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IDENTIFYING THE SOURCES OF GREENHOUSE GAS EMISSIONS RESULTING FROM THE BURNING OF MUNICIPAL SOLID WASTE IN SEOUL, SOUTH KOREA - A BENCHMARK STUDY

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ABSTRACT: In this study, the GHG emissions were calculated from 2000 to 2021 by focusing on the amount of disposal waste (or non-recyclables) in MSW treated by incineration in Seoul. The trend of GHG by incineration has continued to increase over time. The GHG emissions in 2021 were more than 7.3 times higher than those in 2000. The increase in GHG emissions is largely due to an increase in the amount of MSWI, especially plastic waste. Plastic waste consisted of 25% of MSWI, but the GHG emissions accounted for 92% of the total. For 2040, the amount of MSWI was 1676 tons/day, and GHG emissions were 389 kt CO2 eq/yr, all of which decreased by 53% compared to the BAU scenario. This might be attributed to reducing MSW generation and increasing recycling rates, resulting in reduced GHG emissions. Net GHG emissions from MSWI have been increasing since 2005, with an increase of 2.9 times in 2021 compared to 2005. All scenarios' net GHG emissions showed positive values, as the GHG emissions were greater than the GHG reductions. It is expected that GHG emissions in 2050 will be about 12.0 Tg CO2eq, which is 17% less than those in 2010.In order to reduce GHG emissions from MSWI, the first viable option is to reduce the MSW generation by households by implementing more strengthened measures (e.g., disposal fee increase, incentives for consumers to reuse). The second option is to establish material recovery facilities for resource recovery by diverting the waste from landfilling and incineration. During the recovery processes, plastic materials and other recyclable materials can be recovered for recycling. In the long term, GHG emissions could be reduced if CO2 from incineration is captured through CCUS (Carbon Capture Utilization and Storage) technology in the future, along with technical developments. It is expected that Seoul's MSWI will increase over the next few years. In particular, increased plastic consumption in households may be inevitable, resulting in an increase in GHG emissions by incineration if plastics are not reduced and recycled Thus, it is urgent for actions and measures to reduce the plastic waste in MSWI in Seoul by considering the adoption of a landfill ban policy by 2026. The results of this study can be used as climate change mitigation measures and responses for reducing GHG emissions from waste sectors in Seoul and other megacities in many countries. By utilizing the methane emission indicators prepared here and analyzing spatial correlations at a high resolution of 10 km, we found distinct differences in the sources of higher methane concentrations in terms of their distributions in South Korea: (1) fossil fuel use and landfill sites and (2) rice farming, and livestock areas with some regions with multiple emissions. Furthermore, the application of refined national statistical data in examining spatial correlations with satellite observations has been instrumental in identifying the causes of elevated methane concentrations in various areas. This approach holds significant potential to contribute to the enhancement of South Korea's official methane emission inventory, which currently does not have detailed spatial information, also addressing challenges that global methane inventories cannot resolve. Finally, the spatial correlation analysis with satellite data conducted in this study proves highly useful in understanding and validating national methane emission information. This is particularly beneficial in cases like Korea, where spatial information on methane emissions is limited or where there is a high likelihood of unidentified emission sources.

Key words: Greenhouse gas, emissions estimation, waste treatment, waste incineration, greenhouse gas, MSW, carbon dioxide

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INTRODUCTION

Incineration is one of the common methods of municipal solid waste (MSW) treatment **(IPCC, 2001)**. This treatment can reduce the volume of waste by up to 90%, which can help to solve the land-shortage problem caused by disposal. It also has the advantage of a significantly lower possibility of soil and water pollution than landfilling. It has been gaining popularity worldwide, as it can effectively recover energy from waste **(Pablo *et al*., 2020)**. However, various pollutants (e.g., SOx, NOx, heavy metals, and dioxins/furans) and greenhouse gases (GHGs) (e.g., CO_2 and N_2O) can be emitted into the atmosphere through MSW incineration processes **(IPCC, 2006)**. The emitted GHG capture infrared radiation and cause the steady heating of the earth, atmosphere, and surface, affecting global warming and climate change **(UNEP, 2022)**. Therefore, it is important to identify the major contributing factors of GHG emitted from incineration, and to reduce the amount of GHG emissions in response to climate change.

According to the guidelines published by the Intergovernmental Panel on Climate Change (IPCC), GHG emissions are usually to be estimated in various sectors such as energy, transportation, industry, residential and commercial buildings, agriculture and forestry, and waste sectors. Emission estimations by sector are specifically outlined in the IPCC guidelines with the consideration of emission characteristics and data availability in each sector. It is not unusual that the amount of GHG emissions from the waste sector is notably smaller than other sectors. It is noted that GHG emissions from the waste sector has contributed about 2.8% of the total global emissions from anthropogenic sources **(Chung *et al*., 2018)** and a similar trend may be observed in a national perspective. For example, the waste sector in Korea accounts for only 2.2% of national emissions in 2010, which is 14.5 Tg CO_2eq out of 669 Tg CO_2eq. Due to its highly linked with other sectors, the waste sector plays a significant role in national mitigation policies with further GHG reduction opportunities.

Methane (CH_4) is one of the six greenhouse gases (CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs) identified in the Kyoto Protocol, and is known to be responsible for about 30% of global warming **(IPCC, 2021)**. The global warming potential (GWP) of CH_4 is 84 times higher than CO_2, and it has a short residence time (about 10 years), meaning that reducing methane emissions can have a relatively instant impact on global change **(Bousquet *et al*., 2018 and Zhao *et al*., 2019)**. Therefore, the importance of accurate monitoring and reduction efforts is increasing **(IPCC, 2014; Skytt *et al*., 2020 and IPCC, 2021)**.

Methane is mainly emitted from natural sources (wetlands, inland water, termites, etc.) and anthropogenic sources (fossil fuel uses, agriculture, waste, etc.) **(IPCC, 2021)**. Atmospheric methane is mainly removed through chemical reactions with OH radicals in the atmosphere, but recent imbalances between emissions and removals may have caused an increase in methane concentrations **(Peng *et al*., 2022)**.

In Korea, the landfilling of MSW was a dominant method until 2004 (62%), after which both incineration and recycling rates gradually increased **(Korea MOE, 2023)**. The amounts of GHG emitted from incineration increased as the amount of treatment by incineration of MSW increased after 2010 (**Korea MOE, 2023**). Studies on GHG emissions by incineration in Korea have already been investigated by several authors. According to **Kang *et al*. (2019)**, as of 2016, the GHG emissions from the incinerated waste, including MSW in Gyeonggi-do, were predicted to be about 1397 kt CO_2 eq/yr based on the IPCC 2006 guideline. In Gyeonggi-do, about 12,070 tons/day (22% of Korea) of waste was generated in 2016, and 22.4% of the waste was treated by incineration. **Hwang *et al*. (2017)** revealed the GHG emissions and emission factors of nine incineration facilities in Korea. The total emissions from MSWI ranged from 3587 to 11,082 t CO_2 eq. **Kwon *et al*. (2018)** revealed the quantitative effect of reducing GHG emissions from the recycling and energy recovery of MSW in Daejeon Metropolitan City. **Park *et al*. (2011)** estimated the N_2O emission coefficient (from 71 to 153 g N_2O/t waste) of MSWI facilities and calculated the N_2O emissions (from 2.31 to 8.27 tons N_2O/yr). **Kim *et al*. (2016)** studied the calculation of GHG emissions from MSW incineration facilities in three scenarios based on the IPCC guideline, and calculated emissions according to generation characteristics. The GHG emissions based on the IPCC guideline ranged from 244.4 to 322.1 t CO_2 eq/day, while the emissions determined by the assay value method of the study were from 151.8 to 230.3 t CO_2 eq/day.

This study was carried out to determine the GHG emissions including methane from the incineration of MSW in Seoul between 2000 and 2021. Using TROPOMI XCH_4 satellite data from August 2018 to July 2019, the spatial distribution of methane concentrations was analyzed and high-concentration areas were identified, which can provide information for domestic greenhouse gas reduction policies. It also predicted the amount of MSW treated by incineration in Seoul by 2030 and 2040 using linear models and scenario analyses. Based on the predicted amounts of incineration, the characteristics of GHG emissions and the temporal trends of MSW treatment methods were examined. The main influencing factors for the GHG emissions were identified.

Esimated GHG Emissions from MSWI from 2000 to 2021

In Korea, the landfilling rate of MSW was relatively high before 1995, after which the rates of incineration and recycling gradually increased over the next three decades. GHG emissions from incineration consequently tended to increase due to the increased amounts of incineration after 2010 (**Korea MOE, 2023**). In Japan, the proportion of landfilling gradually decreased over the years. Much of the waste was combusted at incineration facilities, along with recycling. As of 2020, 79.5% of waste was disposed of by incineration, 19.6% by recycling, and 0.9% by landfilling (**Japan MOE, 2020**).

Fig. 1 shows the amounts and flows of MSW in Seoul in 2021 (**Korea MOE, 2023**). The total amount of MSW generated was 2899 kt/yr. In Korea, MSW is commonly divided into three major types (i.e., recyclables, food waste, and disposal waste or non-recyclables). Among Seoul's MSW in 2021, disposal waste or non-recyclables was the largest fraction (40%, 1163 kt/yr), followed by recyclables (31%, 901 kt/yr) and food waste (29%, 835 kt/yr). Recyclables (e.g., paper, plastic, metal cans, glass, *etc.*) and food waste were source-separated in all households and commercial areas by adopting pay-as-you-throw schemes Korea Ministry of Environment. Food waste, which has been banned from landfilling since 2005, was commonly treated through animal feed manufacturing, composting, and anaerobic digestion. Disposable waste in plastic bags or non-recyclable waste was typically treated at incineration facilities or disposed of in landfills. In 2021, the fraction of combustible waste accounted for 93% (1086 kt/yr) of the disposal waste, while other fractions included incombustible (69 kt/yr, 6%) and construction (8 kt/yr, 1%) waste. Mixed waste (399 kt/yr, 37%), paper waste (340 kt/yr, 31%), and plastic waste (248 kt/yr, 23%) were the larger fractions in combustible waste streams, while other small fractions included wood (45 kt/yr, 4%), food (26 kt/yr, 2%), textiles (22 kt/yr, 2%), and rubber (6 kt/yr, 1%). Most of the combustible waste was treated by incineration (741 kt/yr, 68%), followed by landfilling (305 kt/yr, 28%) and limited recycling (41 kt/yr, 4%).

Fig. 2 shows the GHG emissions from MSWI by waste component type from 2000 to 2021. In 2000, 74 kt CO_2 eq/yr was emitted into the atmosphere, after which the GHG emissions have been steadily increasing over time. In 2021, the GHG emissions were estimated to be about 545 kt CO_2 eq/yr, more than 7.3 times higher than those in 2000. It should be noted that the CO_2 emissions from biomass wastes (food, wood) were excluded from the calculation, as they are biogenic emissions. Thus, only CO_2 emissions from wastes (plastic, paper, textile, etc.) originating from fossil fuel sources were calculated. In addition, CH_4 and N_2O were calculated according to the Tier 1 emission factor values **(US EPA, 2023)**. According to Park's study (2022), the GHG emissions from four incineration facilities in Seoul were about 876 kt CO_2 eq/yr **(Park, 2022)**, which is higher than those of our study. The reason for the difference between the studies is likely due to the difference in the percentage of waste composition used to calculate GHG emissions. In Park's study, the combustible waste accounted for 86% of the average of the four incinerators. The paper accounted for 43% of the combustible waste, followed by plastics (20%), textiles (12%), food (10%), wood (5%), other (4.5%), and rubber (4.2%) **(Park, 2022)**.

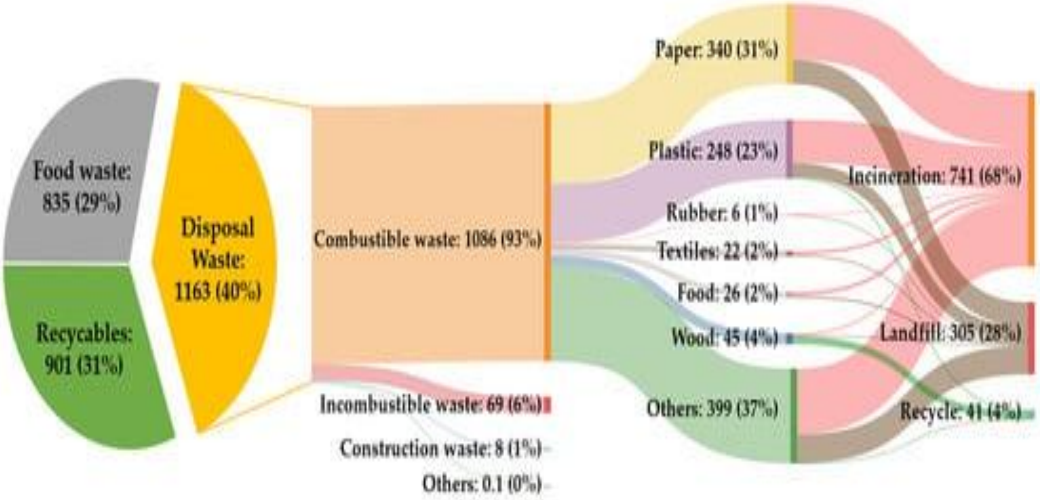

Fig. 1. Waste generation and flow of MSW in Seoul in 2021 (unit: kt/yr or %)

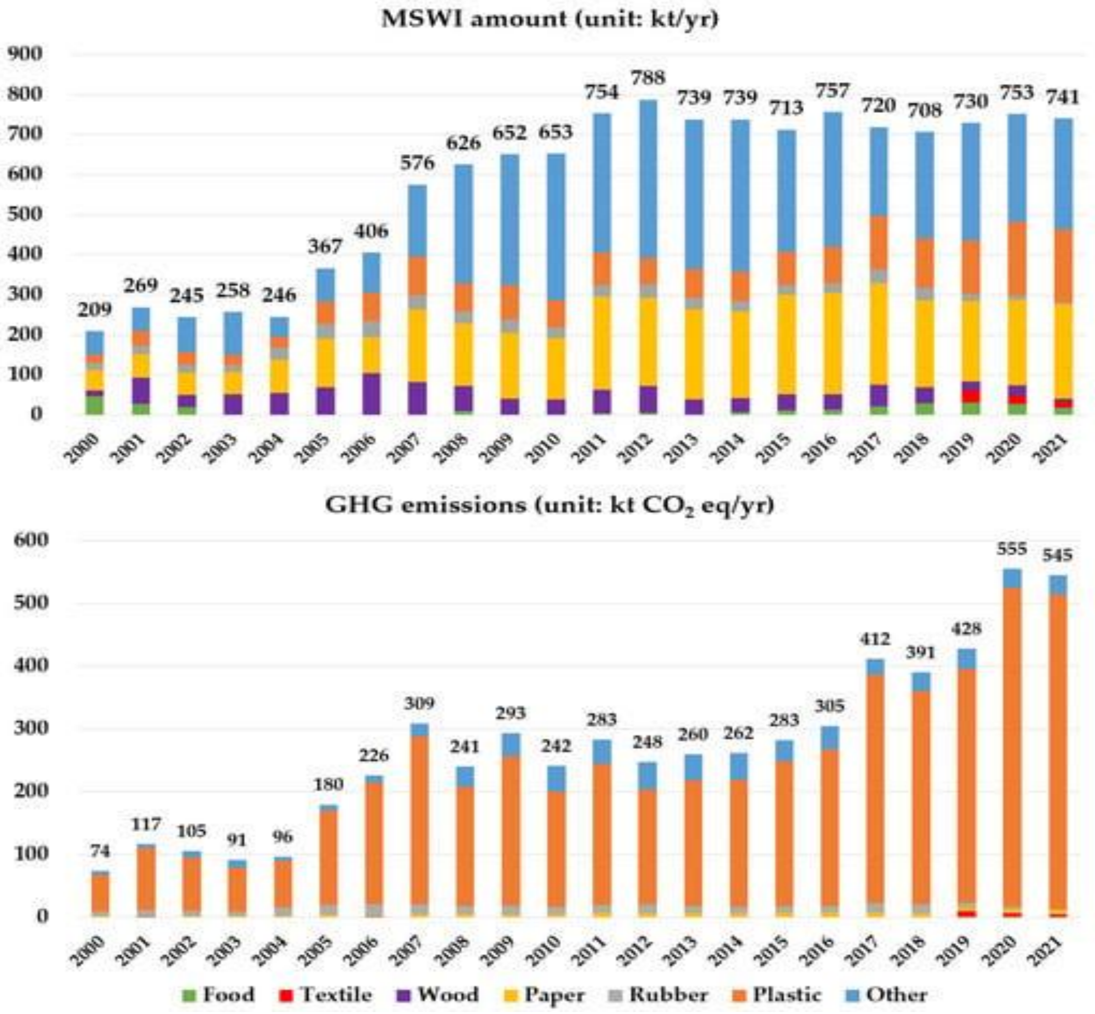

Fig. 2. Amounts of MSWI (above) and trends of GHG emissions (below) in Seoul between 2000 and 2021

The waste type that contributed the most to GHG emissions was plastic waste. Plastic waste treated by incineration has increased over the past two decades. It was 8.6 times higher, from 21 kt plastic waste/yr in 2000 to 182 kt plastic waste/yr in 2021. As plastic waste materials in MSWI increased, GHG emissions also significantly increased. The GHG (CO_2) emitted by the incineration of 1 ton of plastic waste was found to be 2.7 tons, indicating that the contribution to GHG emissions was greater than that of other waste **(IPCC, 2006)**. In particular, there was a sharp increase in GHG emissions in 2021 compared to 2019, likely due to increased amounts of plastic materials (a 34% increase from 2019). It is worth noting the significant contribution of plastic waste to GHG emissions. While the amount of plastic waste in 2021 was 182 kt/yr (25% of total MSWI), the resulting GHG emissions were 501 kt CO_2 eq/yr (92% of total GHG emissions). This corresponds to 2.8 times the GHG of the amount of plastic waste. Because plastics are made from fossil fuels, the increase in plastics has led to an increase in fossil carbon fractions, which contribute to GHG emissions from incineration during oxidation processes **(Liao *et al*., 2022)**.

According to the OECD report, global plastic in 2019 was produced at about 460 million metric tons (Mt), which doubled since 2000. During the same period, plastic waste was 353 Mt, which more than doubled. As plastic production and plastic waste increase globally, it is expected that the amount of GHG emissions will increase (Organization for Economic Co-Operation and Development **(OECD, 2022)**. Because the GHG emissions from incinerated paper and plastic wastes are higher than those of other waste types, there is a need for substantial efforts towards a reduction in such waste materials in MSWI. Material recovery processing (e.g., removal of paper and plastic) for waste disposal bags generated from households along with more strengthened source-separation regulations could be a viable option before incineration.

Emission Estimation for Waste Sector

IPCC (2006) provides overall procedures of emissions estimation for each waste treatment method. It should be noted that energy generated in the process of waste treatment (so called waste-to-energy, WTE) has not been included in this study as recommended by IPCC guidelines, which states that WTE may be analysed in the energy supply sector. Emissions from the Korean waste sector are estimated according to waste treatment method.

CH_4 Emissions from Landfill

Emissions estimation for landfilled wastes is one of the most difficult part because landfill gas (LFG) emissions of an inventory year are highly affected by the past activity data. There have been two available methods to estimate LFG emissions: mass balance model and FOD model. However, **IPCC Guideline (2006)** mandates the adoption of FOD model, and mandatory requirements for an effective application of FOD model include past data on the amount of landfill wastes and information on half-life of landfill wastes. Methane is the most dominant GHG from landfilled wastes. Even if a small amount of CO_2 may also be emitted, it is not included in this study as per IPCC Guidelines. It is mandatory to use disposal data for at least 50 years according to **IPCC Guidelines (2006)**. Considering realistic constraints and difficulties related to data collection, however, it is hardly achievable to collect disposal data for such a long period of time. Furthermore, **Kim *et al*. (2017)** indicates that an FOD model may be effectively employed even with waste disposal data for a shorter period of time. Since activity data after 1986 are only available for the waste sector in Korea, this study adopted alternate methods such as regression and extrapolation for emissions estimation from landfilled wastes.

CO_2 and N_2O Emissions from Incineration

A moderate amount of MSW and INW is treated by incineration from which CO_2 and N_2O are mostly emitted. **IPCC Good Practice Guidelines (2001)** notes that a negligible amount of methane may also be emitted from incineration but it can be excluded from the emissions estimation. Emission estimates for CO_2 and N_2O have been obtained by the equations given in **IPCC (2006)**.

CH_4 and N_2O Emissions from Wastewater

Wastewater can be a source of CH_4 and N_2O emissions. While CH_4 is mostly emitted when treated or disposed anaerobically, N_2O is emitted in the process of nitrogen removal in wastewater treatment. There are two different sources of methane emissions from wastewater, such as domestic and industry. Whereas methane emissions from industry wastewater may simply be obtained by multiplying the amount of industry wastewater by corresponding emission factor, those from domestic wastewater are estimated separately depending on whether treated or untreated. N_2O emissions from wastewater treatment are estimated with the consideration of the amount of per capita protein intake, the percentage of nitrogen in protein, and the emission factor of nitrous oxide.

CH_4 and N_2O Emissions from Biological Treatment

Biological treatment of wastes includes composting and anaerobic digestion, which can be a source of CH_4 and N_2O emissions. The amount of biologically treated wastes is relatively small, and emissions from this source can simply be derived by multiplying the total amount of biologically treated wastes by corresponding emission factor.

As discussed earlier, a variety of activity data and parameters need to be gathered for each treatment method and it is highly desirable to secure country-specific values to improve the accuracy of emission estimation. If unavailable, however, default values prescribed by **IPCC (2006)** may be adopted. Table 1 summarizes activity data and corresponding parameters used in this study for each treatment method.

Predicted Net GHG Emissions from MSWI from 2005 to 2040

To calculate and predict the net GHG emissions from MSWI, operational data of the four incineration plant facilities in Seoul in 2022 were analyzed and are presented in Table 2 **(Seoul Metropolitan Government, 2023)**. All four incinerators were operated by continuous stoker-type methods with an average 80% operation rate in 2022. The total capacity of the four incinerators (Gangnam, Nowon, Mapo, and Yangcheon) currently operated by the Seoul Metropolitan Government was 2850 tons/day. The Mapo and Yangcheon facilities employ steam turbines to generate electricity. The Gangnam and Nowon facilities do not have their own steam turbines, but the neighboring cogeneration plants do. The total electricity produced by the facilities was only 14.6% of the total electricity consumed by the four sites. There have been global efforts to develop and apply technology to recover energy generated by the incineration of waste. Denmark had already implemented a policy to recover waste incineration energy 100 years ago (Heron and Søren, 2023). Materials that were able to be incinerated were prohibited from landfills, and waste-to-energy facilities are actively operated. According to the EU circular economy action plan, the landfilling of waste that could be recycled or recovered energy will be restricted after 2030. It also limits the landfilling of municipal solid waste to 10% after 2035 **(European Commission, 2023)**.

Fig. 3 shows the net GHG emissions from MSWI between 2005 and 2021. GHG reduction can occur through waste heat recovery and electricity generation, by subtracting GHG emissions from incineration, LNG, and electricity (consumed). From 2005 to 2021, the observed and predicted GHG emissions from MSWI were higher than the GHG reductions. Thus, all net GHG emissions showed positive values. Net GHG emissions increased by about 2.9 times, from about 174 kt CO_2 eq/yr in 2005 to about 499 kt CO_2 eq/yr in 2021. Since 2005, net GHG emissions have shown an increasing trend. Especially, it was found that they increased rapidly between 2019 and 2020. This was estimated to be due to an increase in GHG emissions from incineration in 2020. The generation of plastic and paper wastes, which had a significant impact on GHG emissions, increased 1.36 times and 1.06 times, respectively. In addition, wood was also estimated to increase 1.13 times, increasing the GHG emissions.

The net GHG emissions between 2022 and 2040 by scenario analysis were calculated using the difference between the annual MSWI GHG emissions and reductions (Fig. 4). The net GHG emissions for all scenarios were positive values because the GHG emissions were greater than the reductions. For the BAU scenario, the predicted emissions were found to be 621 kt CO_2 eq/yr in 2030 and 753 kt CO_2 eq/yr in 2040. Scenario 1 showed lower GHG emissions (541 kt CO_2 eq/yr in 2030 and 623 kt CO_2 eq/yr in

Table 1. Summary of activity data and parameters for calculating waste GHG

Treatment	Activity data	Parameters
Landfill	Amount of landfilled wastes by composition Amount of methane recovery	Rate constant of biodegradation
		CH_4 correction factor
		Fraction of degradable organic carbon
		CH_4 fraction in generated landfill gas
		Oxidation rate
Incineration	Amount of incinerated wastes by composition	Fraction of carbon content
		Fossil carbon fraction
		Efficiency factor
Wastewater	Amount of industry wastewater	Emission factor
	Amount of treated domestic wastewater	Concentration of biochemical oxygen demand CH_4 emission factor
		Removal rate
		CH_4 recovery rate
	Amount of sewage	N_2O emission factor
		Percentage of nitrogen in protein
		Amount of per capita protein intake
	Amount of untreated domestic wastewater	Concentration of biochemical oxygen demand CH_4 emission factor
Biological treatment	Amount of biologically treated waste	CH_4 emission factor
		N_2O emission factor

Table 2. Operational results of four MSW incineration facilities in Seoul in 2022

Category	Incineration Status			Energy Sales		Energy Consumption	
	Daily Input Amounts (Tons/Day)	**Daily Incinerated Amounts (Tons/Day)**	**Operation Rate * (%)**	**Waste Heat (Gcal)**	**Electricity (Generated) (kWh)**	**LNG (Nm^3)**	**Electricity (Consumed) (kWh)**
Gangnam	888	793	88	442,989	0	333,830	26,491,356
Nowon	591	551	69	247,936	0	234,133	16,629,469
Mapo	629	589	78	795,452	7,878,847	263,414	18,957,875
Yangcheon	406	341	85	171,365	2,479,464	664,489	8,733,110
Total	2514	2274	80 (average)	1,157,742	10,358,311	1,495,866	70,811,810

* Operation rate = average daily incinerate amount (tons/day) ÷ incineration capacity (ton/day) × 100 (%).

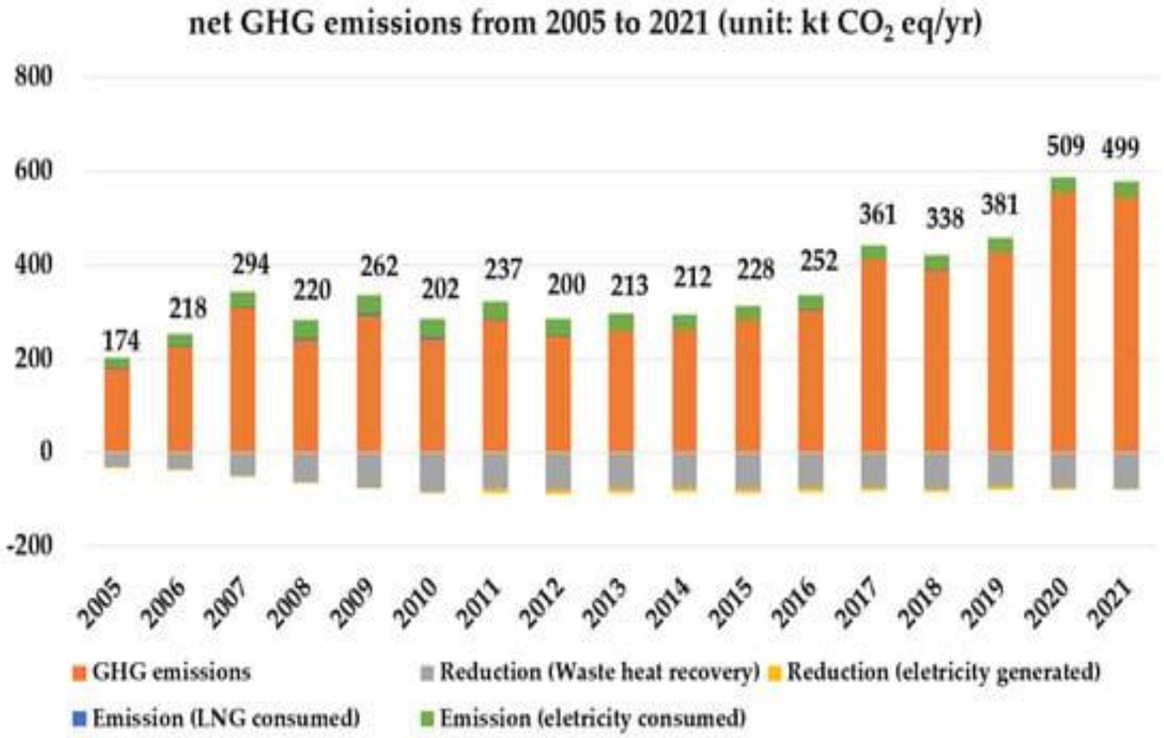

Fig. 3. **Net GHG emission trends from MSWI in Seoul between 2005 and 2021**

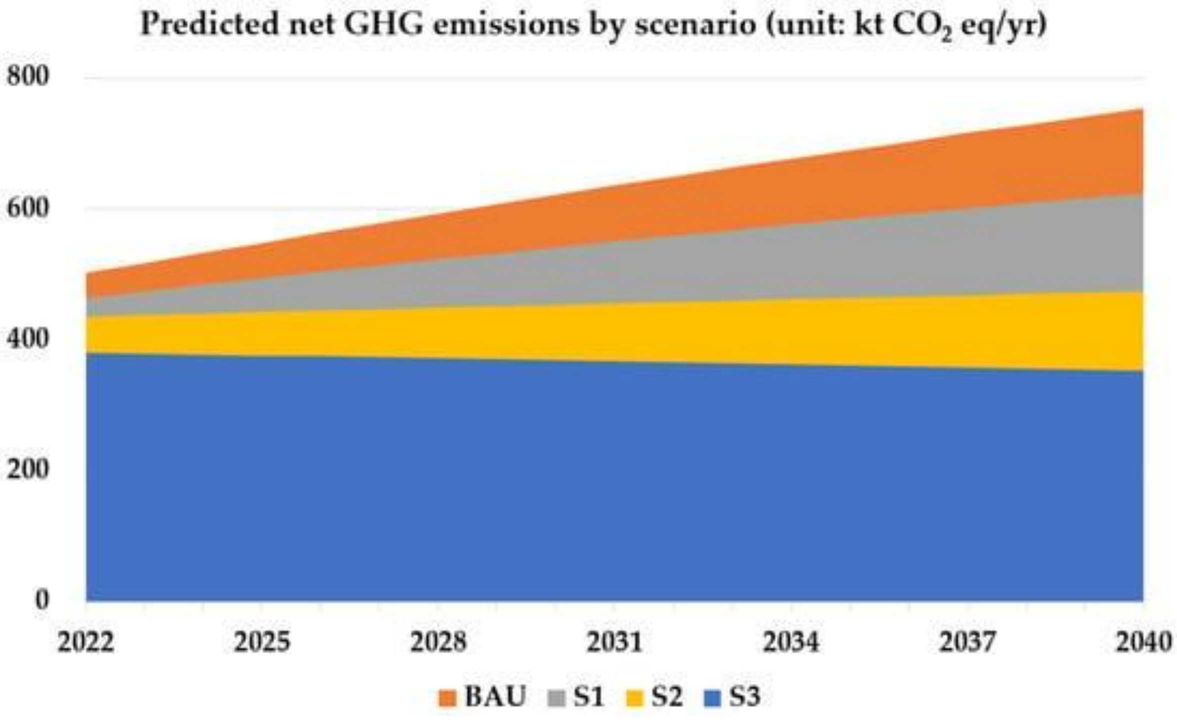

Fig. 4. **Predicted net GHG emissions from MSWI by scenario analysis**

2040) than those of the BAU scenario. The GHG emissions tended to increase 1.25 times for 2040, compared to 2021. Scenario 2 showed a slight increase in emissions to 452 kt CO_2 eq/yr in 2030 and 474 kt CO_2 eq/yr in 2040. There was about a 5% decrease in emissions for 2040 compared to 2021. The net GHG emissions in Scenario 3 showed a decreasing trend to 369 kt CO_2 eq/yr in 2030 and 353 kt CO_2 eq/yr in 2040. Compared to 2021, the GHG emissions for 2040 decreased by 29%. Reducing the generation of MSWI can have a significant impact on GHG emission reduction. According to **Park (2022)**, if 70% of the plastic waste entering the incineration facility is separated, then annual GHG emissions can be reduced by 26%.

Wang and Nakakubo (2020) calculated the net GHG emissions of incinerating waste in a fluidized-bed incinerator under two different scenarios. According to the study, the net GHG emissions of incinerating the waste were 416 kt CO_2 eq/yr without further treatment. After screening and separating the non-combustible waste, the energy efficiency of the fluidized-bed incinerator was improved. This resulted in net GHG emissions of 277 kt CO_2 eq/yr, which was 66.6% less than the net GHG emissions without separation. Fluidized-bed incinerators are known to show better thermal efficiency than stoker incinerators by promoting uniform mixing and heat transfer **(Vukovic and Makogon, 2022)**. Due to these features, GHG emissions from fluidized-bed incinerators are estimated to be less than those from stoker incinerators. According to a study by Kristanto *et al.* (2019), the net GHG emissions from MSWI in Depok, Indonesia, were found to be 83~86 kt CO_2 eq/yr. The MSW in Depok, Indonesia, was mostly food waste, which accounted for 73% of the total. This was followed by paper (7%) and plastic (4%). Despite using the same stoker-type incinerator as those in Seoul, the different components of the waste resulted in lower net GHG emissions. The present study in Korea showed higher fractions of paper and plastics (around 56.4% of the total waste), resulting in high contributions of GHG emissions. This implies that even with the same type of incinerator, different compositions of waste materials can have a significant impact on GHG emissions.

Spatial Correlation between XCH_4 and National Emissions

To examine the characteristics of high-concentration areas, we classified South Korea into eight regions (Fig. 5b) by local administrative districts. The high concentration in the southern parts of region I showed positive correlations with three emissions: rice paddy, livestock, and fossil fuels, with rice paddy appearing to have higher correlations($r = 0.7$) **(Moon *et al.*, 2024)**. Region II was excluded from the analysis because sufficient observation data was not available and relatively lower XCH_4 (mountainous region).

Spatial correlations with rice paddy

Among the four emissions, the rice paddy showed generally higher spatial correlation with methane concentration, indicating positive correlations in the five high-concentration areas with large paddy fields (Fig. 5c). The southern parts of region I showed a high correlation, as it included many areas with large paddy field areas, including the 11th (Hwaseong-si, 32, $r = 0.70$) and 13th (Pyeongtaek-si, 15) largest rice paddy fields in the country, as well as other areas with large paddy fields (29, 36, etc.).

Northwestern region III also showed positive correlations as it included areas with the largest and third-largest paddy fields in the country. The area with the highest correlation ($r = 0.54$) was located in the northeast region III (Cheonan-si, 69), which also showed correlations with other sectors such as livestock and fossil fuels.

In the northwest region V, high correlations were observed in areas with active rice farming (Sangju-si, 127). In the western region (VI), large agricultural land areas also showed high positive correlations, with the highest correlation ($r = 0.51$) observed in the Jeonju-si (84). In Region VII, high correlations were observed due to the influence of large rice paddy fields in the south, with the highest correlation ($r = 0.75$) observed in the southernmost region Wando-gun (117).

Spatial correlations with livestock

The correlation analysis between XCH_4 and the livestock sector showed a similar spatial distribution to those of the rice paddy sector, and positive correlations were observed with some high-concentration areas (Fig. 5d). In the southern

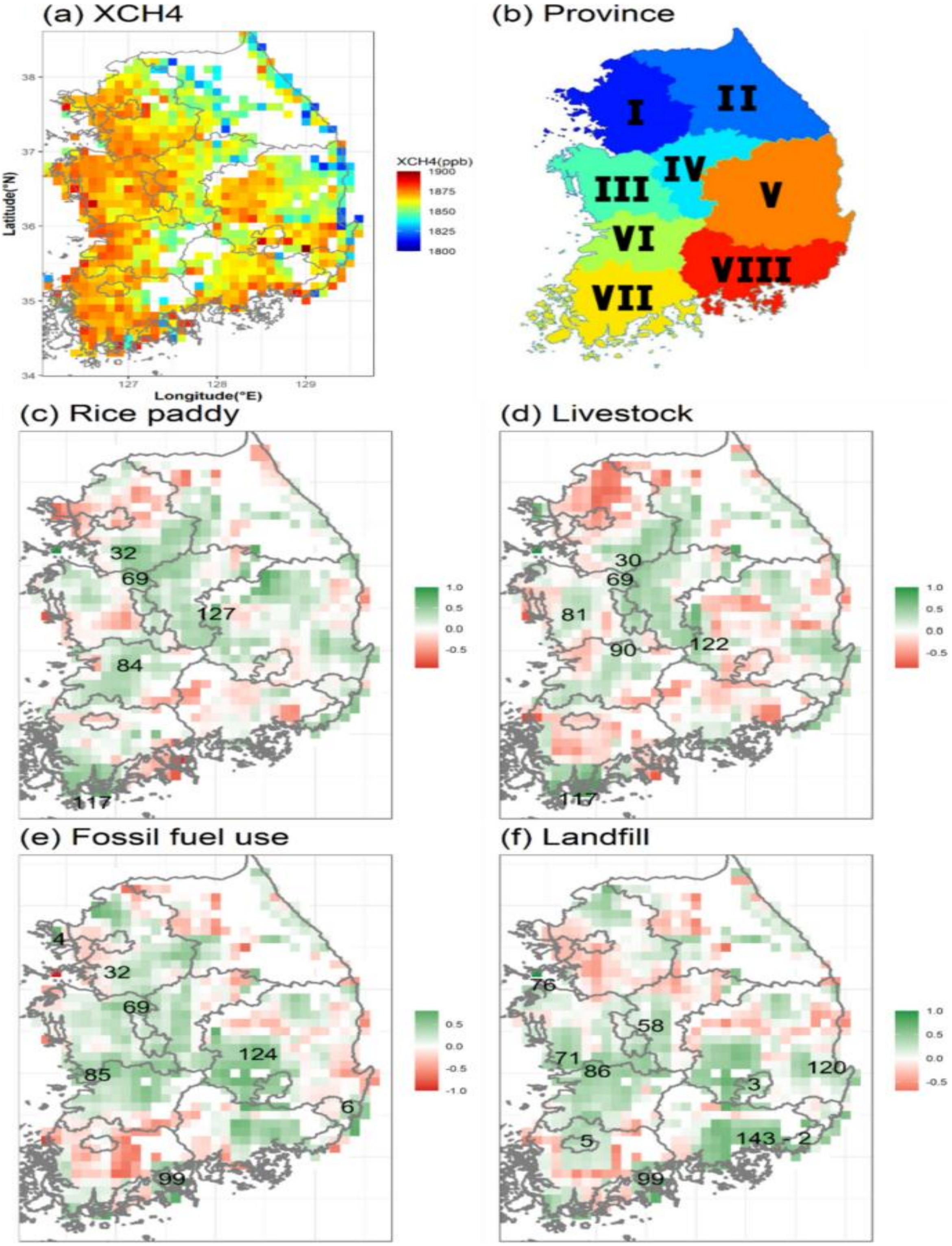

Fig. 5. **a The distributions of annual average concentrations of XCH_4 (August 2019–July 2020) in South Korea. b The locations and numbers of 8 provinces in South Korea. c The spatial correlation between XCH_4 and rice paddy, d the same with livestock industries, e same with fossil fuel uses, and f the same with landfills.**

Source : Moon *et al.* (2024).

parts of Region I, a high correlation was observed in the Anseong-si (30) (r = 0.55), which has the second highest number of livestock households and ammonia emissions from manures in the country, and adjacent area Icheon-si (29) has the 4th highest ammonia emissions.

In central Region III, a positive correlation was observed near Yesan-gun (82) (r=0.36) and the adjacent region Hongseong-gun (81), where has the highest ammonia emissions and the fifth highest number of livestock farms in the country.

In Region IV, a positive correlation was observed due to the influence of methane emissions from Cheonan-si (69) (r=0.55), which has many livestock farms. The higher correlations were observed in Gimcheon-si (122) in region V, Wanju-gun (90) in region VI, and Wando-gun (117) (r = 0.89) in region VII, where the region's main industry includes livestock and rice farming. Table S-4 summarizes the correlation coefficients between the livestock fields and methane concentrations.

Spatial correlations with fossil fuel use (oil and gas)

The spatial correlation analysis between fossil fuel consumption and XCH_4 showed different spatial characteristics from rice paddies and livestock fields, and positive correlations were observed in some parts of high-concentration areas (Fig. 5e).

In Region I, higher correlations were found in the northern region with high energy consumption in Paju-si (28) and in the central-western region with high energy consumption in the transportation sector in Namyangju-si (21) (r = 0.71). In the southern part of Region I, positive correlations were observed in the vicinity of Hwaseong-si (32) and adjacent Pyeongtaek-si (15) (r = 0.50), where there is a high energy use in transportation.

High correlations were also observed in the northern part of Region III, including Cheonan-si (69) with higher vehicular traffic volume, and Cheongju-si (98) nearby (r = 0.57). In the southwest part of region V, positive correlations seem to be influenced by the large city (Daegu, 3) (r = 0.64) and adjacent Gumi-si (124), where industrial complexes are located.

In the northwest part of region VI, Gunsan-si (85) showed a higher positive correlation due to the higher energy consumption of shipping operations in Gunsan harbor (r = 0.63). A high correlation was also observed in the Yeosu-si (99) (r = 0.77), where the largest petrochemical complex in Korea is located, and in the eastern part of region VIII, a clear positive correlation was observed in the Ulsan-si (6) (r = 0.77) where industrial complexes including steelmaking and chemical plants are located.

Spatial correlations with landfills (wastes)

The spatial correlations of landfills with XCH_4 showed a distribution similar to that of fossil fuel use, and higher positive correlations were observed in some of the hot spots (Fig. 5f). In the northwestern part of region III, the higher correlation was observed near the area Dangjin-si (76) (r = 0.50) where self-landfill sites for large power generation facilities are located, and in Cheongju-si (58) in region IV, where an industrial complex is located with a large amount of landfill, showing positive correlations (r = 0.48).

In the southwestern part of region III and northwestern part of region VI, high correlations were observed near areas Boryeong-si (71) and Gunsan-si (85), where large-scale national coal-fired power plants are located (r = 0.50, 0.62, respectively).

In Yeosu-si (99), particularly higher correlations (r = 0.77) were shown due to the influence of 12 landfill sites located near industrial complexes. In the southern part of region VIII, higher positive correlations were observed in Changwon-si (143) and Pohang-si (120) in the eastern region (r = 0.53, 0.66, respectively), where local government landfill facilities, industrial complexes' landfill sites, and final waste treatment facilities all exist, and also in Busan (2), the largest city in the southeastern Korea where local government landfill facilities and final waste treatment facilities are located.

Overall Summary of the Spatial Correlations Over Higher XCH_4: Source Identification of CH_4 hot Spots in South Korea

In order to examine the main sources of higher methane concentrations in Korea, a spatial correlation analysis was performed using TROPOMI XCH_4 data and methane emissions data from four sectors (rice paddy, livestock industry, fossil fuel use, and waste landfill). To summarize the results, Fig. 4 shows the higher methane concentrations with the descriptions of their contributing sources below.

In the capital city of Seoul (region I in Fig. 5b), there were no clear correlations between any of the four emissions. In contrast, the southern part of region I (Hwaseong-si, 32) showed higher concentrations of methane due to the complex effect of rice paddy, livestock, and fossil fuel with the strongest correlation (r = 0.70) found in rice paddies. Area 32 and its surrounding areas are characterized by high amounts of both rice cultivation (12,156 ha) and fossil fuel use in industrial complexes (14,8 92 kg/year), indicating that the higher methane concentrations were caused by a combination of effects from the multiple emissions.

Dangjin-si (76) has the largest industrial complex in Korea and also the largest rice cultivation area (19,120 ha), and also includes a self-disposal facility for thermal power plants. Therefore, it is believed that the higher methane concentrations in this area were caused by emissions from rice paddy and landfills. Boryeong-si (71) showed a weak correlation with fossil fuels and the highest correlation with landfills. Higher XCH_4 in Boryeong-si is explained possibly due to the waste disposal and power generation facility.

The inland area of Cheonan-si (69) showed positive correlations with all four emissions.

Gunsan-si (85), which is a port area, showed positive correlations with two emissions: fossil fuel use and landfills. This area has a large amount of fossil fuel usage (8453 kg/year) related to port facilities and energy transportation, and landfill facilities to handle waste generated in national industrial complexes, which contributes to higher methane concentrations.

Gimje-si (89), which has a large cultivated land area, showed positive correlations with all four emissions, but the large rice cultivation area (15,981 ha) appeared to contribute the most to higher methane concentrations.

Gumi-si (124) in the eastern inland and the Daegu (3) showed higher correlations with two emissions: fossil fuel use and landfills. As many industrial complexes are located, it has a large amount of fossil fuel usage (9242 kg/year, 5041 kg/year, respectively) and a large amount of landfill (387,445 kg/year, 30,056 kg/year, respectively) for waste generated in industrial complexes, which is related to higher methane concentrations.

Pohang-si (120) on the southeast coast showed positive correlations in three emissions: rice paddy, livestock industry, and landfills. The positive correlations between rice paddy and the livestock industry are estimated to be influenced by the neighboring Gyeongju-si (121), while the positive correlation in the landfill area is likely due to a large amount of landfill (421, 097 kg/year) from landfill facilities that handle waste from the largest domestic steel industrial complex in the region. Unlike other industrial complexes, the correlation due to fossil fuel use was lower, which is likely due to the characteristics of the steel industry that uses coal as its main energy source, which was not included in this study.

Ulsan (6), an industrial complex near the coast, showed positive correlations with all four emissions, and in particular, the amount of fossil fuel usage (117,570 kg/year) used in the petrochemical complex appeared to contribute the most to high methane concentrations.

Changwon-si (143), including a southern industrial complex, showed positive correlations in fossil fuel use and landfills. It is estimated that a large amount of fossil fuel usage (15,160 kg/year) and the landfill (216,691 kg/year) generated by the large industrial complex contribute to high methane concentrations, and it is also adjacent to the Busan (2), which is home to the largest port in the country and can also contribute the high XCH_4.Yeosu-si (99), the largest petrochemical complex in Korea, showed positive correlations with fossil fuel use and landfills. The fossil fuel usage (131,844 kg/year) and landfill amount (569,095 kg/year) generated from the petrochemical complex can contribute to the higher methane. The southwest region (Haenam-gun, 111) showed positive correlations with all four emissions, especially in the rice paddies and livestock industry. The III region is known to have the second largest cultivating area (18,467 ha) in Korea. Additionally, it is explained that the higher XCH4 can be influenced by the nearby areas with extensive tidelands (VII area, where 42.5% of Korea's tidelands are located **(KOSIS, 2018)**.

Conclusions

The GHG emissions were calculated in this study, they calculated the GHG emissions from 2000 to 2021 by focusing on the amount of disposal waste (or non-recyclables) in MSW treated by incineration in Seoul. The trend of GHG by incineration has continued to increase over time. The GHG emissions in 2021 were more than 7.3 times higher than those in 2000. The increase in GHG emissions is largely due to an increase in the amount of MSWI, especially plastic waste. Plastic waste consisted of 25% of MSWI, but the GHG emissions accounted for 92% of the total. For 2040, the amount of MSWI was 1676 tons/day, and GHG emissions were 389 kt CO_2 eq/yr, all of which decreased by 53% compared to the BAU scenario. This might be attributed to reducing MSW generation and increasing recycling rates, resulting in reduced GHG emissions. Net GHG emissions from MSWI have been increasing since 2005, with an increase of 2.9 times in 2021 compared to 2005. All scenarios' net GHG emissions showed positive values, as the GHG emissions were greater than the GHG reductions.

It is expected that GHG emissions in 2050 are about 12.0 Tg CO_2eq, which is 17% less than those in 2010.In order to reduce GHG emissions from MSWI, the first viable option is to reduce the MSW generation by households by implementing more strengthened measures (e.g., disposal fee increase, incentives for consumers to reuse). The second option is to establish material recovery facilities for resource recovery by diverting the waste from landfilling and incineration. During the recovery processes, plastic materials and other recyclable materials can be recovered for recycling. In the long term, GHG emissions could be reduced if CO_2 from incineration is captured through CCUS (Carbon Capture Utilization and Storage) technology in the future, along with technical developments.

It is expected that Seoul's MSWI will increase over the next few years. In particular, increased plastic consumption in households may be inevitable, resulting in an increase in GHG emissions by incineration if plastics are not reduced and recycled Thus, it is urgent for actions and measures to reduce the plastic waste in MSWI in Seoul by considering the adoption of a landfill ban policy by 2026. The results of this study can be used as climate change mitigation measures and responses for reducing GHG emissions from waste sectors in Seoul and other megacities in many countries.

By utilizing the methane emission indicators prepared here and analyzing spatial correlations at a high resolution of 10 km, we found distinct differences in the sources of higher methane concentrations in terms of their distributions in South Korea: (1) fossil fuel use and landfill sites and (2) rice farming, and livestock areas with some regions with multiple emissions. Furthermore, the application of refined national statistical data in examining spatial correlations with satellite observations has been instrumental in identifying the causes of elevated methane concentrations in various areas. This approach holds significant potential to contribute to the enhancement of South Korea's official methane emission inventory, which currently does not have detailed spatial information, also addressing challenges that global methane inventories cannot resolve.

Finally, the spatial correlation analysis with satellite data conducted in this study proves highly useful in understanding and validating national methane emission information. This is particularly beneficial in cases like Korea, where spatial information on methane emissions is limited or where there is a high likelihood of unidentified emission sources.

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تحديد مصادر انبعاثات الغازات الدفيئة الناتجة عن حرق النفايات الصلبة البلدية في سيول، كوريا الجنوبية – دراسة مرجعية

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في هذه الدراسة، تم حساب انبعاثات الغازات الدفيئة من عام 2000 إلى عام 2021 من خلال التركيز على كمية نفايات التخلص منها (أو غير القابلة لإعادة التدوير) في النفايات البلدية الصلبة المعالجة عن طريق الحرق في سيول. استمر اتجاه غازات الدفيئة عن طريق الحرق في الزيادة مع مرور الوقت. كانت انبعاثات الغازات الدفيئة في عام 2021 أعلى بأكثر من 7.3 مرة مما كانت عليه في عام 2000. وترجع الزيادة في انبعاثات الغازات الدفيئة إلى حد كبير إلى زيادة كميةMSWI ، وخاصة النفايات البلاستيكية. وتتكون النفايات البلاستيكية من 25% منMSWI ، لكن انبعاثات الغازات الدفيئة تمثل 92% من الإجمالي. بالنسبة لعام 2040، بلغت كمية MSWI 1676 طنًا في اليوم، وبلغت انبعاثات الغازات الدفيئة 389 كيلو طن من مكافئ ثاني أكسيد الكربون سنويًا، وانخفضت جميعها بنسبة 53% مقارنة بسيناريو العمل المعتاد. وقد يعزى ذلك إلى تقليل توليد النفايات البلدية الصلبة وزيادة معدلات إعادة التدوير، مما يؤدي إلى تقليل انبعاثات الغازات الدفيئة. يتزايد صافي انبعاثات الغازات الدفيئة من MSWI منذ عام 2005، مع زيادة قدرها 2.9 مرة في عام 2021 مقارنة بعام 2005. وأظهرت صافي انبعاثات الغازات الدفيئة لجميع السيناريوهات قيمًا إيجابية، حيث كانت انبعاثات الغازات الدفيئة أكبر من تخفيضات الغازات الدفيئة. من المتوقع أن تبلغ انبعاثات غازات الدفيئة في عام 2050 حوالي 12.0 تيرا جرام من مكافئ ثاني أكسيد الكربون، وهو أقل بنسبة 17% عن تلك الموجودة في عام 2010. ومن أجل تقليل انبعاثات غازات الدفيئة منMSWI ، فإن الخيار الأول القابل للتطبيق هو تقليل توليد النفايات البلدية الصلبة بواسطة الأسر من خلال تنفيذ المزيد من التدابير المعززة (على سبيل المثال، زيادة رسوم التخلص، وحوافز للمستهلكين لإعادة الاستخدام). والخيار الثاني هو إنشاء مرافق لاستعادة المواد من أجل استعادة الموارد عن طريق تحويل النفايات من مدافن النفايات والحرق. خلال عمليات الاسترداد، يمكن استعادة المواد البلاستيكية وغيرها من المواد القابلة لإعادة التدوير لإعادة تدويرها. وفي الأمد البعيد، من الممكن خفض انبعاثات الغازات الدفيئة إذا تم احتجاز ثاني أكسيد الكربون الناتج عن حرق الكربون من خلال تكنولوجيا احتجاز الكربون واستخدامه وتخزينه في المستقبل، إلى جانب التطورات التقنية. ومن المتوقع أن يرتفع مؤشر MSWI في سيول خلال السنوات القليلة المقبلة. على وجه الخصوص، قد يكون زيادة استهلاك البلاستيك في المنازل أمرًا لا مفر منه، مما يؤدي إلى زيادة في انبعاثات غازات الدفيئة عن طريق الحرق إذا لم يتم تقليل المواد البلاستيكية وإعادة تدويرها. وبالتالي، فمن الملح اتخاذ إجراءات وتدابير للحد من النفايات البلاستيكية في MSWI في سيول من خلال النظر في اعتماد لسياسة حظر مدافن النفايات بحلول عام 2026. ويمكن استخدام نتائج هذه الدراسة كتدابير للتخفيف من تغير المناخ واستجابات للحد من انبعاثات غازات الدفيئة من قطاعات النفايات في سيول والمدن الكبرى الأخرى في العديد من البلدان. من خلال استخدام مؤشرات انبعاث الميثان المعدة هنا وتحليل الارتباطات المكانية بدقة عالية تبلغ 10 كم، وجدنا اختلافات واضحة في مصادر تركيزات الميثان الأعلى من حيث توزيعها في كوريا الجنوبية: (1) استخدام الوقود الأحفوري ومواقع دفن النفايات و (2) زراعة الأرز، ومناطق تربية الماشية مع وجود بعض المناطق ذات انبعاثات متعددة. علاوة على ذلك، فإن تطبيق البيانات الإحصائية الوطنية المنقحة في دراسة الارتباطات المكانية مع عمليات الرصد عبر الأقمار الصناعية كان له دور فعال في تحديد أسباب ارتفاع تركيزات الميثان في مناطق مختلفة. وينطوي هذا النهج على إمكانات كبيرة للمساهمة في تعزيز المخزون الرسمي لانبعاثات الميثان في كوريا الجنوبية، والذي لا يحتوي حاليا على معلومات مكانية مفصلة، كما يعالج التحديات التي لا تستطيع قوائم الجرد العالمية للميثان حلها. أخيرًا، أثبت تحليل الارتباط المكاني مع بيانات الأقمار الصناعية الذي تم إجراؤه في هذه الدراسة أنه مفيد للغاية في فهم المعلومات الوطنية لانبعاثات الميثان والتحقق من صحتها. وهذا مفيد بشكل خاص في حالات مثل كوريا، حيث تكون المعلومات المكانية حول انبعاثات غاز الميثان محدودة أو حيث يكون هناك احتمال كبير بوجود مصادر انبعاثات غير محددة .

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