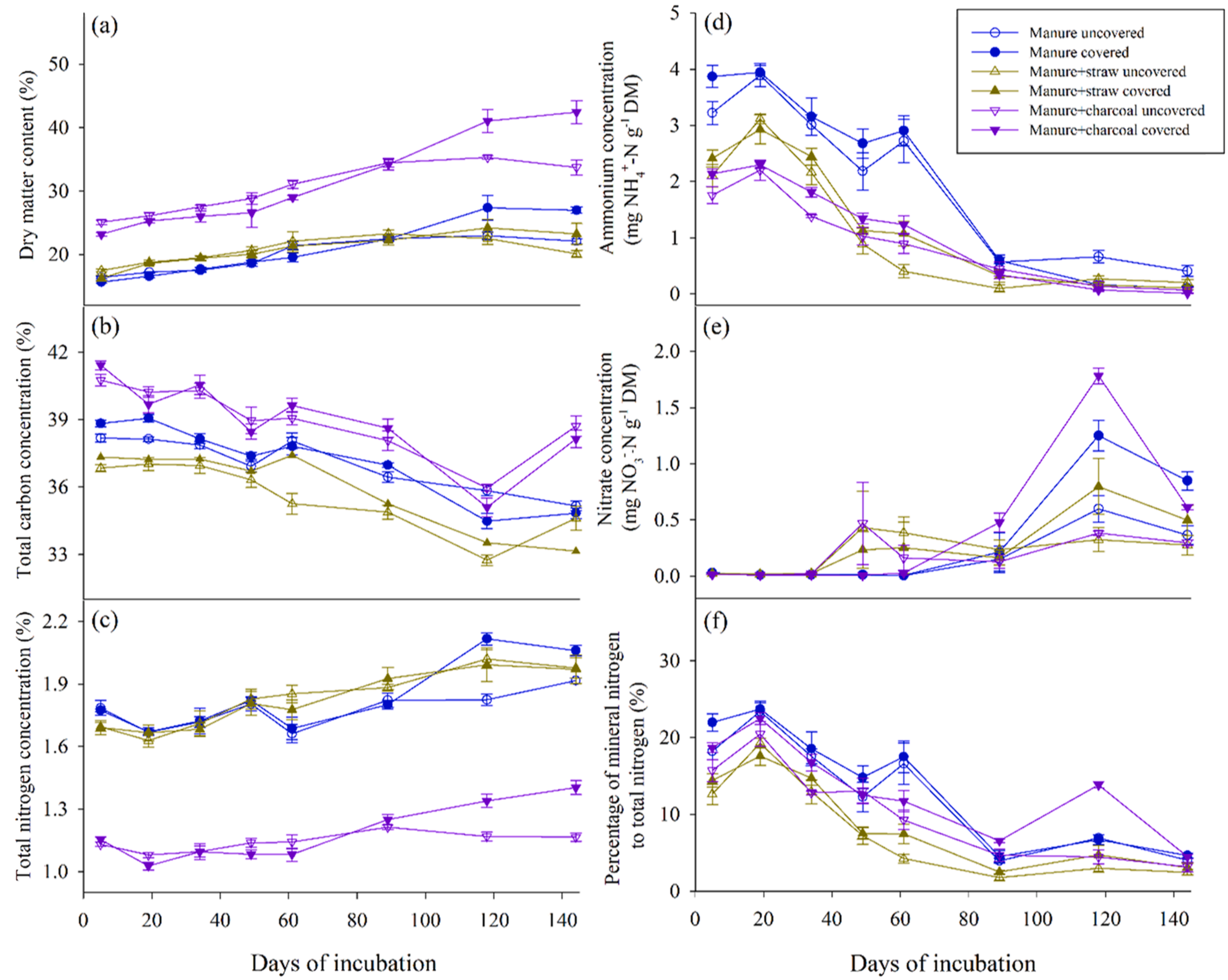

Fig. 1. Dynamics of cattle manure (a) dry matter content, (b) carbon concentration, (c) nitrogen concentration, (d) NH_4^+ and (e) NO_3^- concentrations and (f) percentage of mineral-N to total-N in solid manure heaps over the course of the experiment (145 d). Day 0 is the date when the manure heaps reached their target weight (200 kg FW). Each value represents the mean of five replicates (± standard error).

stabilized (Fig. 1d). Nitrate concentrations were initially negligible but increased in the uncovered treatments after day 54 following heavy rainfall, and they continued to rise thereafter (Fig. 1e). The proportion of mineral-N to total-N peaked after 14 days of incubation (17.6-23.7%) and declined to <5% by the end of the experiment (Fig. 1f).

Charcoal addition significantly reduced initial hemicellulose and cellulose concentrations while increasing the lignin content relative to manure-only and +straw treatments (Fig. S5). Over 144 days, hemicellulose declined by 4-19%, with the largest decrease in the uncovered + straw treatment and the lowest decrease in the covered treatments. Lignin concentrations increased in all treatments by 23 to 65% (Fig. S5).

3.2. Dynamics of carbon and nitrogen loss

During the first 4-6 weeks of the experiment, most CH_4 fluxes were <1.0 mg CH_4-C kg^{-1} DM h^{-1} and N_2O fluxes were <100 μg N_2O-N kg^{-1} DM h^{-1}. Methane fluxes increased after day 46 in all treatments (Fig. 2a), reaching peaks of 15.8-26.4 mg CH_4-C kg^{-1} DM h^{-1} then declining to <5 mg CH_4-C kg^{-1} DM h^{-1} for all treatments after day 125 (Fig. 2a). Dynamics of N_2O fluxes varied among treatments. In the +straw uncovered and covered treatments, N_2O fluxes increased after 19 days and peaked at 905 ± 209 μg N_2O-N kg^{-1} DM h^{-1} after 54 days (Fig. 2b). In most other treatments, N_2O fluxes increased after approximately 45 days and remained stable thereafter. The + charcoal uncovered treatment exhibited a pronounced N_2O peak (3418 ± 197 μg N_2O-N kg^{-1} DM h^{-1}) after 54 days following a heavy rainfall event of 22 mm (Fig. 2b and e).

Daily DOC leaching rates showed similar temporal patterns across all treatments, with high initial losses during the first 10 days followed by a gradual decline and stabilization after 110 days (Fig. 2c). In contrast, daily TDN leaching rates were substantially higher in +straw uncovered and covered treatments (6.6 to 450.4 mg N d^{-1}) compared to other treatments (2.7 to 140.0 mg N d^{-1}) throughout the experiment (Fig. 2d and e).

3.3. Cumulative carbon and nitrogen losses and emission factors

Methane emission factors based on volatile solids (VS) ranged from 18.6 (+charcoal uncovered) to 68.0 g CH_4 kg^{-1} VS (manure only uncovered) (Fig. 3a). The lowest $EF_{CH4\_}VS$ occurred in the +charcoal uncovered treatment and was significantly lower than most other treatments, except + charcoal covered. Emission factors expressed per unit manure-C were similar among treatments (Fig. S4). Nitrous oxide

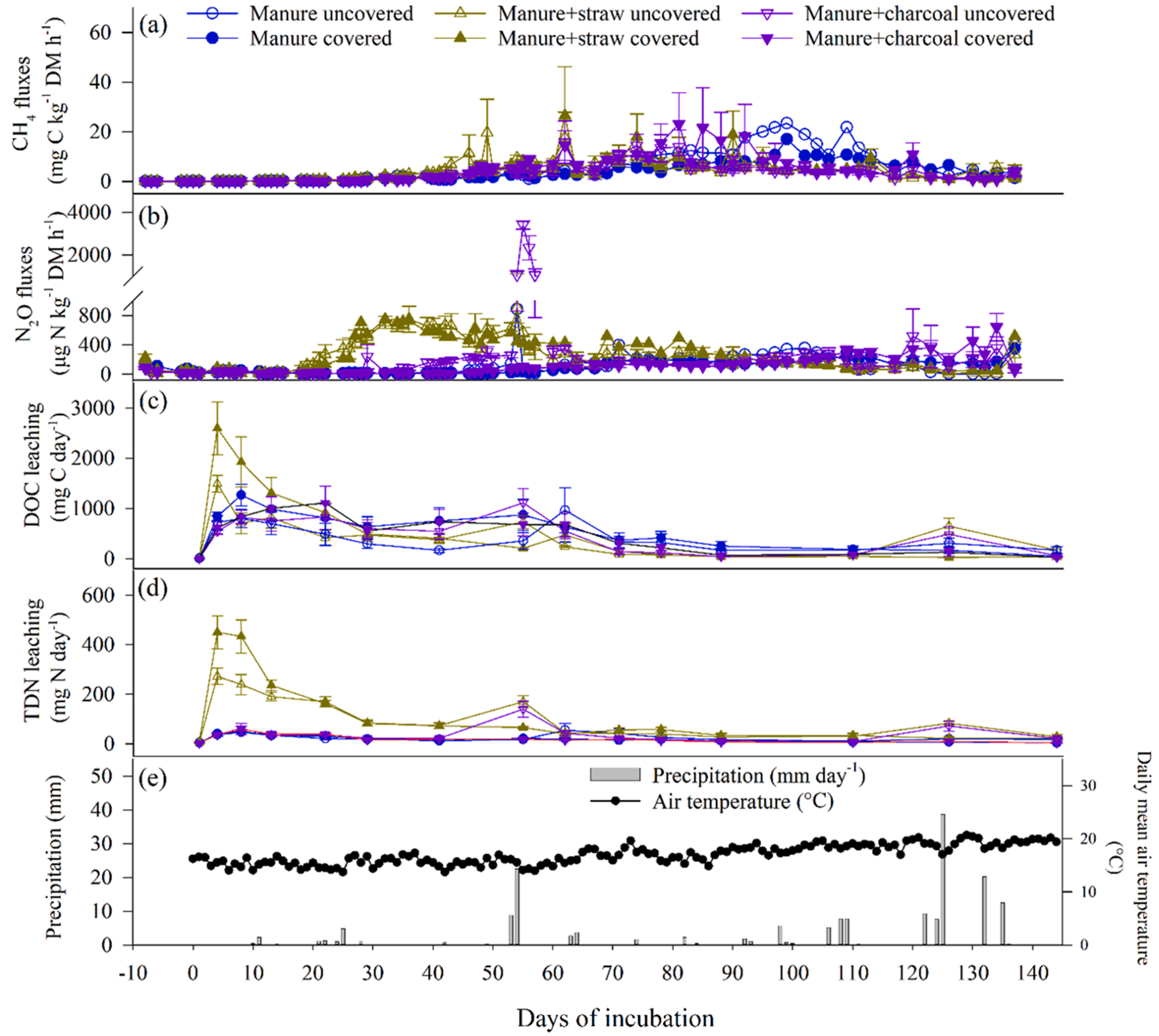

Fig. 2. Dynamics of (a) CH_4 and (b) N_2O fluxes, (c) dissolved organic carbon (DOC) and (d) total dissolved nitrogen (TDN) leaching from manure heaps with different treatments, and (e) precipitation and daily mean air temperature over the experimental period (145 days). Day 0 is the date when the manure heaps reached their target weight. Values represent means of five replicates (± standard error), and different lowercase letters indicate significant differences among treatments ($p < 0.05$). Please note the y-axis break for N_2O in panel b.

emissions factors (EF_{N2O}) ranged from 2.1 ± 0.2% (+charcoal covered) to 4.8 ± 0.5% (+straw covered) (Fig. 3b). Both + straw uncovered and covered treatments had significantly higher EF_{N2O} values than the manure only covered and uncovered treatments and +charcoal covered treatments ($P < 0.05$).

Cumulative DOC leaching accounted for <1% of the total manure C loss across all treatments (Fig. 3c). In contrast, cumulative N loss via TDN leaching differed markedly with the +straw uncovered (2.4 ± 0.1% N) and covered (2.3 ± 0.1% N) treatments losing approximately three times more than other treatments (Fig. 3d).

Dual isotope plots ($\delta^{15}N^{SP}$-N_2O vs. $\delta^{15}N^{bulk}$-N_2O and $\delta^{15}N^{SP}$-N_2O vs. $\delta^{18}O$-N_2O) indicated denitrification as the dominant source of emitted N_2O (Fig. S6). FRAME isotope modelling estimated high N_2O reduction rates across all treatments, with 85-95% of produced N_2O reduced to N_2 and a slight decline over time (Fig. 4). Denitrification accounted for 89 to 95% of total N_2O production.

4. Discussion

4.1. Manure transformation and stability

The limited manure DM loss of <20% observed in this study indicates slow decomposition and incomplete biostabilization during storage, consistent with the predominance of anaerobic or sub-oxic conditions within the manure heap. Reported DM losses were lower than those from tropical composting or vermicomposting studies, where turning and enhanced aeration substantially accelerate decomposition (Sierra et al., 2013). Similarly low decomposition rates (30% mass loss in pit storage, 50% mass loss in heap storage) have been reported for unturned cattle manure heaps under temperate conditions (Tittonell et al., 2010). The absence of significant self-heating further suggests limited microbial activity driven by restricted oxygen availability (Fig. S7). Similar findings were reported in a Danish study in which

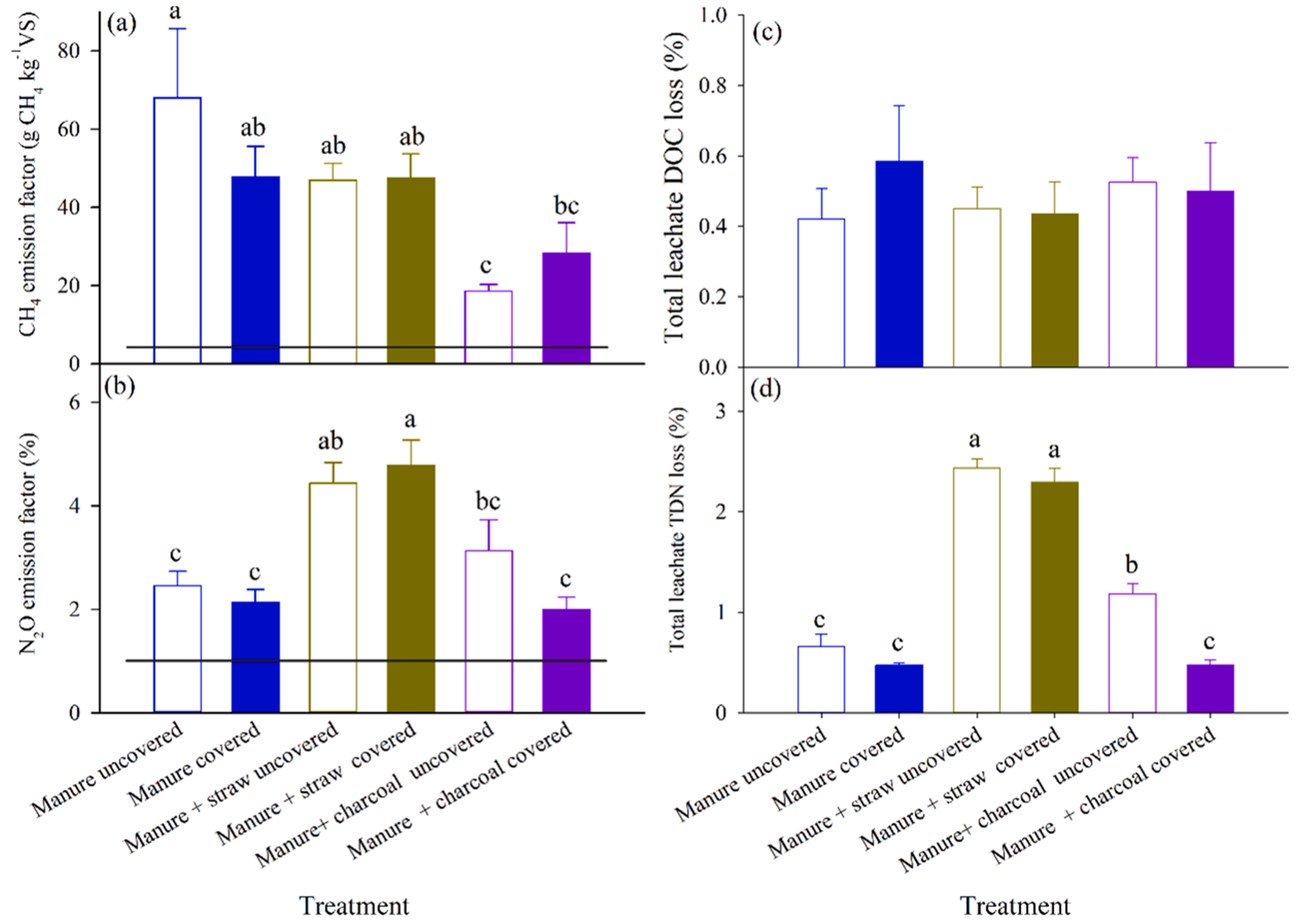

Fig. 3. CH_4 (a) and (b) N_2O emission factors (EFs), and the total cumulative loss of (c) DOC and (d) TDN as a proportion of original manure-C and manure-N. Horizontal lines in panels a and b indicate the IPCC (2019) default values for CH_4 and N_2O EFs for solid storage. Values represent means of five replicates (± standard error). Different lowercase letters indicate significant differences among treatments. There were no significant differences among treatments for total leachate DOC loss.

cattle manure was heaped without turning, resulting in no temperature increase and undetectable mass losses after 14 weeks (Petersen et al., 1998).

Treatment effects on carbon dynamics reflected differences in substrate quality and structure. Straw addition slightly enhanced C loss, likely due to increased availability of labile C and improved aeration (Kaboré et al., 2010). Conversely, charcoal addition reduced apparent C mineralization, consistent with the inherent recalcitrant nature of aromatic C structures in charcoal. This was supported by greater cellulose losses in straw-amended treatments and relatively stable structural components in charcoal-amended manure (Joseph et al., 2021; Lehmann et al., 2021). In contrast, N losses were lower than C losses, consistent with the association of organic N with more recalcitrant lignocellulosic and protein complexes. This pattern agrees with previous syntheses showing greater proportional C than N losses during manure storage (Zhu et al., 2020a; Liu et al., 2023).

In our study, the concentration of NH_4^+ in manure was high throughout the first month, likely reflecting rapid mineralization of labile organic matter and urea hydrolysis (Cai et al., 2017; Markewich et al., 2010). Covering did not affect NH_4^+ concentrations, likely due to the loose covers which allowed air exchange and did not effectively reduce ammonia volatilization. Markewich et al. (2010) similarly presented that covering manure did not affect NH_4^+ concentration, although other studies had found a reduction of NH_3 volatilization (and with that, higher NH_4^+ concentrations) with covering (Chadwick, 2005). Following the first month of the experiment, declining NH_4^+ concentrations coincided with increasing nitrate (NO_3^-), indicating the onset of active nitrification (Sierra et al., 2013; Zhu et al., 2020a, 2024). However, the declining ratio of mineral N to total N suggests that N immobilization exceeded N mineralization from organic pools (Cai and Akiyama, 2016).

4.2. *Efficacy of mitigation strategies and mechanistic drivers*

Contrary to earlier studies carried out in Denmark and the UK (Petersen et al., 1998; Chadwick, 2005), covering manure did not reduce CH_4 emissions. However, both these studies had covered manure with an air-tight tarp, which reduced ventilation and thus slowed down decomposition and reduced internal heap temperature. In addition, Chadwick (2005) had also compacted the manure before covering it with a plastic tarp, which decreased aeration further. In the present study, similar moisture and temperature conditions in covered and uncovered treatments likely explain the lack of a covering effect on CH_4 emissions (Fig. S3&S7).

Similarly, straw addition also did not alter CH_4 emissions, suggesting that increased labile C availability may have offset any aeration-induced suppression of methanogenesis or enhancement of CH_4 oxidation, even though increasing the proportion of bedding material improves the structure and ventilation of the heaps, which should reduce CH_4 production by increasing O_2 supply (Yamulki, 2006; Pardo et al., 2015). Another possible explanation is that the VS content as the biodegradable

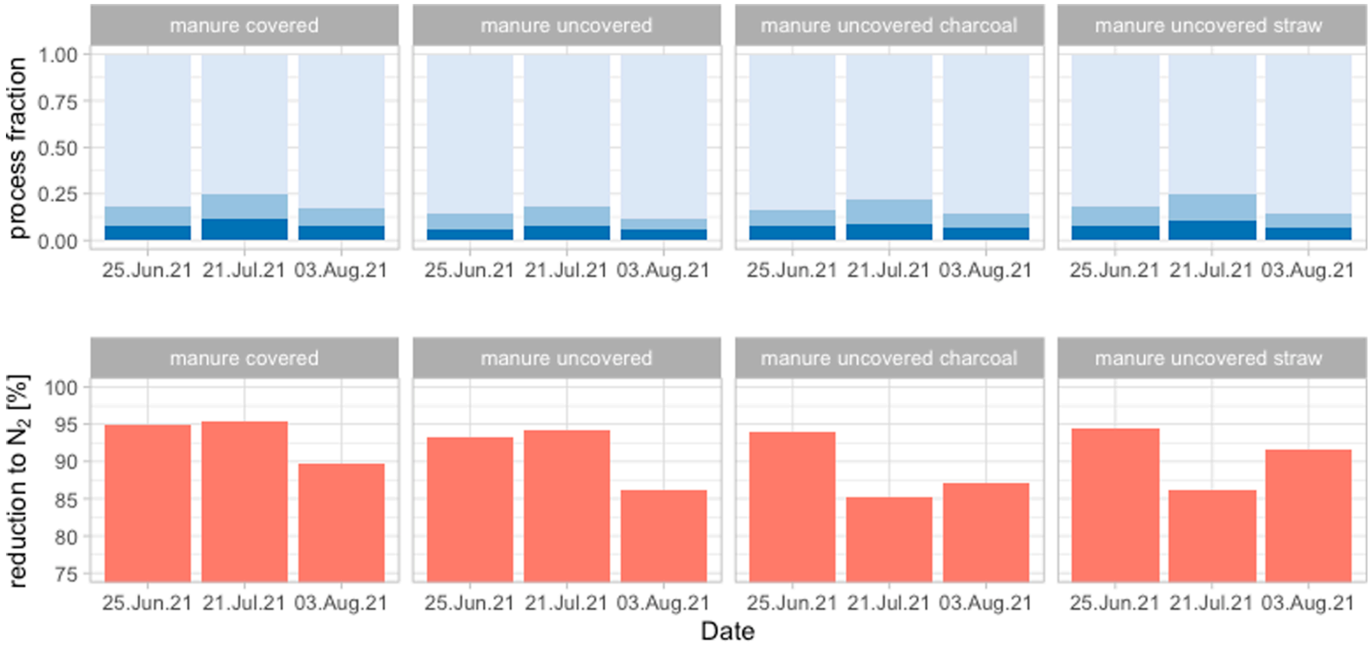

Fig. 4. The upper panel shows the fraction of N_2O producing processes (light blue – denitrification, blue – fungal denitrification, dark blue – nitrification) in solid manure for four different treatments and sampling dates (25.Jun.21, 21.Jul.21 and 03.Aug.21 represent day 8, 34, and 47 of incubation). The lower panel shows the percentage reduction of N_2O to N_2.

fraction did not increase with the addition of straw (Xue et al., 2023).

In contrast, charcoal addition significantly reduced CH_4 emissions in uncovered treatments. This aligns with studies reporting biochar-induced reductions in CH_4 emissions through enhanced aeration and gas diffusion (Harrison et al., 2022). Crucially, in our study, we used regular charcoal produced in traditional earthen mounds, showing that even locally produced charcoal has the potential to reduce CH_4 emissions from manure heaps (Harrison et al., 2022; Joseph et al., 2021).

Generally, CH_4 and N_2O emissions were substantially higher than previously reported for manure heaps in Kenya (Leitner et al., 2021). This likely reflects the lower C:N ratio (22.1 ± 0.5 vs 33.6 ± 6.5) and larger heap sizes (200 kg FW vs 100 kg FW) used in this study, which may have promoted moisture retention and the development of anaerobic microsites. Lower C/N ratios have been reported to promote N_2O production in manure composting because of better N availability for nitrification and denitrification (Liu et al., 2023).

The ^{15}N isotope data confirmed that denitrification was the dominant N_2O producing process, being relatively constant over the measured period and treatments (Fig. 4). In support of this, a steady decrease in NH_4^+ was observed in all treatments while NO_3^- started to increase after about 40 days of incubation, providing the necessary substrate for denitrification. Thus, the overall decline in mineral N was likely a result of consistent overall nitrification and denitrification (Figs. 1f and 4). Manure-associated N_2O production was previously reported during pig manure composting in China (Yang X. et al. 2023) as well as from Kenyan bomas (cattle enclosures) in which manure accumulates overnight (Butterbach-Bahl et al., 2020; Leitner et al., 2024). A follow-up study revealed that the high N_2O production from these bomas is primarily driven by denitrification (Fang et al., 2024). Moreover, Fang et al. (2024) reported 81% reduction of N_2O to N_2 from bomas, which is similar to the reduction rates found in our manure composting heaps (85-95%). These high reduction rates were attributed to strongly anaerobic conditions from the elevated soil/manure bulk density caused by livestock trampling and increased pH by manure accumulation (Šimek et al., 2006).

Straw addition markedly increased N_2O emissions despite similar bulk C:N ratios and moisture contents relative to manure-only treatments (Fig. S3). This suggests that increased availability of degradable C and changes in manure structure enhanced coupled nitrification–denitrification processes, likely through the formation of co-located aerobic and anaerobic microsites reaching favorable redox conditions. These conditions are known to promote high N_2O production in soils and organic waste systems (Hernandez-Ramirez et al., 2009; Highton et al., 2020; Wei et al., 2023). Furthermore, heavy rainfall led to elevated N_2O fluxes in our study, and this was most pronounced in the uncovered + charcoal treatment, which had a large rewetting-induced N_2O pulse around day 53-56. It seems that the rapid rewetting led to a mobilization of mineral N, presumably from the added charcoal, which was then converted to N_2O due to the anaerobic conditions in the manure. In line with this, we also observed high N leaching and elevated NO_3^- concentrations in the same treatment during the same rewetting event. Similarly, in two previous studies in Kenya, we observed high N_2O fluxes after heavy rainfall in cattle excreta patches deposited on pasture (Zhu et al., 2018, 2020b), indicating that the combination of high N availability and O_2 limitation after rewetting are conducive for short, intensive N_2O emission events. From the present study, it seems that this can be exacerbated by charcoal addition. However, another study found that manure additives (including biochar) had no effect on overall nitrogen emissions (N_2O emissions and NH_3 volatilization) for manure solids in a 28-day manure storage study (Holly and Larson, 2017). Therefore, a more comprehensive analysis of the trade-off in gaseous N losses (including NH_3 quantification) after charcoal or biochar addition, as well as the underlying mechanisms, should be considered in future experiments.

Leaching losses showed contrasting patterns for C and N. While DOC losses were similar across treatments, TDN leaching was four-times higher in straw-amended treatments, consistent with previous reports from manure–straw mixtures (Yang F. et al. 2013; Yang X. et al. 2023). The high moisture content of fresh manure likely facilitated leaching of soluble N forms. In contrast to our hypothesis, charcoal addition did not reduce N leaching and, in uncovered treatments, even increased TDN losses, suggesting limited or reversible N sorption under field conditions. However, this effect was markedly reduced by covering charcoal-amended manure, indicating that reduced exposure to rainfall is a critical intervention to reduce N leaching from manure.

In summary, our results show that optimizing manure storage conditions and treatment could promote full denitrification to 'environmentally' benign N_2 (i.e., 85-95% of produced N_2O reduced to N_2 in our study), avoiding harmful N losses through N_2O fluxes or leaching.

4.3. Implications for regional emission inventories

Both CH_4 and N_2O emission factors derived in this study substantially exceeded IPCC default values for solid manure storage of low-producing cattle in warm climates (Gavrilova et al., 2019). In fact, CH_4 emission factors approached those reported for pit or lagoon systems (ranging from 66.2 to 69.7 g CH_4 kg^{-1} VS), likely due to the large size and moisture-retaining properties of manure heaps commonly observed in SSA smallholder systems. During field visits, we observed manure heap sizes in East African smallholder systems ranging from 1 m to over 2 m in height and basal diameters of 4-5 m or more (Fig. S2). Such heaps will likely retain moisture in the core throughout storage (Yan et al., 2024). Similarly, N_2O emission factors were up to four times higher than IPCC defaults, particularly in straw-amended treatments. Given the widespread use of bedding materials in SSA, current inventories likely systematically underestimate manure-related N_2O emissions on the continent. However, we acknowledge that the manure container does not entirely resemble open manure heaps in a real farming scenario and this may have introduced side effects (e.g., limited air flow, rain sheltering, changes in runoff), which might have slightly altered manure moisture and O_2 levels and thus biogeochemical processes. We chose this study design because it enabled us to reliably measure GHG fluxes from the entire heap (as opposed to spot measurements with smaller chambers), to collect all the leachate produced, and to follow the weight loss of the heap over time.

Overall, these findings highlight the need for region-specific emission factors and demonstrate that simple management interventions, such as charcoal addition or improved covering designs, could reduce GHG emissions while improving nutrient retention in smallholder manure management systems. However, without these interventions, the combination of traditional heap storage and warm tropical climates could lead to CH_4 emissions from solid manure heaps that are substantially higher than currently estimated by IPCC default EFs.

5. Conclusion

This study demonstrates that integrating manure storage with bedding materials, a prevalent storage practice in SSA, substantially increases N leakage and CH_4 emissions compared to storing manure without bedding. The effect of covering was inconclusive under the specific experimental design used; however, covering may still reduce leachate N losses under on-farm conditions where manure is frequently exposed to rainfall. Charcoal addition reduced CH_4 emissions but had no measurable effect on N_2O emissions or N leaching, indicating a pathway-specific mitigation potential. This intervention targets the dual benefit of reducing storage emissions while, at the same time, 'charging' charcoal/biochar with nutrients that are often lacking in strongly weathered tropical soils. Importantly, both CH_4 and N_2O emission factors derived in this study exceeded current IPCC default values for solid manure storage, suggesting that existing methodologies underestimate manure-related GHG emissions from smallholder systems in SSA. Incorporating region-specific emission factors and management practices into national inventories is essential to improve the accuracy of GHG accounting and to inform effective, locally adapted mitigation strategies.

CRediT authorship contribution statement

Yuhao Zhu: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Lutz Merbold:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Collins O. Oduor:** Methodology, Investigation. **Matti Barthel:** Writing – review & editing, Visualization, Methodology, Investigation. **Xiantao Fang:** Writing – review & editing, Methodology, Formal analysis. **Johan Six:** Writing – review & editing, Resources, Methodology. **Klaus Butterbach-Bahl:** Writing – review & editing, Investigation, Conceptualization. **Winnie Ntinyari:** Writing – review & editing, Formal analysis. **Sonja M. Leitner:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of generative AI in the manuscript preparation process

During the preparation of this work the authors used Large Language Models (ChatGPT, Gemini) in order to refine the language and improve flow and consistency of the Introduction, Discussion and Conclusions sections. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resenv.2026.100352.

Data availability

Data will be made available on request.

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