ARTICLE IN PRESS

Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

Underestimated Methane Emissions from Solid Waste Disposal Sites Reveal Missed Greenhouse Gas Mitigation Opportunities

Yao Wang [a], Chuanbin Zhou [b], Ziyang Lou [c], Houhu Zhang [d], Abid Hussain [e], Liangtong Zhan [f], Ke Yin [g], Mingliang Fang [h], Xunchang Fei [a,*]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore
[b] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[c] Department of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[d] Nanjing Institute of Environmental Sciences, Ministry of Ecology and Environment, Nanjing 210042, China
[e] Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, K1S 5B6, Canada
[f] Ministry of Education (MOE) Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou 310058, China
[g] Department of Environmental Engineering, School of Biology and the Environment, Nanjing Forestry University, Nanjing 210037, China
[h] Department of Environmental Science and Engineering, Fudan University, Shanghai 200433, China

1. Introduction

Cities are responsible for approximately 70% of all anthropogenic greenhouse gas (GHG) emissions and about 60% of all anthropogenic methane (CH_4) emissions [1,2]. Solid waste disposal sites (including landfills and dumpsites), which are prevalent in global cities, emit CH_4 generated from the anaerobic biodegradation of municipal solid waste (MSW). Notably, the proportions of CH_4 emissions from disposal sites surpass 50% of the total CH_4 emissions in some megalopolises [3]. CH_4 has a high global warming potential (GWP), being 28 times stronger than carbon dioxide (CO_2) over a 100-year period and 80 times stronger over a 20-year period [4]. Understanding and mitigating CH_4 emissions from solid waste disposal sites is particularly pertinent and pressing, considering that the latest Synthesis Report from the Intergovernmental Panel on Climate Change (IPCC) emphasizes that the current pace of mitigation and adaptation policies and measures falls short of restraining global temperature rise to under 1.5 °C within the 21st century [4]. More than 150 countries signed the Global Methane Pledge at the United Nations Climate Change Conference in Glasgow (COP26), which aims to reduce global annual CH_4 emissions by 30% by 2030, compared with emissions in 2020 [5].

Landfilling will remain as the major waste treatment method in the near future, considering the slow pace of implementing source segregation of biowaste for separated treatments in anaerobic digesters or composting facilities. There are 300 000–500 000 operating and closed disposal sites around the world, which receive about 1.5×10^9 t of MSW annually and store approximately 1.0×10^{11} t of MSW cumulatively [6]. Global disposal sites have emitted an annual 30–50 Tg of CH_4 in recent years [2]. Future emissions from disposal sites could exhibit continuous upward trajectories due to the relentless surge in waste generation that is concomitant with rapid urbanization, population growth, and economic development [6]. In this comment, we highlight the two most critical problems related to such emissions. Firstly, the emission quantities are highly uncertain and are often underestimated, which will result in misguided mitigation strategies. Secondly, these emissions receive disproportionately low attention and priority in the various GHG mitigation plans as compared with other sources that have similar levels of emissions and even higher mitigation costs [7]-most notably, fossil fuel production, intensive livestock farming, and transportation [8].

2. Underestimated CH_4 emissions from disposal sites

Establishing accurate site- and city-level inventories of CH_4 emissions from disposal sites is the prerequisite for understanding and mitigating such CH_4 emissions. However, bottom–up field measurements using current ground-based techniques, including flux chamber measurements [9] and mobile analytical platforms [10,11], require certain costs and labor. The mainstream estimation method adopted by the IPCC utilizes a first-order decay (FOD) model, which has been widely used in the 196 countries and regions under the United Nations Framework Convention on Climate Change (UNFCCC). The FOD model incorporates two critical parameters: waste decay rate (k, time^{-1}) and methane generation potential (L_0, volume CH_4 per mass MSW). Waste managers are recommended to choose from a list of default emission parameters based on site conditions to calculate the corresponding annual emissions.

Inventory emission estimations based on FOD model are widely applicable and user-friendly but often have limited accuracy [12]. In its model document, the IPCC acknowledges that the uncertainty range of the default k values is between −40% and +300% [13] and recommends that local emission adjustments be developed. Even using the same inventory estimation method, the annual national emissions in the United States estimated by two research institutes are approximately 150% different [14]. Similarly, several research

* Corresponding author.

https://doi.org/10.1016/j.eng.2023.12.011

institutes reported the annual national emissions in China in the 2000s and 2010s, among which the highest and lowest estimations differ by 170% [15–20]. Without exhaustively enumerating the disparities in the inventoried emission estimations in different countries, it suffices to conclude that the IPCC's current model compromises accuracy in favor of applicability.

In fact, the conventional inventory bottom–up methodology is being challenged by a top–down methodology that uses atmospheric inversion modeling. This new methodology utilizes high-resolution satellites [21] and drones [22] to measure atmospheric CH_4 concentrations and back-calculate site-specific CH_4 emissions, offering potentially more accurate and timely emission estimations than the inventory method [23]. The reported atmospheric inversion results have revealed consistent underestimations of the current inventory values (30 out of 31 sites in four countries), ranging from +4% to +737% (Fig. 1(a)) [3,24–26]. Extrapolating the 10th (+17%) and 90th percentile (+377%) values of the percentage of underestimation in Fig. 1(a) to global disposal sites shows that the underestimated emissions reach 10–150 Tg•a^{-1} globally.

The top five emitters are responsible for about 50% of all underestimated emissions (Fig. 1(b) [27]). As the two leading countries in MSW generation, the United States and China are also the largest two emitters of landfill CH_4. Landfills in the United States are commonly well managed, with a comprehensive reporting scheme known as the Landfill Methane Outreach Program (LMOP) for site-scale emissions. The Environmental Protection Agency (EPA) is making ongoing progress as well in upgrading estimation methods and incorporating remote sensing [28]. In November 2023, the Chinese Ministry of Ecology and Environment also proposed systematic enhancements in monitoring and managing landfill CH_4 emissions for the first time [29]. It should be noted that India-despite having the largest population in the world-is not among

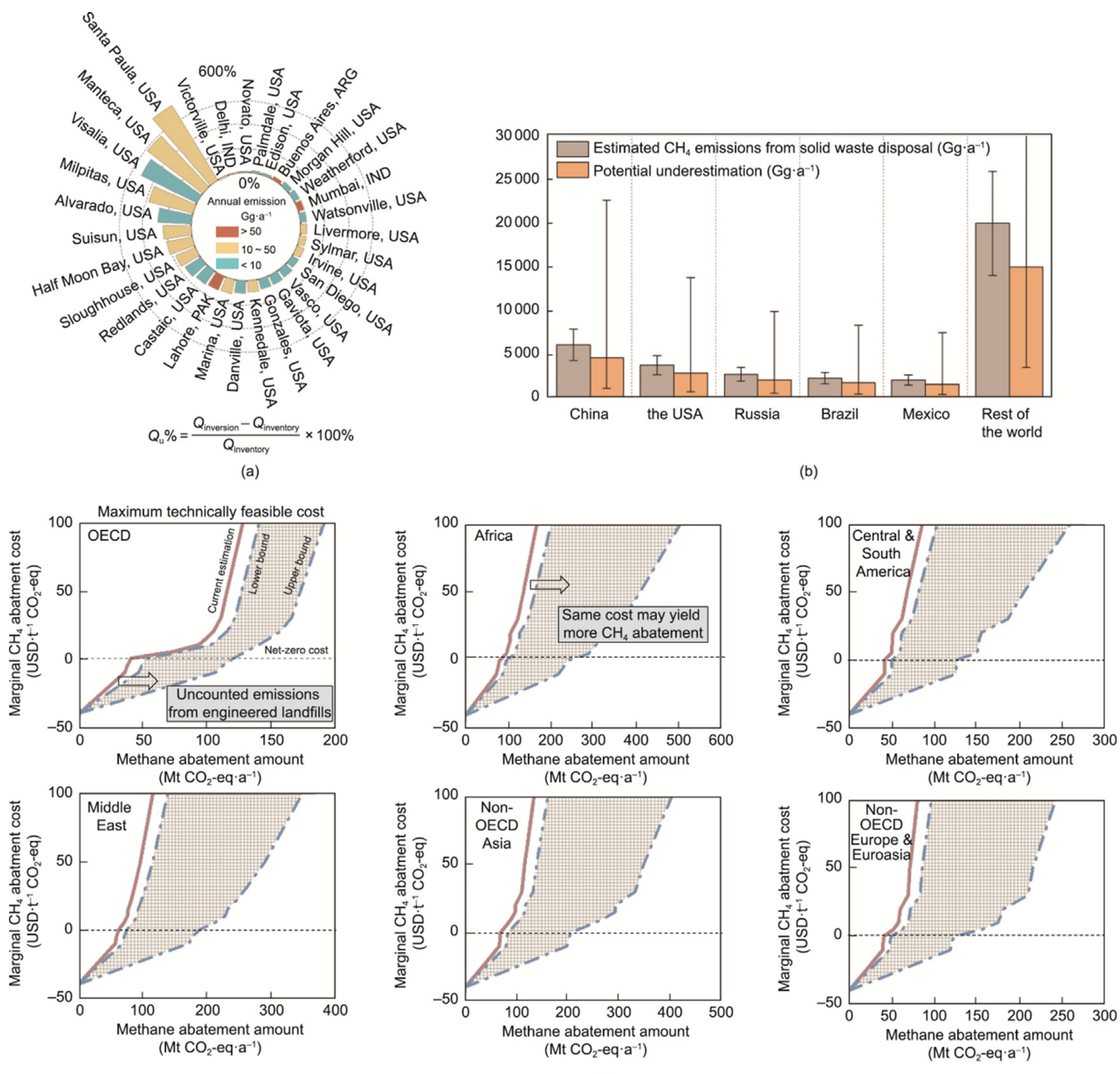

Fig. 1. Potentially underestimated CH_4 emissions from disposal sites and the impacts on regional CH_4 mitigation strategies. (a) Illustration of the percentage of underestimation of CH_4 emissions in 27 landfills by comparing current estimates (Gg CH_4 emissions per year, Gg CH_4•a^{-1}, calculated using the IPCC's model) with the reported atmospheric inversion results (Gg CH_4•a^{-1}) [3,24–26]. Q_u% represents the percentage of underestimation by inventory method compared with inversion method. $Q_{inversion}$ and $Q_{inventory}$ represents the emission estimation using inversion method and inventory method, respectively. (b) Top five emitters' current estimates [29] and potential underestimations (the uncertainty range of underestimation is derived from the 10th and 90th percentile values obtained from part (a)). (c) Differences in marginal CH_4 abatement costs for disposal sites with and without considering underestimated CH_4 emissions in OECD countries, Africa, Central and South America, the Middle East, Non-OECD Asia, and Non-OECD Europe and Eurasia. Marginal CH_4 abatement costs (US Dollar per tonne of CO_2 equivalent emission, USD•t^{-1} CO_2-eq) for countries and detailed country listings in each region were obtained from the US EPA's Non-CO_2 Greenhouse Gas Data Tool [30].

the top five emitters in either the EDGAR database (where India ranks 7th) [27] or the EPA Non-CO_2 GHG database (where it ranks 9th) [30]. This may seem counterintuitive, considering India's amount of waste generation, which is second only to those of the United States and China. A potential reason is the high proportion of food waste in India's MSW, as such waste has a low degradable organic carbon content ($DOC_{food\ waste}$ = 0.15). In addition, much of India's waste is not centrally disposed of in landfills, so it is not included in landfill emission estimates. However, additional *in situ* measurement data and rigorous assessments are needed in the future to validate India's current emission estimates.

The substantial disparities between bottom–up and top–down emission estimations necessitate a reevaluation-and possibly a revamp-of the IPCC's model [31]. Firstly, the IPCC's model needs refinement, and its recommended k and L_0 values need localization. Both the k and L_0 values have been demonstrated to vary widely based on site-specific temperature, precipitation, waste composition, infrastructure, operations, and waste management policies. These variations can exceed the ranges suggested by the IPCC [32]. One exemplar attempt at a refined model is the establishment of the California Landfill Methane Inventory Model (CALMIM) in the United States [12]. Secondly, utilization of the IPCC's model is often hampered by inaccurate, incomplete, or outdated site-specific information. Thus, it is recommended to establish city- and country-level databases, such as the LMOP database, to record the time-dependent environmental and operational conditions of each site. Thirdly, given current technological availability and economic constraints, it is only viable to integrate the bottom–up and top–down approaches, rather than focusing exclusively on a singular approach. The bottom–up methodology can be improved according to top–down results [33] and vice versa. While the emerging satellite-based technique offers an efficient way to identify emission profiles for so-called "super-emitters" [34], mainstream ground-based measurements [35,36] should also be enhanced in order to solve the whole puzzle. Future work should thus focus on streamlining and optimizing a merged and coordinated estimation methodology.

3. Implications for mitigation strategies

Underestimated CH_4 emissions have profound implications for policymakers in devising cost-effective strategies to mitigate GHG emissions. In the context of developed countries (mostly Organisation for Economic Co-operation and Development (OECD) countries), it has been conventionally posited that the amount of technically feasible CH_4 mitigation at disposal sites, at an abatement cost lower than approximately 100 USD·t^{-1} CO_2 equivalent (CO_2-eq, the amount of CO_2 equivalent to CH_4 emissions based on GWP) is limited [37]. This is largely due to the assumed well-engineered and well-managed nature of the disposal sites in these countries, with about 50% of the CH_4 emissions being deemed as "residual emissions," which are very difficult to eliminate. However, once underestimated CH_4 emissions-which may not be "residual"-are taken into account, the potential for emission mitigation at these sites becomes notably higher. For example, landfills in a country that were previously estimated to emit 4 Gg of CH_4 per year with 50% residual emissions may actually emit 6 Gg, as revealed by more accurate measurements. If the additional 2 Gg of emissions could be mitigated at low or net-zero abatement costs via measures such as flexible gas-collection plans, improved gas-collection systems, effective emission monitoring, and routine infrastructure maintenance, the technically feasible abatement potential would increase from 50% to 67% of the total emissions. Under this likely scenario, the marginal abatement cost curve would be altered (Fig. 1(c)), suggesting that increased CH_4 mitigation can be achieved without incurring additional marginal costs.

The disposal infrastructures in developing countries are generally poorly managed, resulting in higher mitigation potential-that is, less current mitigation-in comparison with those in developed countries (Fig. 1(c)). Presuming that the efficacies of mitigation measures remain unchanged, then adding the underestimated CH_4 emissions to regions with developing countries would shift their marginal abatement cost curves to the right. These shifted curves demonstrate that more CH_4 emissions can be mitigated than currently expected at the same cost. As a result, developing countries with various economic and technical constraints would be justified in elevating the priority of mitigating emissions from disposal sites as a cost-effective strategy to bridge the gap between current emissions and future mitigation targets. The anticipated payback period of a landfill CH_4-recovery project is on the order of a few years to a decade [38,39]. Developing countries also need to consider the entire life cycle of carbon emissions. Beyond improvements at the site scale, enhancements in local waste management systems, such as the introduction of waste sorting and "waste-free city" campaigns, can effectively reduce GHG emissions from disposal sites [40].

Technical feasibility and economic capability should be further considered when determining site-specific CH_4 mitigation measures at disposal sites with different scales and local conditions. It is necessary to derive more accurate marginal abatement cost curves based on the achievable cumulative CH_4 emission mitigation over the whole lifespans of disposal sites. Information concerning CH_4 mitigation technologies for future use should also be identified and analyzed [41]. The assessment process consists of the following steps: ① Calculate the total costs and abatement potential for candidate technologies; ② identify possible combinations and incompatibilities; ③ manipulate and standardize data; and ④ derive the corresponding abatement cost curves.

It is vital to realize that disposal sites are huge carbon reservoirs, while CH_4 emissions constitute only one carbon transformation and transport pathway. The embodied carbon in disposed MSW also exists in solid (waste) and liquid (leachate) phases, which are prone to different transformation and transport pathways in the long term [42]. For example, solid waste undergoes off-site transport (via wind, surface water, waste landslide, scavenging, and waste mining) and transformation (through burning, leaching, erosion, and biodegradation), while leachate undergoes physico-, chemo-, and bio-degradation, leakage, and pump-and-treat processing [43]. It is necessary to expand the boundary of interest from the waste–atmosphere interface to the whole site and its vicinity. The notion of calculating carbon emissions from disposal sites should gradually evolve into understanding and managing site-specific carbon budgets.

4. Conclusions

In this paper, we firstly call for an urgent reevaluation and enhancement of current landfill CH_4 emission quantification methodologies. We propose the incorporation of updated emission parameters and landfill information into the widely used IPCC FOD model. Satellite-based and local ground-based measurements are urgently needed to improve inaccurate estimations. Secondly, we underscore that incorporating the underestimated CH_4 into estimations will shift current GHG marginal abatement costs to reveal new mitigation opportunities. In developed countries, improved landfill management could significantly curtail CH_4 leakages at low cost. In developing countries, prioritizing the reduction of landfill CH_4 emissions could effectively contribute to meeting future mitigation targets due to the high mitigation potential and economies of scale. It is essential for policymakers and administrators to adopt local- and region-specific measures to mitigate waste-related GHG emissions.

Acknowledgments

The authors would like to acknowledge Nanyang Technological University, Singapore, for providing research scholarships for this study. The authors thank the supports from Debris of the Anthropocene to Resources (DotA2) Lab at NTU.

References

[1] UNFCCC. United Nations Framework Convention on Climate Change (UNFCCC) Greenhouse Gas Data Interface. Bonn: United Nations Framework Convention on Climate Change; 2022.
[2] Saunois M, Stavert AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, et al. The global methane budget 2000–2017. Earth Syst Sci Data 2020;12(3):1561–623.
[3] Maasakkers JD, Varon DJ, Elfarsdóttir A, McKeever J, Jervis D, Mahapatra G, et al. Using satellites to uncover large methane emissions from landfills. Sci Adv 2022;8(32):eabn9683.
[4] IPCC. Summary for policymakers Synthesis report of the IPCC sixth assessment report (AR6). Report. Geneva: IPCC. 2023.
[5] The UNEP-convened Climate and Clean Air Coalition (CCAC). The Global Methane Pledge. The UNEP-convened Climate and Clean Air Coalition (CCAC); 2021.
[6] Kaza S, Yao L, Bhada-Tata P, Van Woerden F. What a waste 2.0: a global snapshot of solid waste management to 2050. Report. Washington, DC: World Bank. 2018.
[7] Fei X, Fang M, Wang Y. Climate change affects land-disposed waste. Nat Clim Chang 2021;11(12):1004–5.
[8] Lauvaux T, Giron C, Mazzolini M, D'Aspremont A, Duren R, Cusworth D, et al. Global assessment of oil and gas methane ultra-emitters. Science 2022;375 (6580):557–61.
[9] Abichou T, Powelson D, Chanton J, Escoriaza S, Stern J. Characterization of methane flux and oxidation at a solid waste landfill. J Environ Eng 2006;132 (2):220–8.
[10] Bakkaloglu S, Lowry D, Fisher RE, France JL, Nisbet EG. Carbon isotopic characterisation and oxidation of UK landfill methane emissions by atmospheric measurements. Waste Manag 2021;132:162–75.
[11] Mønster J, Samuelsson J, Kjeldsen P, Scheutz C. Quantification of methane emissions from 15 Danish landfills using the mobile tracer dispersion method. Waste Manag 2015;35:177–86.
[12] Spokas KA, Bogner J, Corcoran M. Modeling landfill CH_4 emissions: CALMIM international field validation, using CALMIM to simulate management strategies, current and future climate scenarios. Elem Sci Anth 2021;9 (1):00050.
[13] Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K. 2006 ICCP Guidelines for national greenhouse gas inventories. Report. Japan: the Institute for Global Environmental Strategies (IGES) for the IPCC. 2006.
[14] Powell JT, Townsend TG, Zimmerman JB. Estimates of solid waste disposal rates and reduction targets for landfill gas emissions. Nat Clim Chang 2016;6 (2):162–5.
[15] Zhang B, Chen G. Methane emissions in China 2007. Renew Sustain Energy Rev 2014;30:886–902.
[16] Du M, Peng C, Wang X, Chen H, Wang M, Zhu Q. Quantification of methane emissions from municipal solid waste landfills in China during the past decade. Renew Sustain Energy Rev 2017;78:272–9.
[17] Peng S, Piao S, Bousquet P, Ciais P, Li B, Lin X, et al. Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010. Atmos Chem Phys 2016;16(22):14545–62.
[18] Gong S, Shi Y. Evaluation of comprehensive monthly-gridded methane emissions from natural and anthropogenic sources in China. Sci Total Environ 2021;784:147116.
[19] Cai B, Lou Z, Wang J, Geng Y, Sarkis J, Liu J, et al. CH_4 mitigation potentials from China landfills and related environmental co-benefits. Sci Adv 2018;4(7): eaar8400.
[20] Cai B, Liu J, Gao Q, Nie X, Cao D, Liu L, et al. Estimation of methane emissions from municipal solid waste landfills in China based on point emission sources. Adv Clim Chang Res 2014;5(2):81–91.
[21] Cusworth DH, Duren RM, Thorpe AK, Tseng E, Thompson D, Guha A, et al. Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations. Environ Res Lett 2020;15(5):054012.
[22] Bel Hadj Ali N, Abichou T, Green R. Comparing estimates of fugitive landfill methane emissions using inverse plume modeling obtained with Surface Emission Monitoring (SEM), Drone Emission Monitoring (DEM), and Downwind Plume Emission Monitoring (DWPEM). J Air Waste Manag Assoc 2020;70(4):410–24.
[23] Mønster J, Kjeldsen P, Scheutz C. Methodologies for measuring fugitive methane emissions from landfills-a review. Waste Manage 2019;87:835–59.
[24] Duren RM, Thorpe AK, Foster KT, Rafiq T, Hopkins FM, Yadav V, et al. California's methane super-emitters. Nature 2019;575(7781):180–4.
[25] Cambaliza MOL, Bogner JE, Green RB, Shepson PB, Harvey TA, Spokas KA, et al. Field measurements and modeling to resolve m^2 to km^2 CH_4 emissions for a complex urban source: an Indiana landfill study. Elementa 2017;5:36–47.
[26] Lavoie TN, Shepson PB, Cambaliza MO, Stirm BH, Karion A, Sweeney C, et al. Aircraft-based measurements of point source methane emissions in the Barnett Shale basin. Environ Sci Technol 2015;49(13):7904–13.
[27] Crippa M, Guizzardi D, Solazzo E, Muntean M, Schaaf E, Monforti-Ferrario F, et al. GHG emissions of all world countries. Luxembourg: Publications Office of the European Union; 2021.
[28] Quinn M. EPA agrees to reevaluate MSW landfill emissions measurements in effort to settle lawsuit. Report. Washington, DC: WASTEDIVE; 2023.
[29] Ministry of Ecology and Environment of the People's Republic of China. Notice from the Ministry of Ecology and Environment of People's Republic of China and Other 11 Departments on the Issuance of the "Action Plan for Methane Emission Control". Report. Beijing: Ministry of Ecology and Environment of the People's Republic of China; 2023. Chinese.
[30] EPA. Non-CO_2 greenhouse gas data tool. Boston: US Environmental Protection Agency; 2019.
[31] National Academies of Sciences, Engineering, and Medicine. Improving characterization of anthropogenic methane emissions in the United States. Report. Washington, DC: National Academies Press (US); 2018.
[32] Fei X, Zekkos D, Raskin L. Quantification of parameters influencing methane generation due to biodegradation of municipal solid waste in landfills and laboratory experiments. Waste Manage 2016;55:276–87.
[33] Bergamaschi P, Karstens U, Manning AJ, Saunois M, Tsuruta A, Berchet A, et al. Inverse modelling of European CH_4 emissions during 2006–2012 using different inverse models and reassessed atmospheric observations. Atmos Chem Phys 2018;18(2):901–20.
[34] Erland BM, Thorpe AK, Gamon JA. Recent advances toward transparent methane emissions monitoring: a review. Environ Sci Technol 2022;56 (23):16567–81.
[35] Scheutz C, Kjeldsen P. Guidelines for landfill gas emission monitoring using the tracer gas dispersion method. Waste Manage 2019;85:351–60.
[36] Fredenslund AM, Hinge J, Holmgren MA, Rasmussen SG, Scheutz C. On-site and ground-based remote sensing measurements of methane emissions from four biogas plants: a comparison study. Bioresour Technol 2018;270:88–95.
[37] EPA. Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation Potential: 2015−2050, EPA-430-R-19-010. Report. Washington, DC: EPA; 2019.
[38] Rubio-Romero JC, Arjona-Jiménez R, López-Arquillos A. Profitability analysis of biogas recovery in municipal solid waste landfills. J Clean Prod 2013;55: 84–91.
[39] Cudjoe D, Han MS. Economic and environmental assessment of landfill gas electricity generation in urban districts of Beijing municipality. Sustain Prod Consum 2020;23:128–37.
[40] Ma S, Lu M, Yang G, Zhi Y, Ouyang Z, Huang N, et al. Bottom−up accounting of landfills across 346 cities reveals overlooked carbon stocks. 2022, in press.
[41] Liu Y, Cheng Z, Chen AY, Geng Y, Zhang K, Zhu N, et al. Big disparities in CH_4 emission patterns from landfills between the United States and China and their behind driving forces. Fundam Res. In press.
[42] Ma S, Zhou C, Pan J, Yang G, Sun C, Liu Y, et al. Leachate from municipal solid waste landfills in a global perspective: characteristics, influential factors and environmental risks. J Clean Prod 2022;333:130234.
[43] Fei X, He H, Pi X, Lu X, Chen Q, Ma J, et al. The distribution, behavior, and release of macro-and micro-size plastic wastes in solid waste disposal sites. Crit Rev Environ Sci Technol 2022;53:366–89.