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Quantifying the carbon budget cost of overlooked landfill methane in sub-Saharan Africa

Nkweauseh Reginald Longfor

n-longfor-3r2@sophia.ac.jp

Sophia University https://orcid.org/0000-0003-2702-6297

Robert Istrate

Leiden University https://orcid.org/0000-0002-3409-9702

Joseph Jr. Aduba

Temple University, Japan Campus

Xuepeng Qian

Sophia University

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Abstract

Landfill methane from sub-Saharan Africa is a rapidly growing but systematically overlooked contributor to global warming. Here, we model CH_4 emissions across 44 sub-Saharan African countries (2000–2100) under three waste disposal scenarios and conduct a systematic audit of waste-sector commitments in their nationally determined contributions. Cumulative emissions are equivalent to 1.1–4.5% of the remaining 1.5°C carbon budget by end of century, yet only 5 of 44 countries include an explicit methane target for waste, and none of the 10 largest emitters, which account for 71% of regional landfill CH_4, have such a target. Fourteen countries with zero waste-sector pledges represent 39% of modelled emissions. Stated investments totaling USD 10.5 billion are predominantly conditional on undelivered financing and technologically misaligned with immediate mitigation needs. We identify a development paradox: improving waste collection without building disposal alternatives, a trajectory several NDCs already commit to, brings methane likely already emitted by informal dumps into the scope of formal measurement, without necessarily reducing it.

Introduction

Global anthropogenic methane (CH4) emissions have increased significantly over the past two decades, reaching unprecedented growth rates in the last five year (Schaeffer et al., 2025). As a potent greenhouse gas (GHG) with a global warming potential (GWP) 28 times higher than that of carbon dioxide (CO2), CH4 has become an increasing source of concern, prompting calls for deep cuts in anthropogenic emissions (Saunois et al., 2020). Global waste generation is presently 2.6 billion tonnes, of which 29% is disposed of in landfills, with a further share openly dumped or left uncollected; this is expected to reach 3.86 billion tonnes by 2050 (Cook et al., 2026). Despite receiving less than a third of this waste stream, landfills are the world's largest single disposal method and currently contribute 10–13% of annual anthropogenic CH4 emissions, making them the third largest anthropogenic source of CH4 (Singh et al., 2018; S. Zhang et al., 2025). Satellite surveys further show that open dumps emit substantially more CH4 per unit area than managed landfills (Cusworth et al., 2024; Dogniaux et al., 2025; Wang et al., 2024; X. Zhang et al., 2025), so continued waste growth combined with widespread mismanagement will likely push future emissions higher still. Yet how CH4 emissions from landfilled MSW will actually evolve remains poorly understood.

Sub-Saharan Africa (SSA) represents a region where this urgency is particularly acute. Rapid population growth and urbanization are driving waste generation currently estimated at 231 million tonnes per year, expected to reach 518 million tonnes by 2050 (Cook et al., 2026; Kaza et al., 2018). Only approximately 31% of this waste is collected; of the collected fraction, less than 8% is recycled and approximately 77% ends up in landfills without CH_4 capture systems (Cook et al., 2026; Kaza et al., 2018). Socio-economic constraints, infrastructural limitations, and institutional barriers have hindered effective waste management policy implementation across the region (Z. Zhang et al., 2024). In this context, SSA landfills represent a potentially important but poorly constrained source of future CH_4 emissions. The most recent assessment estimates the remaining budget for a 50% probability of limiting warming to 1.5°C at approximately 250 Gt CO_2 as of January 2023 (equal to roughly six years of current emissions) while the budget for 2°C is approximately 1,200 Gt CO_2 (Lamboll et al., 2023). Key uncertainties in these estimates include the contribution of non-CO_2 forcing agents, particularly CH_4 (Damon Matthews et al., 2021; Lamboll et al., 2023). If landfill CH_4 emissions are growing rapidly in a region (SSA) where it is largely unmonitored, the remaining carbon budget may be eroding faster than climate models estimate.

Compounding this problem is a development paradox. As SSA countries urbanize and expand waste collection services, a stated objective in many nationally determined contributions (NDCs), MSW collection rates will rise from the current regional average of approximately 24%. Uncollected waste does not simply disappear from the climate system: it is likely already generating methane through informal dumping, much of it without the partial oxidation that even minimally managed disposal provides. Formalising collection may therefore do less to create new emissions than to surface ones already occurring, unless alternative disposal pathways, composting, recycling, or engineered landfills with CH4 capture, are built at the same time. This trend stands in contrast to global climate ambitions. The Global Methane Pledge (2021) committed signatories to reducing CH4 emissions 30% below 2020 levels by 2030, yet global methane policy coverage remains limited (Olczak et al., 2023). Modelling suggests that rapid deployment of available CH_4 mitigation measures could avoid a quarter of a degree of additional warming by mid-century (Ocko et al., 2021), and that solid waste interventions could contribute meaningfully toward net-zero warming trajectories if adopted within 9–17 years (Hoy et al., 2023). In SSA countries, the extent to which climate commitments adequately address landfill CH_4 emissions remain

largely unexplored, and the potential gap between policy ambition and physical reality has yet to be systematically quantified.

Here, we address this gap by combining future landfill CH_4 emissions modelling with a comprehensive audit of waste-sector policies in NDCs across 44 SSA countries. Using the U.S. EPA first-order decay model (EPA, 2012, 2022), we project CH_4 emissions associated with the disposal of MSW in landfills between 2000 and 2060 under three scenarios: (i) the SSA regional average of 24% waste reaching landfills (current baseline), (ii) country-specific collection rates (most granular present-day estimate), and (iii) 100% landfilling of all generated MSW (upper bound representing development without disposal alternatives). In parallel, we systematically review 44 updated NDC documents published between 2021 and 2024 across several dimensions of waste-sector policy, including CH_4 targets, quantified reduction commitments, investment pledges, and methodological consistency. This study makes three contributions to the literature. First, our findings highlight that cumulative CH_4 emissions from this single source could consume up to 4.5% of the remaining 1.5°C carbon budget by end of century. Second, we reveal that only 5 of 44 countries include an explicit CH_4 reduction target for the waste sector, none of the top 10 emitters have such a target, and stated investments totaling approximately USD 10.5 billion are predominantly conditional on undelivered international financing. Third, overlaying modelled emissions against NDC pledges lets us quantify the emissions–policy gap and identify a development paradox. Expanding waste collection without building disposal alternatives surfaces methane that informal dumps are likely already emitting but that no inventory currently counts, with no matching plan in place to measure or mitigate it. That risk is already written into the NDCs themselves.

Landfill CH_4 emission scenarios across sub-Saharan Africa

We projected annual MSW generation for each SSA country from 2000 to 2060 using country-specific population projections and per capita waste generation rates, adjusted according to expected changes in GDP and urbanization. Based on projected annual MSW generation, the share of food and green waste, and the landfill disposal rate under each scenario, we then estimated associated CH_4 emissions over the period 2000–2100 using a first-order decay modelling approach (see Methods for further details). Under the 24% collection rate scenario, representing approximate current waste collection conditions across SSA, total annual emissions rise from 0.28 Mt CH_4/yr in 2000 to 2.4 Mt CH_4/yr by 2030 and reach the peak of 4.7 Mt CH_4/yr in 2060 (Fig. 1a). Under the country-specific collection scenario, which applies nationally reported waste collection rates, emissions grow from 0.6 Mt CH_4/yr to 5.1 Mt CH_4/yr in 2030, peaking at 9.8 Mt CH_4/yr in 2060. Under the 100% landfill scenario, representing the upper-bound trajectory in which all generated MSW reaches a landfill, emissions rise from 1.2 Mt CH_4/yr to 10 Mt CH_4/yr in 2030, peaking at 19.3 Mt CH_4/yr in 2060, equivalent to 521 Mt CO_2e/yr considering the 100-year GWP of biogenic CH_4 of 27. The gap between the 24% and 100% landfill rate scenarios (from 2.4 to 10 Mt CH_4/yr in 2030, widening to 4.7 to 19.3 Mt CH_4/yr by 2060) represents the "development risk corridor": the quantity of landfill CH_4 that would shift from SSA's largely unaccounted, uncollected waste stream into the formally modelled system if waste collection improves without simultaneous investment in alternative disposal infrastructure. Emissions beyond 2060 represent residual CH_4 generated from the continued biodegradation of organic waste already disposed of in landfills. In practice, however, waste disposal is expected to continue beyond 2060, meaning that landfill CH_4 emissions would likely continue increasing.

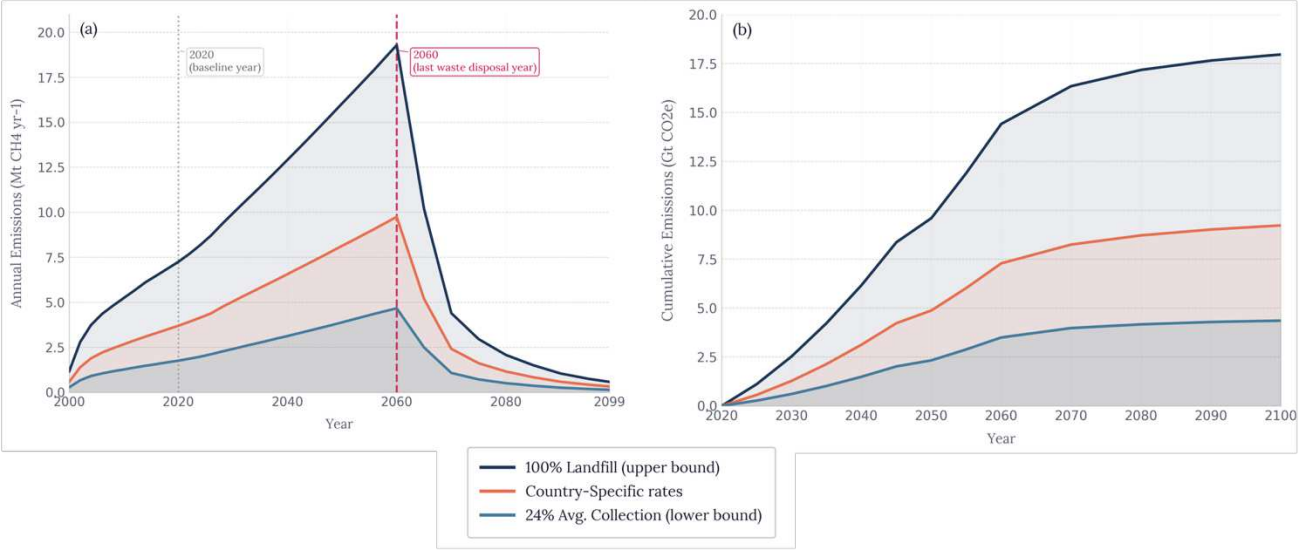


Figure 1: Landfill CH_4 emissions across sub-Saharan Africa under three scenarios: 24% average collection (blue), country-specific rates (orange), and 100% landfilling (dark blue). (a) Annual emissions, 2000–2099; dashed line marks 2060, the last year of waste disposal. (b) Cumulative CO_2-equivalent emissions from a 2020 baseline (GWP-100 = 27).

Carbon budget implications

IPCC remaining carbon budgets are defined strictly in terms of cumulative CO_2; non-CO_2 forcers, including CH_4, enter only as an assumed future trajectory netted out when each budget is derived, not as CO_2-equivalent mass within the stated figure (Damon Matthews et al., 2021; Lamboll et al., 2023). To place SSA landfill CH_4 in a comparable scale, we convert cumulative emissions to CO_2-equivalent using GWP-100 = 27 (IPCC AR6) and express this as a share of four remaining carbon budgets (Fig. 2b). This comparison is illustrative: it communicates the magnitude of SSA landfill CH_4 in budget-comparable units, not a literal claim that this methane directly depletes a CO_2-only budget. The more precise mechanism runs through Rogelj and Lamboll (2024), who show that methane emissions exceeding the trajectory assumed in deriving these budgets shrink the effective remaining budget below its stated value, in some cases exhausting Paris-consistent budgets years earlier than the headline figures suggest. Because SSA landfill CH_4 is accelerating rather than declining, well above what a Paris-consistent pathway would require, this region's growth is part of exactly the kind of excess non-CO_2 emissions that erode these budgets in practice. Across the three scenarios, cumulative CH_4 emissions from SSA landfills amount to 0.61–2.53 Gt CO_2-eq. by 2030, 2.33–9.60 Gt CO_2-eq. by 2050, and 4.36–17.97 Gt CO_2-eq. by end of century (Fig. 2a).

Three features of this analysis merit emphasis. First, even under the most conservative scenario (24% collection rate), cumulative CH_4 emissions cross the 1% threshold of the 1.5°C (<67%) budget by 2070; under the country-specific scenario, this crossing occurs as early as 2046 (Fig. 2b). Under the upper-bound 100% landfill scenario, the threshold is breached by 2036. For a single emission source from a single region, one that receives minimal attention in climate policy, reaching the equivalent of over 1% of the tightest global carbon budget is a significant finding.

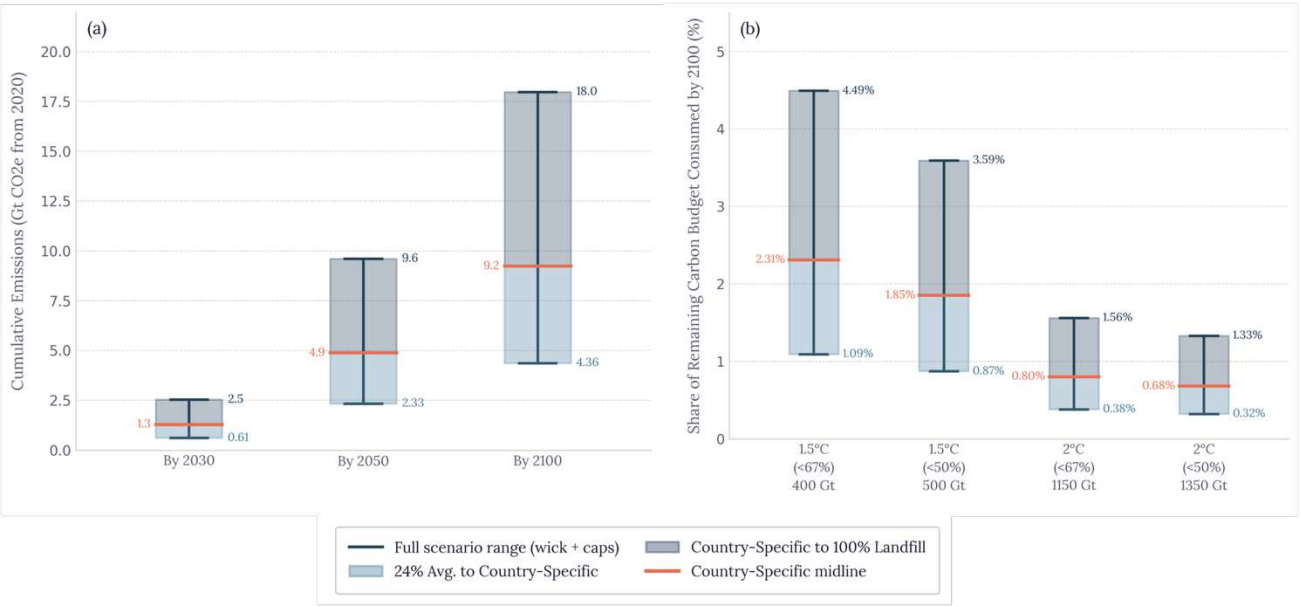


Figure 2: Carbon budget implications of sub-Saharan African landfill methane emissions. (a) Cumulative CO_2-equivalent emissions from 2020 under three landfill scenarios, shown as candlesticks at 2030, 2050, and 2100. Lower cap = 24% average collection rate; upper cap = 100% landfilling; orange midline = country-specific collection rates. (b) Percentage of the remaining IPCC AR6 carbon budget consumed by 2100, shown as candlesticks for four warming-limit/probability thresholds (1.5°C at 67% and 50% likelihood; 2°C at 67% and 50% likelihood; IPCC AR6 WG1 FAQ 5.4), ordered from most to least stringent. Candlestick body height reflects the scenario uncertainty range: under the 1.5°C (67%) budget, SSA landfill methane alone consumes between 1.09% (lower bound) and 4.49% (upper bound) of the remaining global budget by 2100 — a single waste subsector in a single region.

Second, the scenario spread widens markedly over time. By 2030, the range across scenarios is narrow (0.61–2.53 Gt CO_2-eq.), but by 2100 the range spans a factor of four (4.36–17.97 Gt CO_2-eq.), indicating that the choice of waste management trajectory made in the coming decades will determine whether SSA landfill methane is equivalent to approximately 1% or nearly 4.5% of the remaining 1.5°C budget. The upper bound of this range represents the development risk corridor identified above: the volume of landfill CH_4 that would move into the formally modelled system if waste collection improves without parallel investment in alternative disposal.

Third, our analysis is conservative in two respects. We apply GWP-100, which averages methane's climate forcing over a century despite its atmospheric lifetime of roughly 12 years. Evaluated over a 20-year horizon instead, GWP-20 better captures CH_4's near-term radiative impact and puts methane's exchange rate against CO_2 at roughly 80 rather than 27, because its warming effect concentrates within the decade or so it persists in the atmosphere rather than being averaged across a century during which most of it has already broken down. Under GWP-20, all reported percentages roughly triple; we report the full recalculated matrix in the Supplementary Material. We also do not account for progressive depletion of the carbon budget by other sources, which means the effective share of SSA landfill methane in the shrinking remaining budget would be larger than reported here.

Country-level contributions and regional hotspots

Landfill CH_4 emissions are highly concentrated geographically. Under the country-specific scenario, the top five emitters in 2030, Ethiopia (662,170 t CH_4/yr; 13.1%), Nigeria (503,946 t; 10.0%), DRC (452,125 t; 9.0%), South Africa (405,982 t; 8.0%), and Tanzania (314,167 t; 6.2%), collectively account for 46% of the SSA total landfill CH_4 emissions (Fig. 3). Extending to the top ten, which adds Uganda, Mozambique, Madagascar, Ghana, and Kenya, captures 71%. The remaining

34 countries contribute 29%, a share that, while smaller per country, is collectively non-negligible and represents approximately 1.48 Mt CH_4/yr.

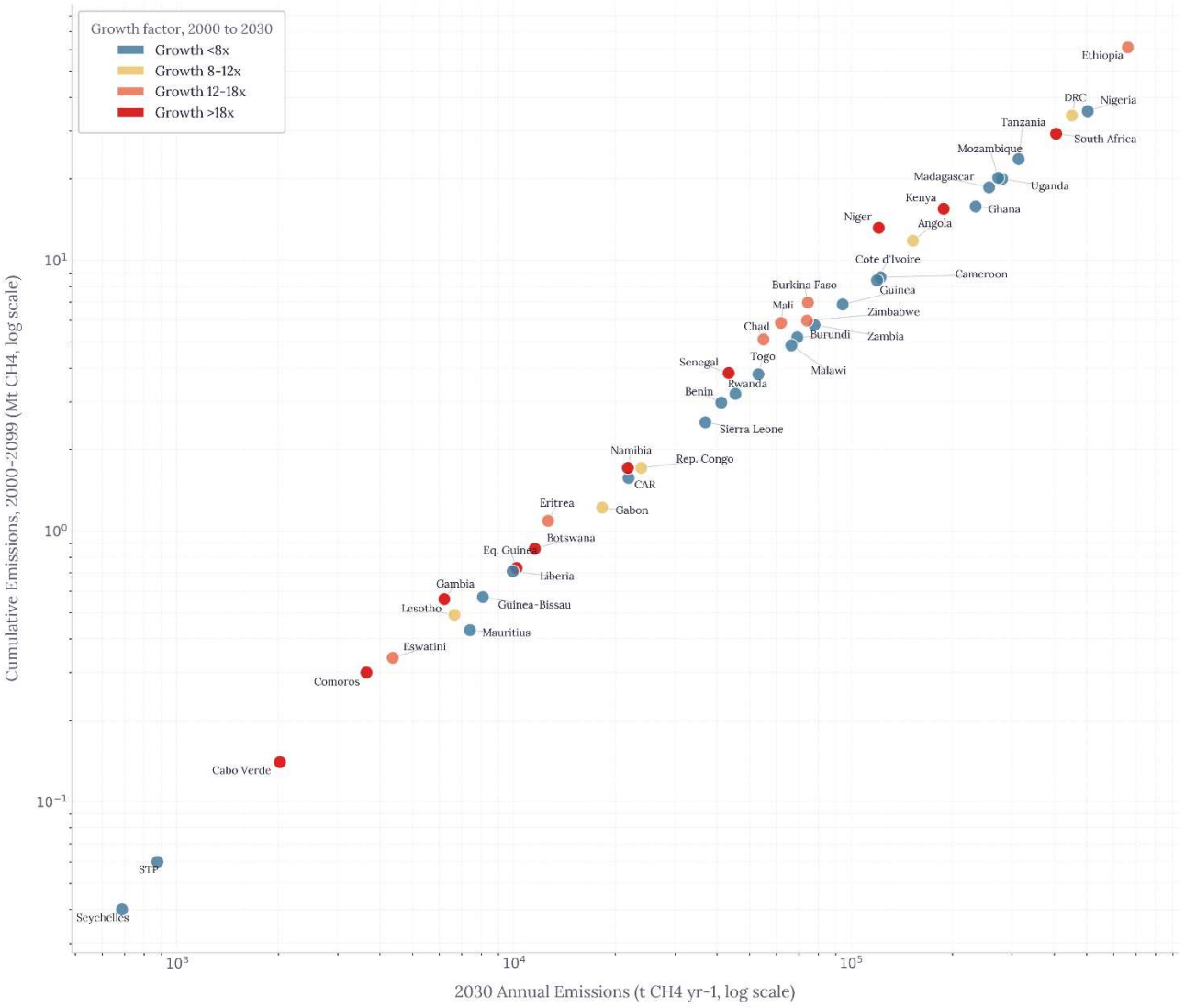


Figure 3: Annual (2030) versus cumulative (2000–2099) landfill CH_4 emissions for all 44 SSA countries, country-specific scenario. Both axes log-scaled to accommodate the ~1000× range across countries; equal spacing reflects equal proportional change, not absolute change. Color indicates growth factor, 2000–2030. South Sudan excluded (zero emissions).

Two patterns emerge from the emissions magnitude and growth rate in Fig. 3. First, the largest emitters are not necessarily the fastest growing. Nigeria and DRC, ranked second and third by absolute emissions, have moderate growth factors of 7.3 and 8.6, respectively, reflecting waste systems already producing substantial CH_4 emissions under current collection rates. By contrast, several countries with moderate absolute emissions exhibit exceptionally high growth, driven by rapid urbanization outpacing waste infrastructure: South Africa (growth factor of 20), Kenya (19), Niger (19), Senegal (20), and Namibia (22). These high-growth countries are generating landfill CH_4 at rates that barely existed two decades ago, and their trajectories suggest continued rapid acceleration. Second, the geographic distribution reveals regional clustering (Fig. 3). East Africa (Ethiopia, Tanzania, Uganda, Kenya, Mozambique, Madagascar) dominates the top 10, collectively contributing 39% of SSA total emissions. West Africa (Nigeria, Ghana, Côte d'Ivoire, Niger, Guinea) contributes 23%. Southern Africa's contribution is dominated by South Africa, which alone accounts for 8%, the only Southern African country in the top 10.

NDC waste-sector policy audit

To assess whether SSA countries' climate commitments address the large volume of landfill CH_4 emissions documented above, we conducted a systematic audit of 44 updated NDC documents (2021–2024) across seven dimensions of waste-sector policy (Fig. 4). Of the 44 countries audited, only five include an explicit CH_4 reduction target for the waste sector: Burkina Faso, Cabo Verde, Lesotho, Seychelles, and Zimbabwe (Fig. 4). All five are smaller emitters; none ranks in the top 15 emitters by 2030. Twenty countries, including the five with explicit CH_4 targets, state some numeric waste-sector reduction target, a percentage cut from a stated baseline or an absolute Gg/kt CO_2e figure, regardless of whether it isolates methane from other waste-sector gases. The remaining 24 (more than half) have no measurable waste-sector commitment of any kind. Twenty-six countries mention waste-to-energy (WtE) in their NDCs, and 26 mention composting, but in most cases these references are aspirational rather than operational, lacking budgets, timelines, or technical specifications.

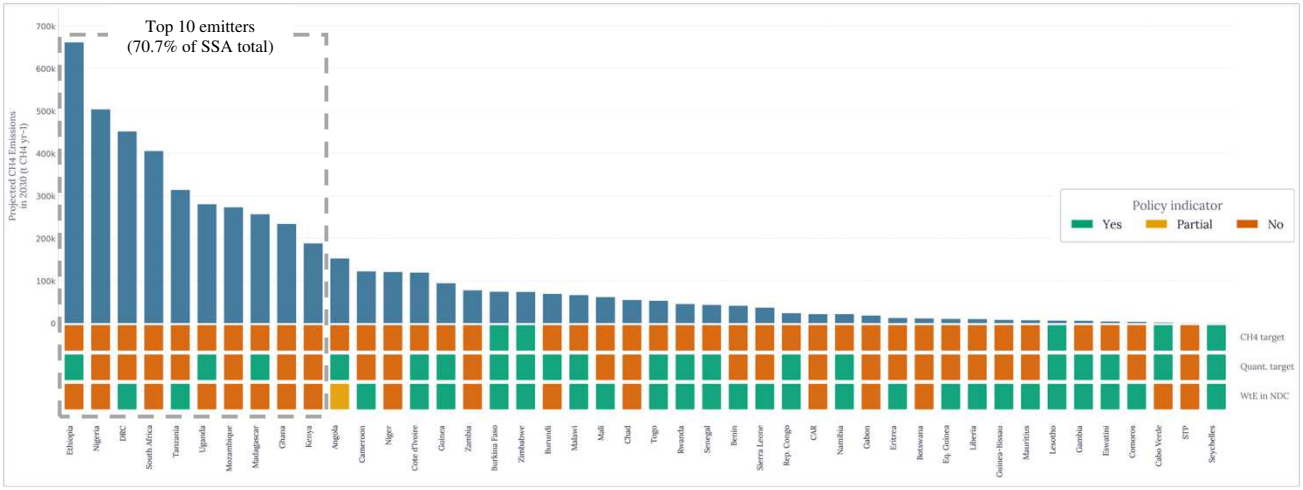


Figure 4: NDC waste-sector policy audit, 44 countries, ranked by projected 2030 landfill CH_4 emissions. Heatmap indicates presence of a CH_4 target, a quantified waste target, and WtE mention in each NDC. Colors are: bluish-green = yes, orange = partial, vermillion = no.

The pattern becomes most striking when NDC ambition is mapped against emission magnitude (Fig. 4). None of the top 10 emitters, which collectively account for 71% of modelled SSA landfill CH_4 emissions, have an explicit CH_4 target. Only three of the top ten (Ethiopia, Uganda, Madagascar) have any quantified waste-sector target, and none is backed by a funded, unconditional implementation plan. Ethiopia, the single largest emitter, lists zero concrete waste mitigation measures in its NDC despite stating a conditional 23.7% waste-sector reduction target by 2035. Uganda's and Madagascar's targets fare no better: nearly all of Uganda's abatement runs through a conditional programme, and Madagascar's target carries no unconditional/conditional split at all, with roughly 96–97% of its associated costs dependent on external financing. South Africa (4th largest), Tanzania (5th), Mozambique (7th), Ghana (9th), and Kenya (10th) have neither a CH_4 target nor a quantified waste-sector target. Twelve countries, including South Africa, Niger, Gabon, Botswana, Zambia, and Central African Republic, list zero waste-specific mitigation measures of any kind.

The audit also reveals systematic methodological inconsistencies that undermine cross-national comparability. Thirty-two of 44 NDCs do not state which GWP value was used for CH_4; among the 12 that do, values range from SAR (GWP=21) to AR5 (GWP=28); a 33% difference that renders waste-sector pledges non-comparable across countries. The IPCC guideline versions applied are similarly fragmented: 16 countries use the 2006 IPCC Guidelines, but through at least eight different modelling tools (GACMO, LEAP, LEAP-IBC, EX-ACT, GEM, and bespoke spreadsheets), while four do not specify their methodology at all. One country (Cameroon) still uses the 1996 Revised IPCC Guidelines. Several NDCs

contain internal inconsistencies: Benin reports its waste sector as both 5.38% and 5.3% of national emissions in different sections of the same document; Lesotho cites both 7% and 6.5%. These discrepancies may appear minor individually, but they reflect a broader absence of quality control in waste-sector reporting that, when aggregated across 44 countries, renders the UNFCCC Global Stocktake process for waste inherently unreliable.

Taken together, these findings point to a structural blind spot. The waste sector is commonly perceived as contributing "just 3%" of global emissions (Wilson et al., 2024), and this framing appears to have depressed policy attention in NDC formulation. Yet our emissions modelling shows that landfill CH_4 from SSA alone is a significant and rapidly growing source. The disconnect between the scale of the emissions problem and the depth of policy response is not a matter of individual country shortcomings but a systemic feature of how waste is treated in the global NDC architecture. Olczak et al. (2023) found that only 13% of global CH_4 emissions are covered by any form of mitigation policy; our audit suggests that for SSA waste-sector CH_4 specifically, the effective coverage is even lower.

The emissions–policy gap

Following the methodology described in Methods section, we compute the emissions–policy gap and coverage for each country by overlaying modelled 2030 landfill CH_4 against NDC pledges.

The gap is vast. Fourteen countries have zero quantified waste-sector pledge, collectively accounting for 53.6 Mt CO_2-eq./yr or 39% of all modelled SSA landfill CH_4 emissions (Fig. 5). These include four of the five largest emitters: Nigeria (13.6 Mt CO_2e/yr), South Africa (11.0 Mt), Tanzania (8.5 Mt), and Kenya (5.1 Mt). Among the remaining 30 countries with some form of pledge, 14 cover less than 20% of their modelled emissions, making their commitments largely symbolic. Ethiopia, the single largest emitter at 17.9 Mt CO_2e/yr, has a conditional pledge covering only 14% of its modelled landfill CH_4 emissions. Uganda (15%) and Madagascar (15%) are similarly undercovered. When countries are grouped by the fraction of modelled emissions covered by their NDC pledge, the picture is stark: zero-pledge countries account for 39% of modelled emissions; countries with less than 20% coverage account for a further 35%; and only 21% of total emissions fall in countries where pledges nominally exceed modelled landfill CH_4 (Fig. 5).

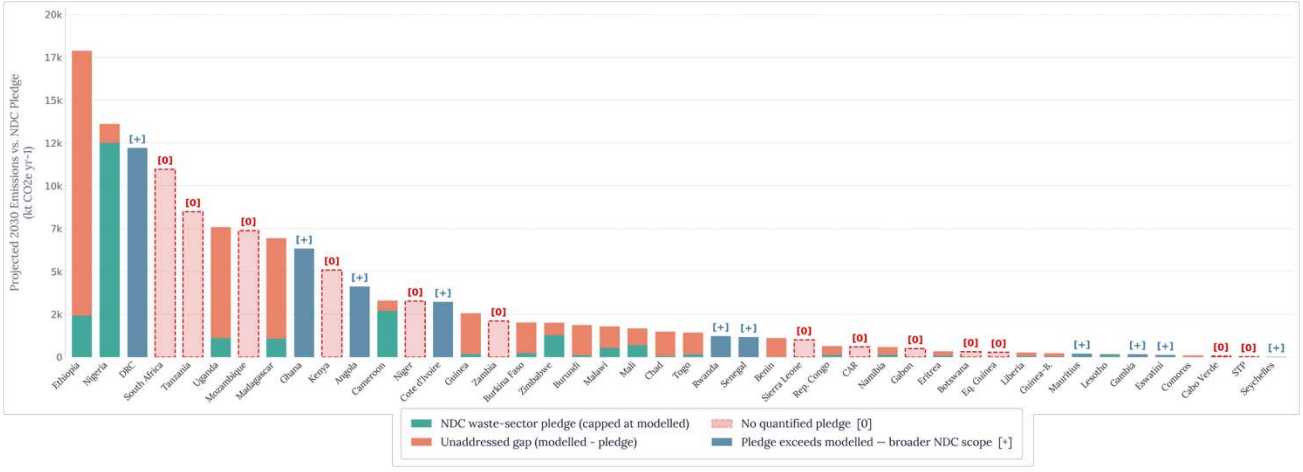


Figure 5: The emissions–policy gap: modelled 2030 landfill CH_4 emissions versus NDC waste-sector reduction pledges across sub-Saharan Africa (kt CO_2e yr^{-1}). Each bar represents one country, ranked from the largest to the smallest modelled emitter under the country-specific waste collection scenario. The bar is composed of two stacked segments: the teal segment shows the maximum waste-sector emission reduction pledged in that country's NDC, capped at the modelled emission level; and the orange segment represents

the unaddressed gap — the portion of modelled landfill methane for which no corresponding policy commitment exists. Together, the full bar height equals total modelled emissions, making the orange gap directly readable as the share of emissions left unaddressed.

Furthermore, nine countries where pledges appear to exceed modelled emissions warrant caution rather than optimism. In every case, the NDC waste-sector scope is broader than landfill CH_4 alone. DRC pledges 37 Mt CO_2-eq. against our modelled 12.2 Mt, but its NDC uses three mutually inconsistent methodologies and bundles wastewater, composting, and institutional waste management into a single figure. Ghana pledges 21.3 Mt CO_2-eq. against a modelled 6.3 Mt, but the pledge covers "alternative urban solid waste management" broadly, not landfill CH_4 specifically. Gambia's pledge (497 kt) exceeds its modelled landfill CH_4 emissions (168 kt) by a factor of three, but includes wastewater treatment, integrated waste management, and organic waste programmes. These scope mismatches mean that apparent overcoverage does not imply that landfill CH_4 is adequately addressed; it reflects incomparable accounting boundaries across NDCs, echoing the methodological inconsistencies documented above.

The investment dimension deepens the concern (Fig. 6). Of the 44 countries audited, only 24 include a quantified waste-sector investment in their NDC, with a stated total of approximately USD 10.5 billion. However, this headline figure is structurally unreliable for three reasons.

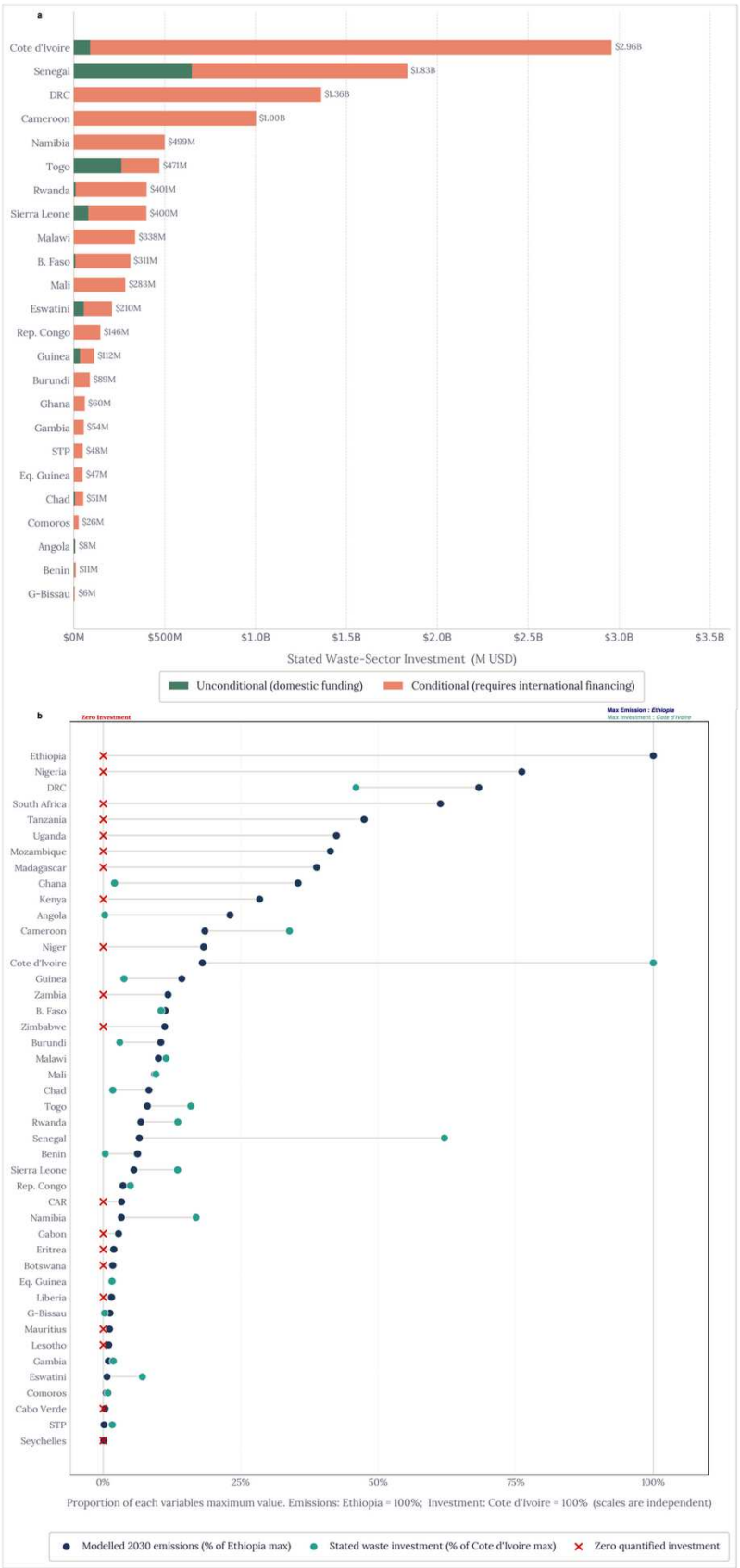


Figure 6a: Stated waste-sector investment by country, disaggregated by conditionality (M USD). Countries are ranked by total stated investment as extracted from their updated nationally determined contributions (NDCs, 2021–2024). Each bar is split into two components: the green segment represents unconditional investment — domestically funded commitments that do not depend on

external financing — while the orange segment represents conditional investment, which is contingent on receiving international climate finance that has not yet been delivered. Figure 6b. Relative mismatch between modelled landfill CH_4 emissions and stated waste-sector investment across sub-Saharan Africa (Cleveland paired dot plot). Each row represents one country, ranked from the largest to the smallest modelled emitter. Two dots are shown per country connected by a horizontal line: the dark blue dot represents that country's projected 2030 landfill methane emissions, and the teal dot represents its stated waste-sector investment. Both variables are expressed as a proportion of their respective regional maximum — emissions are scaled to Ethiopia, the largest emitter (= 100%), and investment is scaled to Côte d'Ivoire, the largest investor (= 100%). These two scales are entirely independent: a country sitting at 50% on emissions emits half of what Ethiopia emits, while a country at 50% on investment has committed half of what Côte d'Ivoire has committed — the two percentages measure different things and cannot be directly compared to each other.

First, approximately 76% of stated investment is conditional on international climate financing (Fig. 6a). Countries such as Malawi (USD 338M), Namibia (USD 499M), DRC (USD 1.36B), and Rep. of Congo (USD 146M) have fully conditional waste budgets. If financing does not materialize, and the track record of waste-sector climate finance delivery in SSA is poor (Isah et al., 2025), these investments remain aspirational. The five largest emitters (Ethiopia, Nigeria, South Africa, Tanzania, Kenya) have zero quantified waste investment; together they account for 41.1% of modelled landfill CH_4 (Fig. 6b).

Second, substantial portions of stated investment are misclassified. Burkina Faso's headline figure of USD 310.7M includes USD 289.9M for water and sanitation resilience, an adaptation measure, not waste-sector GHG mitigation. Only USD 20.8M targets emission reduction. Similar inflation appears in Burundi (USD 74.6M adaptation of USD 88.6M total) and São Tomé & Príncipe (USD 48.25M entirely WASH adaptation with zero mitigation component). The aggregate investment figure therefore substantially overstates climate-relevant waste spending.

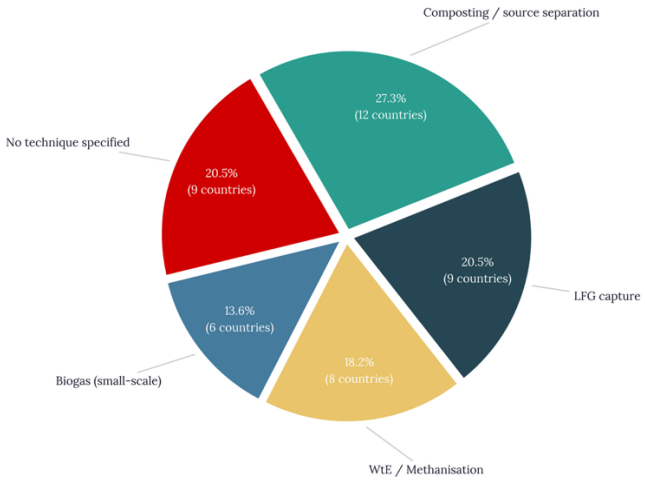


Figure 7: Primary waste mitigation technology stated in NDC waste-sector commitments across sub-Saharan Africa (n = 44 countries). Each segment represents the number and share of countries identifying a given technology as their primary waste mitigation approach in their updated nationally determined contributions (2021–2024).

Third, the technology preferences embedded in NDC investments are misaligned with the timescale of the CH_4 problem (Fig. 7). Capital-intensive waste-to-energy and landfill gas capture dominate stated investments, yet these technologies require grid infrastructure, gas cleaning systems, and technical capacity that most SSA countries will not have operational for at least a decade. Composting and source separation, which eliminate CH_4 generation entirely by diverting organic waste before it reaches a landfill, appear in fewer NDCs as primary techniques despite being immediately deployable at a

fraction of the cost. Namibia's investment profile illustrates this inversion: its NDC is labelled as "LFG" in national reporting, but USD 480M of its USD 499M total is actually composting, the most effective technique is present but misrecognised in the country's own framing.

Discussion

The development paradox: why collection expansion surfaces an accounting gap

Our results reveal a structural tension between development objectives and climate accounting in SSA waste management that, to our knowledge, has not been previously quantified at this regional scale. The development risk corridor identified in Results 2.1 widens from 7.5 Mt CH_4/yr in 2030 to 14.6 Mt CH_4/yr by 2060 (Fig. 1), and the cumulative difference between the two scenarios amounts to 7.3 Gt CO_2e over 2020–2050, the quantity of landfill CH_4 that would shift from SSA's largely unaccounted, uncollected waste stream into the formally modelled system as collection improves without matching investment in alternative disposal.

Uncollected waste is not a zero-emission baseline: much of it likely generates methane through informal dumping, and uncovered dumps emit more CH_4 per unit area than managed landfills, since they lack the partial oxidation even minimal cover provides (Dogniaux et al., 2025). Whether formalizing collection raises, lowers, or leaves the true regional total unchanged depends on what happens to uncollected waste today, a question this dataset cannot resolve. What we show is narrower: the share of SSA's landfill methane that becomes formally measurable as collection expands, regardless of the underlying physical trend.

Several NDCs make this concrete. Our audit shows multiple countries setting waste collection improvement as an adaptation target without linking it to mitigation measures. Ethiopia's NDC lists expanding urban solid waste coverage from 61.3% to 83% as an adaptation priority, yet the same document contains zero concrete waste mitigation measures and places its entire 2.7 Mt CO_2-eq. conditional waste reduction target on unspecified international support. Uganda's "Green Cities Waste Management" programme targets expanded waste access across four cities and fifteen municipalities, but nearly all abatement (~1.1 Mt CO_2-eq.) is conditional. Malawi's three quantified waste measures (landfill gas, waste-to-energy, and wastewater treatment totalling USD 338M) are 100% conditional, contributing zero to the country's 6% unconditional national target. In each case, improving waste collection without guaranteed alternative disposal creates the conditions for the development risk corridor to widen.

The paradox aligns with global patterns. Waste contributes the largest sectoral share of methane growth alongside agriculture (Janardanan et al., 2024), and circular strategies outperform technical fixes alone (Gómez-Sanabria et al., 2022). The acceleration we document (8.5–8.7× growth, 2000–2030) reflects the same urbanization dynamics driving waste generation, and technical fixes applied after landfilling remain inherently less effective than upstream diversion through composting and source separation.

This analysis also has implications for how CH_4 is weighted in climate accounting. The GWP-100 of 27 used throughout this study is conservative for a short-lived climate forcer with an atmospheric lifetime of approximately 12 years. Using GWP-20 (~80), the carbon budget consumption under the upper-bound scenario rises from 4.49% to 13.3% of the remaining 1.5°C budget. While GWP-100 remains the IPCC standard for inventory reporting, the near-term radiative

impact of CH_4 and, therefore, the near-term climate benefit of reducing it, is substantially underweighted by this metric (Ocko et al., 2021).

The policy implication holds regardless of the net physical effect. NDC collection-expansion targets should come paired with disposal-pathway commitments (composting, recycling, capture), because collection is the point where currently invisible methane becomes visible, and the only point where a country can choose whether to capture it, avoid it, or simply landfill it unmanaged.

Implications for the Global Methane Pledge and the Global Stocktake

Our findings expose a fundamental disconnect between the governance architecture for CH_4 mitigation and waste-sector reality in SSA. Under the Global Methane Pledge (2021), most SSA signatories committed to reducing CH_4 emissions 30% below 2020 levels by 2030. Applied to SSA landfill CH_4 emissions scenarios assessed in this study, this would require emissions to fall to approximately 1.2 to 5.1 Mt CH_4/yr by 2030. Instead, our projections show emissions reaching 2.4 to 10.0 Mt CH_4/yr, approximately twice the pledge-consistent level across all scenarios. The pledge and the trajectory are moving in opposite directions: rather than contracting, SSA landfill CH_4 is accelerating along a path that Saunois et al. (2020) identify as globally consistent with scenarios assuming no or minimal mitigation policy.

This divergence raises a structural question about the credibility of the UNFCCC Global Stocktake for the waste sector. The Global Stocktake is intended to assess collective progress toward Paris Agreement goals every five years (Qi et al., 2024), but our NDC audit reveals that the informational basis for such assessment is fundamentally compromised in SSA's waste sector. Three problems compound. First, 14 of 44 countries report no waste-sector pledge at all, creating a 39% blind spot in regional emissions. Second, the 30 countries with some form of pledge use incompatible accounting boundaries: some cover only landfill CH_4, while others bundle wastewater, open burning, and waste diversion into a single figure, making cross-national aggregation meaningless. Third, 32 of 44 NDCs do not state which GWP value was used for methane, with the 12 that do ranging from 21 (SAR) to 28 (AR5), a 33% spread that introduces systematic non-comparability into any aggregate assessment. These findings are consistent with Mulatu et al. (2024), who identify inconsistent reporting timeframes and incomparable methodological approaches as systemic impediments to a comprehensive Global Stocktake across developing countries, and with Worden et al. (2023), who note that satellite-based verification of waste-sector CH_4 trends is currently confounded by low information content at the national level.

Without standardisation, the Global Stocktake cannot meaningfully evaluate whether SSA waste-sector CH_4 is rising or falling, let alone by how much. We recommend that future NDC guidance mandate a standardised waste-sector reporting template requiring: (i) explicit landfill CH_4 quantification separated from other waste sub-sectors; (ii) consistent IPCC methodology and GWP values; and (iii) waste collection rate projections linked to disposal pathway commitments, thereby connecting the adaptation and mitigation dimensions that our analysis shows are currently decoupled.

From waste-to-energy rhetoric to circular economy investment

The investment analysis reveals a technology preference pattern in SSA NDCs that is inverted relative to both feasibility and effectiveness. Capital-intensive WtE and landfill gas capture dominate stated investments, yet life cycle assessments consistently demonstrate that composting-based scenarios outperform thermal and landfill gas alternatives in cost, environmental burden, and climate impact for the SSA context. Richard et al. (2021) show that recycling combined with composting and landfilling produces the lowest economic cost and environmental burden of any scenario modelled for

Arusha, Tanzania (one of our top-10 emitting countries). Muhammad et al. (2021) reach the same conclusion for Nigeria, finding composting to be the most cost-effective waste treatment method across seven criteria using multi-criteria decision analysis. These findings are consistent with a broader literature demonstrating that organic waste diversion through composting and source separation eliminates CH_4 generation entirely by preventing biodegradable waste from entering anaerobic landfill conditions, whereas landfill gas capture typically recovers only 50–75% of generated CH_4, with the remainder escaping through cover soil and lateral pathways (Wang et al., 2024).

The mismatch is compounded by the conditionality structure of these investments documented above: most is contingent on undelivered international climate financing. The track record of climate finance reaching the waste sector is poor: Isah et al. (2025) estimate that annual climate finance needs across developing country NDCs exceed USD 600 billion by 2030 (double the amount pledged under the New Collective Quantified Goal) and the waste sector competes for these constrained resources against higher-profile mitigation sectors such as energy and transport. Moreover, substantial portions of stated waste investment are misclassified as adaptation spending on water and sanitation rather than GHG mitigation, further inflating the apparent commitment.

A reorientation is needed. Climate finance mechanisms and NDC technical assistance should prioritise three interventions in order of deployment readiness. First, composting infrastructure for organic waste diversion delivers immediate CH_4 avoidance at a fraction of WtE capital costs, generates employment, and improves soil quality in agricultural economies (Ddiba et al., 2022). Second, extended producer responsibility (EPR) schemes that reduce the volume of waste requiring disposal and shift financial responsibility upstream. Third, phased WtE and landfill gas capture only where grid infrastructure and technical capacity already exist. This is currently limited to South Africa's major municipalities, parts of Nairobi, and Lagos (Debrah et al., 2022; Z. Zhang et al., 2024). Framing WtE as a near-term solution for countries that lack the basic infrastructure to operate these facilities delays action by decades while methane accumulates.

Limitations and future directions

The first-order decay model assumes homogeneous waste composition and decay rates within each country, whereas real landfills are heterogeneous in both waste input and environmental conditions. No CH_4 oxidation factor is applied. This is a conservative assumption for the unmanaged open dumps that dominate SSA, where cover soil is minimal or absent. However, this assumption may moderately overestimate emissions for the small number of managed landfills in South Africa and parts of Kenya. Bottom-up inventories of this kind have been shown to underestimate landfill CH_4 relative to satellite measurements (Cusworth et al., 2024; Dogniaux et al., 2025; Wang et al., 2024); our estimates are therefore plausibly conservative. Waste generation projections are based on population growth and GDP trajectories from World Bank data (Cook et al., 2026; Kaza et al., 2018). South Sudan could not be included in this analysis due to insufficient population data at the time of estimation; total SSA landfill CH_4 reported here therefore excludes this country's contribution, which we are unable to characterize. Actual generation rates may diverge if urbanization patterns, consumption behaviours, or informal waste recovery systems evolve differently than projected. We do not propagate parameter uncertainty in decay constants or biochemical methane potential, nor do we test sensitivity to alternative population and GDP growth trajectories beyond the three disposal scenarios modelled here. The NDC audit represents a snapshot as of 2024 and covers the most recent updated NDC submission for each country. NDCs are political documents, not technical inventories, and pledges may not reflect actual implementation capacity. Investment figures extracted from NDCs are indicative rather than budgeted, and are not always clearly disaggregated from broader environmental or WASH spending. While we have

documented this limitation where identified, it cannot be fully resolved without disbursement-level data. Waste-sector reduction targets expressed as percentages of BAU are non-comparable across countries where BAU baselines use different methodologies, GWP values, and waste-sector scope definitions. Finally, this study covers landfill CH_4 emissions only. It does not include open burning of waste (which produces CO_2, black carbon, and $PM_{2.5}$), wastewater CH_4, or N_2O from waste. The total waste-sector climate impact across SSA is therefore higher than we report.

Future work should pursue four directions: (i) integration of satellite-based top-down CH_4 measurements from TROPOMI and GHGSat (Cusworth et al., 2024; Maasakkers et al., 2022) to validate bottom-up estimates for SSA landfills, where observational coverage remains sparse (Worden et al., 2023); (ii) tracking NDC revisions through subsequent update cycles to assess whether the policy gaps identified here are closing; (iii) extending the combined emissions-modelling and NDC-audit framework to other developing regions (such as South Asia, Southeast Asia, and Latin America) where similar urbanisation-driven waste trajectories are underway; and (iv) analyzing climate finance disbursement data to assess whether stated NDC investments are reaching SSA waste sectors in practice.

Methods

Landfill CH_4 emissions modelling

Waste generation projections. Annual MSW generation for each country was projected using population data and per capita waste generation rates from the World Bank's *What a Waste 2.0 and 3.0* database (Cook et al., 2026; Kaza et al., 2018), applying country-specific growth factors based on GDP and urbanization trajectories. The 44 countries comprise SSA countries recognized in the UNDP Human Development Report regional classification (UNDP, 2016), with two exceptions: South Sudan, for which population and GDP data required to project waste generation were unavailable, and Mauritania, which fell outside the scope of the source datasets used in this study.

Waste composition and physicochemical parameters. Two biodegradable waste fractions were modelled: food waste and paper waste, which together constitute the dominant CH_4-generating components of MSW in SSA (IPCC, 2006a). The physicochemical parameters used are summarized in Table 2.

Methane emissions from landfills were estimated using a first-order decay (FOD) model consistent with IPCC Guidelines (IPCC, 2006b) and US EPA methodology (EPA, 2012, 2022). The FOD model captures the slow decomposition of biodegradable waste in anaerobic landfill conditions, where CH_4 generation continues for decades after waste disposal.

First-order decay equation. The volume of CH_4 generated by one tonne of waste material j in year y after disposal in country c is given by (Eq. 1):

$$q_{j,y,c} = \sum_{k \in K}\left(1 - moist_j\right) \cdot vs_j \cdot bmp_j \cdot \left(e^{-k_{j,c}\cdot(y-1)} - e^{-k_{j,c}\cdot y}\right),\ \forall\, j \in J, y \in \{1, \ldots, 100\}, c \in C \qquad \text{Eq. 1}$$

where y is the year after waste disposal and ranges from one to 100, $q_{j,y,c}$ is the volume of CH_4 generated by one tonne of waste material j in year y following waste disposal in country c (Nm^3 CH_4tonne^{-1} wet material), $moist_j$ is the moisture content of waste material j (tonne dry material tonne^{-1} wet material), vs_j is the volatile solids content of waste material j (% dry mass), bmp_j is the biochemical CH_4potential of waste material j (Nm^3 CH_4tonne^{-1} volatile solids), and $k_{j,c}$ is the decay rate of waste material j in country c (year^{-1}).

Table 2: Physicochemical properties of waste materials.

Property	Units	Food waste	Paper waste	References
Moisture	% wet mass	60	10	(IPCC, 2006a)
Volatile solids	% dry mass	83	84	(Götze et al., 2016; Krause et al., 2016)
Biochemical CH_4potential	Nm^3 CH_4 $tonne^{-1}$ volatile solids	390	225	(Krause et al., 2016)
Decay rate				
MAP < 1,000 mm $year^{-1}$	$year^{-1}$	0.085	0.045	(IPCC, 2006b)
MAP > 1,000 mm $year^{-1}$	$year^{-1}$	0.400	0.070	(IPCC, 2006b)

Decay rate constants. Decay rates were assigned to each country based on mean annual precipitation (MAP), following IPCC (2006b) guidelines. For food waste: k = 0.085 $year^{-1}$ where MAP < 1,000 mm $year^{-1}$, and k = 0.400 $year^{-1}$ where MAP ≥ 1,000 mm $year^{-1}$. For paper waste: k = 0.045 $year^{-1}$ where MAP < 1,000 mm $year^{-1}$, and k = 0.070 $year^{-1}$ where MAP ≥ 1,000 mm $year^{-1}$. MAP data were sourced from the World Bank Climate Change Knowledge Portal. Country-level decay rate assignments are provided in Supplementary Material.

Temporal scope and aggregation. Waste disposal was modelled from 2000 to 2060, with emissions from each year's deposited waste tracked through a 100-year decay window (i.e., to 2099 for the earliest deposits and to 2160 for the latest, though we report only through 2099). The total CH_4 emitted from a country's landfills in a given calendar year is the sum of contributions from all waste cohorts deposited in that year and all preceding years:

$$Q_{c,t} = \sum_{t_0=2000}^{\min(t,2060)} \sum_{j \in J} W_{j,c,t_0} \cdot q_{j,(t-t_0),c} \qquad \text{Eq. 2}$$

where $Q_{\subset,t}$ is the total CH_4 emission from country c in calendar year t (Nm^3 CH_4 $year^{-1}$); $W_{j,,to}$ is the mass of waste material j disposed in landfills in country c in year t_0 (tonnes wet material); and $q_{j,(t\text{-}t0),\subset}$ is the CH_4 generated per tonne from Eq. 1 with $y = t - t_0$. Volumetric CH_4 was converted to mass using the density of methane at standard conditions (0.0007168 tonnes m^{-3}) and reported in tonnes CH_4 $year^{-1}$.

Three waste disposal scenarios. To bracket the plausible range of present and future landfill CH_4 emissions, we modelled three scenarios:

Scenario 1 (24% average landfill rate): Applies the SSA regional average waste collection and landfilling rate of approximately 24% (Cook et al., 2026; Kaza et al., 2018) uniformly across all countries. This represents an approximation of current aggregate conditions, where the majority of waste is uncollected or disposed of through informal channels (open dumping, open burning).

Scenario 2 (Country-specific collection rates): Applies nationally reported waste collection-to-landfill rates to each country individually, providing the most granular present-day estimate. These rates range from less than 10% in several low-income countries to over 60% in South Africa and Mauritius.

Scenario 3 (100% landfill): Assumes all MSW generated reaches a landfill. This upper-bound scenario represents the trajectory toward which SSA countries may converge as urbanisation improves waste collection services without

simultaneous investment in composting, recycling, or other alternative disposal infrastructure. The gap between Scenario 1 and Scenario 3 defines the development risk corridor discussed above.

No methane oxidation was applied in any scenario. This is a conservative assumption for the unmanaged open dumps that constitute the vast majority of waste disposal sites in SSA, where cover soil is minimal or absent and oxidation rates are negligible. For the small number of managed sanitary landfills in the region (primarily in South Africa), this assumption may moderately overestimate emissions.

Carbon budget analysis

Cumulative CH_4 emissions were computed for each scenario by summing annual emissions from 2020 onward — consistent with the baseline year for IPCC AR6 remaining carbon budgets — for three time horizons: by 2030, by 2050, and by 2100.

Conversion to CO_2-equivalent. Cumulative CH_4 (in tonnes) was converted to CO_2-equivalent using GWP-100 = 27, as specified in the IPCC AR6 (Calvin et al., 2023) and adopted by the US EPA. This conversion is expressed as:

$$E_{CO_2e} = \sum_{t=2020}^{T} Q_{c,t} \cdot GWP_{100} \qquad \text{Eq. 3}$$

where $E CO_2e$ is the cumulative CO_2-equivalent emission (tonnes CO_2e) and T is the terminal year (2030, 2050, or 2100).

Carbon budget share. The percentage of the remaining carbon budget consumed by SSA landfill CH_4 was calculated as:

$$Budget\ Share\ (\%) = \frac{E_{CO_2e}}{B} \times 100 \qquad \text{Eq. 4}$$

where B is the remaining carbon budget from 2020 (in tonnes CO_2). Four budgets were used, drawn from the IPCC AR6 Synthesis Report (Calvin et al., 2023): 400 Gt CO_2 (1.5°C, <67% probability), 500 Gt CO_2 (1.5°C, <50%), 1,150 Gt CO_2 (2°C, <67% probability), and 1,350 Gt CO_2 (2°C, <50%).

Three aspects of this approach are conservative. First, the carbon budget is treated as static from 2020; in reality, other sources progressively deplete it, meaning the effective share of landfill CH_4 would be larger than reported. Second, no methane oxidation is subtracted. Third, GWP-100 is used rather than GWP-20 (~80), which would approximately triple all reported percentages.

Systematic NDC audit

We conducted a systematic audit of waste-sector commitments in the nationally determined contributions of 44 SSA countries. For each country, the most recently submitted updated NDC (2021–2024) was retrieved from the UNFCCC NDC Registry (https://unfccc.int/NDCREG). Where countries had submitted multiple updates, the latest available version was used.

Audit dimensions. Each NDC was assessed across seven dimensions:

(i) *Explicit CH_4 target:* whether the NDC contains a methane-specific reduction target for the waste sector (binary: yes/no).

(ii) *Quantified sectoral target:* whether the NDC contains any numeric emission reduction target specific to the waste sector, regardless of gas species (binary: yes/no).

(iii) *Number of waste mitigation measures:* count of discrete, identifiable waste-sector mitigation actions listed in the NDC (integer).

(iv) *Waste-to-energy (WtE) mentioned:* whether the NDC references WtE, landfill gas capture, methanisation, or similar thermal/energy recovery from waste (binary: yes/no).

(v) *Composting mentioned:* whether the NDC references composting, organic waste diversion, or source separation as a mitigation strategy (binary: yes/no).

(vi) *IPCC methodology and GWP value:* which IPCC guideline version (1996, 2006, 2019 refinements) and GWP value (SAR, AR4, AR5, AR6) the NDC states it used for waste-sector emissions accounting.

(vii) *Internal consistency:* whether the NDC contains self-contradictory waste-sector data (e.g., different waste share percentages cited on different pages, conflicting GWP values within the same document).

Investment and conditionality analysis. For each NDC, we additionally extracted: (a) stated waste-sector investment amounts (in USD or local currency, converted at the exchange rate prevailing at NDC submission); (b) conditionality status (unconditional, conditional on international support, or mixed); and (c) primary waste mitigation technology specified. Investment figures were cross-referenced against the itemised NDC text to identify misclassification of WASH (water, sanitation, and hygiene) adaptation spending as waste-sector GHG mitigation investment.

Waste-sector reduction targets. Where NDCs stated percentage reduction targets for the waste sector relative to a business-as-usual (BAU) baseline, we extracted and verified both unconditional and conditional targets. Targets stated for years other than 2030 (e.g., 2035, 2040) were noted but not interpolated to 2030 in the main analysis. All extracted targets were fact-checked against the original NDC text and corrected where discrepancies were found (Supplementary Tables S3 and S4).

Emissions–policy gap calculation

Modelled emissions. For each country, the projected 2030 annual landfill CH_4 emission under the country-specific collection scenario (Scenario 2) was converted to CO_2-equivalent using GWP-100 = 27:

$$E_{c,2030}^{CO_2e} = Q_{c,2030} \cdot \rho_{CH_4} \cdot GWP_{100} \qquad \text{Eq. 5}$$

where $Q_{⊂,2030}$ is the volumetric CH_4 emission, ρCH_4 is the density of methane (0.0007168 t m^{-3}), and $GWP_{100} = 27$.

NDC pledged reduction. The maximum waste-sector emission reduction pledged in each country's NDC was extracted, combining both unconditional and conditional commitments under the most generous interpretation. Where NDCs stated reductions in absolute terms (e.g., kt CO_2e yr^{-1}), these were used directly. Where reductions were stated as percentages of a waste BAU, the absolute reduction was computed using the NDC's own stated BAU value. Where neither was available, the country was classified as having zero pledge.

Gap and coverage metrics. Two metrics were computed for each country:

$$Gap_c = E_{c,2030}^{CO_2e} - P_c \qquad \text{Eq. 6a}$$

$$Coverage_c = \frac{P_c}{E_{c,2030}^{CO_2e}} \times 100\% \quad \text{Eq. 6b}$$

Data Availability

All the landfill CH4 emission data and referenced data used in this study are available in the publicly accessible Mendeley repository (https://doi.org/ 10.17632/rjpjyykxvf.3).

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