Responses to reviewer1 comments

We sincerely thank you for the referee who read our manuscripts and give valuable and insightful comments. These have significantly improved the clarity and quality of the manuscript.

This document contains step-by-step response (in bold) to the referees' comments (in italic). All changes made to the manuscript text are highlighted in blue. The revised submission will reflect the changes accordance to the comments of the referees.

#1 The Introduction would benefit from a clearer justification of why including meteorological factors (temperature and precipitation) in landfill CH4 modeling is necessary. Although these variables are often cited as key environmental controls on microbial methane production, it remains unclear whether landfill CH4 generation is indeed strongly sensitive to them. Existing models such as IPCC FOD and LandGEM do not explicitly account for meteorological parameters, yet they sometimes perform equally well or even better. Without evidence that temperature and precipitation substantially improve predictive accuracy, the rationale for incorporating them is not fully convincing at this stage.

Thank you for your valuable comments. We agree that the Introduction should more clearly justify why including meteorological factors is necessary for landfill CH_4 modeling.

Landfill methane generation originates from microbial degradation of organic matter, and the microbial activity is strongly affected by meteorological conditions such as temperature and moisture. Consequently, landfill CH4 generation is sensitive to climatic variability in particularly in regions like Korea, where there is pronounced seasonality. Conventional FOD models represent biodegradation using a single rate constant k for each broad climate zone. It makes easy to adopt the model but difficult to capture annual and interannual variability by actual conditions. Moreover, the importance of explicitly representing meteorological drivers is not limited to regions.

We modified the manuscript to imply your comments in the Introduction (page 4, L14–29).

"Although previous models have been useful for estimating landfill CH_4 emissions, they are insufficient for predicting future emissions under changing climate conditions. Landfill CH_4 generation is driven by anaerobic microbial degradation of organic matter, and meteorological conditions strongly influence the extent and rate of these biological process. (Bai et al., 2025; Scheutz et al., 2009; Sacramento et al., 2024). In regions with pronounced seasonality, such as Korea, microbial decomposition rates vary substantially with seasonal changes in temperature and moisture (Kang et al., 2024). In the FOD models, the CH_4 generation rate constants (k) represents the biodegradation rate of organic matter in landfills (Purmessur & Surroop, 2019), however the IPCC and LandGEM models remain too simplified to consider climate impacts, by using default k values based on climate zones (Alexander et al., 2005; Eggleston et al., 2006). As climate change is expected to intensify landfill CH_4 emissions, accurately representing and quantifying the impacts of meteorological drivers on CH_4 generation is becoming increasingly important (Fei et al., 2021). By contrast, the CLEEN model, which explicitly incorporates temperature and precipitation, appears to reproduce field-based emissions well; however further calibration and optimization of these parameters are required before the model can be applied to other regions. (Karanjekar et al., 2015)."

Bai, S., Li, F., Yan, Y., Huang, Q., Jiang, F., Chen, H., and Zhang, Y.: Seasonal variations of methane emissions from a Urumqi landfill in China and its driving factors using hyperspectral satellite time-series observations, J. Geophys. Res.-Atmos., 130, e2025JD044272, https://doi.org/10.1029/2025JD044272, 2025.

Kang, M., Cho, S., Lee, Y., Lee, K.-H., Sohn, S., Choi, S.-W., Kim, J., and Park, J.: Quantification of methane and carbon dioxide surface emissions from a metropolitan landfill based on quasi-continuous eddy covariance measurement, Waste Manag., 186, 355–365, https://doi.org/10.1016/j.wasman.2024.06.020, 2024.

Park, J.-W. and Shin, H.-C.: Surface emission of landfill gas from solid waste landfill, Atmos. Environ., 35, 3445–3451, 2001.

Purmessur, B. and Surroop, D.: Power generation using landfill gas generated from new cell at the existing landfill site, J. Environ. Chem. Eng., 7, 103060, https://doi.org/10.1016/j.jece.2019.103060, 2019.

Sacramento, F. C. C., Rangel, G., Zanta, V. M., and Queiroz, L. M.: Climate variability impacts on methane recovery in a municipal solid waste landfill: A case study in a humid tropical climate region, Environ. Res., 247, 118181, https://doi.org/10.1016/j.envres.2024.118181, 2024.

Scheutz, C., Kjeldsen, P., Bogner, J. E., De Visscher, A., Gebert, J., Hilger, H. A., Huber-Humer, M., and Spokas, K.: Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions, Waste Manag. Res., 27, 409–455, https://doi.org/10.1177/0734242X09339325, 2009.

#2 Consider a more explicit discussion on potential transferability of CLEENopt to other climatic or waste management contexts. While the model is convincingly optimized for the SLS, it would strengthen the paper to discuss its applicability to other regions with different climatic regimes, waste compositions, or operational practices. A short evaluation of how the calibration parameters (e.g., temperature, precipitation sensitivity, or waste composition factors) could be generalized, or what site-specific adjustments would be required, could broaden the scientific impact of the study and highlight its potential for international or large-scale applications.

Thank you for your helpful suggestion. We agree that a more explicit discussion of the transferability of CLEEN$_{opt}$ is important for clarifying its broader applicability. In the revised manuscript, we have added a new paragraph in the Discussion section (page 23, L19–page 24, L3) that address this point.

"To extend the CLEEN$_{opt}$ framework to landfills with different climates, waste compositions, and operational practices, sufficient site-specific data are required for model calibration. The most critical inputs are field measurements of landfill gas (including surface emissions, gas collection, and gas flaring), along with detailed records of the amount of waste disposal and local temperature and precipitation. To adequately capture seasonal dynamics, these datasets should ideally have at least monthly or seasonal temporal resolution over several years. In addition, L_0 should be carefully constrained based on the amount and composition of degradable organic matter at the target landfill. In data-limited cases, one might use parameter sets derived from SLS for landfills that share similar conditions and waste management practices. However, such a parameter transfer would likely introduce substantial additional uncertainty, and parameter sets should be rigorously evaluated against local field measurements before being applied. Overall, the transferability of CLEEN$_{opt}$ to other regions depends strongly on the availability of long-term, temporally resolved landfill gas and activity data. Where such data exist, the framework can provide high-resolution and locally optimized CH_4 generation estimates, thereby enabling more robust applications across diverse climatic and waste management contexts."

#3 In the Discussion, a short paragraph linking these findings to national inventory improvement or IPCC Tier 2/3 applications could strengthen the applied relevance. Since one of the key motivations of this work is to enhance methane emission estimation accuracy, it would be valuable to explicitly connect the results to national GHG inventory frameworks. For example, discussing how the CLEENopt model could inform refinement of Tier 2/3 parameters under the IPCC guidelines, or contribute to improving uncertainty estimates in landfill CH4 inventories, would clearly position this research within broader

policy and reporting contexts.

Thank you for your valuable advice. We fully agree that explicitly linking our findings to national GHG inventory and IPCC Tier 2/3 applications strengthens the applied relevance of the study.

In the revised manuscript, we now clarify in the Discussion (page 24, L4–15).

"Optimization of the emission factor within the $CLEEN_{opt}$ framework provides a facility-specific approach that is consistent with an IPCC Tier 3 methodology. By calibrating constant k under site-specific meteorological conditions, the model yields facility-level emission factors that can be used to refine Tier 3 parameterization in national landfill CH_4 inventory methods. When combined with reliable, high-resolution activity data, $CLEEN_{opt}$ can enhance both the accuracy and transparency of landfill CH_4 emission estimates and support a more explicit quantification of inventory uncertainties. Systematically application of this framework at the national scale would enable country-specific, higher-tier emission estimates, aligning with IPCC guidelines. In turn, this could directly inform the improvement of national GHG inventory systems, support the design of effective CH_4 mitigation strategies, and provide a scientific basis for assessing progress toward national NDC (Nationally Determined Contribution) targets."

Responses to reviewer2 comments

We sincerely thank you for the referee who read our manuscripts and give valuable and insightful comments. These have significantly improved the clarity and quality of the manuscript.

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However, the work in its current form suffers from significant methodological ambiguities and a critical oversimplification of the environmental drivers governing CH4 generation. The conclusions are therefore not fully supported by the analysis as presented. The manuscript has the potential to be a strong contribution, but only after these core issues are addressed.

Therefore, the recommendation is that a minor revision is required before this manuscript can be further considered for publication. The following are some comments that require attention.

Omission of Synergistic Effects in Meteorological Analysis:

The analysis of meteorological impacts, presented in Section 3.4 and Figure 5, is based on an incomplete and potentially misleading 1-dimensional (1D) sensitivity analysis. The authors examine the effect of temperature (Figure 5a) and precipitation (Figure 5b) independently. The methodology in Section 2.5 confirms this approach, describing scenarios such as "(b) using a fixed mean temperature... and observed precipitation" and "(c) using observed temperature and a fixed mean precipitation".

This "one-at-a-time" (OAT) analytical approach fundamentally prevents the discovery or analysis of interaction effects between the variables. Methanogenesis is a biogeochemical process, and its drivers are not merely additive. The "linear correlation" with temperature shown in Figure 5a is an artifact of averaging across all precipitation conditions; this apparent linearity would almost certainly fail under extreme-dry (desiccation) or extreme-wet (pore saturation) scenarios. A "hot-wet" scenario (characterized by high temperatures and high precipitation) will exhibit a vastly different biogeochemical response than a "hot-dry" scenario (characterized by high temperatures and low precipitation), yet the current analysis cannot distinguish between them.

This flaw raises questions about the subsequent quantification of relative contributions in Figure 6. The analysis improperly partitions the variance from these coupled variables and, by design, ignores the contribution of the interaction term (Temperature x Precipitation), which may be a significant driver in itself.

The authors might need to replace the 1D plots in Figure 5 with a 2-dimensional (2D) sensitivity analysis. A 2D heatmap (e.g., Temperature on the X-axis, Precipitation on the Y-axis, and CH4generation as the color scale) would be appropriate. This would visualize the true response surface of the model, allowing for a much more robust discussion of the coupled meteorological impacts and identifying the actual optimal and pessimistic conditions that are currently obscured by the OAT analysis.

We appreciate this insightful comment and agree that the previous one-at-a-time (OAT) analysis was insufficient to capture interaction effects between meteorological drivers. In the revised manuscript, the plots in Figure 5 have been updated with a 2D heatmap in line with the reviewer's suggestion in the Results (page 19, L7 – page 20, L12)

In addition, we performed an ordinary least squares (OLS) regression, including linear, quadratic, and interaction (temperature × precipitation) terms. The results are now summarized in a new Table 4. The corresponding text has been expanded to provide a more in-depth interpretation of the model response, including a more detailed discussion of the combined effects of meteorological variables and the identification of meteorological conditions associated with optimal and pessimistic CH_4 generation.

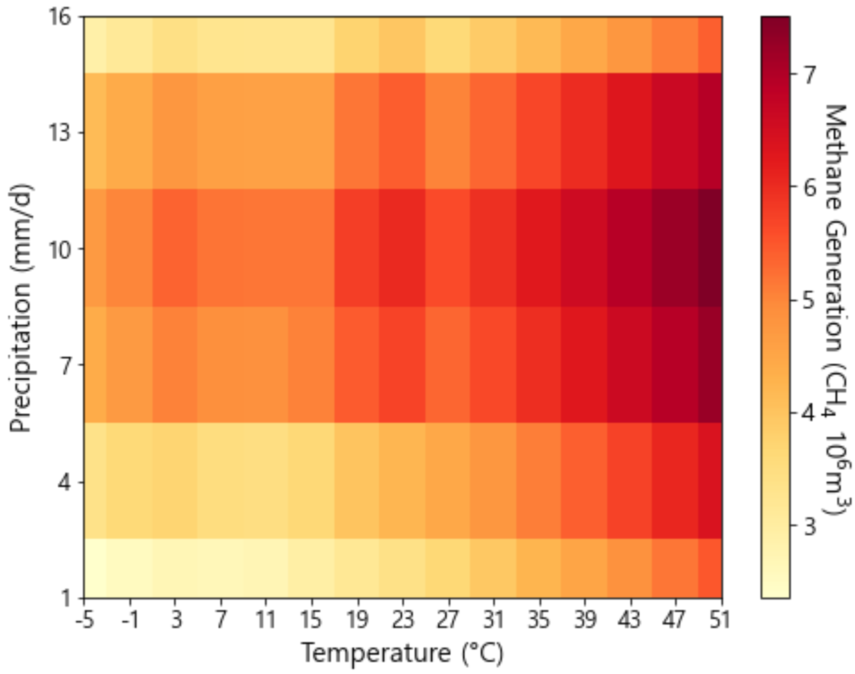

Fig. 5. Heatmap of simulated methane generation as a function of temperature and precipitation.

Table 1. Assessment of climate-induced CH_4 generation using OLS regression analysis.

$$CH_4\ Generation = \beta_0 + \beta_T T + \beta_P P + \beta_{TP}(TP) + \beta_{P2} P^2 + \varepsilon$$

Variables	Coefficient	std err	t-value	p-value
Intercept	5756.798	51.749	111.245	<0.001
T	47.828	1.946	24.575	<0.001
P	38.480	6.565	5.862	<0.001
T × P	-1.035	0.380	-2.724	0.008
P^2	-36.350	1.498	-24.262	<0.001

"Fig. 5 shows a 2D heatmap of simulated CH_4 generation as a function of temperature and precipitation. As temperature increases, CH_4 generation consistently rises across the full range of precipitation. In case of precipitation, CH_4 generation increases up to approximately 9–10 mm d^{-1}, but declines at higher precipitation level.

To statistically quantify these relationships, we applied ordinary least squares (OLS) using centered predictors to mitigate multicollinearity (Iacobucci et al., 2016; Kraemer et al., 2004). The regression results summarized in Table 4 show a strong positive association with temperature ($p < 0.001$). Under average conditions, the OLS coefficient for temperature (47.8 units per 1 °C) corresponds to an increase of approximately 0.8–1.0 % in simulated CH_4 generation per 1 °C warming. In contrast, precipitation indicates a significant nonlinear effect: the combination of a positive linear and negative quadratic term (both $p < 0.001$) produce the inverted–U shaped relationship, with emissions peaking at intermediate precipitation levels around 9–10 mm d^{-1}. In addition, the temperature–precipitation interaction term is statistically significant ($p = 0.008$), indicating that increasing precipitation reduces the effect of temperature on CH_4 generation. In other words, under dry conditions, the effect of temperature on CH_4 generation is relatively more pronounced, whereas under moist conditions, the influence of precipitation becomes comparatively more important."

Iacobucci, D., Schneider, M. J., Popovich, D. L., and Bakamitsos, G. A.: Mean centering helps alleviate "micro" but not "macro" multicollinearity, Behav. Res. Methods, 48, 1308–1317, 2016.

Kraemer, H. C. and Blasey, C. M.: Centring in regression analyses: a strategy to prevent errors in statistical inference, Int. J. Methods Psychiatr. Res., 13, 141–151, 2004.

Page 1 (Title): "emission" -> "emissions". The plural form is more appropriate as the paper discusses emissions from multiple sources, processes, and sites.

Thank you for this helpful comment. We have revised the title by changing "emission" to "emissions" in page 1.

Page 1 (Abstract, L18): "...6.57 million m3 CH4 a mean absolute error..." -> "...6.57 million m3 CH4, a mean absolute error..." (A comma is missing in the list of metrics).

We have added the comma in Page 1. (Abstract, L18)

Page 1 (Abstract, L22): "...emphasize the need of stronger and faster..." -> "...emphasize the need for stronger and faster..." (Incorrect preposition).

We have corrected the preposition error. The corrected term is now in Page 1. (Abstract, L25)

Page 2 (Intro, L7): "...approximately 30% of to global warming..." -> "...approximately 30% to global warming..." (Duplicate word)

We have corrected the preposition error. The corrected term is now in Page 1. (Intro, L6)

Page 2 (Intro, L9): "(IPOC Change, 2007; Prather..." -> This appears to be a significant typographical error. It should almost certainly be "IPCC, 2007; Prather...".

We have corrected the reference information. The corrected term is now in Page 2. (Intro, L8)

Solomon, S. (Ed.): Climate Change 2007 – The Physical Science Basis, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp., 2007.

Page 3 (Intro, L2): "...contributing CH4 emissions..." -> "...contributing to CH4 emissions...".

We have corrected the preposition error. The corrected term is now in Page 3. (Intro, L1)

Page 4 (Intro, L7): "...LandGEM provides an estimation of..." -> "...LandGEM provides an estimate of..." ('Estimation' is the process; 'estimate' is the resulting value).

Thank you for pointing this out. We have corrected the wording. The corrected term is now in Page 4. (Intro, L7)

Page 4 (Intro, L21): "...with greater accuracy than those of the LandGEM..." -> "...with greater accuracy than that of the LandGEM..." (The antecedent is the singular "accuracy").

Thank you for this comment. During the revision of the Introduction, we rewrote this passage, and the sentence in question has been removed.

Page 6 (Data, L12): "plastic (26.1± 4.7%)" -> "plastic (26.1 ± 4.7%)". Please check for consistent spacing around '±' symbols throughout the manuscript.

Thank you for pointing this out. We have corrected the spacing and carefully checked the entire manuscript including Page 7. (Data, L7 - 9)

Page 7 (Data, L2): "...47.5 m3 CH4I Mg..." -> "... 47.5 m3 CH4 Mg...". (There is a stray 'I' character).

We have corrected a spelling error in Page 7. (Data, L13)

Page 7 (Data, L13): "...simplicity, and flexibility, compared to other..." -> "...simplicity, and flexibility compared to other..." (The comma after "flexibility" is unnecessary).

We have removed the comma in Page 7. (Data, L24)

Page 7 (Data, L17): "...it is estimated based on stable..." -> "...it was estimated based on stable..." (Past tense should be used for actions taken during the study).

We have corrected the tense error in Page 7. (Data, L27)

Page 8 (Method, L5): The list of six citations for a general statement (Amini et al., 2012; Amini et al., 2013; Lay et al., 1996; Machado et al., 2009; Tolaymat et al., 2010) may be excessive and could be streamlined per journal style.

Thank you for your suggestion. We have streamlined the citation list in Page 7. (Data, L27)

Page 9 (Method, L15): "...field measurement data has been used..." -> "...field measurement data have been used..." ('Data' is a plural noun).

We have corrected the verb agreement in Page 10. (Method, L9)

Page 10 (Method, L10): "...suitable for site-scale monitoring." -> "...suitable for site-scale monitoring." (Hyphenate the compound adjective).

Thank you for the correction in Page 11. (Method, L1)

Page 10 (Method, L24): "...its insensitive to outliers." -> "...it is insensitive to outliers." (Missing verb 'is').

We have corrected the verb in Page 11. (Method, L15)

Page 10 (Method, L26): "...that is it does not estimate..." -> "...that is, it does not estimate..." (A comma is needed to set off the appositive phrase).

We have added the comma in Page 11. (Data, L16)

Page 11 (Method, L6): "...waste disposed that entered..." -> "...waste disposed of that entered..." or "...waste that entered...".

We have corrected the tense error in Page 11. (Data, L25)

Page 11 (Method, L12): "...kIal was calculated..." -> "...klab was calculated..." (Typo 'Ial' instead of 'lab').

We have corrected a typo error in Page 12. (Data, L5)

Page 14 (Results, L4): "...value of klab calculated using..." -> "...value of klab, calculated using..." (The appositive phrase requires a setting comma).

We have added the comma in Page 14. (Results, L25)

Page 14 (Table 2): The extreme values for klab and their corresponding errors (+2585% and +7269%) are a major finding and should be explicitly discussed in the main text of Section 3.1, not just presented in the table.

We appreciate your suggestion. We agree that extreme values of k_{lab} should be explicitly highlighted in the main text. In the revised manuscript, we have added a more detailed discussion in Page 14, L28 – Page 15, L4.

"Among all models, k_{lab} exhibited by far the largest discrepancy from k_{actual} with errors ranging from 2,585 % to 7,269 %. This overestimation arises because k_{lab} is derived under idealized laboratory conditions, which do not fully represent the heterogeneous and often less favorable conditions in actual landfills. Regarding this, Karanjekar et al. (2015) emphasized that laboratory-derived k values must be calibrated against field data before applied to real landfill systems."

Page 14 (Results, L22): "...million CH4m3.r=0.64..." -> "...million CH4m3, r=0.64..." (An incorrect period(.) is used mid-sentence. It should be changed to comma(,)).

We have corrected the comma error in Page 15. (Results, L19)

Page 16 (Fig. 4 Caption): "...CLEENopt, CLEEN and actual..." -> "...CLEENopt, CLEEN, and actual..." (Use of a serial comma is recommended for clarity).

We have added the comma Page 17. (Fig. 4 Caption)

Page 18 (Fig. 5 Caption): "...range across all simulated years, and colored shading is the seasonal..." -> This is a run-on sentence. It should be split: "...range across all simulated years. Colored shading represents the seasonal...".

Thank you for this comment. During the revision of the Result, we changed the Fig 5, and the sentence in question has been removed.

Page 18 (Results, L11): "...thereby gas diffusion..." -> "...thereby inhibiting gas diffusion..." (A verb is missing).

We have corrected the verb error in Page 20. (Result, L20)

Page 20 (Discussion, L26): "...positive correlation between temperature and CH4 generations was..." -> "...temperature and CH4 generation was..." ('Generation' should be singular).

We have corrected the spelling error in Page 22. (Discussion, L14)

Page 21 (Discussion, L23): "future studies should consider more accurate oxidation rates..." -> This is a key point. The use of a 10% default value is a major assumption and source of uncertainty that warrants more emphasis in the discussion.

Thank you for highlighting this important point. We agree that the use of a 10% default oxidation rate is a major assumption and that it warrants emphasis in the Discussion.

We have revised the manuscript to expand and clarify our use of this default value. Specifically, we now (1) state that the 10% oxidation rate applied in this study follows the IPCC guidelines, (2) note that CH4 oxidation is strongly influenced by climatic conditions, and (3) emphasize that our results should be interpreted as conditional on this assumed oxidation efficiency on page 23. (Discussion, L7-L14).

"To ensure consistency with national inventory practice, we applied a default oxidation rate of 10%, following the IPCC guidelines (Eggleston et al., 2006). However, this value represents a major assumption and an important source of uncertainty in our emission estimates. In reality, CH4 oxidation is also strongly influenced by climatic conditions, particularly temperature and precipitation (Christophersen et al., 2000). To achieve more accurate and policy-relevant estimates of atmospheric CH4 emissions, future studies should aim to use oxidation rates that reflect local environmental variability, rather than relying on a default value (Chanton et al., 2009; Scheutz et al., 2009)”

Page 22 (Conclusion, L6): "...linear correlation with temperature and a parabolic correlation with precipitation." -> "...linear response to temperature and a parabolic response to precipitation." ('Response' is more accurate than 'correlation' in this context, as it describes a modeled functional relationship, not a statistical correlation).

Thank you for this helpful comment. We have changed “correlation” to “response” on page 24. (Conclusion, L24)

Page 24 (References): "IPOC Change, 2007" -> This citation is repeated from Page 2. It MUST be corrected to "IPCC, 2007".

We have corrected the reference information on Page 30 (Reference, L38).

Solomon, S. (Ed.): Climate Change 2007 – The Physical Science Basis, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp., 2007.

Page 27 (References): "Sil, A., Kumar, S., and Wong, J. W.:...model suiting Indian condition..." -> "...model suiting Indian conditions...".

Thank you for your pointing this out. The phrase ‘Indian condition’ appears as part of the original article title (Sil et al., 2019), and we have retained it exactly as published in the reference list on Page 30 (Reference, L32).

Page 28 (References): "Wang, Y., Pelkonen, M., and Kaila, J.:...Open Waste Manag. J., 5, 2012." -> Page numbers appear to be missing from this journal citation. Please verify.

Thank you for your correction. We have revised the reference on Page 31 (References, L24)

Wang, Y., Pelkonen, M., and Kaila, J.: Effects of temperature on the long-term behaviour of waste degradation, emissions and post-closure management based on landfill simulators, Open Waste Manag. J., 5, 19-27, 2012.