

Aerobic and Energy-Recovery Treatment Processes of Sanitary Waste to Reduce End-of-Life Carbon Emissions

Supplementary Information (S1) Sensitivity and Uncertainty Support for Scenario Results

This Supplementary Information provides transparent sensitivity/uncertainty support for the scenario-based comparison of sanitary waste (SW) end-of-life management pathways presented in the main manuscript. The objective is to demonstrate how key assumptions influence the magnitude of the results while confirming the robustness of the comparative interpretation (i.e., the relative ranking of scenarios). The sensitivity checks follow a one-at-a-time (OAT) approach, varying one parameter while holding the others constant at baseline values.

S1.1 Definitions and baseline quantities used in the sensitivity check

Functional unit and reporting

All yields and emission factors are reported per functional unit (FU): **1 tonne of sanitary waste (SW), wet basis**. Scenario results are presented as annual totals (t yr⁻¹) by multiplying the FU-based emission factor by the annual generation of SW.

Total climate indicator

To enable a consistent scenario comparison, the study reports a “total climate indicator” (TI), defined as:

- **TI = CO₂ + CH₄-derived CO₂e**, where methane is converted to CO₂-equivalent using GWP₁₀₀.

Mathematically:

$$TI = Y_{CO_2} + (Y_{CH_4} * GWP_{100})$$

where:

- Y_{CO_2} = CO₂ yield per FU (t t⁻¹ SW, wet basis)
- Y_{CH_4} = CH₄ yield per FU (t t⁻¹ SW, wet basis)
- GWP_{100} = 100-year global warming potential for methane (baseline used in the manuscript: 28)

Baseline annual scenario totals

The baseline annual totals used for this sensitivity support correspond to those reported in the main manuscript scenario comparison:

- Scenario A (uncontrolled anaerobic): 7.89 t yr⁻¹
- Scenario B (controlled anaerobic with capture and flaring, 75% capture): 2.59 t yr⁻¹
- Scenario C (predominantly aerobic): 0.943 t yr⁻¹

These baseline values are taken as the reference point (“base case”) for the sensitivity checks below.

S1.2 Sensitivity design and parameters tested (OAT approach)

Reviewer feedback emphasized that, although the scenario framing and results were clear, the manuscript would be strengthened by explicitly demonstrating robustness to uncertain parameters. Accordingly, three sensitivity elements were evaluated:

1. Methane capture efficiency (Scenario B)

Capture performance is time-dependent and site-specific. A range is therefore tested to represent plausible performance bounds.

2. Stoichiometric yield/degradability uncertainty

Waste composition and effective degradability vary, influencing theoretical gas yields and resulting emission totals. A transparent “envelope” approach is applied as a minimum uncertainty bound.

3. Choice of GWP time horizon (qualitative sensitivity)

Methane dominates climate impacts under anaerobic pathways. The relative emphasis of CH₄ increases under shorter time horizons (e.g., GWP₂₀). A qualitative sensitivity statement is included to show directional robustness of conclusions.

Each test is performed one-at-a-time (OAT), meaning only the parameter of interest is changed while all other assumptions remain at their baseline values.

S1.3 Sensitivity to methane capture efficiency (Scenario B)

Scenario B represents an anaerobic end-of-life pathway with landfill gas capture and combustion (flaring). In the baseline manuscript case, methane capture efficiency is assumed to be $\eta = 75\%$. Because methane capture efficiency can vary widely, the reviewer requested that the manuscript justify the selected value and, at minimum, provide a sensitivity analysis.

Assumptions used for this sensitivity

- Captured methane is assumed to be combusted (flaring).
- Uncaptured methane is assumed to be emitted directly.
- Oxidation of methane in cover soils is not included in the baseline scenario boundary (this omission is applied consistently to maintain comparability across scenarios).

- The sensitivity is implemented by varying η while keeping all other parameters constant.

Results

The annual total climate indicator for Scenario B (t yr^{-1}) under each capture efficiency is:

- $\eta = 50\%$: **4.36 t yr^{-1}**
- $\eta = 75\%$: **2.59 t yr^{-1} (baseline)**
- $\eta = 90\%$: **1.53 t yr^{-1}**

This sensitivity confirms the expected behavior: Scenario B totals decrease as capture efficiency increases, approximately tracking the fraction of methane that remains uncaptured. Importantly, even under the conservative case (50% capture), Scenario B remains substantially below Scenario A, indicating that methane capture and combustion provides meaningful mitigation across plausible performance bounds.

S1.4 Sensitivity to stoichiometric yield / degradability uncertainty ($\pm 20\%$ envelope)

Several inputs that influence yields—such as effective degradability, waste composition variability, and the fraction of carbon routed to methane—can introduce uncertainty in absolute emission totals. As a minimum uncertainty demonstration, an envelope approach is used by applying a uniform multiplicative perturbation to the baseline scenario totals.

For each scenario, annual totals are scaled by:

- **-20%** (lower-bound)
- **base** (baseline)
- **+20%** (upper-bound)

This results (annual totals, t yr^{-1}) in a transparent uncertainty band without altering scenario definitions or rewriting the core calculation structure.

Scenario A:	Scenario B:	Scenario C:
-20%: 6.31	-20%: 2.07	-20%: 0.75
base: 7.89	base: 2.59	base: 0.943
+20%: 9.47	+20%: 3.11	+20%: 1.13

This envelope confirms that while absolute values shift proportionally, the comparative ordering remains unchanged across the tested range:

Scenario A > Scenario B > Scenario C

Thus, the central conclusion—uncontrolled anaerobic degradation yields the highest climate penalty, methane control/combustion substantially reduces impacts, and predominantly aerobic pathways yield the lowest totals—remains stable under reasonable yield/degradability uncertainty.

S1.5 Sensitivity to GWP time horizon

The manuscript expresses methane as CO₂-equivalent using GWP100, which is standard for many inventory and policy contexts. However, methane's short atmospheric lifetime means that shorter time horizons (e.g., GWP₂₀) increase its weighting relative to CO₂. The reviewer requested either a sensitivity test or justification. Here, a qualitative sensitivity statement is provided because the directional effect is unambiguous for scenario ranking.

Qualitative outcome

- Scenarios dominated by methane emissions (A and B) will increase under shorter horizons (e.g., GWP₂₀), because methane carries a higher CO₂e multiplier.
- Scenario C is minimally affected because it assumes negligible methane formation and is dominated by biogenic CO₂ (reported with factor 1 under the manuscript's indicator convention).

Changing the time horizon would primarily amplify the penalty of methane-driven scenarios. Therefore, the key conclusion—methane avoidance and/or effective methane capture and combustion is the dominant mitigation lever—is reinforced rather than weakened under shorter horizons.

Table S1. Sensitivity check for scenario-based annual totals (total climate indicator)

Parameter varied	Levels tested	Scenario A (t yr ⁻¹)	Scenario B (t yr ⁻¹)	Scenario C (t yr ⁻¹)	Interpretation
CH ₄ capture efficiency (Scenario B)	50% / 75% / 90%	—	4.36 / 2.59 / 1.53	—	B remains well below A; near-linear dependence on uncaptured CH ₄ .
Stoichiometric yield / degradability (applied to baseline totals)	−20% / base / +20%	6.31 / 7.89 / 9.47	2.07 / 2.59 / 3.11	0.75 / 0.943 / 1.13	Proportional change; ranking unchanged (A > B > C).
GWP time horizon (qualitative check)	GWP100 vs shorter horizon (e.g., GWP20)	↑↑	↑	~	Shorter horizon amplifies methane-driven scenarios (A, B); C changes minimally.

* Notes: Baseline totals are taken from the main manuscript scenario results (Fig. 4). For the capture-efficiency sensitivity, captured CH₄ is assumed to be combusted (flaring) and uncaptured CH₄ is assumed to be emitted directly. The ±20% envelope is applied multiplicatively to baseline totals as a transparent uncertainty bound.

S1.6 Robustness summary and implications

Across all sensitivity elements, the comparative interpretation remains stable:

1. **Uncontrolled anaerobic degradation (Scenario A)** consistently shows the largest climate penalty, driven primarily by methane formation and emission.
2. **Methane capture and combustion (Scenario B)** yields substantial reductions relative to Scenario A across plausible capture performance ranges; the absolute magnitude depends on capture efficiency, but the mitigation benefit remains strong even under conservative assumptions.
3. **Predominantly aerobic pathways (Scenario C)** consistently exhibit the lowest total climate indicator, with minimal sensitivity to methane weighting because methane formation is assumed negligible.

Overall, these checks reinforce that the study's main conclusion is robust: the dominant mitigation leverage for sanitary waste end-of-life management is methane avoidance and/or effective methane capture and combustion, and the scenario ranking remains stable under plausible parameter uncertainty.