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Urban organic waste management via anaerobic digestion as a climate mitigation opportunity in cities of global south: A case study of Itahari, Nepal

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Abstract

Methane from unmanaged urban organic waste is a growing and underused mitigation target in rapidly warming cities of the Global South. This study quantifies the biodegradable municipal solid waste resource in Itahari Sub-Metropolitan City, Nepal, and assesses the technical potential for anaerobic digestion to convert this waste stream into useful energy and fertilizer. Using stratified random sampling across residential, commercial, and institutional generators, total municipal solid waste generation is estimated at 50.5 tons day^{-1}, of which 65.2% (approx. 33 tons day^{-1}) is organic and suitable for digestion. A 30 tons day^{-1} continuous stirred-tank reactor system operating under mesophilic conditions (35–38 °C) with a 25-day hydraulic retention time is evaluated. The system is projected to produce approx. 2,000 m^3 day^{-1} of biogas with 60% methane, enabling approx. 4,177 kWh day^{-1} of electricity at 35% combined heat and power efficiency, equivalent to the average demand of about 962 households. In addition to reducing landfill dependence, the process produces digestate suitable for nutrient recovery, supporting circular economy objectives. The results highlight anaerobic digestion as a scalable option for urban methane mitigation and renewable energy co-production in low-altitude, warm-climate municipalities, and provide an implementable blueprint for secondary cities across Nepal and comparable Global South contexts.

1. Introduction

Rapid urbanization is transforming patterns of municipal solid waste generation across the Global South, intensifying pressures on waste management systems that are already constrained by limited infrastructure and governance capacity. In many low- and middle-income cities, municipal solid waste is dominated by organic fractions derived from food waste, markets, and household biomass residues. When disposed of through landfilling or open dumping, these organic materials decompose anaerobically and emit methane, a greenhouse gas with a global warming potential far exceeding that of carbon dioxide over short time horizons [1]. As global climate policy increasingly emphasizes near-term mitigation pathways compatible with 1.5 to 2 °C temperature targets, reducing methane emissions from urban waste systems has emerged as a critical and underutilized climate action lever. National transition evidence for Nepal indicates that electrification-led mitigation requires parallel investment in grid reinforcement and system flexibility, including storage, to ensure reliable energy services [2]. Recent evidence also shows that high electricity access can still coincide with low electricity use when distribution capacity and affordability constrain high-load end uses such as electric cooking [3]. Anaerobic digestion offers a pathway to transform organic waste from a source of uncontrolled emissions into a managed system for renewable energy recovery and nutrient recycling. By capturing methane that would otherwise be released to the atmosphere, anaerobic digestion can deliver dual climate benefits through direct emission avoidance and displacement of fossil-based energy sources [4]. In addition, the digestate produced

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can substitute synthetic fertilizers, thereby reducing upstream emissions associated with industrial fertilizer production and supporting circular resource flows [5]. Despite these advantages, the role of anaerobic digestion in urban climate mitigation strategies remains insufficiently examined, particularly in rapidly growing cities of the Global South.

Existing research on waste-to-energy systems has largely concentrated on reactor performance, process optimization, or site-specific energy yields, often treating waste management as a technical or municipal service issue rather than a climate-relevant system [6]. Conversely, climate mitigation literature has tended to focus on energy supply, transport, and industrial sectors, with comparatively limited attention to urban waste as a source of short-lived climate pollutants. This separation has resulted in a gap between engineering feasibility studies and climate policy discussions, limiting the integration of organic waste management into nationally determined contributions and urban climate action plans. Climatic and geographic conditions play a decisive role in shaping the performance of biological waste treatment systems. Methanogenic activity is strongly temperature dependent, with mesophilic conditions favoring higher biogas yields and improved process stability [7]. Low-altitude cities in South Asia, which experience higher average temperatures and reduced seasonal thermal variability compared to highland urban centers, may therefore offer favorable conditions for climate-effective anaerobic digestion [8]. However, empirical assessments that link local waste composition, climatic context, and mitigation-relevant energy recovery in such settings remain scarce.

Nepal provides a representative case of these dynamics [9]. Rapid urban expansion has increased municipal solid waste generation, while waste management systems continue to rely largely on unsorted collection and landfill disposal. Prior studies have explored waste-to-energy potential in Kathmandu Valley, but cooler temperatures at higher elevations constrain biological conversion efficiency and complicate year-round operation. In contrast, emerging lowland cities such as Itahari are characterized by warmer climates, high organic waste fractions, and rising urban energy demand, yet remain largely absent from climate-oriented waste management research. This study addresses this gap by evaluating anaerobic digestion as a climate-relevant urban waste management strategy in Itahari Sub-Metropolitan City, Nepal. Using empirically derived municipal waste characterization combined with process-based system modelling, the study quantifies organic waste availability, estimates biogas and electricity generation potential under local climatic conditions, and assesses the implications for methane mitigation and renewable energy supply. By situating engineering analysis within a broader climate and urban sustainability framework, the study contributes evidence from a rapidly urbanizing Global South context to ongoing debates on scalable and near-term climate mitigation options [10]. The findings highlight the importance of integrating organic waste management into urban climate strategies and demonstrate how locally tailored anaerobic digestion systems can support mitigation objectives in warming cities.

This study aims to quantify the climate-relevant potential of anaerobic digestion of urban organic waste in Itahari Sub-Metropolitan City by linking empirical waste characterization with process-based biogas and electricity modeling. The novelty of this work lies in integrating mesophilic anaerobic digestion performance assumptions with a low-altitude, warm-climate urban context in Nepal, thereby extending prior highland-focused assessments to a representative secondary city of the Global South. While the analysis provides a technically grounded estimate of methane recovery and renewable energy generation, it is limited by assumed operational parameters, absence of seasonal waste variability assessment, and the lack of full life-cycle greenhouse gas accounting. Future research should incorporate seasonal sampling, pilot-scale validation, and comprehensive climate and economic analyses to refine scalability and policy relevance.

2. Material and methods

2.1. Municipal waste sampling and data sources

Municipal solid waste availability in Itahari Sub-Metropolitan City was quantified using a stratified random sampling approach across residential, commercial, and institutional sectors to capture heterogeneity in urban organic waste generation. Population data from the 2021 national census, reporting 198,098 residents, were used to scale residential waste generation, while inventories of commercial and institutional establishments were obtained from municipal records [11]. Sampling focused on waste generators with high organic fractions, including households, hotels and restaurants, retail shops, vegetable and fruit markets, and educational institutions. Sample sizes were determined at a 95 percent confidence level with a 3 percent margin of error, resulting in coverage of 320 households, 40 hotels and restaurants, 20 retail shops, 12 vegetable and fruit shops, and 12 schools and colleges. Waste samples were collected, weighed, and segregated into organic and inorganic fractions to estimate sectoral generation rates and organic substrate availability for anaerobic digestion.

2.2. Waste generation rates and composition

Survey results indicate a total municipal solid waste generation of 50,504 kg day^{-1}. Organic materials account for 65.2 percent of the waste stream, corresponding to 32,932 kg day^{-1}, while inorganic fractions constitute the remaining 34.8 percent as shown in the Table 1. Residential sources dominate total generation, followed by commercial and institutional sectors. Per capita waste generation is estimated at 0.258 kg person^{-1} day^{-1}, including 0.168 kg person^{-1} day^{-1} of organic waste suitable for biological treatment.

At the time of the survey, source-level segregation was not practiced. Waste was collected in mixed form, manually sorted at collection facilities to recover recyclables, and the residual fraction disposed of at a landfill site approximately 6 km from the city center. This system results in uncontrolled methane emissions from decomposing organic waste, highlighting the mitigation potential of controlled anaerobic treatment.

2.3. Process assumptions and kinetic formulation

Anaerobic digestion performance was evaluated using standard mass balance and kinetic relationships for municipal organic waste under mesophilic conditions. Hydraulic retention time (HRT) was calculated as [12]

$$HRT = \frac{V_r}{Q} \tag{1}$$

Where in the equation 1, V_r is the effective digester volume and Q is the daily influent flow rate. For a digester volume of 2,000 m^3 and an average inflow of 83 m^3 day^{-1}, including dilution water, the resulting HRT is approximately 25 days. Organic loading rate (OLR) was defined as

$$OLR = \frac{Q \times S_0}{V_r} \tag{2}$$

where in the equation 2, S_0 represents the volatile solids concentration of the feedstock. Based on measured waste properties and operational stability considerations, OLR was set at 1.4 kg VS m^{-3} day^{-1}, within recommended ranges for municipal solid waste digestion [13]. Methane potential was estimated as

$$\mathrm{CH}_4 = M_{org} \times f_{VS} \times Y_{bg} \times f_{\mathrm{CH}_4} \tag{3}$$

Where in the equation 3, M_{org} denotes the mass of organic waste, f_{VS} is the volatile solids fraction in the organic waste, Y_{bg} represents the specific biogas yield per unit of volatile solids, and f_{CH_4} is the methane content of the produced biogas [14].

2.4. Mass balance and biogas yield estimation

Measured waste characteristics fall within typical ranges reported for urban organic waste in South Asia, with total solids of 25 percent as shown in the Table 2, volatile solids representing 80 percent of total solids, and a carbon to nitrogen ratio of approximately 29. A specific biogas yield of 0.33 m^3 kg^{-1} VS and a methane concentration of 60 percent were assumed.

Under these assumptions, daily biogas production is estimated at approximately 2,000 m^3, corresponding to 1,200 m^3 of methane. After purification to remove carbon dioxide, hydrogen sulfide, and moisture, upgraded biomethane production is estimated at approximately 1,000 m^3 day^{-1}, equivalent to around 800 kg day^{-1} as seen in Table 3.

2.5. System configuration

A continuous stirred-tank reactor configuration was selected due to its suitability for heterogeneous municipal waste streams and its capacity to maintain stable microbial activity under variable loading conditions. The system is designed to operate under mesophilic conditions between 35 and 38 °C and at a pH range of 6.5 to 7.5, reflecting both biological requirements and the ambient thermal advantages of Itahari's low-altitude climate. The facility comprises five integrated subsystems: pretreatment, anaerobic digestion, biogas purification, storage and utilization, and digestate management. Pretreatment removes inert materials and homogenizes feedstock to improve biodegradability. Digestion occurs in a mechanically agitated steel reactor, while biogas purification enables efficient energy conversion. Digestate is commonly separated into solid and liquid fractions, enabling targeted agricultural and nutrient recovery applications that support circular resource use [15]. The facility comprises five integrated subsystems: pretreatment, anaerobic digestion, biogas purification, storage and utilization, and digestate management. Figure 1 presents the overall waste-to-energy with CHP system boundary adopted in this study [16].

2.6. Baseline methane emissions and GHG mitigation accounting

Baseline methane emissions from uncontrolled disposal of the organic fraction were estimated following the IPCC waste-sector framework, which relates methane generation to the degradable organic content of disposed

Table 1: Field-derived sectoral municipal solid waste generation and composition in Itahari (measured from stratified sampling; values reported in kg day^{-1} and percent)

Sector	Waste generation (kg day^{-1})	Organic fraction (%)	Inorganic fraction (%)
Residential	43,350	64.8	35.2
Commercial	6,123	73.2	26.8
Institutional	1,030	34.8	65.2
Total	50,504	65.2	34.8

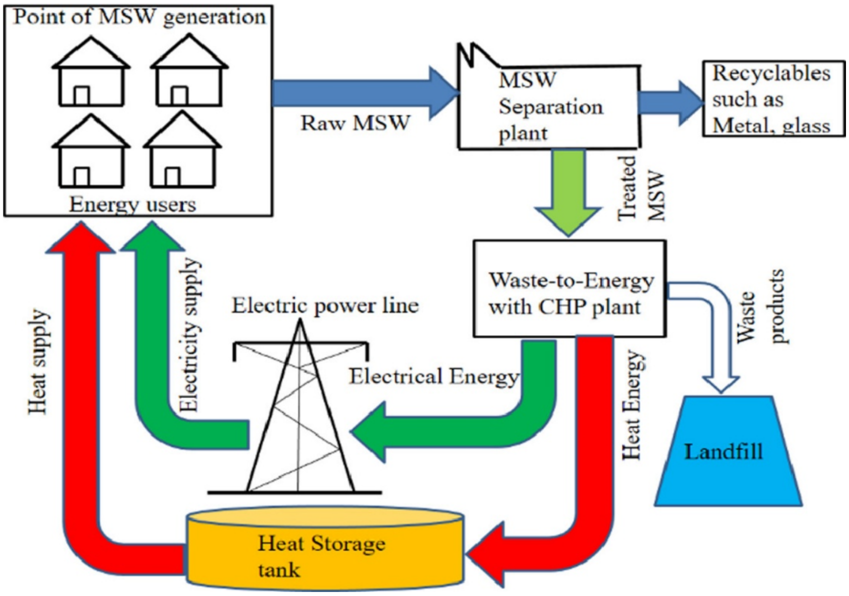

Figure 1: Conceptual schematic of MSW separation and waste-to-energy with a CHP plant and heat storage [16].

Table 2: Assumed substrate characteristics and process design parameters used for anaerobic digestion modeling (model inputs; not directly measured in this study)

Parameter	Value
Organic waste input	30,000 kg day^{-1}
Total solids	25 percent
Volatile solids (of TS)	80 percent
Carbon to nitrogen ratio	29
Biogas yield	0.33 m^3 kg^{-1} VS
Methane content	60 percent

waste and adjusts for oxidation and recovery. For annualized screening estimates consistent with limited time-series data, methane generation potential was linked to the study's process-based methane estimate (Equation 3, and baseline emissions were computed as:

$$CH_{4,\mathrm{BAU}} = CH_{4,\mathrm{pot}}\,(1 - \mathrm{OX}) \tag{4}$$

where $CH_{4,\mathrm{pot}}$ is the methane generation potential (m^3 day^{-1}), and OX is the oxidation factor (default 0.1). An alternative baseline scenario with landfill gas capture is evaluated as:

$$CH_{4,\mathrm{LFG}} = CH_{4,\mathrm{pot}}\left(1 - \eta_{\mathrm{cap}}\right)(1 - \mathrm{OX}) \tag{5}$$

where η_{cap} is landfill gas recovery efficiency. For developing-country contexts, recovery is conservatively capped at 50 percent. For the anaerobic digestion (AD) scenario, methane is recovered in a controlled system; residual losses are represented as a leakage fraction η_{leak}:

$$CH_{4,\mathrm{AD}} = CH_{4,\mathrm{pot}}\,\eta_{\mathrm{leak}} \tag{6}$$

Annual climate impact is reported in tCO$_2$-eq yr^{-1} as:

$$\mathrm{GHG} = m_{CH_4} \times \mathrm{GWP}_{100} \tag{7}$$

where m_{CH_4} is the annual methane mass (t yr^{-1}).

Table 3: Sample calculation for biogas, methane, and electricity estimation

Step	Parameter / Expression	Value	Result
1	Organic waste input	30,000 kg day^{-1}	–
2	TS fraction	25%	–
3	VS fraction of TS	80%	–
4	VS fraction of wet waste	0.25×0.80	0.20
5	Mass of VS	$30{,}000 \times 0.20$	6,000 kg VS day^{-1}
6	Biogas yield (Y_{bg})	0.33 m^3 kg^{-1} VS	–
7	Biogas production	$6{,}000 \times 0.33$	1,980 m^3 day^{-1} $\approx$ 2,000
8	Methane fraction	60%	–
9	Methane production	$1{,}980 \times 0.60$	1,188 m^3 day^{-1} $\approx$ 1,200
10	Methane LHV	9.97 kWh m^{-3}	–
11	CHP electrical efficiency	35%	–
12	Electricity generation	$1{,}188 \times 9.97 \times 0.35$	$\approx$ 4,150 kWh day^{-1}

2.7. Sensitivity and uncertainty analysis

A one-way sensitivity analysis was performed on key parameters affecting methane and electricity estimates: biogas yield (Ybg), methane fraction (fCH_4), CHP electrical efficiency (η_{el}), oxidation factor (OX), and landfill gas capture efficiency (η_{cap}). The IPCC default oxidation factor ($OX = 0.1$) and representative decay and recovery assumptions were used to define plausible ranges for baseline uncertainty [17][18].

Uncertainty bounds for outputs (biogas, methane, electricity, and annual tCO_2-eq) are reported using the resulting min–max range across parameter perturbations.

A screening attributional boundary is defined from waste collection through treatment and end-of-life management, including collection and transport, preprocessing, digestion, biogas utilization (CHP), digestate handling, and residual disposal. Avoided burdens include displaced grid electricity and avoided mineral fertilizer from digestate use. This is consistent with cradle-to-grave MSW treatment boundaries applied in Nepal-focused MSW LCA studies [19][20]. The resulting annual methane mitigation can be directly mapped to Nepal's NDC mitigation accounting for the waste sector, which reports quantified national emissions-reduction totals through 2030 and 2035, allowing Itahari-scale projects to be interpreted as modular contributors to national targets [21]. A ±20% variation in Y_{bg} produces an approximately ±20% change in biogas, methane, and electricity outputs because Equation 3 and the electricity calculation are linear in Y_{bg} and f_{CH_4}; uncertainty bounds are therefore reported as min–max across tested parameter ranges. For scenario framing (BAU landfill/open dumping vs landfill gas capture vs anaerobic digestion), the comparative logic follows established MSW methane mitigation scenario approaches [22].

3. Results

Itahari generates approximately 50.5 tons of municipal solid waste per day, of which 65.2 percent is biodegradable which is seen in the Table 6. This corresponds to about 33 tons per day of organic feedstock suitable for anaerobic digestion. Based on measured waste properties and system design assumptions, a continuous stirred-tank reactor with an effective working volume of 2,000 m^3 and a hydraulic retention time of 25 days is expected to operate stably under mesophilic conditions. Estimated biogas production is approximately 2,000 m^3 per day, containing about 1,200 m^3 per day of methane at a methane fraction of 60 percent. When utilized for electricity generation at an assumed combined heat and power efficiency of 35 percent, this output corresponds to an electrical energy potential of about 4,177 kWh per day. This level of generation is equivalent to the average daily electricity demand of approximately 962 households.

4. Discussion

The results indicate that anaerobic digestion represents a climate-relevant waste management option for Itahari, where a high organic fraction of municipal solid waste aligns with profiles commonly observed in rapidly urbanizing cities of the Global South. The availability of approximately 33 tons per day of biodegradable waste supports the design of a 30-ton-per-day facility capable of treating most organic waste currently destined for landfill disposal. This shift has implications for both local environmental quality and methane mitigation, given the city's reliance on unsorted collection and landfill

Table 4: Scenario definition

Scenario	Description	Key assumption(s)
S0 (BAU)	Landfill/open dumping, no gas recovery	OX = 0.1
S1 (LFG)	Landfill gas capture + flare/use	$\eta_{\text{cap}} = 0.5$ (cap for developing countries)
S2 (AD)	Anaerobic digestion + CHP	Controlled recovery; η_{leak} tested in sensitivity

Table 5: Annual GHG mitigation using current methane estimate (1,200 m^3 day^{-1})

Item	Expression	Value
Methane potential	$CH_{4,\text{pot}}$	1,200 m^3 day^{-1}
Annual methane (volume)	1200×365	438,000 m^3 yr^{-1}
BAU emitted methane	$438{,}000 \times (1 - \text{OX})$	$438{,}000 \times 0.9 = 394{,}200$ m^3 yr^{-1} (OX = 0.1)
LFG emitted methane	$438{,}000(1 - \eta_{\text{cap}})(1 - \text{OX})$	$438{,}000 \times 0.5 \times 0.9 = 197{,}100$ m^3 yr^{-1}
AD emitted methane	$438{,}000 \times \eta_{\text{leak}}$	Report range (example: 0–5%)
Annual mitigation (BAU → AD)	$CH_{4,\text{BAU}} - CH_{4,\text{AD}}$	Report as m^3 yr^{-1} and convert to tCO_2-eq yr^{-1}

Table 6: Modeled/calculated outputs with measured inputs referenced

Indicator	Value
Total MSW generation	50.5 tons day^{-1}
Biodegradable fraction	65.2 percent
Organic feedstock for AD	33 tons day^{-1}
Digester working volume	2,000 m^3
Hydraulic retention time	25 days
Biogas production	2,000 m^3 day^{-1}
Methane production	1,200 m^3 day^{-1}
Electrical energy potential	4,177 kWh day^{-1}
Household electricity equivalent	962 households

deposition near the Seuti River. Recent studies in Nepal highlight persistent gaps in seasonal waste characterization and energy potential assessment, particularly outside major metropolitan areas. Evidence from Godawari indicates a strong dominance of organic waste and limited seasonal variability in calorific value, reinforcing the suitability of municipal solid waste for energy recovery [23]. These findings are consistent with the assumptions underpinning the present analysis and support the generalizability of the results to other secondary cities with similar waste composition and climatic conditions. The projected biogas yield of 2,000 m³ per day with a methane content of 60 percent falls within reported ranges for municipal organic waste digestion under mesophilic operation, typically 0.3 to 0.5 m^3 per kilogram of volatile solids [24]. Itahari's warmer low-altitude climate, with summer temperatures reaching 33 to 36 °C, is likely to favor stable methanogenic activity compared with higher-elevation cities such as Kathmandu, where cooler conditions can constrain biological conversion efficiency. The selection of a continuous stirred-tank reactor further supports process stability for heterogeneous, high-solids feedstocks and is associated with higher methane recovery than batch systems [25].

From a climate perspective, the estimated electricity generation of 4,177 kWh per day represents more than a local energy benefit. By capturing methane that would otherwise be emitted during uncontrolled decomposition and displacing fossil-based electricity, the system contributes to near-term climate mitigation through reductions in short-lived climate pollutants. Additional co-benefits arise from the production of approximately 6,000 kg per day of dry digestate, which can substitute synthetic fertilizers and support circular nutrient management in surrounding agricultural areas. Despite these advantages, several constraints must be acknowledged. Capital investment requirements, the absence of source-level waste segregation, and operational challenges related to gas purification, particularly hydrogen sulfide removal, may affect implementation. The observed biogas yield, while within expected ranges, suggests scope for optimization through co-digestion with agricultural residues or improved feedstock preconditioning. Pilot-scale operation would therefore be essential to validate performance under real-world municipal conditions and to refine design parameters prior to large-scale deployment.

5. Conclusion

This study demonstrates that anaerobic digestion can function as a viable and climate-relevant urban waste management strategy in Itahari Sub-Metropolitan City, Nepal. Approximately 30 tons per day of organic municipal waste can be converted into around 2,000 m^3 per day of biogas, yielding an estimated 4,177 kWh per day of electricity, sufficient to meet the average demand of nearly 1,000 households. By reducing reliance on landfill disposal, capturing methane emissions, and recovering renewable energy and nutrients, the proposed system advances both mitigation and circular economy objectives. More broadly, the findings highlight the importance of integrating organic waste management into urban climate strategies, particularly in low-altitude, rapidly urbanizing cities where warmer climatic conditions favor biological conversion processes. With appropriate policy support, institutional coordination, and incremental implementation through pilot projects, anaerobic digestion could serve as a scalable model for methane mitigation and sustainable urban development across similar contexts in South Asia and beyond.

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