

Assessing net climate impacts and avoided impacts of sewage sludge management options: A case study of Ulaanbaatar, Mongolia

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ABSTRACT

Wastewater treatment plants, which are essential for protecting water quality, can generate substantial greenhouse gas (GHG) emissions through biological treatment, energy consumption, and sludge management. This study applies life cycle and avoided-impact assessments to quantify GHG emissions and evaluate mitigation options for the Central Wastewater Treatment Plant in Ulaanbaatar, Mongolia, using 2024 operational data. The functional unit was 1 m³ of treated wastewater. Four scenarios were evaluated: continued long-term sludge storage (S1), a 20% reduction in electricity consumption (S2), anaerobic digestion with combined heat and power (CHP) generation (S3), and controlled composting (S4). The baseline climate change impact was 1.2969 kg CO₂-eq/m³, corresponding to approximately 90,137 t CO₂-eq attributable to wastewater received in 2024, including cumulative sludge-storage emissions over an assumed four-year period. Direct emissions accounted for 81.71% of the total impact. CH₄ emissions from sludge storage and wastewater treatment collectively contributed 61.58%, whereas electricity consumption contributed 17.32%. S2 reduced the impact to 1.2520 kg CO₂-eq/m³, a 3.46% reduction relative to S1. S3 achieved the greatest modelled mitigation by avoiding baseline sludge-storage CH₄ emissions and substituting grid electricity and coal-based heat with recovered biogas energy. Its net impact was 0.6379 kg CO₂-eq/m³, a 50.81% reduction. In contrast, S4 increased the net impact to 1.4473 kg CO₂-eq/m³, an 11.60% increase, because emissions from composting and subsequent compost application outweighed avoided sludge-storage emissions and fertilizer-substitution credits. Under the modelled assumptions, AD with CHP showed the greatest mitigation potential among the evaluated options. These results provide quantitative evidence to inform sludge-management and climate-mitigation planning in Ulaanbaatar.

Keywords: life cycle assessment, avoided-impact analysis, sewage sludge management, greenhouse gas emissions, anaerobic digestion, biogas recovery.

INTRODUCTION

Wastewater treatment plants (WWTPs) remove organic matter, nutrients, suspended solids, pathogens, and other pollutants from municipal and industrial wastewater, making them critical for protecting human health and aquatic environments (Xi et al., 2021). However, their operation generates substantial greenhouse gas (GHG) emissions through biological treatment processes,

electricity and chemical consumption, transportation, and sludge management. Methane (CH₄) and nitrous oxide (N₂O) are important because their global warming potentials (GWPs) exceed that of carbon dioxide (CO₂) (Bartram et al., 2019). Globally, wastewater treatment contributes approximately 2% of total anthropogenic GHG emissions (Han et al., 2024), primarily through direct CH₄ and N₂O emissions and indirect emissions from electricity consumption, chemical use, and sludge

management (Dickin et al., 2020). Consequently, reducing emissions from wastewater and sludge treatment has become the increasingly important for low-carbon urban infrastructure and mitigating global climate change.

WWTPs generate direct GHG emissions from the biological conversion of organic carbon and nitrogen during wastewater and sludge treatment. CH₄ is produced under anaerobic conditions and may be emitted from wastewater-processing units, sludge storage, anaerobic treatment, and incomplete biogas capture. N₂O results from nitrification, denitrification, and sludge composting (Han et al., 2024). Although biological wastewater treatment generates CO₂, biogenic CO₂ was reported separately and excluded from net GHG totals, whereas fossil-derived CO₂ remains within the accounting boundaries. The indirect emissions originate from purchased electricity, chemical production, transportation, and other operational sources (Doorn et al., 2019). Therefore, direct and indirect emission sources must be comprehensively assessed, considering potential environmental credits from energy and resource recovery.

Sewage sludge management markedly influences the overall carbon footprint of WWTPs. Long-term storage and uncontrolled disposal may generate CH₄ through the anaerobic degradation of residual organic matter (Yoshida et al., 2018). Conversely, anaerobic digestion (AD) can stabilize sludge, recover biogas, and generate electricity and useful heat through combined heat and power (CHP) systems. Improvements to energy efficiency can reduce dependence on grid electricity (Brown & Herrera, 2021). Sludge management also includes composting; however, its environmental performance depends on aeration, moisture, temperature, and process control because CH₄ and N₂O may be produced. Therefore, mitigation options should be evaluated using a consistent functional unit (FU) and system boundary to avoid shifting the environmental burden between the treatment stages.

WWTPs in cold climates encounter additional operational and environmental challenges. Low temperatures can impact biological reaction rates, sludge stabilization and dewatering, and the energy required for aeration and process heating. These constraints may influence direct and indirect emissions from energy consumption. Nevertheless, cold-climate wastewater treatment systems remain underrepresented in life cycle assessment (LCA) studies, particularly in

developing regions. This knowledge gap is relevant to rapidly urbanizing cities in Central and East Asia, where aging infrastructure and limited adoption of energy and resource recovery technologies can intensify the environmental burdens of wastewater and sludge management.

LCA provides a systematic framework for quantifying the direct and indirect environmental impacts across a defined system boundary (Hauschild et al., 2018; Korres, 2013). Avoided-impact analysis complements conventional emissions accounting by quantifying the benefits when electricity, heat, fuels, or other products replace conventional alternatives. For sludge-management systems, this approach is relevant to AD and CHP generation because the environmental benefits depend on biogas production, CH₄ capture efficiency, fugitive losses, internal energy demand, and the extent to which the generated electricity is used on-site or exported to the grid. Therefore, avoided-impact credits must be reported separately and applied transparently to prevent double counting.

Ulaanbaatar, the capital of Mongolia, faces growing wastewater management pressures from rapid urbanization, population growth, industrial activity, and aging infrastructure. The Central Wastewater Treatment Plant (CWWTP) treats most of the city's municipal wastewater, with approximately 69.5 million m³ of wastewater treated in 2024. Its operation generates direct emissions from wastewater treatment and long-term sludge storage and indirect emissions from electricity and chemical consumption and transportation (Yoshida et al., 2018). Ulaanbaatar's severe continental climate, characterized by long, extremely cold winters, intensifies these challenges. Despite the environmental importance of the CWWTP, its GHG emissions and the mitigation potential of alternative sludge-management strategies have not yet been comprehensively evaluated within a consistent life cycle and avoided-impact framework.

Accordingly, this study aimed to quantify the GHG emissions of the Ulaanbaatar CWWTP and compare sludge-management and energy-saving options using LCA and avoided-impact assessment. The assessment used plant-specific 2024 operational records, including wastewater flow and quality, sludge generation, electricity consumption, and chemical use, with a functional unit of 1 m³ of treated wastewater. Four scenarios were evaluated: baseline sludge storage, a 20% reduction in electricity consumption, AD with

CHP, and controlled composting. The contribution of this study is a CWWTP-specific quantitative comparison that distinguishes gross emissions, energy and fertilizer substitution credits, and net climate change impacts. Measured operational data and scenario assumptions were identified separately to support interpretation of the modelled mitigation potential.

MATERIALS AND METHODS

Study area and plant description

The National Statistics Office of Mongolia (2024) reported that Ulaanbaatar ($47^{\circ}38'48''$ N, $106^{\circ}45'48.6''$ E) encompasses 4,704.4 km² with a population of approximately 1.6 million, representing nearly half of the country's total population of approximately 3.4 million (Munkh-Erdene et al., 2022). Ulaanbaatar is situated at an elevation of approximately 1,350 m above sea level within the Tuul River basin and is surrounded by mountainous terrain. Its temperature varies seasonally, with minimum values reaching approximately -20°C in winter (January–February) and maximum temperatures of $15\text{--}18^{\circ}\text{C}$ in summer (July–August), representing a continental climate (Byamba & Ishikawa, 2017). Over the past decade, Ulaanbaatar's population growth has outpaced the national average, driven by rural-to-urban migration. Rapid urbanization has increased the pressure on urban infrastructure,

including water supply, wastewater treatment, heating systems, solid waste management, and energy consumption, increasing environmental pollution and waste generation.

The CWWTP ($47^{\circ}54'07.5''$ N, $106^{\circ}45'48.6''$ E in southwestern Ulaanbaatar) has been operational since 1964. Even with partial reconstruction and system upgrades, the operational conditions of the CWWTP have worsened over time. The plant receives wastewater through two inlet lines: (1) a 1,200 mm diameter domestic sewage line and (2) a 1,400 mm diameter industrial wastewater line from the industrial area (Figure 1) (Nyamjav et al., 2023). The CWWTP is the

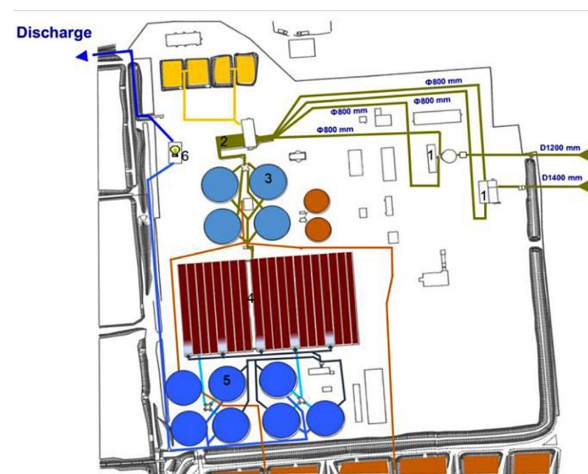


Figure 1. Diagram of the CWWTP in Ulaanbaatar: 1 – screening, 2 – sand trap, 3 – primary clarifier, 4 – aeration tank, 5 – secondary clarifier, 6 – disinfection

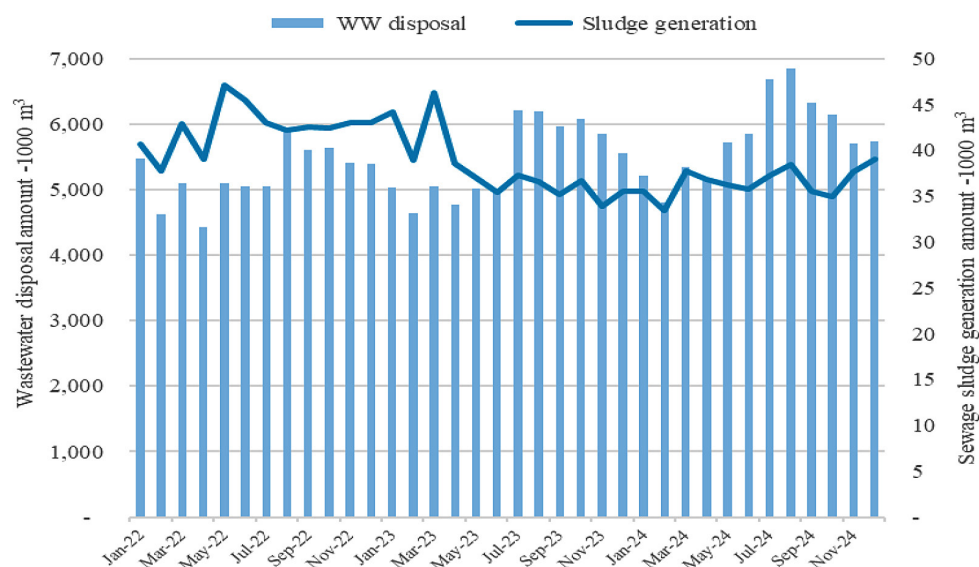


Figure 2. Monthly trends of total treated wastewater and sewage sludge generation at the Ulaanbaatar CWWTP (2022–2024). Note: Sewage sludge generation values correspond to the right y-axis. All units are in 1000 m³

city's primary treatment facility and manages approximately 85% of total municipal and industrial wastewater, with a maximum design capacity of 170,000–190,000 m³/day. Figure 2 presents the monthly distribution of treated wastewater and sewage sludge generation for 2022–2024. The data show moderate monthly fluctuations, with an upward trend in wastewater volume during the last 6 months of 2024. In particular, the average daily treated wastewater volume in 2024 reached approximately 189,787 m³, an annual increase of approximately 9.2 million m³ compared with the previous year. These results indicate that the facility currently operates at its full design capacity, posing substantial hydraulic overload. This upward trend, particularly in late 2024, may be attributed to seasonal factors, such as increased precipitation and population influx into the city, despite the stable rate of sewage sludge observed during this period.

Goal and scope

This study applied LCA and avoided-impact assessment to quantify the climate change impact of wastewater treatment and evaluate alternative sewage sludge-management strategies at the Ulaanbaatar CWWTP. The assessment was conducted in accordance with the principles and frameworks of ISO 14040 and 14044 (Yang et al., 2024).

The FU was defined as 1 m³ of treated wastewater. The assessment considered operational activities associated with wastewater treatment and sludge management, including direct CH₄ and N₂O emissions, electricity and chemical consumption, transportation, and avoided impacts associated with energy and fertilizer substitution.

The system boundaries of this study were defined to include the major operational processes involved in wastewater treatment at the Ulaanbaatar CWWTP (Figure 3). The assessment covered the operational phase of the treatment system, from influent wastewater entering the plant to the discharge of the treated effluent, together with the associated sludge-management processes. The treatment processes included within the system boundaries were preliminary treatment, primary clarification, biological treatment using an activated sludge process, secondary clarification, disinfection, sludge treatment, and management. Sludge generated during primary and secondary treatments was also included, including sludge handling, long-term storage, and alternative treatment pathways evaluated in the scenario analysis.

Infrastructure construction, capital equipment, and other background processes outside the defined operational system boundary were excluded because this study focused on operational GHG emissions and alternative sludge-management strategies. However, the production

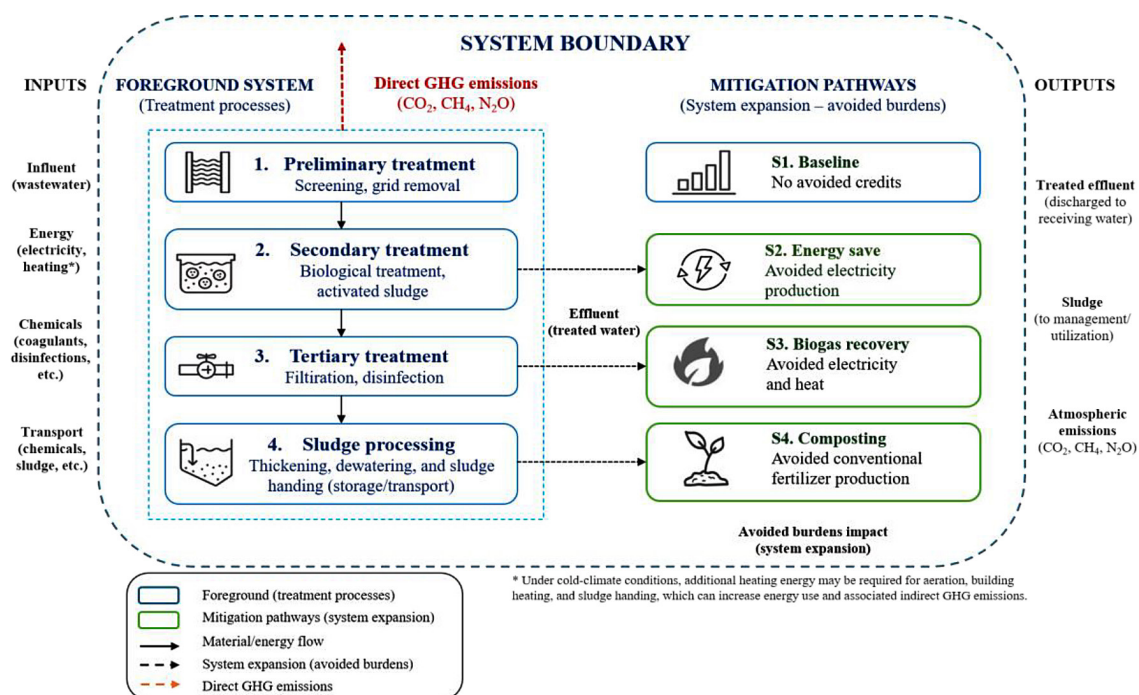


Figure 3. System boundary and GHG mitigation pathways considered in the LCA of the CWWTP in Ulaanbaatar, Mongolia

of treatment chemicals was included within the system boundary, as these chemicals are operational inputs to the treatment system.

Life cycle inventory and data sources

The life cycle inventory was developed using 2024 operational records and routine monitoring data provided by the Water Supply and Sewerage Authority of Ulaanbaatar. These included wastewater flow and quality, sludge generation, electricity consumption, and chemical use. The CWWTP received approximately 69.5 million m³ of wastewater in 2024, corresponding to an average flow of approximately 189,787 m³/day. Annual electricity consumption was approximately 20.82 million kWh.

Wastewater characteristics were derived from the facility's routine monitoring summary (Table 1). Influent concentrations combined two incoming streams using monthly flow weighting. The reported values are arithmetic averages of monthly means, covering 12 months for pH, COD, BOD₅, TSS, and ammonia, and four months for TKN, total P, and total Cr.

For wastewater-process CH₄ estimation, the COD entering biological treatment was represented by the average of monthly mean concentrations measured after mechanical treatment, 679.8 mg/L. Biological COD removal efficiency was calculated from the post-mechanical and final effluent COD concentrations and was 0.4485. The influent TKN concentration used to estimate wastewater-process N₂O emissions was 111.46 mg N/L.

Annual sludge generation was 341,105 m³. Using an assumed sludge density of 1000 kg/m³, the wet sludge mass was calculated as 4.9078 kg/FU. Operational data, calculated quantities, adopted model inputs, and scenario assumptions are distinguished in Tables 2–6.

Life cycle impact assessment

The life cycle impact assessment phase quantified the potential climate change impact associated with the treatment of 1 m³ of wastewater at the Ulaanbaatar CWWTP. The impact of climate change expressed as CO₂ equivalents using 100-year GWP factors from the IPCC Fourth Assessment Report. The applied GWP values were 25 kg CO₂-eq/kg CH₄ and 298 kg CO₂-eq/kg N₂O. Biogenic CO₂ emissions were reported separately and excluded from the total climate change impact. GHG emissions estimated using process based equations and established emission factors. CH₄ emissions from wastewater treatment were estimated using an oxygen-demand-based approach (Eq. 1), whereas those from sludge storage over the assumed four-year period were estimated using a first-order decay model (Eq. 2). Direct N₂O emissions from wastewater treatment were estimated using influent total Kjeldahl nitrogen (TKN) and an N₂O emission factor (Eq. 3). The resulting CH₄ and N₂O emissions were converted to CO₂ equivalents using the above GWP factors. Total climate change impacts were expressed per FU to enable comparison among the evaluated scenarios.

Direct emissions included CH₄ from wastewater treatment, sludge storage, anaerobic digestion

Table 1. Influent and effluent wastewater characteristics at the CWWTP

Pollution parameters, unit		Design parameters for existing CWWTP (MNS 6561:2024)	2024		
			Influent	National standard (MNS 4943:2015)	Effluent
pH		6-9	7.0	6-8	7.3
COD	mg/L	800	1,867.5	50	374.9
BOD ₅	mg/L	400	676.0	20	139.6
TSS	mg/L	400	1,086.1	30	79.3
Total P	mg/L	5	11.7	1.5	5.4
Total Cr	mg/L	1	0.160	0.3	0.375
Ammonia	mg/L	20	48.5	-	44.3
TKN	mg/L	40	111.46	15	67.08

Note: Values are averages of monthly means from the CWWTP's 2024 routine monitoring summary, covering four months for TKN, total P, and total Cr and 12 months for other parameters. Influent values combine two streams using monthly flow weighting. Separately recorded additional analyses were excluded. Data were provided by the Water Supply and Sewerage Authority of Ulaanbaatar.

leakage, and composting, as applicable to each scenario. They also included N₂O from wastewater treatment, composting, and subsequent compost application to soil. Indirect emissions included purchased electricity, treatment chemical production, and transportation of treatment chemicals.

The parameters used in the emission calculations and scenario models are summarized in Tables 2–6. Operational data were distinguished from calculated quantities, adopted model inputs, and scenario assumptions. Parameters not measured at the CWWTP were treated as modelling assumptions rather than site-specific observations. Wastewater-process CH₄ emissions were estimated using the oxygen-demand model presented by RTI International (2010), adapted to express emissions in kg CH₄ per functional unit.

$$CH_{4,WW} = 10^{-3} \times Q_{WW} \times OD \times Eff_{OD} \times CF_{CH_4} \times [(MCF_{WW} \times BG_{CH_4})(1-\lambda)] \quad (1)$$

where: $CH_{4,WW}$ is the methane emission from wastewater treatment (kg CH₄/FU), Q_{WW} is wastewater flow per FU (m³/FU), OD is the oxygen demand entering the biological treatment unit (g COD/m³), Eff_{OD} is the biological chemical oxygen demand removal efficiency, CF_{CH_4} is the conversion factor for maximum CH₄ generation (g CH₄/g COD), MCF_{WW} is the methane correction factor, BG_{CH_4} is the fraction of carbon present as CH₄ in the generated biogas, and λ is the biomass yield.

The factor 10⁻³ converts grams of CH₄ to kilograms.

$$CH_{4,storage} = W_{sludge,FU} \times DOC \times DOC_f \times MCF \times F \times 16/12 \times (1 - e^{-k(t-t_d)}) \quad (2)$$

where $CH_{4,storage}$ is the modelled cumulative methane emission from sludge storage over the assumed storage period (kg CH₄/FU), $W_{sludge,FU}$ is the amount of wet sludge per FU (kg wet sludge/FU), DOC is degradable organic carbon (kg C/kg wet sludge), DOC_f is the fraction of decomposable DOC, MCF is the CH₄ correction factor for sludge storage, F is the fraction of CH₄ in generated gas, k is the decay rate (yr⁻¹), t is the storage period (yr), and t_d is the delay time (yr).

The ratio 16/12 converts carbon mass to methane mass. The parameter values used to estimate

cumulative CH₄ emissions from sludge storage are presented in Table 2. For sludge storage, a four-year storage period was assumed, with a decomposition delay of 0.5 years. The storage period represents a modelling assumption rather than a measured sludge residence time. The resulting storage emissions represent cumulative emissions attributed to the sludge generated per functional unit over this assumed period. The decay rate of 0.185 yr⁻¹ was adopted from the wet-climate sewage-sludge category in RTI International (2010) as a proxy and was not calibrated for local storage conditions.

$$N_2O_{WW} = Q_i \times TKN_i \times EF_{N_2O} \times 44/28 \times 10^{-3} \quad (3)$$

where: N_2O_{WW} is the nitrous oxide emission from wastewater treatment (kg N₂O/FU), Q_i is influent wastewater flow per FU (m³/FU), TKN_i is influent total Kjeldahl nitrogen concentration (g N/m³), and EF_{N_2O} is the emission factor expressed as g N₂O-N per g influent TKN-N.

The ratio 44/28 converts N₂O-N to N₂O, and 10⁻³ converts grams to kilograms. The overloaded aerated-treatment category in RTI International (2010) was adopted as a modelling assumption, using $MCF_{WW} = 0.30$ and $\lambda = 0.45$. This choice was informed by the reported operation near design capacity and high influent pollutant concentrations. However, anoxic conditions and these parameter values were not verified by site-specific measurements.

Worked calculations showing the substitution of parameter values into Eqs. (1)–(3) are provided in Supplementary Material S1. The calculation model, operational source tables, monthly monitoring summary, selected laboratory records, and 2024 sludge-characterization records are provided in Supplementary Material S2. Raw laboratory records are supplied for traceability; additional analyses were not included in the routine monitoring averages. The available files did not specify the analytical method numbers or the exact sample count underlying every monthly mean.

Electricity-related emissions were calculated by multiplying electricity consumption per functional unit by the selected grid emission factor of 0.75 kg CO₂/kWh for Mongolia's Central Energy System (Energy Regulatory Commission of Mongolia, 2021). Chemical-production emissions were calculated using emission factors of 2.85 kg CO₂-eq/kg active PAM, 6.19 kg CO₂-eq/kg Al³⁺ in PAC, and 2.86 kg CO₂-eq/kg Fe³⁺ in

FeCl₃, respectively (Wang et al., 2025). Chemical quantities were expressed on the corresponding active-substance or metal-mass basis before applying these factors. Transportation emissions were calculated from the mass of treatment chemicals transported, the assumed transport distance

of 50 km, and the selected truck emission factor of 0.50546 kg CO₂-eq/t-km for diesel rigid trucks with a gross vehicle weight of >3.5–7.5 t under average loading conditions (Bramwell et al., 2024). This UK-based factor was used as a proxy for transport in Mongolia and covers fuel

Table 2. Parameters used to estimate cumulative CH₄ emissions from sludge storage

Parameter	Symbol	Value	Unit	Source or basis
Wet sludge generated per FU	$W_{sludge,FU}$	4.9078	kg wet sludge/FU	Calculated from CWWTP 2024 sludge volume and influent wastewater volume, assuming a sludge density of 1,000 kg/m ³
Degradable organic carbon content	DOC	0.05	kg C/kg wet sludge	(Epa & Policy Division, 2010), Table 2-1
Fraction of decomposable DOC	DOC_f	0.50	-	(Epa & Policy Division, 2010), Table 2-2
Methane correction factor	MCF	0.40	-	Storage-condition modelling assumption; not calibrated at the CWWTP
Methane fraction in generated gas	F	0.50	-	(Epa & Policy Division, 2010), Table 2-2
Decay rate	k	0.185	yr ⁻¹	(Epa & Policy Division, 2010), Table 2-1
Assumed storage period	t	4.0	yr	Assumed storage period; not a measured sludge residence time.
Decomposition delay	td	0.5	yr	(Epa & Policy Division, 2010), Table 2-2

Note: Sludge-storage emissions are cumulative emissions attributed to the sludge generated per FU over the assumed storage period.

Table 3. Parameters used to estimate wastewater-process CH₄ and N₂O emissions

Parameter	Symbol	Value	Unit	Source or basis
Wastewater flow per FU	Q_{WW}, Q_i	1.0	m ³ /FU	Functional-unit definition
COD entering biological treatment	OD	679.75	g COD/m ³	CWWTP 2024 post-mechanical-treatment data
Biological COD removal efficiency	Eff_{OD}	0.44853	-	Calculated from post-mechanical and effluent COD concentrations; rounded input used in the model
CH ₄ conversion factor	CF_{CH_4}	0.50	g CH ₄ /g COD	(Epa & Policy Division, 2010), Table 3-2
Wastewater methane correction factor	MCF_{WW}	0.30	-	(Epa & Policy Division, 2010), Table 3-1
Carbon fraction present as CH ₄ in biogas	BG_{CH_4}	0.65	-	(Epa & Policy Division, 2010)
Biomass yield	λ	0.45	g C in biomass/g C consumed	(Epa & Policy Division, 2010), Table 3-1
Influent TKN concentration	TKN_i	111.46	g N/m ³	CWWTP 2024 influent data
Wastewater N ₂ O emission factor	EF_{N_2O}	0.0050	g N ₂ O-N/g influent TKN-N	(Epa & Policy Division, 2010)

Table 4. Parameters and assumptions used for anaerobic digestion and CHP in S3

Parameter	Symbol	Value	Unit	Source or basis
Sludge density	ρ_{sludge}	1,000	kg/m ³	Volume-to-mass conversion assumption
Sludge dry-matter fraction	TS	0.25	kg DM/kg wet sludge	Adopted 75% moisture content
Dry matter per FU	DM_{FU}	1.2269	kg DM/FU	Calculated from wet sludge mass × dry-matter fraction
Volatile-solids fraction	f_{VS}	0.6236	kg VS/kg DM	Adopted sludge-characterization input, corresponding to 37.64% ash
Methane yield	Y_{CH_4}	0.20	Nm ³ CH ₄ /kg VS fed	Assumed yield used in the scenario model
Fugitive methane fraction	f_{leak}	0.05	-	(Doorn et al., 2019) Vol. 5, Ch. 4

Note: FU = 1 m³ of treated wastewater. Parameters were varied individually, with all other assumptions held constant.

combustion emissions. The operational inventory inputs were based on actual CWWTP data for 2024. Electricity-related emissions were calculated using the grid emission factor published in 2021, based on 2019 Central Energy System production data. Transport, fertilizer-production, and composting emission factors were adopted from external sources and were not validated against local measurements.

Operational scenarios

Four operational scenarios were developed to evaluate alternative strategies for reducing the climate change impact of sludge management at CWWTP. All scenarios were evaluated using the same FUs and system boundaries.

- S1: Baseline scenario – represented existing long-term sludge storage practices for 2024 and served as the reference scenario for comparison.
- S2: Energy-saving scenario – assumed a hypothetical 20% reduction in electricity consumption compared to the baseline, with improved aeration control and equipment optimization considered possible energy-efficiency measures. Aeration control, variable-frequency drives, and pump optimization were considered possible measures, but their individual savings were not quantified.
- S3: AD with CHP – assumed that sludge was diverted from long-term storage to AD, with recovered biogas used for CHP generation. Baseline sludge-storage CH₄ emissions were therefore excluded from S3, while fugitive CH₄ emissions and additional AD electricity demand were included. Recovered electricity and useful heat were credited separately for substituting grid electricity and coal-based heat, respectively. The parameters and assumptions used in these calculations are presented in Table 4, modelled electricity and heat balance for S3 is presented in Table 5. Sludge-storage emissions were calculated over an assumed four-year period with a 0.5-year delay. Changes in methane yield and leakage affected fugitive CH₄ emissions and recovered electricity and heat; methane recovery efficiency was calculated as one minus the leakage fraction. Heat-utilization percentages apply only to surplus CHP heat after meeting internal AD heating demand under the warmer-feed assumptions in Table 5. These

deterministic sensitivity tests do not represent statistical uncertainty intervals.

- S4: Controlled composting – assumed that sludge was diverted from long-term storage to controlled aerobic composting. Baseline sludge-storage CH₄ emissions were excluded, while composting CH₄ and N₂O emissions and N₂O emissions following compost application to soil were included. Fertilizer-substitution credits comprised avoided mineral-fertilizer production and avoided field N₂O emissions from the displaced mineral fertilizer. Compost-application N₂O emissions and avoided mineral-fertilizer field N₂O emissions were calculated separately. The parameters and assumptions are presented in Table 6.

Compost dry matter was calculated by multiplying sludge dry matter by the assumed retention fraction of 0.70. Mineral-fertilizer substitution was calculated from the retained compost mass, nutrient contents, and substitution fractions in Table 6. Potassium content was expressed directly as K₂O; no additional conversion was applied. Avoided fertilizer-production impacts were calculated by multiplying the substituted N, P₂O₅, and K₂O quantities by their respective production emission factor. Compost-application N₂O was calculated from total compost nitrogen applied, whereas avoided mineral-fertilizer field N₂O was calculated only from the substituted mineral nitrogen.

Net climate change impacts were calculated by subtracting total substitution credits from

Table 5. Modelled electricity and heat balance for S3 per functional unit under the warmer-feed assumption

Energy-balance item	Value per FU	Unit
Baseline electricity demand	0.29952	kWh
Additional AD electricity demand	0.06000	kWh
Total S3 electricity demand	0.35952	kWh
CHP electricity generation	0.50599	kWh
On-site electricity use	0.35952	kWh
Potential electricity surplus	0.14646	kWh
Residual grid electricity import	0.00000	kWh
CHP heat generation	2.34199	MJ
Internal AD heat requirement	1.69247	MJ
Surplus heat after internal AD heating	0.64952	MJ
Heat assumed to substitute coal-based heat (75% of surplus)	0.48714	MJ
Surplus heat receiving no substitution credit (25%)	0.16238	MJ
Supplementary external heat requirement	0.00000	MJ

Table 6. Parameters and assumptions used for composting and fertilizer substitution in S4

Parameter	Symbol	Value	Unit	Source or basis
Dry matter entering composting	DM_{FU}	1.2269	kg DM/FU	Calculated from wet sludge mass × TS; same input as S3
Composting CH ₄ emission factor	$EF_{CH_4, comp}$	0.010	kg CH ₄ /kg DM	(Doorn et al., 2019), Vol. 5, Ch. 4, Table 4.1
Composting N ₂ O emission factor before adjustment	$EF_{N_2O, comp}$	0.0006	kg N ₂ O/kg DM	(Doorn et al., 2019), Vol. 5, Ch. 4, Table 4.1
Adjusted composting N ₂ O factor	$EF_{N_2O, adj}$	0.00060	kg N ₂ O/kg DM	Calculated
Dry-matter retention after composting	$f_{retained}$	0.70	-	Scenario assumption
Compost nitrogen content	w_N	0.01780	kg N/kg compost DM	(Kulikowska & Bernat, 2023)
Compost phosphorus content, expressed as P ₄ O ₂	$w_{P_2O_5}$	0.02090	kg P ₂ O ₅ /kg compost DM	(Kulikowska & Bernat, 2023)
Compost potassium content, expressed as K ₂ O	w_{K_2O}	0.01342	kg K ₂ O/kg compost DM	(Kulikowska & Bernat, 2023)
Nitrogen substitution fraction	$f_{N, sub}$	0.05	-	Literature-based assumption informed by (Oladeji et al., 2020)
P ₄ O ₂ substitution fraction	$f_{P, sub}$	1.00	-	Assumed full substitution
K ₂ O substitution fraction	$f_{K, sub}$	1.00	-	Assumed full substitution
N-fertilizer production factor (urea)	$EF_{N, prod}$	5.00	kg CO ₂ -eq/kg N	(Kulikowska & Bernat, 2023; Vellinga et al., 2013)
P-fertilizer production factor (triple superphosphate)	$EF_{P, prod}$	0.45	kg CO ₂ -eq/kg P ₂ O ₅	(Kulikowska & Bernat, 2023; Vellinga et al., 2013)
K-fertilizer production factor (potassium chloride)	$EF_{K, prod}$	0.69	kg CO ₂ -eq/kg K ₂ O	(Kulikowska & Bernat, 2023; Vellinga et al., 2013)
Direct soil N ₂ O emission factor	$EF_{1, dry}$	0.005	kg N ₂ O-N/kg N applied	(Doorn et al., 2019), Vol. 4, Ch. 11, Table 11.1

gross impacts (Eq. 4). The absolute and percentage reductions relative to the baseline scenario (S1) were calculated using Eqs. (5) and (6), respectively. Net impacts and reductions relative to S1 were calculated as follows:

$$I_{net,i} = I_{gross,i} - C_{sub,i} \quad (4)$$

$$\Delta I_i = I_{net,S1} - I_{net,i} \quad (5)$$

$$R_i = (I_{net,S1} - I_{net,i}) / (I_{net,S1}) \times 100 \quad (6)$$

where: $I_{net,i}$ and $I_{gross,i}$ are the net and gross climate change impacts of scenario (i), respectively; $C_{sub,i}$ is the total substitution credit, expressed as a positive value; and ΔI_i is the absolute impact reduction relative to S1.

These quantities are expressed in kg CO₂-eq/FU. R_i is the percentage reduction relative to S1. Negative values of ΔI_i and R_i indicate a higher net impact than S1.

Sensitivity analysis

A one-at-a-time sensitivity analysis examined the sludge-storage decay rate (0.06 and 0.185 yr⁻¹) and three S3 parameters: methane yield (0.16–0.24 Nm³ CH₄/kg VS), methane leakage

(1–10%), and heat utilization (50–100%). Each parameter was varied individually while other inputs remained at baseline values. Methane recovery and both energy credits were recalculated when leakage changed. These tests represent exploratory parameter ranges rather than statistical uncertainty intervals.

RESULTS AND DISCUSSION

Baseline GHG emissions (S1) from the CWWTP

The total GHG emission intensity of the Ulaanbaatar CWWTP under S1 was 1.2969 kg CO₂-eq per m³ of treated wastewater. Applied to the approximately 69.50 million m³ of wastewater received in 2024, this intensity corresponds to approximately 90,137 t CO₂-eq, including cumulative sludge-storage emissions over the assumed four-year period. Biogenic CO₂ generated during biological wastewater treatment reported separately and excluded from the total GHG results, in accordance with the accounting boundary adopted in this study. The estimated emission intensity lies near the upper end of the values reported

for WWTPs in previous LCA studies (Mancini et al., 2021; Viotti et al., 2024). However, facilities should be directly compared with caution because the reported results depend strongly on the plant configuration, influent characteristics, electricity sources, sludge-management practices, system boundaries, and emission factors.

Direct emissions accounted for 1.0597 kg CO₂-eq/m³, representing 81.71% of the baseline climate change impact. Wastewater-process CH₄ was the largest direct contributor, accounting for 0.4087 kg CO₂-eq/m³ (31.52%). Long-term CH₄ emissions from sludge storage contributed 0.3899 kg CO₂-eq/m³ (30.06%), reflecting anaerobic degradation of residual organic matter during long-term sludge storage under the assumed CH₄ correction factor of 0.40. Together, CH₄ emissions from sludge storage and wastewater treatment processes accounted for 0.7986 kg CO₂-eq/m³, representing 61.58% of the total impact. N₂O generated during wastewater treatment contributed 0.2611 kg CO₂-eq/m³ (20.13%), highlighting the importance of controlling organic-carbon degradation and nitrogen-conversion processes.

Indirect emissions accounted for 0.2372 kg CO₂-eq/m³, representing 18.29% of the total impact. Electricity consumption remained the dominant indirect source, contributing 0.2246 kg CO₂-eq/m³ (17.32%), based on an annual electricity consumption of approximately 20.82 million kWh and a grid emission factor of 0.75 kg CO₂/kWh. Chemical production and transport contributed 0.0125 kg CO₂-eq/m³ (0.96%) and approximately 0.0001 kg CO₂-eq/m³ (<0.01%), respectively.

Figure 4 summarizes the baseline emission profile. Overall, direct CH₄ and N₂O emissions

dominated the GHG footprint, whereas electricity was the principal indirect contributor. These results demonstrate that an integrated mitigation strategy combining improved sludge management, control of process-related CH₄ and N₂O, energy-efficiency measures, and energy recovery is required.

Scenario analysis

Three mitigation scenarios were evaluated against S1 to identify the potential GHG reduction pathways for the CWWTP.

S2 — energy efficiency improvement

S2 assumed a hypothetical 20% reduction in electricity consumption through operational improvements such as aeration control, variable-frequency drives, and pump optimization. Electricity-related emissions decreased from 0.2246 to 0.1797 kg CO₂-eq/m³, reducing the total climate change impact from 1.2969 to 1.2520 kg CO₂-eq/m³.

This represents an impact reduction of 0.0449 kg CO₂-eq/m³, or 3.46% relative to S1. At the annual wastewater flow of approximately 69.5 million m³, this reduction is equivalent to approximately 3,123 t CO₂-eq/year. The modest reduction reflects the substantial contribution of direct CH₄ and N₂O emissions to the baseline impact, particularly emissions from sludge storage and wastewater treatment. Nevertheless, energy-efficiency measures remain important for reducing the climate change impact of wastewater treatment, particularly in Mongolia, where electricity supply has a relatively high carbon intensity. Although electricity-saving measures

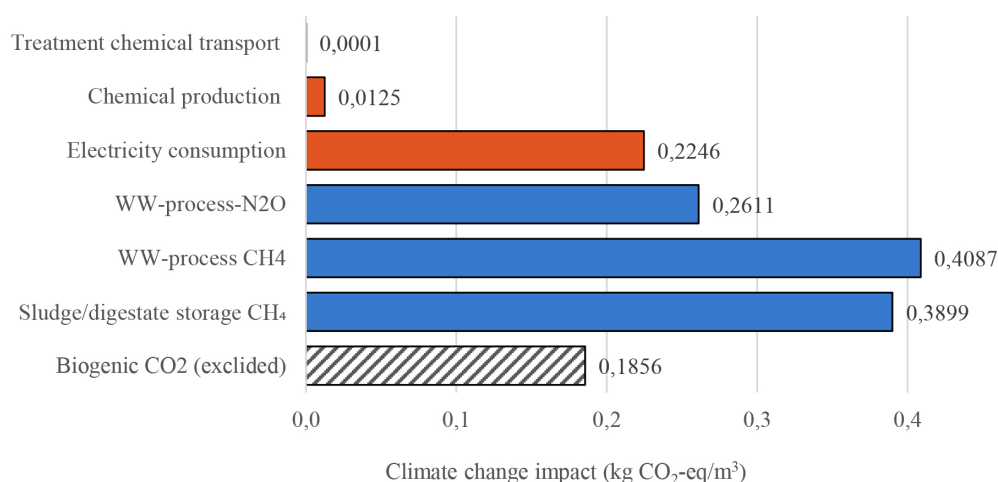


Figure 4. Contributions of individual emission sources to the baseline climate change impact of the Ulaanbaatar CWWTP (S1).

alone provide a limited reduction in total GHG emissions, they can serve as practical operational measures and complement sludge-management strategies (Brown & Herrera, 2021; Rodriguez-Garcia et al., 2012).

S3 — biogas recovery

S3 assumed that sewage sludge would be treated through AD, with the recovered biogas used for CHP generation. Baseline sludge-storage CH₄ emissions were avoided by diverting sludge from long-term storage to AD. Recovered electricity and useful heat were assumed to substitute for grid electricity and coal-based heat, respectively.

S3 resulted in a gross impact of 1.0890 kg CO₂-eq/m³, including fugitive CH₄ emissions from AD (0.1370 kg CO₂-eq/m³), wastewater-process CH₄ (0.4087 kg CO₂-eq/m³), process N₂O (0.2611 kg CO₂-eq/m³), electricity consumption (0.2696 kg CO₂-eq/m³), chemical production (0.0125 kg CO₂-eq/m³), and transportation (approximately 0.0001 kg CO₂-eq/m³). The baseline sludge-storage CH₄ contribution of 0.3899 kg CO₂-eq/m³ was excluded from the S3 gross impact under the assumed diversion of sludge to AD.

The recovered biogas provided electricity and heat substitution credits of 0.3795 and 0.0716 kg CO₂-eq/m³, respectively. The heat credit assumed that internal AD heating demand was met first and that 75% of the remaining surplus heat was effectively utilized under the warmer-feed assumption. The total substitution credit was 0.4511 kg CO₂-eq/m³. Subtracting these credits from the gross impact resulted in a net impact of 0.6379 kg CO₂-eq/m³. Compared with the baseline impact of 1.2969 kg CO₂-eq/m³, S3 achieved an impact reduction of 0.6590 kg CO₂-eq/m³, or 50.81%.

S3 demonstrated the greatest GHG mitigation potential among the evaluated scenarios because it combined avoidance of sludge-storage emissions with energy recovery. Electricity and heat credits were accounted for separately to represent the displacement of grid electricity and coal-based heat. However, the magnitude of these benefits depends on recovered-energy utilization, CH₄ recovery efficiency, fugitive CH₄ losses, AD energy requirements, and digestate management (Arjun V G et al., 2025). If the recovered heat or electricity cannot be effectively utilized, the corresponding avoided-impact credits would be lower, and the overall GHG reduction would decrease.

Overall, the S3 results indicate that AD with CHP has the highest GHG mitigation potential among the evaluated management options, highlighting the importance of integrating sludge treatment with renewable energy recovery in the Ulaanbaatar wastewater management system (Daelman et al., 2012; Singh et al., 2020).

S4 — sludge composting

S4 assumed that the sewage sludge would be diverted from long-term storage to controlled aerobic composting. Composting-related CH₄ emissions were estimated using an emission factor of 0.010 kg CH₄/kg dry matter, resulting in an impact of 0.3067 kg CO₂-eq/m³. Composting-related N₂O emissions were 0.2194 kg CO₂-eq/m³ under the assumed process-management conditions. In addition, the use of compost as an organic fertilizer provided environmental credits through the substitution of conventional chemical fertilizer production and associated field N₂O emissions.

The gross impact of S4 was 1.4689 kg CO₂-eq/m³. This included wastewater-process CH₄ (0.4087 kg CO₂-eq/m³), process N₂O (0.2611 kg CO₂-eq/m³), composting-related CH₄ (0.3067 kg CO₂-eq/m³), composting-related N₂O (0.2194 kg CO₂-eq/m³), fertilizer-related field N₂O (0.0358 kg CO₂-eq/m³), electricity consumption (0.2246 kg CO₂-eq/m³), chemical production (0.0125 kg CO₂-eq/m³), and transportation (0.0001 kg CO₂-eq/m³). The baseline long-term CH₄ emission from sludge storage of 0.3899 kg CO₂-eq/m³ was excluded from the S4 gross burden because sludge was assumed to be diverted from long-term storage to composting.

The environmental credits associated with fertilizer substitution were 0.0216 kg CO₂-eq/m³, comprising 0.0199 kg CO₂-eq/m³ from avoided chemical-fertilizer production and 0.0018 kg CO₂-eq/m³ from avoided fertilizer-related field N₂O emissions. Consequently, the net impact of S4 was 1.4473 kg CO₂-eq/m³. Compared with the baseline impact of 1.2969 kg CO₂-eq/m³, S4 resulted in a net increase of 0.1504 kg CO₂-eq/m³, an 11.60% increase in climate change impact. Under the assumptions applied in this study, controlled composting did not provide a net climate change benefit relative to S1.

Avoided sludge-storage CH₄ emissions and fertilizer-substitution credits were insufficient to offset emissions from composting and subsequent compost application. These results

highlight the influence of CH₄ and N₂O emission factors, process management, and nutrient-substitution effectiveness on the climate change performance of composting.

Sensitivity analysis

S3 remained the lowest-impact scenario in all individual sensitivity tests presented in Table 7. Its reduction relative to S1 ranged from 37.67% to 61.33%. Using the lower sludge-storage decay rate of 0.06 yr⁻¹ reduced the S1 impact to 1.0620 kg CO₂-eq/m³ and the relative reduction achieved by S3 to 39.93%. Changes in methane yield and leakage affected both fugitive CH₄ emissions and recovered energy production. Heat substitution credits were calculated only for utilized surplus heat after meeting internal AD heating demand under the warmer-feed assumption. These results show that the magnitude of mitigation depends on the selected parameters, although the scenario ranking remained unchanged within the tested ranges. Combined parameter changes and statistical uncertainty were not assessed.

In the additional tests reported in Supplementary Material S2, varying the wastewater N₂O factor by $\pm 50\%$ changed the S3 net impact to 0.5074–0.7684 kg CO₂-eq/m³. At a storage MCF of 0.80, the S1 impact increased to 1.6868 kg CO₂-eq/m³, exceeding the S4 net impact of 1.4473 kg CO₂-eq/m³. This result shows that the composting comparison depends on the assumed storage conditions. No additional composting N₂O reduction was applied in the revised default calculation.

Comparative analysis and implications

The comparatively high baseline result was primarily associated with direct CH₄ and N₂O emissions, particularly CH₄ emissions from long-term sludge storage and wastewater treatment processes, contributing 0.3899 kg CO₂-eq/m³ (30.06%) and 0.4087 kg CO₂-eq/m³ (31.52%), respectively. Together, these CH₄ sources accounted for 0.7986 kg CO₂-eq/m³ (61.58%) of the total baseline impact. Electricity consumption contributed 0.2246 kg CO₂-eq/m³ (17.32%), reflecting the high carbon intensity of Mongolia's electricity supply. These findings indicate that direct process emissions and energy consumption are important determinants of the CWWTP carbon footprint. Nevertheless, international comparisons should be interpreted cautiously, because the reported emission intensities depend on system boundaries, wastewater characteristics, treatment technologies, sludge-management pathways, grid emission factors, characterization factors, and the inclusion of biogenic and infrastructure-related emissions.

Among the evaluated scenarios, S3 demonstrated the greatest mitigation potential. The net impact decreased from 1.2969 kg CO₂-eq/m³ in S1 to 0.6379 kg CO₂-eq/m³ in S3, an avoided impact of 0.6590 kg CO₂-eq/m³ and a 50.81% reduction relative to the baseline. This substantial reduction resulted from the combined effects of diverting sludge from long-term storage, thereby eliminating the associated baseline storage CH₄ emissions, and recovering useful energy through CHP. The avoided electricity and coal-based heat credits were 0.3795 and 0.0716 kg CO₂-eq/m³,

Table 7. Sensitivity of S3 net climate change impact and mitigation performance to selected model parameters.

Parameter	Tested value	S1 net impact, kg CO ₂ -eq/m ³	S3 net impact, kg CO ₂ -eq/m ³	S3 reduction relative to S1 (%)
Baseline	—	1.2969	0.6379	50.81
Storage decay rate	0.06 yr ⁻¹	1.0620	0.6379	39.93
Methane yield	0.16 Nm ³ /kg VS	1.2969	0.7380	43.09
Methane yield	0.24 Nm ³ /kg VS	1.2969	0.5378	58.53
Methane leakage	1%	1.2969	0.5015	61.33
Methane leakage	10%	1.2969	0.8084	37.67
Heat utilization	50%	1.2969	0.6618	48.97
Heat utilization	100%	1.2969	0.6140	52.65

Note: Parameters were varied individually, with all other assumptions held constant. Storage emissions were recalculated using a four-year storage period and a 0.5-year delay. Changes in methane yield and leakage affected fugitive CH₄ emissions and recovered electricity and heat. Internal AD heat demand was met before applying the heat-utilization fraction to surplus heat. Calculations retained the warmer-feed assumptions in Table 5.

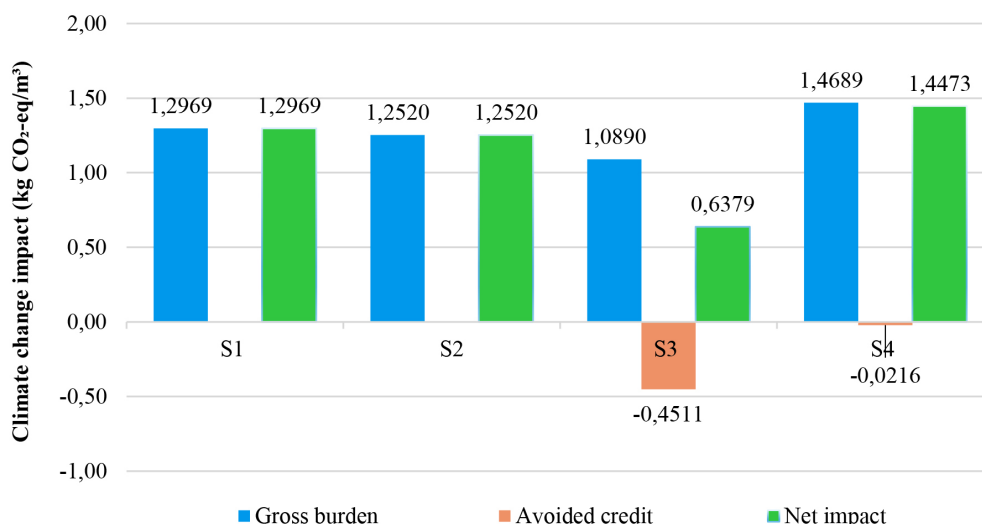


Figure 5. Gross climate change impacts, substitution credits, and net impacts of the four scenarios. Substitution credits are plotted as negative values

respectively, providing a combined avoided energy credit of 0.4511 kg CO₂-eq/m³ (Figure 5). The heat credit was calculated after meeting internal AD heating demand, assuming effective utilization of 75% of the remaining surplus heat under the warmer-feed assumption. Thus, the modelled mitigation potential was greater than the reductions associated with energy recovery alone because the scenario simultaneously addressed sludge-storage emissions and fossil energy displacement.

S2 produced a more modest reduction of 3.46%, with the net impact decreasing to 1.2520 kg CO₂-eq/m³. This result demonstrates that electricity-saving measures can provide a practical reduction in the CWWTP carbon footprint but are insufficient on their own to address the dominant direct CH₄ and N₂O sources. In contrast, S4 resulted in a net impact of 1.4473 kg CO₂-eq/m³, corresponding to a negative avoided impact of −0.1504 kg CO₂-eq/m³, or an 11.60% increase. Although compost utilization provided credits through avoided chemical-fertilizer production and fertilizer-related field N₂O emissions, these credits could not compensate for the additional CH₄ and N₂O emissions associated with composting under the assumptions applied in this study. The scenario results suggest that combining AD and CHP energy recovery with CH₄ leak control and operational energy efficiency could provide a substantial reduction in the CWWTP climate change impact. However, achieving the modelled benefits would require effective utilization

of recovered electricity and heat and appropriate digestate management.

The results depend on the adopted emission factors and assumptions regarding sludge storage, CH₄ recovery and leakage, energy utilization, and composting. The four-year sludge-storage period was assumed rather than measured, and wastewater-process emissions were estimated rather than directly monitored. Future studies should incorporate site-specific CH₄ and N₂O measurements, seasonal variation under cold-climate conditions, and technical and economic assessments of AD, CHP, and digestate management. Reducing the sludge-storage decay rate from 0.185 to 0.06 yr^{−1} decreased the S1 impact from 1.2969 to 1.0620 kg CO₂-eq/m³. S3 remained the lowest-impact scenario, although its reduction relative to S1 decreased from 50.81% to 39.93%. S4 remained higher than S1, with the increase rising from 11.60% to approximately 36.3%. Thus, the scenario ranking was unchanged in this comparison, but the magnitude of the relative benefits depended on the assumed storage decay rate.

CONCLUSIONS

This study quantified GHG emissions and evaluated sustainable sludge-management options for the Ulaanbaatar CWWTP using LCA and avoided-impact assessment. The baseline climate change impact was 1.2969 kg CO₂-eq/m³ of treated wastewater, with cumulative CH₄ emissions from sludge storage and wastewater-process

CH₄ collectively contributing 61.58% of the total impact, whereas electricity consumption contributed 17.32%. Direct CH₄ emissions therefore dominated the baseline footprint.

Mitigation performance differed between scenarios. S2 achieved a 3.46% reduction, whereas S3 reduced the net impact to 0.6379 kg CO₂-eq/m³, a 50.81% reduction relative to S1. This reduction resulted from avoiding baseline sludge-storage CH₄ emissions and substituting grid electricity and coal-based heat with recovered biogas energy. Heat substitution was credited only for the utilized surplus remaining after internal AD heating demand was met under the warmer-feed assumption. In contrast, S4 increased the net impact to 1.4473 kg CO₂-eq/m³, an 11.60% increase, because emissions from composting and subsequent compost application outweighed avoided sludge-storage emissions and fertilizer-substitution credits. AD with CHP consequently showed the greatest GHG mitigation potential among the evaluated scenarios under the modelled assumptions.

The avoided-impact assessment demonstrated the importance of resource recovery. S3 provided combined electricity and heat substitution credits of 0.4511 kg CO₂-eq/m³, whereas S4 provided a fertilizer-substitution credit of 0.0216 kg CO₂-eq/m³. These results demonstrate that the net climate change performance of sludge-management options depends on both the emissions generated by treatment and resource recovery and the emissions avoided through substitution.

Acknowledgments

The authors gratefully acknowledge the staff of the Water Supply and Sewerage Authority in Ulaanbaatar city for providing essential data for this study. The authors also thank the reviewers for their valuable comments and suggestions, which helped improve the manuscript. The author also acknowledges the M-JEED program and MUST for their study and institutional support.

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