7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1 and Figure 7-2). Landfills accounted for approximately 16.9 percent of total U.S. anthropogenic methane (CH_4) emissions in 2021, the third largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and discharge, composting of organic waste, and anaerobic digestion at biogas facilities accounted for approximately 2.9 percent, 0.4 percent, and less than 0.1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions resulted from the discharge of wastewater treatment effluents into aquatic environments were estimated, the wastewater treatment process itself, and composting. Together, these waste activities account for 5.9 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2. Overall, in 2021, waste activities generated emissions of 169.2 MMT CO_2 Eq., or 2.7 percent of total U.S. greenhouse gas emissions.

Emissions from landfills contributed 72.5 percent of waste sector emissions in 2021 and are primarily comprised of CH_4 emissions from municipal solid waste landfills (see Figure 7-1). Landfill emissions decreased by 2.2 MMT CO_2 Eq. (1.7 percent) since 2020. Emissions from wastewater treatment were the second largest source of waste-related emissions in 2021, accounting for 24.8 percent of sector emissions. The remaining two sources of emissions, composting and anaerobic digestion at biogas facilities, account for 2.6 percent and 0.1 percent of waste sector emissions in 2021, respectively.

Figure 7-1: 2021 Waste Sector Greenhouse Gas Sources

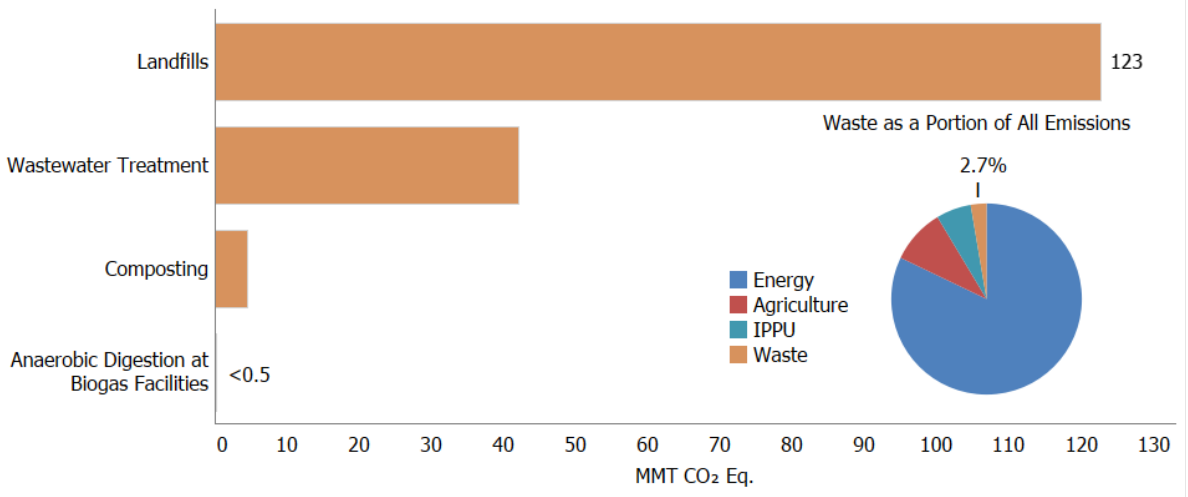


Figure 7-2: Trends in Waste Sector Greenhouse Gas Sources

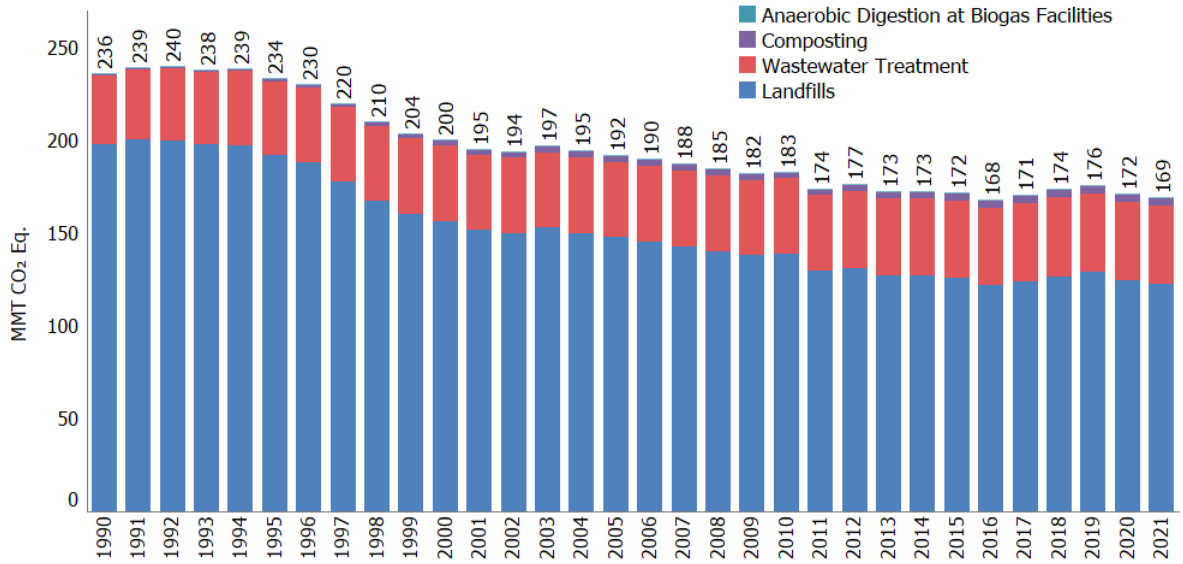


Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2017	2018	2019	2020	2021
CH_4	**220.9**	**172.5**	**148.3**	**150.8**	**152.9**	**148.8**	**146.4**
Landfills	197.8	147.7	123.9	126.7	129.0	124.8	122.6
Wastewater Treatment	22.7	22.7	21.5	21.4	21.2	21.3	21.1
Composting	0.4	2.1	2.7	2.5	2.5	2.6	2.6
Anaerobic Digestion at Biogas Facilities	+	+	0.2	0.2	0.2	0.2	0.2
N_2O	**15.1**	**19.5**	**22.6**	**22.9**	**23.1**	**22.7**	**22.7**
Wastewater Treatment	14.8	18.1	20.6	21.2	21.3	20.9	20.9
Composting	0.3	1.5	1.9	1.8	1.8	1.8	1.8
Total	**236.0**	**192.1**	**170.9**	**173.7**	**176.0**	**171.5**	**169.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2017	2018	2019	2020	2021
CH_4	**7,889**	**6,161**	**5,297**	**5,384**	**5,460**	**5,315**	**5,230**
Landfills	7,063	5,275	4,424	4,525	4,607	4,456	4,379
Wastewater Treatment	811	809	770	763	755	761	753
Composting	15	75	98	90	91	92	92
Anaerobic Digestion at Biogas Facilities	1	2	6	6	6	6	6
N_2O	**57**	**74**	**85**	**87**	**87**	**86**	**86**
Wastewater Treatment	56	68	78	80	80	79	79
Composting	1	6	7	7	7	7	7

Note: Totals by gas may not sum due to independent rounding.

Carbon dioxide (CO_2), CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2021 resulted in 12.8 MMT CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.5. Greenhouse gas precursor emissions from the waste sector are presented in Section 7.6.

Each year, some emission and sink estimates in the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2020) to ensure that the trend is accurate. For the current Inventory, minor improvements were implemented beyond routine activity data updates, including revising the industrial food waste disposal factor for estimating emissions from industrial landfills. In total, the methodological and historic data improvements made to the Waste sector in this Inventory resulted in an average increase in greenhouse gas emissions across the time series by 0.7 MMT CO_2 Eq. (0.4 percent). In addition, estimates of CO_2-equivalent emissions totals of CH_4 and N_2O have been revised to reflect the 100-year global warming potentials (GWPs) provided in the IPCC *Fifth Assessment Report* (AR5) (IPCC 2013)[1]. AR5 GWP values differ slightly from those presented in the IPCC *Fourth Assessment Report* (AR4) (IPCC 2007) (used in the previous Inventories). For more information on specific methodological updates, please see the Recalculations Discussion for each category in this chapter.

Due to lack of data availability, EPA is not able to estimate emissions associated with sludge generated from the treatment of industrial wastewater or the amount of CH_4 flared at composting sites. Emissions reported in the Waste chapter for landfills, wastewater treatment, and anaerobic digestion at biogas facilities include those from all 50 states, including Hawaii and Alaska, the District of Columbia, and U.S. Territories. Emissions from landfills include modern, managed sites in most U.S. Territories except for outlying Pacific Islands. Emissions from domestic wastewater treatment include most U.S. Territories except for outlying Pacific Islands. Those emissions are likely insignificant as those outlying Pacific Islands (e.g., Baker Island) have no permanent population. No industrial wastewater treatment emissions are estimated for U.S. Territories, due to lack of data availability. However, industrial wastewater treatment emissions are not expected for outlying Pacific Islands and assumed to be small for other U.S. Territories. Emissions for composting include all 50 states, including Hawaii and Alaska, and Puerto Rico, but not the remaining U.S. Territories. Composting emissions from U.S. Territories are assumed to be small. Similarly, EPA is not aware of any anerobic digestion at biogas facilities in U.S. Territories but will review this on an ongoing basis to include these emissions if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this Inventory.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to Greenhouse Gas Reporting Data

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all

[1] As specified in UNFCCC reporting guidelines, the GWPs used are those listed in table 8.A.1 in Annex 8.A of Chapter 8 of the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change, excluding the value for fossil methane.

nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and sinks provided in the Waste chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals from waste management and treatment activities.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. See Annex 9 "Use of EPA Greenhouse Gas Reporting Program in Inventory" for more information.

Waste Data from EPA's Greenhouse Gas Reporting Program

EPA uses annual GHGRP facility-level data in the Landfills category to compile the national estimate of emissions from Municipal Solid Waste (MSW) landfills (see Section 7.1 of this chapter for more information). EPA uses directly reported GHGRP data for net CH_4 emissions from MSW landfills for the years 2010 to 2021 of the Inventory. MSW landfills subject to the GHGRP began collecting data in 2010. These data are also used to recalculate emissions from MSW landfills for the years 2005 to 2009 to ensure time-series consistency.

7.1 Landfills (CRF Source Category 5A1)

In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 7-3. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-2. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the timeframe of 1990 to the current Inventory year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but are used to dispose of industrial solid waste, such as RCRA Subtitle D wastes (e.g., non-hazardous industrial solid waste defined in Title 40 of the Code of Federal Regulations [CFR] in section 257.2), commercial solid wastes, or conditionally exempt small-quantity generator wastes (EPA 2016a).

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These methane (CH_4) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition byproducts or volatilization of biodegradable wastes (EPA 2008).

Box 7-2: Description of a Modern, Managed Landfill in the United States

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. A modern, managed landfill is EPA's interpretation of the IPCC's terminology of a managed solid waste disposal site. Municipal solid waste (MSW) landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream. Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas);
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (e.g., final cover construction); and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the NSPS 40 CFR Part 60 Subpart WWW and XXX.[2] Additionally, state and tribal requirements may exist.

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. Net carbon dioxide flux from carbon stock changes of materials of biogenic origin in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this Inventory). Nitrous oxide (N_2O) emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount and composition of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas – that is not collected by a gas collection system – passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills employ similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids,

[2] For more information regarding federal MSW landfill regulations, see http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm.

and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is disposed of in a landfill and will continue for 10 to 50 or more years as the degradable waste decomposes over time.

In 2021, landfill CH_4 emissions were approximately 122.6 MMT CO_2 Eq. (4,379 kt), representing the third largest source of CH_4 emissions in the United States, behind enteric fermentation and natural gas systems. Emissions from MSW landfills accounted for approximately 85 percent of total landfill emissions (103.7 MMT CO_2 Eq.), while industrial waste landfills accounted for the remainder (18.9 MMT CO_2 Eq.). Nationally, there are significantly less industrial waste landfills (hundreds) compared to MSW landfills (thousands), which contributes to the lower national estimate of CH_4 emissions for industrial waste landfills. Additionally, the average organic content of waste streams disposed in industrial waste landfills is lower than MSW landfills. Estimates of operational MSW landfills in the United States have ranged from 1,700 to 2,000 facilities (EPA 2022a; EPA 2022b; EPA 2020c; Waste Business Journal [WBJ] 2016; WBJ 2010). The Environment Research & Education Foundation (EREF) conducted a nationwide analysis of MSW management and counted 1,540 operational MSW landfills in 2013 (EREF 2016). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure data is known, (EPA 2022b; WBJ 2010). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to as few as 1,540 in 2013, the average landfill size has increased (EPA 2022a; EREF 2016; BioCycle 2010). Larger landfills may have deeper cells where a greater amount of area will be anaerobic (more CH_4 is generated in anaerobic versus aerobic areas) and larger landfills tend to generate more CH_4 compared to a smaller landfill (assuming the same waste composition and age of waste). Regarding industrial waste landfills, the WBJ database includes approximately 1,200 landfills accepting industrial and/or construction and demolition debris for 2016 (WBJ 2016). Only 169 facilities with industrial waste landfills met the reporting threshold under Subpart TT (Industrial Waste Landfills) in the first year (2011) of EPA's Greenhouse Gas Reporting Program for this subpart (GHGRP codified in 40 CFR part 98), indicating that there may be several hundred industrial waste landfills that are not required to report under EPA's GHGRP. Less industrial waste landfills meet the GHGRP eligibility threshold because they typically accept waste streams with low to no organic content, which will not decompose and generate CH_4 when disposed.

The annual amount of MSW generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The estimated annual quantity of waste placed in MSW landfills increased 10 percent from approximately 205 MMT in 1990 to 226 MMT in 2000, then decreased by 11 percent to 202 MMT in 2010, and then increased by 7 percent to approximately 216 MMT in 2021 (see Annex 3.14, Table A-220). Emissions decreased between 1990 to 2021 largely because of increased use of landfill gas collection and control systems, closure of older landfills, better management practices, and increased diversion of organics through state and local policy and regulations. The total amount of MSW generated is expected to increase as the U.S. population continues to grow. The impacts of the coronavirus (COVID-19) pandemic with respect to landfilled waste cannot be quantified as data sources such as the EPA's *Advancing Sustainable Materials Management: Facts and Figures* report have not been published for 2019 through 2021. The quantities of waste landfilled for 2014 to 2021 (presented in Annex 3.14) are extrapolated based on population growth and the last national assessment of MSW landfilled from 2013 (EREF 2016). Net CH_4 emissions from MSW landfills have decreased since 1990 (see Table 7-3 and Table 7-4).

The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper, and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 11.2 MMT in 2021 (see Annex 3.14, Table A-219). CH_4 emissions from industrial waste landfills have also remained at similar levels recently, ranging from 16.1 MMT CO_2 Eq. in 2005 to 18.9 MMT CO_2 Eq. in 2021 when accounting for both CH_4 generation and oxidation. The EPA has focused the industrial waste landfills source category on industrial sectors known to generate and dispose of by-products that are organic and contribute to CH_4 generation, which are the pulp and paper and food processing sectors. Construction and demolition (C&D) landfills, another type of industrial waste landfill, may accept waste that could degrade (e.g., treated wood), but these waste streams are unlikely to generate significant amounts of CH_4 and are therefore not as relevant to the purpose of national greenhouse gas emissions estimate. There is also a general lack of data on annual quantities of waste disposed in industrial waste

landfills and the GHGRP Subpart TT (Industrial Waste Landfills) dataset has confirmed C&D landfills, for example, are insignificant CH_4 generators.

EPA's Landfill Methane Outreach Program (LMOP) collects information on landfill gas energy projects currently operational or under construction throughout the United States. LMOP's Landfill and Landfill Gas Energy Database contains certain information on the gas collection and control systems in place at landfills provided by organizations that are a part of the program, which can include the amount of landfill gas collected and flared. In 2021, LMOP identified 7 new landfill gas-to-energy (LFGE) projects (EPA 2022b) that began operation.

Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990	2005	2017	2018	2019	2020	2021
MSW CH_4 Generation[a]	230.0	303.7	327.0	332.6	341.4	342.2	334.8
Industrial CH_4 Generation	13.6	17.9	20.4	20.6	20.7	20.9	21.0
MSW CH_4 Recovered[a]	(23.8)	(148.4)	(192.9)	(195.2)	(201.4)	(206.3)	(201.5)
MSW CH_4 Oxidized[a]	(20.6)	(23.6)	(28.6)	(29.2)	(29.6)	(29.9)	(29.6)
Industrial CH_4 Oxidized	(1.4)	(1.8)	(2.0)	(2.1)	(2.1)	(2.1)	(2.1)
MSW net CH_4 Emissions	185.5	131.6	105.5	108.2	110.4	106.0	103.7
Industrial CH_4 Emissions[b]	12.2	16.1	18.4	18.5	18.6	18.8	18.9
Total	**197.8**	**147.7**	**123.9**	**126.7**	**129.0**	**124.8**	**122.6**

[a] For years 1990 to 2004, the Inventory methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2021, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 167 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2021 (EPA 2022a).

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 7-4: CH_4 Emissions from Landfills (kt)

Activity	1990	2005	2017	2018	2019	2020	2021
MSW CH_4 Generation[a]	8,214	10,845	11,680	11,878	12,193	12,222	11,958
Industrial CH_4 Generation	484	638	729	734	739	745	750
MSW CH_4 Recovered[a]	(851)	(5,301)	(6,891)	(6,970)	(7,193)	(7,367)	(7,195)
MSW CH_4 Oxidized[a]	(736)	(843)	(1,021)	(1,044)	(1,058)	(1,069)	(1,059)
Industrial CH_4 Oxidized	(48)	(64)	(73)	(73)	(74)	(75)	(75)
MSW net CH_4 Emissions	6,627	4,701	3,768	3,864	3,942	3,786	3,704
Industrial net CH_4 Emissions[b]	436	575	656	661	665	671	675
Total	**7,063**	**5,275**	**4,424**	**4,525**	**4,607**	**4,456**	**4,379**

[a] For years 1990 to 2004, the Inventory methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2021, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 167 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2021 (EPA 2022a).

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Methodology and Time-Series Consistency

Methodology Applied for MSW Landfills

A combination of IPCC Tier 2 and 3 approaches (IPCC 2006) are used over the reported timeseries to calculate emissions from MSW Landfills, using two primary methods. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH_4 in a landfill that is oxidized to CO_2 as it passes through the landfill cover (e.g., soil, clay, geomembrane). This method is presented below and is similar to Equation HH-6 in 40 CFR Part 98.343 for MSW landfills, and Equation TT-6 in 40 CFR Part 98.463 for industrial waste landfills.

Equation 7-1: Landfill Methane Generation

$$\mathrm{CH_{4,MSW}} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,MSW}$	=	Net CH_4 emissions from solid waste
$G_{CH4,MSW}$	=	CH_4 generation from MSW landfills, using emission factors for DOC, k, MCF, F from IPCC (2006) and other peer-reviewed sources
R	=	CH_4 recovered and combusted
Ox	=	CH_4 oxidized from MSW landfills before release to the atmosphere, using Ox values from IPCC (2006) and other peer-reviewed or scientifically validated literature (40 CFR Part 98)

The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based on directly measured amounts of recovered CH_4 from the landfill gas and is expressed below and by Equation HH-8 in 40 CFR Part 98.343. The two parts of the equation consider the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system, and the portion that is collected. First, the recovered CH_4 is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH_4 in the landfill gas that is not captured by the collection system; this amount is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH_4 in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

The current Inventory uses both methods to estimate CH_4 emissions across the time series within EPA's Waste Model, as summarized in Figure 7-3 below. This chapter provides a summary of the methods, activity data, and parameters used. Additional step-wise explanations to generate the net emissions are provided in Annex 3.14.

Equation 7-2: Net Methane Emissions from MSW Landfills

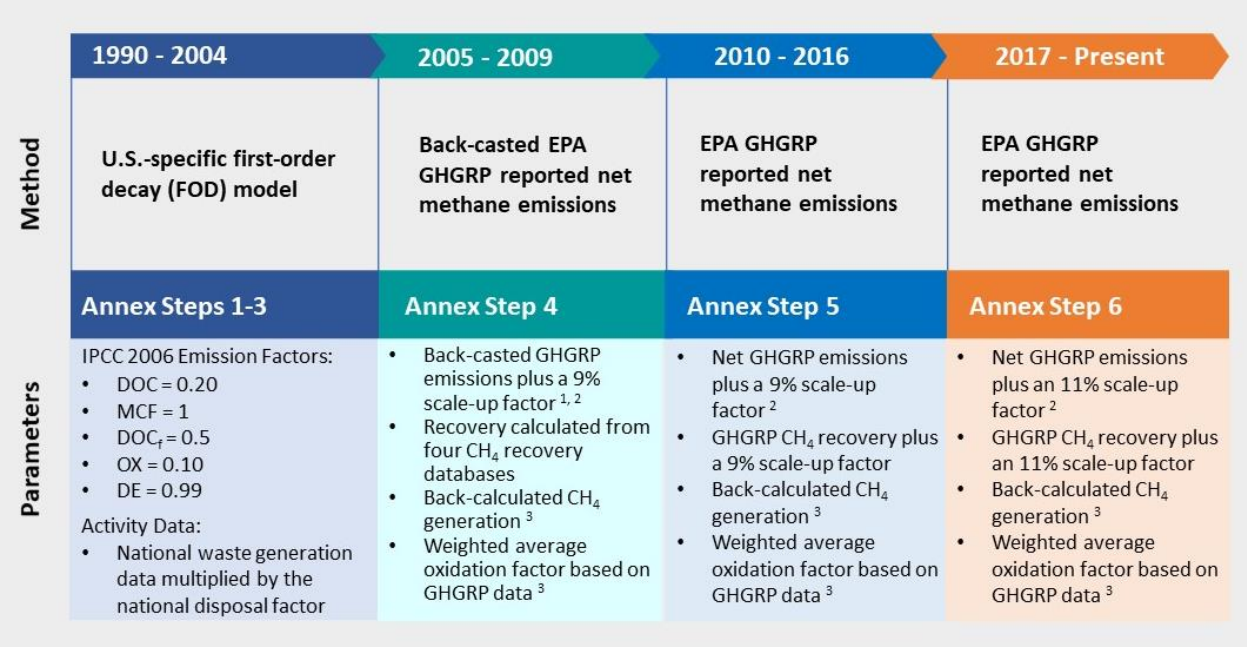
$$\mathrm{CH_{4,Solid\ Waste}} = [\left(\frac{R}{CE\ x\ f_{REC}} - R\right) x(1 - OX) + R\ x\ \left(1 - (DE\ x\ f_{Dest})\right)]$$

where,

$CH_{4,Solid\ Waste}$	=	Net CH_4 emissions from solid waste
R	=	Quantity of recovered CH_4 from Equation HH-4 of EPA's GHGRP
CE	=	Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA's GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used (percent)
f_{REC}	=	fraction of hours the recovery system was operating (percent)

OX = oxidation factor (percent)
DE = destruction efficiency (percent)
f_{Dest} = fraction of hours the destruction device was operating (fraction)

Figure 7-3: Methodologies Used Across the Time Series to Compile the U.S. Inventory of Emission Estimates for MSW Landfills



[1] The intent of the scale-up factor is to estimate emissions from landfills that do not report to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. The back-casted emissions are calculated using directly reported net methane emissions for GHGRP reporting years 2010 to 2016. The back-casted emissions are subject to change in each Inventory based on new reporting year reports and resubmitted greenhouse gas reports for previous years. This method is compatible with the *2006 IPCC Guidelines* because facilities reporting to the GHGRP either use the FOD method, or directly measured methane recovery data with default emission factors either directly included in the *2006 IPCC Guidelines* or scientifically validated through peer review.

[2] Emission factors used by facilities reporting to GHGRP Subpart HH are facility-specific defaults derived from peer-reviewed literature and the *2006 IPCC Guidelines*.

[3] Methane generation is back-calculated from the net MSW emissions, estimated methane recovery data, and the weighted average oxidation factor based on GHGRP Subpart HH reported data of 0.18 between 2010 to 2016, and 0.21 between 2017 to 2020, and 0.22 in 2021.

The Waste Model is a spreadsheet developed by the IPCC for purposes of estimating methane emissions from solid waste disposal sites, adapted to the United States by the inclusion and usage of U.S.-specific parameters. The Waste Model contains activity and waste generation information from both the MSW and Industrial landfill sectors and estimates the amount of CH_4 emissions from each sector for each year of the time series, using both methods. Prior to the 1990 through 2015 Inventory, only the FOD method was used. Methodological changes were made to the 1990 through 2015 Inventory to incorporate higher tier data (i.e., CH_4 emissions as directly reported to EPA's GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The technique used to merge the directly reported GHGRP data with the previous methodology is described as the overlap technique in the Time-Series Consistency chapter of the *2006 IPCC Guidelines*. Additional details on the technique used is included in Annex 3.14, and a technical memorandum (RTI 2017).

A summary of the methodology used to generate the current 1990 to 2021 Inventory estimates for MSW landfills is as follows and is also illustrated in Annex Figure A-19:

- **1940 to 1989:** These years are included for historical waste disposal amounts. Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For the Inventory calculations, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in managed, anaerobic landfills (Methane Conversion Factor, MCF, of 1) and those disposed in uncategorized solid waste disposal waste sites (MCF of 0.6) (IPCC 2006). Uncategorized sites represent those sites for which limited information is known about the management practices. All calculations after 1980 assume waste is disposed in managed, anaerobic landfills. The FOD method was applied to estimate annual CH_4 generation. Methane recovery amounts were then subtracted, and the result was then adjusted with a 10 percent oxidation factor to derive the net emissions estimates. A detailed explanation of the methods used are presented in Annex 3.14 Step 1.

- **1990 to 2004:** The Inventory time series begins in 1990. The FOD method is exclusively used for this group of years. The national total of waste generated (based on state-specific landfill waste generation data) and a national average disposal factor for 1989 through 2004 were obtained from the State of Garbage (SOG) survey every two years (i.e., 2002, 2004 as published in BioCycle 2006). In-between years were interpolated based on population growth. For years 1989 to 2000, directly reported total MSW generation data were used; for other years, the estimated MSW generation (excluding construction and demolition waste and inerts) were presented in the reports and used in the Inventory. The FOD method was applied to estimate annual CH_4 generation. Landfill-specific CH_4 recovery amounts (calculated from four CH_4 recovery databases) were then subtracted from CH_4 generation and the result was adjusted with a 10 percent oxidation factor to derive the net emissions estimates. A detailed explanation of the methods used are presented in Annex 3.14 Steps 1 through 3.

- **2005 to 2009:** Emissions for these years are estimated using net CH_4 emissions that are reported by landfill facilities under EPA's GHGRP. Because not all landfills in the United States are required to report to EPA's GHGRP, a 9 percent scale-up factor is applied to the GHGRP emissions for completeness. The intent of the scale-up factor is to account for emissions from landfills that do not report to the GHGRP. Supporting information, including details on the technique used to estimate emissions for 2005 to 2009, to develop the scale-up factor, and to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in Annex 3.14 Step 4 and in RTI 2018a. Separate estimates of CH_4 generation, CH_4 recovery, and oxidation are calculated from the net CH_4 emissions. Landfill-specific CH_4 recovery is calculated from four CH_4 recovery databases. A single oxidation factor is not applied to the annual CH_4 generated as is done for 1990 to 2004 because the GHGRP emissions data are used, which already take oxidation into account. The GHGRP allows facilities to use varying oxidation factors (i.e., 0, 10, 25, or 35 percent) depending on their facility-specific calculated CH_4 flux rate. The effectively applied average oxidation factor between 2005 to 2009 averages to 0.14. Methane generation is then back-calculated using net CH_4 emissions, CH_4 recovery, and oxidation. A detailed explanation of the methods used to develop the back-casted emissions and revised scale-up factor are presented in Annex 3.14 Step 4.

- **2010 to 2016:** Net CH_4 emissions as directly reported to the GHGRP are used with a 9 percent scale-up factor to account for landfills that are not required to report to the GHGRP. A combination of the FOD method and the back-calculated CH_4 emissions were used by the facilities reporting to the GHGRP. Landfills reporting to the GHGRP without gas collection and control apply the FOD method, while most landfills with landfill gas collection and control apply the back-calculation method. Methane recovery is calculated using reported GHGRP recovery data plus a 9 percent scale-up factor. Methane generation and oxidation are back-calculated from the net GHGRP CH_4 emissions applied and estimated CH_4 recovery. The

average oxidation factor effectively applied is 0.18 percent. A detailed explanation of the methods used to develop the revised scale-up factor are presented in Annex 3.14 Step 5.

- **2017 to 2021:** The same methodology is applied as for 2010 through 2016 where a scale-up factor is applied to account for landfills that are not required to report to the GHGRP. The scale-up factor was revised for the 1990 to 2020 Inventory to change the methodology from total waste-in-place to only considering waste disposed for non-reporting landfills in the past 50 years (i.e., since 1970). Additional revisions made included incorporating facilities that have stopped reporting to the GHGRP, new additions to the 2021 LMOP Database (EPA 2022b), corrections to the underlying database of non-reporting landfills used to develop the 9 percent scale-up factor that were identified. For 2017 to 2021, a scale-up factor of 11 percent is applied annually to the GHGRP net reported CH_4 emissions. Methane recovery is calculated using reported GHGRP recovery data plus an 11 percent scale-up factor. Separate estimates of CH_4 generation and oxidation are calculated from the net CH_4 emissions applied. The average oxidation factor effectively applied is 0.22 percent. A detailed explanation of the methods used to develop the revised scale-up factor are presented in Annex 3.14 Step 6.

With regard to the time series and as stated in *2006 IPCC Guidelines Volume 1: Chapter 5 Time-Series Consistency* (IPCC 2006), "the time series is a central component of the greenhouse gas inventory because it provides information on historical emissions trends and tracks the effects of strategies to reduce emissions at the national level. All emissions in a time series should be estimated consistently, which means that as far as possible, the time series should be calculated using the same method and data sources in all years" (IPCC 2006). In some cases, it may not be possible to use the same methods and consistent data sets for all years because of limited data (activity data, emission factors, or other parameters) directly used in the calculation of emission estimates for some historical years. In such cases, emissions or removals may need to be recalculated using alternative methods. In this case, this chapter provides guidance on techniques to splice, or join methodologies together instead of back-casting emissions back to 1990. One of those techniques is referred to as the overlap technique. The overlap technique is recommended when new data becomes available for multiple years. This was the case with EPA's GHGRP data for MSW landfills, where directly reported CH_4 emissions data became available for more than 1,200 MSW landfills beginning in 2010. The GHGRP emissions data had to be merged with emissions from the FOD method to avoid a drastic change in emissions in 2010, when the datasets were combined. EPA also had to consider that according to IPCC's good practice, efforts should be made to reduce uncertainty in Inventory calculations and that, when compared to the GHGRP data, the FOD method presents greater uncertainty.

In evaluating the best way to combine the two datasets, EPA considered either using the FOD method from 1990 to 2009, or using the FOD method for a portion of that time and back-casting the GHGRP emissions data to a year where emissions from the two methodologies aligned. Plotting the back-casted GHGRP emissions against the emissions estimates from the FOD method showed an alignment of the data in 2004 and later years which facilitated the use of the overlap technique while also reducing uncertainty. A detailed explanation and a chart showing the estimates across the time series considering the two method options is included in Annex 3.14. EPA ultimately decided to back-cast the GHGRP emissions from 2009 to 2005 only, to merge the datasets and adhere to the IPCC *Good Practice Guidance* for ensuring time-series consistency.

Supporting information, including details on the techniques used to ensure time-series consistency by incorporating the directly-reported GHGRP emissions is presented in Annex 3.14.

Methodology Applied for Industrial Waste Landfills

Emissions from industrial waste landfills are estimated using a Tier 2 approach (IPCC 2006) and a tailored (country-specific) IPCC waste model. Activity data used are industrial production data (ERG 2021) for two sectors (pulp and paper manufacturing, and food and beverage manufacturing) to which country-specific default waste disposal factors are applied (a separate disposal factor for each sector). The disposal factors, as described below, are based on scientifically reviewed data, and are the same across the entire time series. The emission factors are based on those recommended by the *2006 IPCC Guidelines* and are the same across the entire time series.

The FOD equation from IPCC 2006 is used via the waste model to estimate methane emissions:

Equation 7-3: Net Methane Emissions from Industrial Waste Landfills

$$CH_{4,IND} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,Solid\ Waste}$ = Net CH_4 emissions from solid waste
$G_{CH4,Ind}$ = CH_4 generation from industrial waste landfills, using production data multiplied by a disposal factor and emission factors for DOC, k, MCF, F (IPCC 2006)
R = CH_4 recovered and combusted (no recovery is assumed for industrial waste landfills)
OX = CH_4 oxidized from industrial waste landfills before release to the atmosphere (using the *2006 IPCC Guidelines* value for OX of 0.10)

The activity data used in the emission calculations are production data (e.g., the amount of meat, poultry, vegetables processed; the amount of paper produced) versus disposal data. There are currently no facility-specific data sources that track and report the amount and type of waste disposed of in the universe of industrial waste landfills in the United States. EPA's GHGRP provides some insight into waste disposal in industrial waste landfills but is not comprehensive. Data reported to the GHGRP on industrial waste landfills suggests that most of the organic waste which would result in methane emissions is disposed at pulp and paper and food processing facilities. Of the 168 facilities that reported to Subpart TT of the GHGRP in 2019, 92 (54 percent) are in the North American Industrial Classification System (NAICS) for Pulp, Paper, and Wood Products (NAICS 321 and 322) and 12 (7 percent) are in Food Manufacturing (NAICS 311).

Based on this limited information, the Inventory methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors, thus estimates of industrial landfill emissions focused on these two sectors. EPA validated this assumption through an analysis of the Subpart TT of the GHGRP in the 2016 reporting year (RTI 2018b). The Subpart TT waste disposal information for pulp and paper facilities correlates well with the activity data currently used to estimate Inventory emissions; however, the waste disposal information in Subpart TT related to food and beverage facilities are approximately an order of magnitude different than the Inventory disposal estimates for the entire time series.

EPA conducted a literature review between 2020 and 2022 to investigate other sources of industrial food waste and annual waste disposal quantities. As a result of this effort, EPA decided to revise the food waste disposal factor in the 1990 to 2021 Inventory for select years. A waste disposal factor of 4.86 percent is used for 1990 to 2009 and a revised factor of 6 percent is used for 2010 to the current year. The 6 percent waste disposal factor is derived from recent surveys of the food and beverage industry where approximately 94 percent of food waste generated is repurposed (FWRA 2016). The 4.86% disposal factor is based on available data from a 1993 Report to Congress (EPA 1993).

The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills. The amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14.

Landfill CH_4 recovery is not accounted for in industrial waste landfills and is believed to be minimal based on available data collected under EPA's GHGRP for industrial waste landfills (Subpart TT), which shows that only one of the 167 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2022a). However, because EPA's GHGRP is not a national database and comprehensive data regarding gas collection systems have not been published for industrial waste landfills, assumptions regarding a percentage of landfill gas collection systems, or a total annual amount of landfill gas collected for the non-reporting industrial waste landfills have not been made for the Inventory methodology.

The amount of CH_4 oxidized by the landfill cover at industrial waste landfills was assumed to be 10 percent of the CH_4 generated (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for all years.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste (MSW) generated in the United States can be managed through a variety of methods. MSW that is not recycled, composted, combusted with energy recovery, or digested is assumed to be landfilled. In addition to these management pathways, waste or excess food from the food manufacturing and processing sector may be disposed through the sewerage network, used for animal feed, land application, donated for human consumption, and rendered or recycled into biofuels in the case of animal by-products, fats, oils and greases.

There have been three main sources for nationwide solid waste management data in the United States that the Inventory has used (see Annex 3.14, Box A-3 for comparison of estimates from these data sources):

- The *BioCycle* and Earth Engineering Center of Columbia University's SOG in America surveys [no longer published];
- The EPA's *Advancing Sustainable Materials Management: Facts and Figures* reports; and
- The EREF's *MSW Generation in the United States* reports.

The SOG surveys and, most recently EREF, collected state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. These data sources used a 'bottom-up' method. The survey asked for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown was not available, the survey asked for total tons landfilled. The data were adjusted for imports and exports across state lines so that the principles of mass balance were adhered to for completeness, whereby the amount of waste managed did not exceed the amount of waste generated. The SOG and EREF reports present survey data aggregated to the state level.

The EPA *Advancing Sustainable Materials Management: Facts and Figures* report characterizes national post-consumer municipal solid waste (MSW) generation and management using a top-down materials flow (mass balance) methodology. It captures an annual snapshot of MSW generation and management in the United States for specific products. Data are gathered from U.S. Government (e.g., U.S. Census Bureau and U.S. Department of Commerce), state environmental agencies, industry and trade groups, and sampling studies. The materials flow methodology develops MSW waste generation estimates of quantities of MSW products in the marketplace (using product sales and replacement data) and assessing waste generation by component material based on product lifespans. The data are used to estimate tons of materials and products generated, recycled, combusted with energy recovery, managed via other food waste management pathways, or landfilled nationwide. MSW that is not recycled or composted is assumed to be combusted or landfilled, except for wasted food, which uses a different methodology and includes nine different management pathways. The 2018 Facts and Figures Report (EPA 2020) uses a methodology that expanded the number of management pathways to include: animal feed; bio-based materials/biochemical processing (i.e., rendering); co-digestion/anaerobic digestion; composting/aerobic processes; combustion; donation; land application; landfill; and sewer/wastewater treatment.

In this Inventory, emissions from solid waste management are presented separately by waste management option, except for recycling of waste materials. Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery and are presented in the stationary combustion chapter in the Energy sector, although the emissions estimates are not called out separately. Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting sections in the Waste sector of this report. Emissions from anaerobic digesters are presented in three different sections depending on the digester category. Emissions from on-farm digesters are included in the Agriculture sector; emissions from digesters at wastewater treatment plants emissions from stand-alone digesters are presented in separate sections in the Waste sector of this report. In the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial

facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report.

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills when the FOD method is applied directly for 1990 to 2004 in the Waste Model and, to some extent, in the GHGRP methodology. The approach used in the MSW emission estimates assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, the FOD method as applied in this Inventory is not facility-specific modeling and while this approach may over- or underestimate CH_4 generation at some landfills if used at the facility-level, the result is expected to balance out because it is being applied nationwide.

There is a high degree of uncertainty associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006). There is less uncertainty in EPA's GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used.

Uncertainty also exists in the scale-up factors (both 9 percent and 11 percent) applied for years 2005 to 2016 and 2017 to 2021, respectively, and in the back-casted emissions estimates for 2005 to 2009. As detailed in RTI (2018a), limited information is available for landfills that do not report to the GHGRP. RTI developed an initial list of landfills that do not report to the GHGRP with the intent of quantifying the total waste-in-place for these landfills that would add up to the scale-up factor. Input was provided by industry, LMOP, and additional EPA support. However, many gaps existed in the initial development of this Non-Reporting Landfills Database. Assumptions were made for hundreds of landfills to estimate their waste-in-place and the subsequent scale-up factors. The waste-in-place estimated for each landfill is likely not 100 percent accurate and should be considered a reasonable estimate. Additionally, a simple methodology was used to back-cast emissions for 2005 to 2009 using the GHGRP-reported emissions from 2010 to 2021. This methodology does not factor in annual landfill to landfill changes in landfill CH_4 generation and recovery. Because of this, an uncertainty factor of 25 percent is applied to the scale-up factor and years (emission estimates) the scale-up factor is applied to.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized at MSW landfills. Facilities directly reporting to EPA's GHGRP can use oxidation factors ranging from 0 to 35 percent, depending on their facility-specific CH_4 flux. As recommended by the *2006 IPCC Guidelines* for managed landfills, a 10 percent default oxidation factor is applied in the Inventory for both MSW landfills (those not reporting to the GHGRP and for the years 1990 to 2004 when GHGRP data are not available) and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system.

Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the Inventory's CH_4 recovery databases (used for years 1990 to 2004). Four CH_4 recovery databases are used to estimate nationwide CH_4 recovery for MSW landfills for 1990 to 2009. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 to 2013 Inventory report (two years before the full GHGRP data set started being used for net CH_4 emissions for the Inventory). Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. The methodology and assumptions that go into each database differ. For example, the flare database assumes the

midpoint of each flare capacity at the time it is sold and installed at a landfill; the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered. Additionally, two databases, the EIA database and flare vendor database, could no longer be updated for the entire time series due to external factors. For example, the EIA database has not been updated since 2006 because the EIA stopped collected landfill recovery data. The EIA database has, for the most part, been replaced by the GHGRP MSW landfills database. The flare database was populated annually until 2015, but decreasing, voluntary participation from flare vendors sharing their flare sales data for several years prior to 2015.

To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data and the EIA data are given precedence because facility data were directly reported; the LFGE data are given second priority because CH_4 recovery is estimated from facility-reported LFGE system characteristics; and the flare data are given the lowest priority because this database contains minimal information about the flare, no site-specific operating characteristics, and includes smaller landfills not included in the other three databases (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery; however, the number of unique landfills between the four databases does differ.

The *2006 IPCC Guidelines* default value of 10 percent for uncertainty in recovery estimates was used for two of the four recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the four databases in addition to the uncertainties associated with the FOD method and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5.

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary source of uncertainty with respect to the industrial waste generation and emission estimates. The approach used here assumes that most of the organic waste disposed of in industrial waste landfills that would result in CH_4 emissions consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, a straight disposal factor is applied over the entire time series to the amount produced to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the Inventory methodology for the pulp and paper sector. A 10 percent oxidation factor is also applied to CH_4 generation estimates for industrial waste landfills and carries the same amount of uncertainty as with the factor applied to CH_4 generation for MSW landfills.

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. There is considerable uncertainty for the MSW landfills estimates due to the many data sources used, each with its own uncertainty factor.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2021 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(MMT CO_2 Eq.)	(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	**CH_4**	**122.6**	**99.0**	**154.8**	**-19%**	**26%**
MSW	CH_4	103.7	83.0	137.5	-20%	33%
Industrial	CH_4	18.9	15.9	25.7	-16%	36%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval. Individual uncertainty factors are applied to activity data and emission factors in the Monte Carlo analysis.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the *U.S. Inventory* QA/QC plan, which is in accordance with Vol. 1, Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). QA/QC checks are performed for the transcription of the published data set (e.g., EPA's GHGRP dataset) used to populate the Inventory data set in terms of completeness and accuracy against the reference source. Additionally, all datasets used for this category have been checked to ensure they are of appropriate quality and are representative of U.S. conditions. The primary calculation spreadsheet is tailored from the *2006 IPCC Guidelines* waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values and calculations were verified by secondary QA/QC review. Stakeholder engagements sessions in 2016 and 2017 were used to gather input on methodological improvements and facilitate an external expert review on the methodology, activity data, and emission factors.

Category-specific checks include the following:

- Evaluation of the secondary data sources used as inputs to the Inventory dataset to ensure they are appropriately collected and are reliable;
- Cross-checking the data (activity data and emissions estimates) with previous years to ensure the data are reasonable, and that any significant variation can be explained through the activity data;
- Conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies; and
- Reviewing secondary datasets to ensure they are nationally complete and supplementing where necessary (e.g., using a scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP).

A primary focus of the QA/QC checks in past Inventories was to ensure that CH_4 recovery estimates were not double-counted and that all LFGE projects and flares were included in the respective project databases. QA/QC checks performed in the past for the recovery databases were not performed in this Inventory, because new data were not added to the recovery databases in this Inventory year.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[3] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with several general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. For the MSW Landfills sector, under Subpart HH of the GHGRP, MSW Landfills with gas collection are required to report emissions from their site using both a forward- (using a first order decay model as a basis) and back-calculating (using parameters specific to the landfill itself, such as measured recovery and collection efficiency of the landfill gas) methodology. Details on the forward- and back-calculation approach can be found in Annex 3.14 and 40 CFR Subpart HH of Part 98. Reporters can choose which of these two methodologies they believe best represents the emissions at their landfill and are required to submit that value as their total Subpart HH emissions. Facilities are generally not expected to switch between the two equations each year, as the emissions calculated using each method can vary greatly and can have a significant effect on emission trends for that landfill, and potentially the entire MSW Landfill sector under the GHGRP. Key checks are in place to assure that emissions are trending in a sensible way year over year for each reporting landfill.

[3] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Recalculations Discussion

Revisions to the individual facility reports submitted to EPA's GHGRP can be made at any time and a portion of facilities have revised their reports since 2010 for various reasons, resulting in changes to the total net CH_4 emissions for MSW landfills. Each Inventory year, the back-casted emissions for 2005 to 2009 will be recalculated using the most recently verified data from the GHGRP. Changes in these data result in changes to the back-casted emissions. The impact of the revisions to the GHGRP Subpart HH annual greenhouse gas reports resubmitted for 2010 to 2021 slightly increased or decreased total Subpart HH reported net emissions up to 0.5 percent in the years the Subpart HH data are applied (i.e., 2005 to 2020). The resubmissions resulted in annual increases ranging from 0.1 percent to 0.3 percent to the net MSW emissions between 2005 to 2009, no net emission changes for 2010 to 2015, and a slight decrease averaging -0.15 percent of emissions is observed between 2016 to 2019. A 0.5 percent increase is observed for 2020. Between 2005 to 2020, on average, the impact or change was very small (less than 0.1% percent) in emissions across all reporters. A change in net Subpart HH reported emissions results in the same percentage change in the Inventory emissions for that year.

The revision to the industrial food waste disposal factor from 4.86 percent to 6 percent increased net industrial emissions between 2010 to 2020 from a low of 2.1 percent in 2011 to a high of 10.9 percent in 2020. Combined, these two recalculations increased net landfill emissions for all years between 2005 to 2020. Emissions increased by less than 1 percent between 2005 to 2014 (low of 0.3 percent in 2005 and a high of 0.8 percent in 2014) and up to 1.9 percent between 2015 to 2020 (low of 1.0 percent in 2015 to a high of 1.9 percent in 2020).

In addition, for the current Inventory, estimates of CO_2 equivalent emissions totals of CH_4 emissions from landfills have been revised to apply the 100-year global warming potentials (GWPs) provided in the IPCC *Fifth Assessment Report* (AR5) (IPCC 2013). AR5 GWP values differ slightly from those presented in the IPCC *Fourth Assessment Report* (AR4) (IPCC 2007) (used in the previous inventories). The GWP of CH_4 has increased from 25 to 28, leading to an overall increase in CO_2-equivalent CH_4 emissions. The AR5 GWPs have been applied across the entire time series for consistency. Compared to the previous Inventory which applied 100-year GWP values from AR4, the change in CH_4 emissions was a 12 percent increase for each year of the time series. Further discussion on this update and the overall impacts of updating the inventory GWPs to reflect the IPCC *Fifth Assessment Report* can be found in Chapter 9, Recalculations and Improvements.

Planned Improvements

EPA received recommendations from industry stakeholders regarding the DOC values and decay rates (k values) required to be used in the GHGRP calculations. Stakeholders have suggested that newer, more up-to-date default values considering recent trends in the composition of waste disposed in MSW landfills for both k and DOC in the GHGRP should be developed and reflected in the 2005 and later years of the Inventory. In response, EPA developed a multivariate analysis using publicly available Subpart HH GHGRP data, solving for optimized DOC and k values across the more than 1,100 landfills reporting to the program. The results of this analysis could help inform a current GHGRP rulemaking (87 FR 36920) where changes could be made to the default DOC and k values contained within Subpart HH, which could then be carried over to the Inventory emissions estimates for MSW landfills upon promulgation of any revisions to 40 CFR part 98. This potential improvement may be long-term.

With respect to the scale-up factor, EPA received comments on revisions made to the scale-up for the 1990 to 2020 inventory from a total waste-in-place approach to a time-based threshold of 50 years. Commenters noted that this time-based threshold approach does not adjust for the non-linearity of methane production of landfill gas. In response, EPA will further investigate how best to account for emissions from MSW landfills that do not report to the GHGRP, including using the FOD model for these landfills based on estimated annual waste disposed for this subset of landfills between 2005 to 2021, reverting to the total waste-in-place approach, or modifying the time-based threshold approach. Any methodological revisions to accounting for emissions from this subset of landfills will be made in the future (1990 to 2022) Inventory.

Relatedly, EPA will periodically assess the impact to the waste-in-place and emissions data from GHGRP facilities that have resubmitted annual reports during any reporting years, are new reporting facilities, and from facilities that have stopped reporting to the GHGRP to ensure national estimates are as complete as possible. Facilities may stop reporting to the GHGRP when they meet the "off-ramp" provisions (reported less than 15,000 metric tons of CO_2 equivalent emissions for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent emissions for 5 consecutive years). If warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the Inventory. EPA considered public comments received on the 1990-2019 Inventory specific to using a time-based threshold to calculate the scale-up factor instead of a total waste-in-place approach. The rationale supporting the comments was that older, closed landfills with large quantities of waste-in-place are driving up the scale-up factor but have little impact on total methane generation. EPA assessed two time-based scenarios for developing the scale-up factor – one scenario looking at the past 30 years of waste disposed, and the second looking at the past 50 years of waste disposed. The 50-year time-based threshold was applied and resulted in the 11 percent scale-up factor used between 2017 and 2021.

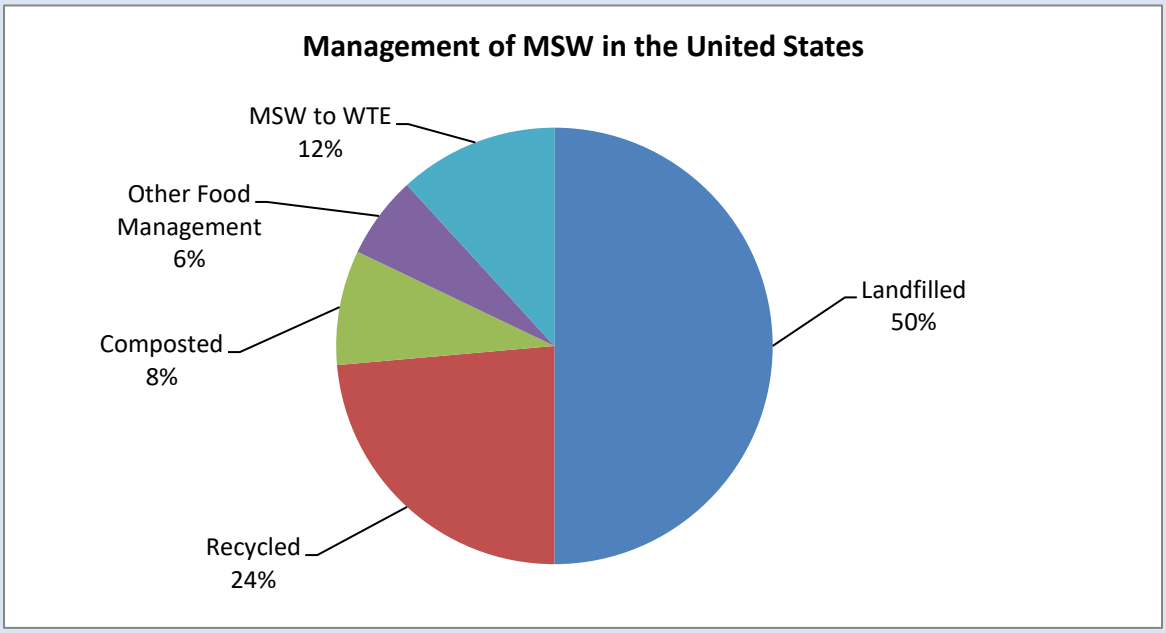
EPA is planning to account for unmanaged landfills in Puerto Rico and other U.S. Territories to the landfill emissions estimates. Data limitations for historical waste received at these sites make this challenging. Presently, emissions from managed sites in Puerto Rico and Guam are accounted for in 2005 to present as part of the GHGRP Subpart HH dataset.

Additionally, with the recent publication of the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019), EPA will begin to update applicable emission factors, methodologies, and assumptions underlying emission estimates for landfills and make any applicable changes during the next (1990 to 2022) Inventory cycle per the *2019 Refinement*.

Box 7-4: Overview of U.S. Solid Waste Management Trends

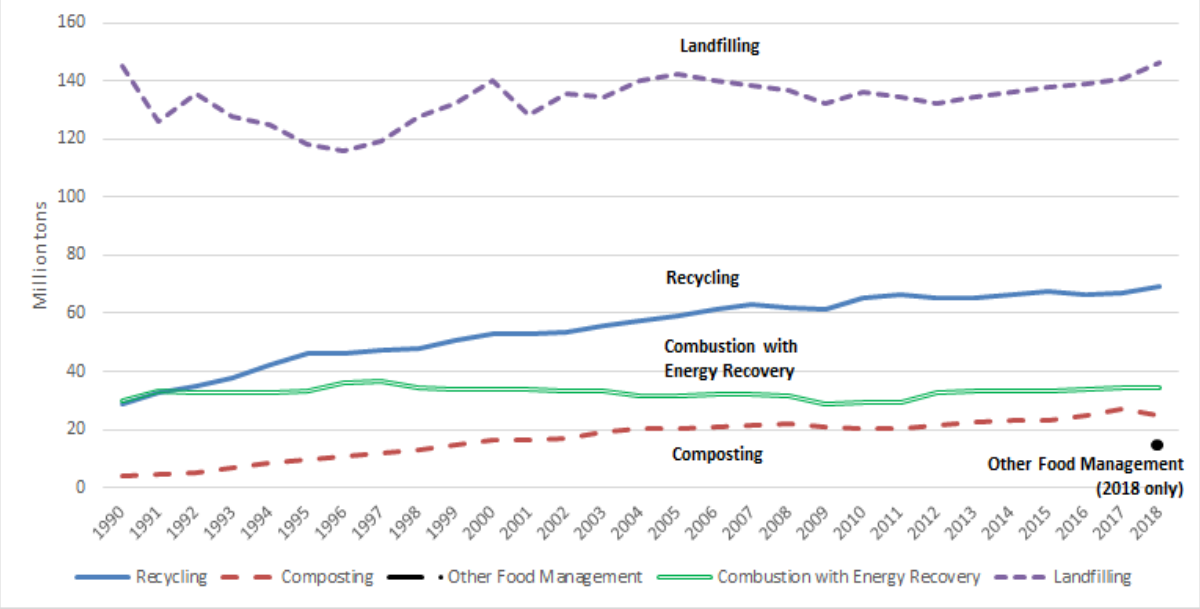
As shown in Figure 7-4 and Figure 7-5 landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have previously been disposed in a landfill.

Figure 7-4: Management of Municipal Solid Waste in the United States, 2018



Note: 2018 is the latest year of available data. Data taken from Table 35 of EPA (2020a). MSW to WTE is combustion with energy recovery (WTE = waste-to-energy).
Source: EPA (2020b)

Figure 7-5: MSW Management Trends from 1990 to 2018



Note: 2018 is the latest year of available data. Only one year of data (2018) is available for the "Other Food Management" category.
Source: EPA (2020b). The EPA Advancing Sustainable Materials Management reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA 2020b for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request but are no longer on the EPA's Advancing Sustainable Materials Management web site.[4]

Table 7-6 presents the national-level material composition of waste disposed across typical MSW landfills in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6.

Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH_4 as they break down in a modern MSW landfill), is important for estimating greenhouse gas emissions. Increased diversion of degradable materials so that they are not disposed of in landfills reduces the CH_4 generation potential and CH_4 emissions from landfills. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste diversion through recycling and composting (see Table 7-6 and Figure 7-6). As shown in Figure 7-6, the diversion of food scraps has been consistently low since 1990 because most cities and counties do not practice curbside collection of these materials, although the quantity has been slowly increasing in recent years. Neither Table 7-6 nor Figure 7-6 reflect the frequency of backyard composting of yard trimmings and food waste because this information is largely not collected nationwide and is hard to estimate.

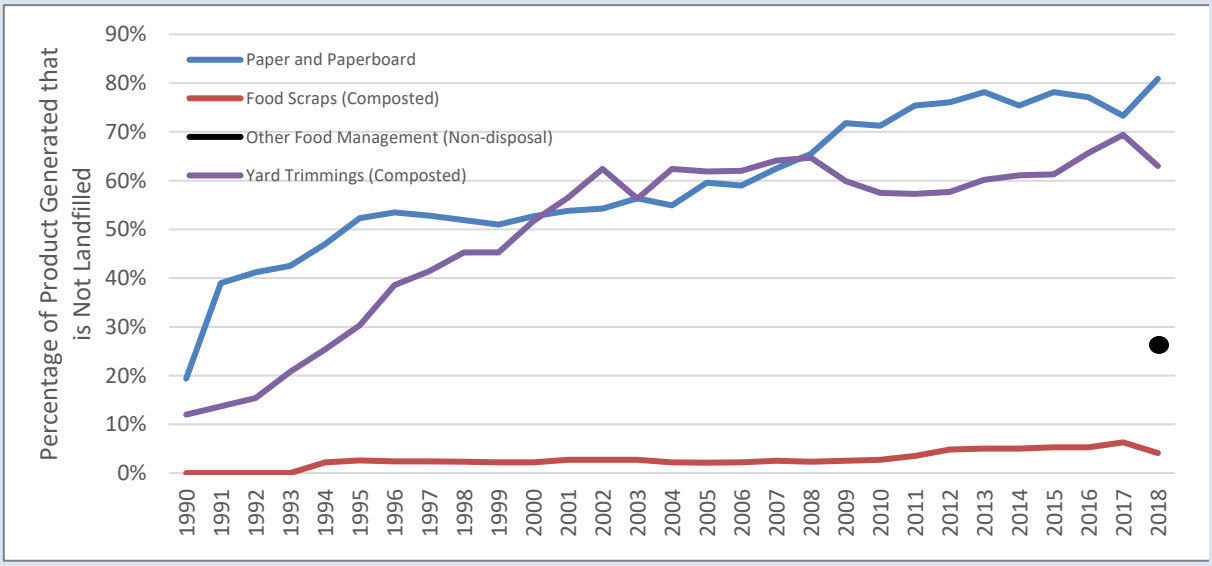
[4] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2018 (Percent)

Waste Type	1990	2005	2015	2016	2017	2018
Paper and Paperboard	30.0%	24.7%	13.3%	12.7%	13.1%	11.8%
Glass	6.0%	5.8%	5.0%	4.9%	4.9%	5.2%
Metals	7.2%	7.9%	9.5%	9.8%	9.9%	9.5%
Plastics	9.5%	16.4%	18.9%	18.9%	19.2%	18.5%
Rubber and Leather	3.2%	2.9%	3.3%	3.4%	3.5%	3.4%
Textiles	2.9%	5.3%	7.7%	8.0%	8.0%	7.7%
Wood	6.9%	7.5%	8.0%	8.8%	8.7%	8.3%
Other	1.4%	1.8%	2.2%	2.2%	2.2%	2.0%
Food Scraps	13.6%	18.5%	22.0%	22.1%	22.0%	24.1%
Yard Trimmings	17.6%	7.0%	7.8%	6.9%	6.2%	7.2%
Miscellaneous Inorganic Wastes	1.7%	2.2%	2.3%	2.3%	2.3%	2.3%

Source: EPA (2020b)

Figure 7-6: Percent of Degradable Materials Diverted from Landfills from 1990 to 2018 (Percent)



Note: The data shown in this chart are for recycling of paper and paperboard, composting of food scraps and yard trimmings, and alternative management pathways for the Other Food Management (non-disposal) category. The Other Food Management (non-disposal) category is a new addition and only one year of data are available for 2018 (28 percent of the food waste generated was beneficially reused or managed using a method that was not landfilling, recycling, or composting). The Other Food Management pathways include animal feed, bio-based materials/biochemical processing, co-digestion/anaerobic digestion, donation, land application, and sewer/wastewater treatment.

Source: EPA (2020b). The EPA Advancing Sustainable Materials reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA (2020b) for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request, but are not longer on the EPA's Advancing Sustainable Materials Management website.[5]

7.2 Wastewater Treatment and Discharge (CRF Source Category 5D)

Wastewater treatment and discharge processes are sources of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, nutrients, pathogenic organisms, and chemical contaminants.[6] Treatment of domestic wastewater may either occur on site, most commonly through septic systems, or off site at centralized treatment systems, most commonly at publicly owned treatment works (POTWs). In the United States, approximately 17 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2019). Treatment of industrial wastewater may occur at the industrial plant using package or specially designed treatment plants or be collected and transferred off site for co-treatment with domestic wastewater in centralized treatment systems.

Centralized Treatment. Centralized wastewater treatment systems use sewer systems to collect and transport wastewater to the treatment plant. Sewer collection systems provide an environment conducive to the formation of CH_4, which can be substantial depending on the configuration and operation of the collection system (Guisasola et al. 2008). Recent research has shown that at least a portion of CH_4 formed within the collection system enters the centralized system where it contributes to CH_4 emissions from the treatment system (Foley et al. 2015).

The treatment plant may include a variety of processes, ranging from physical separation of material that readily settles out (typically referred to as primary treatment), to treatment operations that use biological processes to convert and remove contaminants (typically referred to as secondary treatment), to advanced treatment for removal of targeted pollutants, such as nutrients (typically referred to as tertiary treatment). Not all wastewater treatment plants conduct primary treatment prior to secondary treatment, and not all plants conduct advanced or tertiary treatment (EPA 1998a).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream and may be further biodegraded under aerobic or anaerobic conditions, such as anaerobic sludge digestion. Sludge can be produced from both primary and secondary treatment operations. Some wastewater may also be treated using constructed (or semi-natural) wetland systems, though this is much less common in the United States and represents a relatively small portion of wastewater treated centrally (<0.1 percent) (ERG 2016). Constructed wetlands are a coupled anaerobic-aerobic system and may be used as the primary method of wastewater treatment, or are more commonly used as a final treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants (IPCC 2014). Constructed wetlands do not produce secondary sludge (sewage sludge).

The generation of N_2O may also result from the treatment of wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, proteins, and ammonia. Ammonia N is converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic/anaerobic conditions, whereby anaerobic or facultative organisms reduce oxidized forms of nitrogen (e.g., nitrite, nitrate) in the absence of free oxygen to produce nitrogen gas (N_2). Nitrous oxide is generated as a by-

[5] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

[6] Throughout the Inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

product of nitrification, or as an intermediate product of denitrification. No matter where N_2O is formed it is typically stripped (i.e., transferred from the liquid stream to the air) in aerated parts of the treatment process. Stripping also occurs in non-aerated zones at rates lower than in aerated zones.

On-site Treatment. The vast majority of on-site systems in the United States are septic systems composed of a septic tank, generally buried in the ground, and a soil dispersion system. Solids and dense materials contained in the incoming wastewater (influent) settle in the septic tank as sludge. Floatable material (scum) is also retained in the tank. The sludge that settles on the bottom of the tank undergoes anaerobic digestion. Partially treated water is discharged in the soil dispersal system. The solid fraction accumulates and remains in the tank for several years, during which time it degrades anaerobically. The gas produced from anaerobic sludge digestion (mainly CH_4 and biogenic CO_2) rises to the liquid surface and is typically released through vents. The gas produced in the effluent dispersal system (mainly N_2O and biogenic CO_2) is released through the soil.

Discharge. Dissolved CH_4 and N_2O that is present in wastewater discharges to aquatic environments has the potential to be released (Short et al. 2014; Short et al. 2017), and the presence of organic matter or nitrogen in wastewater discharges is generally expected to increase CH_4 and N_2O emissions from these aquatic environments. Where organic matter is released to slow-moving aquatic systems, such as lakes, estuaries, and reservoirs, CH_4 emissions are expected to be higher. Similarly, in the case of discharge to nutrient-impacted or hypoxic waters, N_2O emissions can be significantly higher.

In summary, the principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20°C, or BOD_5. Throughout the rest of this chapter, the term "BOD" refers to BOD_5. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production, since CH_4 is produced only in anaerobic conditions. Where present, biogas recovery and flaring operations reduce the amount of CH_4 generated that is actually emitted. Per IPCC guidelines (IPCC 2019), emissions from anaerobic sludge digestion, including biogas recovery and flaring operations, where the digester's primary use is for treatment of wastewater treatment solids, are reported under Wastewater Treatment. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential. The methods and underlying data sources to estimate emissions from are described in further detail in the "Methodology and Time Series Consistency" section below for treatment of domestic and industrial wastewater.

Overall, treatment of wastewater emitted 42.0 MMT CO_2 Eq. in 2021. Methane (CH_4) emissions from domestic wastewater treatment and discharge were estimated to be 11.9 MMT CO_2 Eq. (424 kt CH_4) and 2.0 MMT CO_2 Eq. (72 kt CH_4), respectively, totaling 13.9 MMT CO_2 Eq. (496 kt CH_4) in 2021. Emissions remained fairly steady from 1990 through 2002 but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, generally including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004a; U.S. Census Bureau 2019). In 2021, CH_4 emissions from industrial wastewater treatment and discharge were estimated to be 6.6 MMT CO_2 Eq. (237 kt CH_4) and 0.5 MMT CO_2 Eq. (19 kt CH_4), respectively, totaling 7.2 MMT CO_2 Eq. (256 kt CH_4). Industrial emissions from wastewater treatment have generally increased across the time series through 1999 and then fluctuated up and correspond with production changes from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries. Industrial wastewater emissions have generally seen an uptick since 2016. Table 7-7 and Table 7-8 provide CH_4 emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O, emissions from domestic wastewater treatment and discharge in 2021 were estimated to be 16.2 MMT CO_2 Eq. (61 kt N_2O) and 4.2 MMT CO_2 Eq. (16 kt N_2O), respectively, totaling 20.4 MMT CO_2 Eq. (77 kt N_2O). Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series because of increasing U.S. population and protein consumption. In 2021, N_2O emissions from industrial wastewater treatment and discharge were estimated to be 0.4 MMT CO_2 Eq. (1.5 kt N_2O) and 0.1 MMT CO_2 Eq. (0.3 kt N_2O), respectively, totaling 0.5 MMT CO_2 Eq. (1.7 kt N_2O). Industrial emission sources have gradually increased across the time series with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, petroleum refining, and brewery industries. Table 7-7 and Table 7-8 provide N_2O emission estimates from domestic wastewater treatment.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2017	2018	2019	2020	2021
CH_4	**22.7**	**22.7**	**21.5**	**21.4**	**21.2**	**21.3**	**21.1**
Domestic Treatment	15.1	14.6	12.6	12.3	11.9	12.1	11.9
Domestic Effluent	1.4	1.4	2.0	2.0	2.0	2.0	2.0
Industrial Treatment[a]	5.5	6.1	6.4	6.5	6.6	6.6	6.6
Industrial Effluent[a]	0.7	0.6	0.6	0.6	0.6	0.5	0.5
N_2O	**14.8**	**18.1**	**20.6**	**21.2**	**21.3**	**20.9**	**20.9**
Domestic Treatment	10.5	13.7	15.7	16.2	16.4	16.1	16.2
Domestic Effluent	3.9	3.9	4.4	4.5	4.5	4.3	4.2
Industrial Treatment[b]	0.3	0.4	0.4	0.4	0.5	0.4	0.4
Industrial Effluent[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**37.5**	**40.7**	**42.2**	**42.5**	**42.5**	**42.2**	**42.0**

[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.

[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

Note: Totals may not sum due to independent rounding.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2017	2018	2019	2020	2021
CH_4	**811**	**809**	**770**	**763**	**755**	**761**	**753**
Domestic Treatment	539	521	449	438	426	433	424
Domestic Effluent	49	49	72	73	73	72	72
Industrial Treatment[a]	196	216	229	232	236	237	237
Industrial Effluent[a]	27	22	20	20	20	19	19
N_2O	**56**	**68**	**78**	**80**	**80**	**79**	**79**
Domestic Treatment	40	52	59	61	62	61	61
Domestic Effluent	15	15	17	17	17	16	16
Industrial Treatment[b]	1	1	1	2	2	1	1
Industrial Effluent[b]	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.

[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

Note: Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2019) form the basis of the CH_4 and N_2O emission estimates for both domestic and industrial wastewater treatment and discharge.[7] Domestic wastewater treatment follows the IPCC Tier 2 methodology for key pathways, while domestic wastewater discharge follows IPCC Tier 2 discharge methodology and emission factors. Default factors from IPCC (2019) or IPCC (2006) are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor, though IPCC default factors are often based in part on data from or representative of U.S. wastewater treatment systems. Industrial wastewater treatment follows IPCC Tier 1 and wastewater treatment discharge follows Tier 1 or Tier 2 methodologies, depending on the industry. EPA will continue to implement the Tier 2 discharge methodology for more industries as data are investigated and time and resource constraints allow (see the Planned Improvements section below). Similar to domestic wastewater, IPCC default factors are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2021. In the following cases, the source used to capture activity data changed over the time series. EPA transitioned to these newer data sources to continue estimating emissions in a way that ensured both accuracy and continuity. For example:

- Starch-based ethanol production data: the source used for 1990 to 2017 production was no longer available after 2017. A new, publicly available source was identified and is used for production in 2015-2021. However, this source does not have sufficient data for the earlier timeseries. EPA confirmed with experts familiar with the sources that combining these two sources to populate the time series was accurate (ERG 2019; Lewis 2019) and does not present any significant discontinuities in the time series.
- Brewery production data: the source used for production changed in 2007 to publish craft brewery production broken out by size but does not include data prior to 2007. Therefore, rather than estimating total production data prior to 2007 with this source, another data source was used to ensure accuracy of production data through the time series (ERG 2018b).

Refer to the Recalculations section below for details on updates implemented to improve accuracy, consistency and/or completeness of the time series.

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems. Within these centralized systems, CH_4 emissions can arise from aerobic systems that liberate dissolved CH_4 that formed within the collection system or that are designed to have periods of anaerobic activity (e.g., constructed wetlands and facultative lagoons), anaerobic systems (anaerobic lagoons and anaerobic reactors), and from anaerobic sludge digesters when the captured biogas is not completely combusted. Emissions will also result from the discharge of treated effluent from centralized wastewater plants to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries). The systems with emissions estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);

[7] IPCC (2019) updates, supplements, and elaborates the *2006 IPCC Guidelines* where gaps or out-of-date science have been identified. EPA used these methodologies to improve completeness and include sources of greenhouse gas emissions that have not been estimated prior to the 1990-2019 Inventory, such as N_2O emissions from industrial wastewater treatment, and to improve emission estimates for other sources, such as emissions from wastewater discharge and centralized wastewater treatment.

- Centralized anaerobic systems (C);
- Anaerobic sludge digesters (D); and
- Centralized wastewater treatment effluent (E).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic CH_4 emissions are estimated as follows:

Equation 7-4: Total Domestic CH_4 Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic } CH_4 \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D + E$$

Table 7-9 presents domestic wastewater CH_4 emissions for both septic and centralized systems, including anaerobic sludge digesters and emissions from centralized wastewater treatment effluent, in 2021.

Table 7-9: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2021, kt, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (kt)	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems (A)	223	6.2	45.0
Centrally-Treated Aerobic Systems (B)	74	2.1	14.8
Centrally-Treated Anaerobic Systems (C)	119	3.3	24.1
Anaerobic Sludge Digesters (D)	8	0.2	1.6
Centrally-Treated Wastewater Effluent (E)	72	2.0	14.5
Total	**496**	**13.9**	**100**

Emissions from Septic Systems:

Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 17 percent in 2021; U.S. Census Bureau 2019) and an emission factor and then converting the result to kt/year.

U.S. population data were taken from historic U.S. Census Bureau national population totals data and include the populations of the United States and Puerto Rico (U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau 2021a and 2021b; Instituto de Estadísticas de Puerto Rico 2021). Population data for American Samoa, Guam, Northern Mariana Islands, and the U.S. Virgin Islands were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2022). Table 7-12 presents the total U.S. population for 1990 through 2021. The fraction of the U.S. population using septic systems or centralized treatment systems is based on data from the *American Housing Surveys* (U.S. Census Bureau 2019).

Methane emissions for septic systems are estimated as follows:

Equation 7-5: CH_4 Emissions from Septic Systems

$$\textit{Emissions from Septic Systems}\,(\text{U.S. Specific}) = A$$
$$= US_{POP} \times (T_{SEPTIC}) \times (EF_{SEPTIC}) \times 1/10^9 \times 365.25$$

Table 7-10: Variables and Data Sources for CH_4 Emissions from Septic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: US Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021)

Variable	Variable Description	Units	Inventory Years: Source of Value
			2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021a) 2020-2021: U.S. Census Bureau (2021b) U.S. Territories other than Puerto Rico: 1990-2021: U.S. Census Bureau (2022)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2019: U.S. Census Bureau (2019) Data for intervening years obtained by linear interpolation 2020-2021: Forecasted from the rest of the time series
EF_{SEPTIC}	Methane emission factor – septic systems (10.7)	g CH_4/capita/day	1990-2021: Leverenz et al. (2010)
$1/10^9$	Conversion factor	g to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of activity data varies over the Inventory time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Methane emissions from POTWs depend on the total organics in wastewater. Table 7-12 presents the total organically degradable material in wastewater, or TOW, for 1990 through 2021. The TOW was determined using BOD generation rates per capita weighted average both with and without kitchen scraps as well as an estimated percent of housing units that utilize kitchen garbage disposals. Households with garbage disposals (with kitchen scraps or ground up food scraps) typically have wastewater with higher BOD than households without garbage disposals due to increased organic matter contributions (ERG 2018a). The equations are as follows:

Equation 7-6: Total Wastewater BOD_5 Produced per Capita (U.S.-Specific [ERG 2018a])

$$BOD_{gen\ rate}\ (kg/capita/day) = BOD_{without\ scrap} \times (1 - \%kitchen\ disposal) + BOD_{with\ scraps} \times (\%kitchen\ disposal)$$

Equation 7-7: Total Organically Degradable Material in Domestic Wastewater (IPCC 2019 [Eq. 6.3])

$$TOW\ (Gg/year) = US_{POP} \times BOD_{gen\ rate} \times 365.25 \times 1/10^6$$

Table 7-11: Variables and Data Sources for Organics in Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
$BOD_{gen\ rate}$	Total wastewater BOD produced per capita	kg/capita/day	1990-2021: Calculated
$BOD_{without\ scrap}$	Wastewater BOD produced per capita without kitchen scraps[a]	kg/capita/day	1990-2003: Metcalf & Eddy (2003) 2004-2013: Linear interpolation 2014-2021: Metcalf & Eddy (2014)
$BOD_{with\ scraps}$	Wastewater BOD produced per capita with kitchen scraps[a]	kg/capita/day	
% kitchen disposal	Percent of housing units with kitchen	%	1990-2013: U.S. Census

	kitchen disposal[a]		Bureau (2013) 2014-2021: Forecasted from the rest of the time series
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2021: Calculated, ERG (2018a)
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: US Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau (2011) 2010-2019: U.S. Census Bureau (2021a) 2020-2021: U.S. Census Bureau (2021b) U.S. Territories other than Puerto Rico: 1990-2021: U.S. Census Bureau (2022)
365.25	Conversion factor	Days in a year	Standard conversion
$1/10^6$	Conversion factor	kg to Gg	Standard conversion

[a] Value of activity data varies over the Inventory time series.

Table 7-12: U.S. Population (Millions) and Domestic Wastewater TOW (kt)

Activity	1990	2005	2017	2018	2019	2020	2021
Population	253	300	329	330	332	335	336
TOW	8,131	9,624	9,894	9,958	10,019	10,132	10,159

Sources: U.S. Census Bureau (2002); U.S. Census Bureau (2011); U.S. Census Bureau (2021a and 2021b); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2022); ERG (2018a).

Methane emissions from POTWs were estimated by multiplying the total organics in centrally treated wastewater (total BOD_5) produced per capita in the United States by the percent of wastewater treated centrally, or percent collected (about 83 percent in 2021), the correction factor for additional industrial BOD discharged to the sewer system, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands), constructed wetlands only, and anaerobic systems, and the emission factor[8] for aerobic systems, constructed wetlands only, and anaerobic systems. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

In the United States, the removal of sludge[9] from wastewater reduces the biochemical oxygen demand of the wastewater that undergoes aerobic treatment. The amount of this reduction (S) is estimated using the default IPCC (2019) methodology and multiplying the amount of sludge removed from wastewater treatment in the United States by the default factors in IPCC (2019) to estimate the amount of BOD removed based on whether the treatment system has primary treatment with no anaerobic sludge digestion (assumed to be zero by expert

[8] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of domestic wastewater (B_0, 0.6 kg CH_4/kg BOD) and the appropriate methane correction factors (MCF) for aerobic (0.03) and anaerobic (0.8) systems (IPCC 2019, Table 6.3) and constructed wetlands (0.4) (IPCC 2014, Table 6.4).

[9] Throughout this document, the term "sludge" refers to the solids separated during the treatment of municipal wastewater. The definition includes domestic septage. "Biosolids" refers to treated sewage sludge that meets the EPA pollutant and pathogen requirements for land application and surface disposal.

judgment), primary treatment with anaerobic sludge digestion, or secondary treatment without primary treatment. The organic component removed from anaerobic wastewater treatment and the amount of CH_4 recovered or flared from both aerobic and anaerobic wastewater treatment were set equal to the IPCC default of zero.

The methodological equations for CH_4 emissions from aerobic and anaerobic systems are:

Equation 7-8: Total Domestic CH_4 Emissions from Centrally Treated Aerobic Systems

$$\textit{Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)}\ (B1) + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)}\ (B2) + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)}\ (B3) = B$$

where,

Equation 7-9: Total Organics in Centralized Wastewater Treatment [IPCC 2019 (Eq. 6.3A)]

$$TOW_{CENTRALIZED}\ (\text{Gg BOD/year}) = TOW \times T_{CENTRALIZED} \times I_{COLLECTED}$$

Table 7-13: Variables and Data Sources for Organics in Centralized Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
Centrally Treated Organics (Gg BOD/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2021: Calculated
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2021: Calculated, ERG (2018a)
$T_{CENTRALIZED}$	Percent collected[a]	%	1990-2019: U.S. Census Bureau (2019) Data for intervening years obtained by linear interpolation 2020-2021: Forecasted from the rest of the time series
$I_{COLLECTED}$	Correction factor for additional industrial BOD discharged (1.25)	No units	1990-2021: IPCC (2019) Eq. 6.3a

[a] Value of this activity data varies over the time series.

Equation 7-10: Organic Component Removed from Aerobic Wastewater Treatment (IPCC 2019 [Eq. 6.3B])

$$S_{aerobic}\ (\text{Gg/year}) = S_{mass} \times [(\%\ \text{aerobic w/primary} \times K_{rem,aer\_prim}) + (\%\ \text{aerobic w/out primary} \times K_{rem,aer\_noprim}) + (\%\text{aerobic+digestion} \times K_{rem,aer\_digest})] \times 1000$$

Equation 7-11: Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.1])

$$B1\ (\text{kt } CH_4\text{/year}) = [(TOW_{CENTRALIZED}) \times (\%\ \text{aerobic}_{OTCW}) - S_{aerobic}] \times EF_{aerobic} - R_{aerobic}$$

Table 7-14: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt CH_4/year)			
$S_{aerobic}$	Organic component removed from aerobic wastewater treatment[a]	Gg BOD/year	1990-2021: Calculated
S_{mass}	Raw sludge removed from wastewater treatment as dry mass[a]	Tg dry weight/year	1988: EPA (1993c); EPA (1999)

Variable	Variable Description	Units	Inventory Years: Source of Value
			1990-1995: Calculated based on sewage sludge production change per year EPA (1993c); EPA (1999); Beecher et al. (2007) 1996: EPA (1999) 2004: Beecher et al. (2007) Data for intervening years obtained by linear interpolation 2005-2017: Interpolated 2018: NEBRA (2022), as described in ERG (2022) 2019-2021: Forecasted from the rest of the time series. Methodology for estimating sludge generated from the U.S. territories provided in ERG (2022).
% $aerobic_{OTCW}$	Percent of flow to aerobic systems, other than wetlands[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2021: Forecasted from the rest of the time series
% aerobic w/primary	Percent of aerobic systems with primary treatment and no anaerobic sludge digestion (0)	%	
% aerobic w/out primary	Percent of aerobic systems without primary treatment[a]	%	
%aerobic+digestion	Percent of aerobic systems with primary and anaerobic sludge digestion[a]	%	
K_{rem,aer_prim}	Sludge removal factor for aerobic treatment plants with primary treatment (mixed primary and secondary sludge, untreated or treated aerobically) (0.8)	kg BOD/kg sludge	1990-2021: IPCC (2019) Table 6.6a
K_{rem,aer_noprim}	Sludge removal factor for aerobic wastewater treatment plants without separate primary treatment (1.16)	kg BOD/kg sludge	
K_{rem,aer_digest}	Sludge removal factor for aerobic treatment plants with primary treatment and anaerobic sludge digestion (mixed primary and secondary sludge, treated anaerobically) (1)	kg BOD/kg sludge	
$EF_{aerobic}$	Emission factor – aerobic systems (0.018)	kg CH_4/kg BOD	1990-2021: IPCC (2019) Table 6.3
$R_{aerobic}$	Amount CH_4 recovered or flared from aerobic wastewater treatment (0)	kg CH_4/year	1990-2021: IPCC (2019) Eq. 6.1
1000	Conversion factor	metric tons to kilograms	Standard conversion

[a] Value of this activity data varies over the time series.

Constructed wetlands exhibit both aerobic and anaerobic treatment (partially anaerobic treatment) but are referred to in this chapter as aerobic systems. Constructed wetlands may be used as the sole treatment unit at a centralized wastewater treatment plant or may serve as tertiary treatment after simple settling and biological treatment. Emissions from all constructed wetland systems were included in the estimates of emissions from centralized wastewater treatment plant processes and effluent from these plants. Methane emissions equations from constructed wetlands used as sole treatment were previously described. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

For constructed wetlands, an IPCC default emission factor for surface flow wetlands was used. This is the most conservative factor for constructed wetlands and was recommended by IPCC (2014) when the type of constructed wetland is not known. A median BOD_5 concentration of 9.1 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. This median value is based on plants generally utilizing simple settling and biological treatment (EPA 2013). Constructed wetlands do not have secondary sludge removal.

Equation 7-12: Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) [IPCC 2014 (Eq. 6.1)]

$$\text{B2 (kt CH}_4\text{/year)} = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\text{aerobic}_{\text{CW}})] \times (\text{EF}_{\text{CW}})$$

Equation 7-13: Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S. Specific)

$$\text{B3 (kt CH}_4\text{/year)} = [(\text{POTW\_flow\_CW}) \times (\text{BOD}_{\text{CW,INF}}) \times 3.785 \times (\text{EF}_{\text{CW}})] \times 1/10^6 \times 365.25$$

Table 7-15: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2021: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs.[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2021: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2021: IPCC (2014)
Emissions from Constructed Wetlands used as Tertiary Treatment (kt CH_4/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2021: Forecasted from the rest of the time series
$BOD_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (9.1)	mg/L	1990-2021: EPA (2013)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2021: IPCC (2014)
$1/10^6$	Conversion factor	kg to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the time series.

Data sources and methodologies for centrally treated anaerobic systems are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-14: Emissions from Centrally Treated Anaerobic Systems [IPCC 2019 (Eq. 6.1)]

$$C\ (\text{kt } CH_4/\text{year}) = [(TOW_{CENTRALIZED}) \times (\%\ \text{anaerobic}) - S_{anaerobic}] \times EF_{anaerobic} - R_{anaerobic}$$

Table 7-16: Variables and Data Sources for CH_4 Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2021: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2021: Forecasted from the rest of the time series
$S_{anaerobic}$	Organic component removed from anaerobic wastewater treatment (0)	Gg/year	1990-2021: IPCC (2019) Table 6.3
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0.48)	kg CH_4/kg BOD	
$R_{anaerobic}$	Amount CH_4 recovered or flared from anaerobic wastewater treatment (0)	kg CH_4/year	

[a] Value of this activity data varies over the time series.

Emissions from Anaerobic Sludge Digesters:

Total CH_4 emissions from anaerobic sludge digesters were estimated by multiplying the wastewater influent flow to POTWs with anaerobic sludge digesters, the cubic feet of digester gas generated per person per day divided by the flow to POTWs, the fraction of CH_4 in biogas, the density of CH_4, one minus the destruction efficiency from burning the biogas in an energy/thermal device and then converting the results to kt/year.

Equation 7-15: Emissions from Anaerobic Sludge Digesters (U.S. Specific)

$$D\ (\text{kt } CH_4/\text{year}) = [(\text{POTW\_flow\_AD}) \times (\text{biogas gen})/(100)] \times 0.0283 \times (\text{FRAC\_}CH_4) \times 365.25 \times (662) \times (1\text{-DE}) \times 1/10^9$$

Table 7-17: Variables and Data Sources for Emissions from Anaerobic Sludge Digesters

Variable	Variable Description	Units	Inventory years: Source of Value
Emissions from Anaerobic Sludge Digesters (kt CH_4/year)			
POTW_flow_AD	POTW Flow to Facilities with Anaerobic Sludge Digesters[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, and 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2021: Forecasted from the rest of the time series

Variable	Variable Description	Units	Inventory years: Source of Value
biogas gen	Gas Generation Rate (1.0)	ft^3/capita/day	1990-2021: Metcalf & Eddy (2014)
100	Per Capita POTW Flow (100)	gal/capita/day	1990-2021: Ten-State Standards (2004)
0.0283	Conversion factor	ft^3 to m^3	Standard Conversion
FRAC_CH_4	Proportion of Methane in Biogas (0.65)	No units	1990-2021: Metcalf & Eddy (2014)
365.25	Conversion factor	Days in a year	Standard conversion
662	Density of Methane (662)	g CH_4/m^3 CH_4	1990-2021: EPA (1993a)
DE	Destruction Efficiency (99% converted to fraction)	No units	1990-2021: EPA (1998b); CAR (2011); Sullivan (2007); Sullivan (2010); and UNFCCC (2012)
$1/10^9$	Conversion factor	g to kt	Standard conversion

[a] Value of this activity data varies over the time series.

Emissions from Discharge of Centralized Treatment Effluent:

Methane emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge. The BOD in treated effluent was determined by multiplying the total organics in centrally treated wastewater by the percent of wastewater treated in primary, secondary, and tertiary treatment, and the fraction of organics remaining after primary treatment (one minus the fraction of organics removed from primary treatment, secondary treatment, and tertiary treatment).

Equation 7-16: Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$\mathrm{E\ (kt\ CH_4/year)} = (\mathrm{TOW_{RLE}} \times \mathrm{EF_{RLE}}) + (\mathrm{TOW_{Other}} \times \mathrm{EF_{Other}})$$

where,

Equation 7-17: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.3D])

$$\mathrm{TOW_{EFFtreat,CENTRALIZED}\ (Gg\ BOD/year)} = [\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{primary} \times (1\text{-}\mathrm{TOW_{rem,PRIMARY}})] + [\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{secondary} \times (1\text{-}\mathrm{TOW_{rem,SECONDARY}})] + [\mathrm{TOW_{CENTRALIZED}} \times \%\ \mathrm{tertiary} \times (1\text{-}\mathrm{TOW_{rem,TERTIARY}})]$$

Equation 7-18: Total Organics in Effluent Discharged to Reservoirs, Lakes, or Estuaries (U.S.-Specific)

$$\mathrm{TOW_{RLE}\ (Gg\ BOD/year)} = \mathrm{TOW_{EFFtreat,CENTRALIZED}} \times \mathrm{Percent_{RLE}}$$

Equation 7-19: Total Organics in Effluent Discharged to Other Waterbodies (U.S.-Specific)

$$\mathrm{TOW_{Other}\ (Gg\ BOD/year)} = \mathrm{TOW_{EFFtreat,CENTRALIZED}} \times \mathrm{Percent_{Other}}$$

Table 7-18: Variables and Data Sources for CH_4 Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$\mathrm{TOW_{EFFtreat,CENTRALIZED}}$	Total organics in centralized treatment effluent[a]	Gg BOD/year	1990-2021: Calculated
$\mathrm{TOW_{CENTRALIZED}}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2021: Calculated

Variable	Variable Description	Units	Source of Value
% primary	Percent of primary domestic centralized treatment[a]	%	1990,1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation. 2013-2021: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	
$TOW_{rem,PRIMARY}$	Fraction of organics removed from primary domestic centralized treatment (0.4)	No units	1990-2021: IPCC (2019) Table 6.6B
$TOW_{rem,SECONDARY}$	Fraction of organics removed from secondary domestic centralized treatment (0.85)	No units	
$TOW_{rem,TERTIARY}$	Fraction of organics removed from tertiary domestic centralized treatment (0.90)	No units	
TOW_{RLE}	Total organics in effluent discharged to reservoirs, lakes, and estuaries[a]	Gg BOD/year	1990-2021: Calculated
TOW_{Other}	Total organics in effluent discharge to other waterbodies[a]	Gg BOD/year	
EF_{RLE}	Emission factor (discharge to reservoirs/lakes/estuaries) (0.114)	kg CH_4/kg BOD	1990-2021: IPCC (2019) Table 6.8
EF_{Other}	Emission factor (discharge to other waterbodies) (0.021)	kg CH_4/kg BOD	
$Percent_{RLE}$	% discharged to reservoirs, lakes, and estuaries[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2021: Set equal to 2012
$Percent_{Other}$	% discharged to other waterbodies[a]	%	

[a] Value of this activity data varies over the time series.

Industrial Wastewater CH_4 Emission Estimates

Industrial wastewater CH_4 emissions originate from on-site treatment systems, typically comprised of biological treatment operations. The collection systems at an industrial plant are not as extensive as domestic wastewater sewer systems; therefore, it is not expected that dissolved CH_4 will form during collection. However, some treatment systems are designed to have anaerobic activity (e.g., anaerobic reactors or lagoons), or may periodically have anaerobic conditions form (facultative lagoons or large stabilization basins). Emissions will also result from discharge of treated effluent to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries).

Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the Inventory. The main criteria used to identify U.S. industries likely to generate CH_4 from wastewater treatment are whether an industry generates high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The

top six industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; petroleum refining; and breweries. Wastewater treatment and discharge emissions for these sectors for 2021 are displayed in Table 7-19 below. Further discussion of wastewater treatment for each industry is included below.

Table 7-19: Total Industrial Wastewater CH_4 Emissions by Sector (2021, MMT CO_2 Eq. and Percent)

Industry	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	5.7	78.9
Pulp & Paper	0.8	11.6
Fruit & Vegetables	0.2	3.3
Ethanol Refineries	0.2	2.3
Breweries	0.1	2.2
Petroleum Refineries	0.2	1.6
Total	**7.2**	**100**

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

Equation 7-20 presents the general IPCC equation (Equation 6.4, IPCC 2019) to estimate methane emissions from each type of treatment system used for each industrial category.

Equation 7-20: Total CH_4 Emissions from Industrial Wastewater

$$CH_4 \text{ (industrial sector)} = [(TOW_i - S_i) \times EF - R_i]$$

where,

CH_4 (industrial sector) = Total CH_4 emissions from industrial sector wastewater treatment (kg/year)
i = Industrial sector
TOW_i = Total organics in wastewater for industrial sector *i* (kg COD/year)
S_i = Organic component removed from aerobic wastewater treatment for industrial sector *i* (kg COD/year)
EF = System-specific emission factor (kg CH_4/kg COD)
R_i = Methane recovered for industrial sector *i* (kg CH_4/year)

Equation 7-21 presents the general IPCC equation to estimate the total organics in wastewater (TOW) for each industrial category.

Equation 7-21: TOW in Industry Wastewater Treatment Systems

$$TOW_i = P_i \times W_i \times COD_i$$

where,

TOW_i = Total organically degradable material in wastewater for industry *i* (kg COD/yr)
i = Industrial sector
P_i = Total industrial product for industrial sector *i* (t/yr)
W_i = Wastewater generated (m^3/t product)
COD_i = Chemical oxygen demand (industrial degradable organic component in wastewater) (kg COD/m^3)

The annual industry production is shown in Table 7-20, and the average wastewater outflow and the organics loading in the outflow is shown in Table 7-21.

For some industries, U.S.-specific data on organics loading is reported as BOD rather than COD. In those cases, an industry-specific COD:BOD ratio is used to convert the organics loading to COD.

The amount of organics treated in each type of wastewater treatment system was determined using the percent of wastewater in the industry that is treated on site and whether the treatment system is anaerobic, aerobic or partially anaerobic. Table 7-22 presents the industrial wastewater treatment activity data used in the calculations and described in detail in ERG (2008a), ERG (2013a), ERG (2013b), and ERG (2021a). For CH_4 emissions, wastewater treated in anaerobic lagoons or reactors was categorized as "anaerobic", wastewater treated in aerated stabilization basins or facultative lagoons were classified as "ASB" (meaning there may be pockets of anaerobic activity), and wastewater treated in aerobic systems such as activated sludge systems were classified as "aerobic/other."

The amount of organic component removed from aerobic wastewater treatment as a result of sludge removal ($S_{aerobic}$) was either estimated as an industry-specific percent removal, if available, or as an estimate of sludge produced by the treatment system and IPCC default factors for the amount of organic component removed (K_{rem}), using one of the following equations. Table 7-23 presents the sludge variables used for industries with aerobic wastewater treatment operations (i.e., pulp and paper, fruit/vegetable processing, and petroleum refining).

Equation 7-22: Organic Component Removed from Aerobic Wastewater Treatment – Pulp, Paper, and Paperboard

$$S_{pulp,asb} = TOW_{pulp} \times \% \text{ removal w/primary}$$

where,

$S_{pulp,asb}$	=	Organic component removed from pulp and paper wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
TOW_{pulp}	=	Total organically degradable material in pulp and paper wastewater (Gg COD/yr)
% removal w/primary	=	Percent reduction of organics in pulp and paper wastewater associated with sludge removal from primary treatment (%)

Equation 7-23: Organic Component Removed from Aerobic Treatment Plants

$$S_{aerobic} = S_{mass} \times K_{rem} \times 10^{-6}$$

where,

$S_{aerobic}$	=	Organic component removed from fruit and vegetable or petroleum refining wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
S_{mass}	=	Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
K_{rem}	=	Sludge factor (kg BOD/kg sludge)
10^{-6}	=	Conversion factor, kilograms to Gigagrams

Equation 7-24: Raw Sludge Removed from Wastewater Treatment as Dry Mass

$$S_{mass} = (S_{prim} + S_{aer}) \times P \times W$$

where,

S_{mass}	=	Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
S_{prim}	=	Sludge production from primary sedimentation (kg sludge/m^3)
S_{aer}	=	Sludge production from secondary aerobic treatment (kg sludge/m^3)
P	=	Production (t/yr)
W	=	Wastewater Outflow (m^3/t)

Default emission factors[10] from IPCC (2019) were used. Information on methane recovery operations varied by industry. See industry descriptions below.

Table 7-20: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, Breweries, and Petroleum Refining Production (MMT)

Year	Pulp and Paper[a]	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol Production	Breweries	Petroleum Refining
1990	83.6	27.3	14.6	40.8	2.5	23.9	702.4
2005	92.4	31.4	25.1	45.3	11.7	23.1	818.6
2017	80.3	35.4	28.9	42.4	47.6	21.8	933.5
2018	78.7	36.4	29.4	42.3	48.1	21.5	951.7
2019	76.3	37.4	30.1	41.8	47.1	21.1	940.0
2020	74.7	37.8	30.5	40.6	41.6	21.1	806.5
2021	73.6	38.1	30.5	39.4	44.8	21.2	857.3

[a] Pulp and paper production is the sum of market pulp production plus paper and paperboard production.

Sources: Pulp and Paper – FAO (2022a) and FAO (2022b); Meat, Poultry, and Fruits and Vegetables – USDA (2022a and 2022b), ERG (2022); Ethanol – Cooper (2018) and RFA (2022a and 2022b); Breweries – Beer Institute (2011) and TTB (2022); Petroleum Refining – EIA (2022).

Table 7-21: U.S. Industrial Wastewater Characteristics Data (2021)

Industry	Wastewater Outflow (m^3/ton)	Wastewater BOD (g/L)	Wastewater COD (kg/m^3)	COD:BOD Ratio
Pulp and Paper	See Table 7-25	0.3	--	2.5
Meat Processing	5.3	2.8	--	3
Poultry Processing	12.5	1.5	--	3
Fruit/Vegetable Processing	See Table 7-26		--	1.5
Ethanol Production – Wet Mill	10[a]	1.5	--	2
Ethanol Production – Dry Mill	1.25[a]	3[b]	--	2
Petroleum Refining	0.8	--	0.45	2.5
Breweries – Craft	3.09	--	17.6	1.67
Breweries – NonCraft	1.94	--	17.6	1.67

[a] Units are gallons per gallons ethanol produced.

[b] Units are COD (g/L).

Sources: Pulp and Paper (BOD, COD:BOD) – Malmberg (2018); Meat and Poultry (Outflow, BOD) – EPA (2002); Meat and Poultry (COD:BOD) – EPA (1997a); Fruit/Vegetables (Outflow, BOD) – CAST (1995), EPA (1974), EPA (1975); Fruit/Vegetables (COD:BOD) – EPA (1997a); Ethanol Production – Wet Mill (Outflow) – Donovan (1996), NRBP (2001), Ruocco (2006a); Ethanol Production – Wet Mill (BOD) – White and Johnson (2003); Ethanol Production – Dry Mill (Outflow and COD) – Merrick (1998), Ruocco (2006a); Ethanol Production (Dry and Wet, COD:BOD) – EPA (1997a); Petroleum Refining (Outflow) – ERG (2013b); Petroleum Refining (COD) – Benyahia et al. (2006); Petroleum Refining (COD:BOD) – EPA (1982); Breweries – Craft BIER (2017); ERG (2018b); Breweries – NonCraft ERG (2018b); Brewers Association (2016a); Breweries (Craft and NonCraft; COD and COD:BOD) – Brewers Association (2016b).

[10] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of wastewater (B_0, 0.25 kg CH_4/kg COD) and the appropriate methane correction factors (MCF) for aerobic (0), partially anaerobic (0.2), and anaerobic (0.8) systems (IPCC 2019), Table 6.3.

Table 7-22: U.S. Industrial Wastewater Treatment Activity Data

Industry	% Wastewater Treated On Site	% Treated Anaerobically	% Treated Aerobically	% Treated Aerobically	
				% Treated in ASBs	% Treated in Other Aerobic
Pulp and Paper[b]	60	5.2	75.9	38.5	37.4
Meat Processing	33	33[a]	33	0	33
Poultry Processing	25	25[a]	25	0	25
Fruit/Vegetable Processing	11	0	11	5.5	5.5
Ethanol Production – Wet Mill	33.3	33.3	66.7	0	0
Ethanol Production – Dry Mill	75	75	25	0	0
Petroleum Refining	62.1	0	62.1	23.6	38.5
Breweries – Craft	0.5	0.5	0	0	0
Breweries – NonCraft	100	99	1	0	1

[a] Wastewater is pretreated in anaerobic lagoons prior to aerobic treatment.
[b] Remaining onsite treated in other treatment assumed to be non-emissive and not shown here.
Note: Due to differences in data availability and methodology, zero values in the table are for calculation purposes only and may indicate unavailable data.
Sources: ERG (2008b); ERG (2013a); ERG (2013b); ERG (2021a).

Table 7-23: Sludge Variables for Aerobic Treatment Systems

Variable	Industry		
	Pulp and Paper	Fruit/Vegetable Processing	Petroleum Refining
Organic reduction associated with sludge removal (%)	58		
Sludge Production (kg/m^3)			
Primary Sedimentation		0.15	
Aerobic Treatment		0.096	0.096
Sludge Factor (kg BOD/kg dry mass sludge)			
Aerobic Treatment w/Primary Sedimentation and No Anaerobic Sludge Digestion		0.8	
Aerobic Treatment w/out Primary Sedimentation			1.16

Sources: Organic reduction (pulp) – ERG (2008a); Sludge production – Metcalf & Eddy (2003); Sludge factors – IPCC (2019), Table 6.6a.

Emissions from Discharge of Industrial Wastewater Treatment Effluent:

Methane emissions from discharge of industrial wastewater treatment effluent are estimated via a Tier 1 method for all industries except for pulp, paper, and paperboard. Emissions from discharge of pulp, paper, and paperboard treatment effluent is estimated via a Tier 2 method and is described in the industry-specific data section. Tier 1 emissions from effluent are estimated by multiplying the total organic content of the discharged wastewater effluent by an emission factor associated with the discharge:

Equation 7-25: CH_4 Emissions from Industrial Wastewater Treatment Discharge

$$CH_4\ \text{Effluent}_{IND} = TOW_{EFFLUENT,IND} \times EF_{EFFLUENT}$$

where,

$CH_4\ \text{Effluent}_{IND}$ = CH_4 emissions from industrial wastewater discharge for inventory year (kg CH_4/year)
$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)

$EF_{EFFLUENT}$ = Tier 1 emission factor for wastewater discharged to aquatic environments (0.028 kg CH_4/kg COD or 0.068 kg CH_4/kg BOD) (IPCC 2019)

The COD or BOD in industrial treated effluent ($TOW_{EFFLUENT,IND}$) was determined by multiplying the total organics in the industry's untreated wastewater that is treated on site by an industry-specific percent removal where available or a more general percent removal based on biological treatment for other industries. Table 7-22 presents the percent of wastewater treated onsite, while Table 7-24 presents the fraction of TOW removed during treatment.

Equation 7-26: TOW in Industrial Wastewater Effluent

$$TOW_{EFFLUENT,IND} = TOW_{IND} * \%onsite * (1 - TOW_{REM})$$

where,

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)
TOW_{IND} = Total organics in untreated wastewater for industry for inventory year (kg COD/year)
%onsite = Percent of industry wastewater treated on site (%)
TOW_{REM} = Fraction of organics removed during treatment

Table 7-24: Fraction of TOW Removed During Treatment by Industry

Industry	TOW_{REM}	Source
Pulp, Paper, and Paperboard	0.905	Malmberg (2018)
Red Meat and Poultry	0.85	IPCC (2019), Table 6.6b
Fruits and Vegetables	0.85	IPCC (2019), Table 6.6b
Ethanol Production		
Biomethanator Treatment	0.90	ERG (2008a), ERG (2006b)
Other Treatment	0.85	IPCC (2019), Table 6.6b
Petroleum Refining	0.93	Kenari, Sarrafzadeh, and Tavakoli (2010)
Breweries	0.85	IPCC (2019), Table 6.6b

Discussion of Industry-Specific Data:

Pulp, Paper, and Paperboard Manufacturing Wastewater Treatment. Wastewater treatment for the pulp, paper, and paperboard manufacturing (hereinafter referred to as "pulp and paper") industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999; Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. About 60 percent of pulp and paper mills have on-site treatment with primary treatment and about half of these also have secondary treatment (ERG 2008). In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b).

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Pulp and paper mill wastewater treated using anaerobic ponds or lagoons or unaerated ponds were classified as anaerobic (with an MCF of 0.8). Wastewater flow treated in systems with aerated stabilization basins or facultative lagoons was classified as partially anaerobic (with an MCF of 0.2, which is the *2006 IPCC Guidelines*-suggested MCF for shallow lagoons). Wastewater flow treated in systems with activated sludge systems or similarly aerated biological systems was classified as aerobic.

A time series of CH_4 emissions for 1990 through 2021 was developed based on paper and paperboard production data and market pulp production data. Market pulp production values were available directly for 1998, 2000 through 2003, and 2010 through 2020. Where market pulp data were unavailable, a percent of woodpulp that is

market pulp was applied to woodpulp production values from FAOSTAT to estimate market pulp production (FAO 2022a). The percent of woodpulp that is market pulp for 1990 to 1997 was assumed to be the same as 1998, 1999 was interpolated between values for 1998 and 2000, 2000 through 2009 were interpolated between values for 2003 and 2010, and 2021 was forecasted from the rest of the time series. A time series of the overall wastewater outflow in units of cubic meters of wastewater per ton of total production (i.e., market pulp plus woodpulp) is presented in Table 7-25. Data for 1990 through 1994 varies based on data outlined in ERG (2013a) to reflect historical wastewater flow. Wastewater generation rates for 1995, 2000, and 2002 were estimated from the 2014 *American Forest and Paper Association* (AF&PA) *Sustainability Report* (AF&PA 2014). Wastewater generation rates for 2004, 2006, 2008, 2010, 2012, and 2014 were estimated from the 2016 AF&PA Sustainability Report (AF&PA 2016). Data for 2005 and 2016 were obtained from the 2018 AF&PA Sustainability Report (AF&PA 2018), data for 2018 were obtained from the 2020 AF&PA Sustainability Report (AF&PA 2020), and data for 2020 were obtained from a 2022 AF&PA sustainability update (AF&PA 2022). Data for intervening years were obtained by linear interpolation, while 2021 was set equal to 2020. The average BOD concentration in raw wastewater was estimated to be 0.4 grams BOD/liter for 1990 to 1998, while 0.3 grams BOD/liter was estimated for 2014 through 2021 (EPA 1997b; EPA 1993b; World Bank 1999; Malmberg 2018). Data for intervening years were obtained by linear interpolation.

Table 7-25: Wastewater Outflow (m^3/ton) for Pulp, Paper, and Paperboard Mills

Year	Wastewater Outflow (m^3/ton)
1990	68
2005	43
2017	39
2018	40
2019	39
2020	39
2021	39

Sources: ERG (2013a), AF&PA (2014), AF&PA (2016), AF&PA (2018), AF&PA (2020); AF&PA (2022)

Pulp, Paper, and Paperboard Wastewater Treatment Effluent. Methane emissions from pulp, paper, and paperboard wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge.

Equation 7-27: Emissions from Pulp and Paper Discharge (U.S. Specific)

$$\textit{Emissions from Pulp and Paper Discharge}\ (\text{U.S. Specific, kt } CH_4/\text{year}) = (\text{TOW}_{\text{RLE,pulp}} \times \text{EF}_{\text{RLE}}) + (\text{TOW}_{\text{Other,pulp}} \times \text{EF}_{\text{Other}})$$

Equation 7-28: Total Organics in Pulp and Paper Effluent Discharged to Reservoirs, Lakes, Or Estuaries (U.S. Specific)

$$\text{TOW}_{\text{RLE,pulp}}\ (\text{Gg BOD/year}) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{RLE,pulp}}$$

Equation 7-29: Total Organics in Pulp and Paper Effluent Discharged to Other Waterbodies (U.S. Specific)

$$\text{TOW}_{\text{Other,pulp}}\ (\text{Gg BOD/year}) = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{Percent}_{\text{Other,pulp}}$$

where,

$TOW_{RLE,pulp}$ = Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to reservoirs, lakes, or estuaries (Gg BOD/year)

EF_{RLE} = Emission factor (discharge to reservoirs/lakes/estuaries) (0.114 kg CH_4/kg BOD) (IPCC 2019)

$TOW_{Other,pulp}$ = Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to other waterbodies (Gg BOD/year)

EF_{Other} = Emission factor (discharge to other waterbodies) (0.021 kg CH_4/kg BOD) (IPCC 2019)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in pulp, paper, and paperboard manufacturing wastewater effluent for inventory year (Gg BOD/year)

$Percent_{RLE,pulp}$ = Percent of wastewater effluent discharged to reservoirs, lakes, and estuaries (ERG 2021b)

$Percent_{Other,pulp}$ = Percent of wastewater effluent discharged to other waterbodies (ERG 2021b)

The percent of pulp, paper, and paperboard wastewater treatment effluent routed to reservoirs, lakes, or estuaries (3 percent) and other waterbodies (97 percent) were obtained from discussions with NCASI (ERG 2021b). Data for 2019 were assumed the same as the rest of the time series due to lack of available data. Default emission factors for reservoirs, lakes, and estuaries (0.114 kg CH_4/kg BOD) and other waterbodies (0.021 kg CH_4/kg BOD) were obtained from IPCC (2019).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. Although all meat and poultry processing facilities conduct some sort of treatment on site, about 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems.

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. About half of the operations that treat and discharge wastewater use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Wastewater treated in partially anaerobic systems were assigned the IPCC default emission factor of 0.12 kg CH_4/kg BOD. Outflow and BOD data, presented in Table 7-26, were obtained from CAST (1995) for apples, apricots, asparagus, broccoli, carrots, cauliflower, cucumbers (for pickles), green peas, pineapples, snap beans, and spinach; EPA (1974) for potato and citrus fruit processing; and EPA (1975) for all other commodities.

Table 7-26: Wastewater Outflow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	Organic Content in Untreated Wastewater (g BOD/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	9.85	0.751
Fruit		
Apples	9.08	8.16
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.59	1.226
Grapes (for wine)	2.78	1.831

Sources: CAST (1995); EPA (1974); EPA (1975).

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises a very small percent of ethanol production in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other sugar or starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement and is more efficient in terms of actual ethanol production (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic sludge digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006b).

About 33 percent of wet milling facilities and 75 percent of dry milling facilities treat their wastewater anaerobically. A default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment was used to estimate the CH_4 produced from these on-site treatment systems. The amount of CH_4 recovered through the use of biomethanators was estimated, and a 99 percent destruction efficiency was used. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006b). For facilities using biomethanators, approximately 90 percent of BOD is removed during on-site treatment (ERG 2006b, 2008). For all other facilities, the removal of organics was assumed to be equivalent to secondary treatment systems, or 85 percent (IPCC 2019).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[11] Facilities that reported using non-aerated surface impoundments or other biological treatment units (trickling filter, rotating biological contactor), which have the potential to lead to anaerobic conditions, were assigned the IPCC default emission factor of 0.05 kg CH_4/kg COD. In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product, or 0.8 m^3/ton (ERG 2013b).

Breweries. Since 2010, the number of breweries has increased from less than 2,000 to more than 8,000 (Brewers Association 2021). This increase has primarily been driven by craft breweries, which have increased by over 250 percent during that period. Craft breweries were defined as breweries producing less than six million barrels of beer per year, and non-craft breweries produce greater than six million barrels. With their large amount of water use and high strength wastewater, breweries generate considerable CH_4 emissions from anaerobic wastewater treatment. However, because many breweries recover their CH_4, their emissions are much lower.

The Alcohol and Tobacco Tax and Trade Bureau (TTB) provides total beer production in barrels per year for different facility size categories from 2007 to the present (TTB 2022). For years prior to 2007 where TTB data were not readily available, the Brewers Almanac (Beer Institute 2011) was used, along with an estimated percent of craft and non-craft breweries based on the breakdown of craft and non-craft for the years 2007 through 2020.

[11] Available online at https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector.

To determine the overall amount of wastewater produced, data on water use per unit of production and a wastewater-to-water ratio were used from the Benchmarking Report (Brewers Association 2016a) for both craft and non-craft breweries. Since brewing is a batch process, and different operations have varying organic loads, full-strength brewery wastewater can vary widely on a day-to-day basis. However, the organic content of brewery wastewater does not substantially change between craft and non-craft breweries. Some breweries may collect and discharge high strength wastewater from particular brewing processes (known as "side streaming") to a POTW, greatly reducing the organics content of the wastewater that is treated on site. Subsequently, the MCF for discharge to a POTW was assumed to be zero (ERG 2018b).

Breweries may treat some or all of their wastewater on site prior to discharge to a POTW or receiving water. On-site treatment operations can include physical treatment (e.g., screening, settling) which are not expected to contribute to CH_4 emissions, or biological treatment, which may include aerobic treatment or pretreatment in anaerobic reactors (ERG 2018b). The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment and 0 for aerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems (IPCC 2006). The amount of CH_4 recovered through anaerobic wastewater treatment was estimated, and a 99 percent destruction efficiency was used (ERG 2018b; Stier J. 2018). Very limited activity data are available on the number of U.S. breweries that are performing side streaming or pretreatment of wastewater prior to discharge.

Domestic Wastewater N_2O Emission Estimates

Domestic wastewater N_2O emissions originate from both septic systems and POTWs. Within these centralized systems, N_2O emissions can result from aerobic systems, including systems like constructed wetlands. Emissions will also result from discharge of centrally treated wastewater to waterbodies with nutrient-impacted/eutrophic conditions. The systems with emission estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C); and
- Centralized wastewater treatment effluent (D).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic N_2O emissions are estimated as follows:

Equation 7-30: Total Domestic N_2O Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic } N_2O \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D$$

Table 7-27 presents domestic wastewater N_2O emissions for both septic and centralized systems, including emissions from centralized wastewater treatment effluent, in 2021.

Table 7-27: Domestic Wastewater N_2O Emissions from Septic and Centralized Systems (2021, kt, MMT CO_2 Eq. and Percent)

	N_2O Emissions (kt)	N_2O Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater N_2O
Septic Systems	3	0.8	3.8
Centrally-Treated Aerobic Systems	58	15.4	75.5
Centrally-Treated Anaerobic Systems	+	+	+
Centrally-Treated Wastewater Effluent	16	4.2	20.7
Total	**77**	**20.4**	**100**

+ Does not exceed 0.5 kt or 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Emissions from Septic Systems:

Nitrous oxide emissions from domestic treatment depend on the nitrogen present, in this case, in the form of protein. Per capita protein consumption (kg protein/person/year) was determined by multiplying per capita annual food availability data and its protein content. Those data are then adjusted using a factor to account for the fraction of protein actually consumed. The methodological equations are:

Equation 7-31: Annual per Capita Protein Supply (U.S. Specific)

$$\text{Protein}_{\text{SUPPLY}}\ (\text{kg/person/year}) = \text{Protein}_{\text{per capita}}/1000 \times 365.25$$

Equation 7-32: Consumed Protein [IPCC 2019 (Eq. 6.10A)]

$$\text{Protein}\ (\text{kg/person/year}) = \text{Protein}_{\text{SUPPLY}} \times \text{FPC}$$

Table 7-28: Variables and Data Sources for Protein Consumed

Variable	Variable Description	Units	Inventory Years: Source of Value
Protein			
$\text{Protein}_{\text{SUPPLY}}$	Annual per capita protein supply[a]	kg/person/year	1990-2021: Calculated
$\text{Protein}_{\text{per capita}}$	Daily per capita protein supply[a]	g/person/day	1990-2021: USDA (2021b)
1000	Conversion factor	g to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
FPC	Fraction of Protein Consumed[a]	kg protein consumed / kg protein available	1990-2010: USDA (2021) 2011-2019: FAO (2022c) and scaling factor 2020-2021: Forecasted from the rest of the time series

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 17 percent in 2021; U.S. Census Bureau 2019), consumed protein per capita (kg protein/person/year), the fraction of N in protein, the correction factor for additional nitrogen from household products, the factor for industrial and commercial co-discharged protein into septic systems, the factor for non-consumed protein added to wastewater and an emission factor and then converting the result to kt/year. All factors obtained from IPCC (2019).

U.S. population data were taken from historic U.S. Census Bureau national population totals data and include the populations of the United States and Puerto Rico (U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau 2021a and 2021b, Instituto de Estadísticas de Puerto Rico 2021). Population data for American Samoa, Guam, Northern Mariana Islands, and the U.S. Virgin Islands were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2022). Table 7-12 presents the total U.S. population for 1990 through 2021. The fraction of the U.S. population using septic systems, as well as centralized treatment systems (see below), is based on data from *American Housing Survey* (U.S. Census Bureau 2019). The methodological equations are:

Equation 7-33: Total Nitrogen Entering Septic Systems (IPCC 2019 [Eq. 6.10])

$$\text{TN}_{\text{DOM\_SEPTIC}}\ (\text{kg N/year}) = (\text{US}_{\text{POP}} \times \text{T}_{\text{SEPTIC}}) \times \text{Protein} \times \text{F}_{\text{NPR}} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON\_septic}} \times \text{F}_{\text{IND-COM\_septic}}$$

Equation 7-34: Emissions from Septic Systems (IPCC 2019 [Eq. 6.9])

$$\text{A (kt } N_2O\text{/year)} = TN_{DOM\_SEPTIC} \times (EF_{SEPTIC}) \times 44/28 \times 1/10^6$$

Table 7-29: Variables and Data Sources for N_2O Emissions from Septic System

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Septic Systems			
TN_{DOM_SEPTIC}	Total nitrogen entering septic systems	kg N/year	1990-2021: Calculated
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: US Census Bureau 2002; Instituto de Estadísticas de Puerto Rico 2021 2000-2009: U.S. Census Bureau 2011 2010-2019: U.S. Census Bureau (2021a) 2020-2021: U.S. Census Bureau (2021b) U.S. Territories other than Puerto Rico: 1990-2021: U.S. Census Bureau (2022)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2019: U.S. Census Bureau (2019) Data for intervening years obtained by linear interpolation 2020-2021: Forecasted from the rest of the time series
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2021: IPCC (2019) Eq. 6.10
N_{HH}	Additional nitrogen from household products (1.17)	No units	1990-2021: IPCC (2019) Table 6.10a
$F_{NON\text{-}CON\_septic}$	Factor for Non-Consumed Protein Added to Wastewater (1.13)	No units	
$F_{IND\text{-}COM\_septic}$	Factor for Industrial and Commercial Co-Discharged Protein, septic systems (1)	No units	1990-2021: IPCC (2019)
EF_{SEPTIC}	Emission factor, septic systems (0.0045)	kg N_2O-N/kg N	1990-2021: IPCC (2019) Table 6.8a
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Nitrous oxide emissions from POTWs depend on the total nitrogen entering centralized wastewater treatment. The total nitrogen entering centralized wastewater treatment was estimated by multiplying the U.S. population by the percent of wastewater collected for centralized treatment (about 83 percent in 2021), the consumed protein per capita, the fraction of N in protein, the correction factor for additional N from household products, the factor for

industrial and commercial co-discharged protein into wastewater treatment, and the factor for non-consumed protein added to wastewater.

Equation 7-35: Total Nitrogen Entering Centralized Systems (IPCC 2019 [Eq. 10])

$$TN_{DOM\_CENTRAL}\ (kg\ N/year) = (US_{POP} \times T_{CENTRALIZED}) \times Protein \times F_{NPR} \times N_{HH} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}$$

Table 7-30: Variables and Data Sources for Non-Consumed Protein and Nitrogen Entering Centralized Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	United States and Puerto Rico: 1990-1999: U.S. Census Bureau (2002); Instituto de Estadísticas de Puerto Rico (2021) 2000-2009: U.S. Census Bureau 2011 2010-2019: U.S. Census Bureau (2021a) 2020-2021: U.S. Census Bureau (2021b) U.S. Territories other than Puerto Rico: 1990-2021: U.S. Census Bureau (2022)
$T_{CENTRALIZED}$	Percent collected[a]	%	Odd years from 1989 through 2019: U.S. Census Bureau (2019) Data for intervening years obtained by linear interpolation 2020-2021: Forecasted from the rest of the time series
Protein	Consumed protein per capita[a]	kg/person/year	1990-2021: Calculated
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2021: IPCC (2019), Eq. 6.10
N_{HH}	Factor for additional nitrogen from household products (1.17)	No units	1990-2021: IPCC (2019), Table 6.10a
$F_{NON\text{-}CON}$	Factor for U.S. specific non-consumed protein (1.13)	No units	
$F_{IND\text{-}COM}$	Factor for Industrial and Commercial Co-Discharged Protein (1.25)	No units	1990-2021: IPCC (2019) Table 6.11

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from POTWs were estimated by multiplying the total nitrogen entering centralized wastewater treatment, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands) and anaerobic systems, aerobic systems with constructed wetlands as the sole treatment, the emission factor for aerobic systems and anaerobic systems, and the conversion from N_2 to N_2O.

Table 7-34 presents the data for U.S. population, population served by centralized wastewater treatment plants, available protein, and protein consumed. The methodological equations are:

Equation 7-36: Total Domestic N_2O Emissions from Centrally Treated Aerobic Systems

Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (B1) + *Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)* (B2) + *Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)* (B3) = B (kt N_2O/year)

where,

Equation 7-37: Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.9])

$$B1\ (\text{kt}\ N_2O/\text{year}) = [(TN_{DOM\_CENTRAL}) \times (\%\ \text{aerobic}_{OTCW})] \times EF_{aerobic} \times 44/28 \times 1/10^6$$

Table 7-31: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt N_2O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized systems[a]	kg N/year	1990-2021: Calculated
% $aerobic_{OTCW}$	Flow to aerobic systems, other than constructed wetlands only / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2021: Forecasted from the rest of the time series
$EF_{aerobic}$	U.S.-specific emission factor – aerobic systems (0.015)	kg N_2O-N/kg N	1990-2021: IPCC (2022)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from constructed wetlands used as sole treatment include similar data and processes as aerobic systems other than constructed wetlands. See description above. Nitrous oxide emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow to constructed wetlands used as tertiary treatment, wastewater N concentration entering tertiary treatment, constructed wetlands emission factor, and converting to kt/year.

Equation 7-38: Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) (IPCC 2014 [Eq. 6.9])

$$B2\ (\text{kt}\ N_2O/\text{year}) = [(TN_{DOM\_CENTRAL}) \times (\%\text{aerobic}_{CW})] \times EF_{CW} \times 44/28 \times 1/10^6$$

Equation 7-39: Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S.-Specific)

$$B3\ (\text{kt}\ N_2O/\text{year}) = [(\text{POTW\_flow\_CW}) \times (N_{CW,INF}) \times 3.785 \times (EF_{CW})] \times 1/10^6 \times 365.25$$

Table 7-32: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt N_2O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2021: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2021: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2021: IPCC (2014) Table 6.7
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
Emissions from Constructed Wetlands used as Tertiary Treatment (kt N_2O/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment [a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2021: Forecasted from the rest of the time series
$N_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (25)	mg/L	1990-2021: Metcalf & Eddy (2014)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2021: IPCC (2014) Table 6.7
$1/10^6$	Conversion factor	mg to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Data sources and methodologies are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-40: Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 [Eq. 6.9])

$$C\ (\text{kt}\ N_2O/\text{year}) = [(TN_{DOM\_CENTRAL}) \times (\%\ \text{anaerobic})] \times EF_{anaerobic} \times 44/28 \times 1/10^6$$

Table 7-33: Variables and Data Sources for N_2O Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2021: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: (EPA 1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2021: Forecasted from the rest of the time series
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0)	kg N_2O-N/kg N	1990-2021: IPCC (2019) Table 6.8A
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	mg to kg	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Table 7-34: U.S. Population (Millions) Fraction of Population Served by Centralized Wastewater Treatment (percent), Protein Supply (kg/person-year), and Protein Consumed (kg/person-year)

Year	Population	Centralized WWT Population (%)	Protein Supply	Protein Consumed
1990	253	75.6	43.1	33.2
2005	300	78.8	44.9	34.7
2017	329	82.1	44.7	34.5
2018	330	82.9	45.5	35.1
2019	332	83.6	45.4	35.0
2020	335	82.7	44.6	34.4
2021	336	83.0	44.6	34.4

Sources: Population – U.S. Census Bureau 2002; U.S. Census Bureau 2011; U.S. Census Bureau (2021a and 2021b); Instituto de Estadísticas de Puerto Rico (2021); U.S. Census Bureau (2022); WWTP Population – U.S. Census Bureau (2019); Available Protein – USDA (2021), FAO (2022c); Protein Consumed – FAO (2022c).

Emissions from Discharge of Centralized Treatment Effluent:

Nitrous oxide emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total nitrogen in centrally treated wastewater effluent by the percent of wastewater treated in primary, secondary, and tertiary treatment and the fraction of nitrogen remaining after primary, secondary, or tertiary treatment and then multiplying by the percent of wastewater volume routed to waterbodies with nutrient-impaired/eutrophic conditions and all other waterbodies (ERG 2021a) and emission factors for discharge to impaired waterbodies and other waterbodies from IPCC (2019). The methodological equations are:

Equation 7-41: Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$D\ (\text{kt}\ N_2O/\text{year}) = [(N_{EFFLUENT,IMP} \times EF_{IMP}) + (N_{EFLUENT,NONIMP} \times EF_{NONIMP})] \times 44/28 \times 1/10^6$$

where,

Equation 7-42: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.8])

$$N_{EFFULENT,DOM}\ (\text{kg N/year}) = [TN_{DOM\_CENTRAL}[12] \times \%\ \text{primary} \times (1\text{-}N_{rem,PRIMARY})] + [TN_{DOM\_CENTRAL} \times \%\ \text{secondary} \times (1\text{-}N_{rem,SECONDARY})] + [TN_{DOM\_CENTRAL} \times \%\ \text{tertiary} \times (1\text{-}N_{rem,TERTIARY})]$$

Equation 7-43: Total Nitrogen in Effluent Discharged to Impaired Waterbodies (U.S.-Specific)

$$N_{EFFLUENT,IMP}\ (\text{kg N/year}) = (N_{EFFULENT,DOM} \times Percent_{IMP})/1000$$

Equation 7-44: Total Nitrogen in Effluent Discharged to Nonimpaired Waterbodies (U.S.-Specific)

$$N_{EFFLUENT,NONIMP}\ (\text{kg N year}) = (N_{EFFULENT,DOM} \times Percent_{NONIMP})/1000$$

Table 7-35: Variables and Data Sources for N_2O Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$N_{EFFULENT,DOM}$	Total organics in centralized treatment effluent[a]	kg N/year	1990-2021: Calculated
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2021: Calculated
1000	Conversion factor	kg to kt	Standard Conversion
% primary	Percent of primary domestic centralized treatment[a]	%	1990,1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation. 2013-2021: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	
$N_{rem,PRIMARY}$	Fraction of nitrogen removed from primary domestic centralized treatment (0.1)	No units	1990-2021: IPCC (2019) Table 6.10c
$N_{rem,SECONDARY}$	Fraction of nitrogen removed from secondary domestic centralized treatment (0.4)	No units	
$N_{rem,TERTIARY}$	Fraction of nitrogen removed from tertiary domestic centralized treatment (0.9)	No units	

[12] See emissions from centrally treated aerobic and anaerobic systems for methodological equation calculating $TN_{DOM\_CENTRAL}$.

Variable	Variable Description	Units	Source of Value
$N_{EFFLUENT,IMP}$	Total nitrogen in effluent discharged to impaired waterbodies	kg N/year	1990-2021: Calculated
$N_{EFFLUENT,NONIMP}$	Total nitrogen in effluent discharged to nonimpaired waterbodies	kg N/year	
EF_{IMP}	Emission factor (discharge to impaired waterbodies) (0.19)	kg N_2O-N/kg N	1990-2021: IPCC (2019) Table 6.8a
$EF_{NONIMPr}$	Emissions factor (discharge to nonimpaired waterbodies) (0.005)	kg N_2O-N/kg N	
$Percent_{IMP}$	Percent of wastewater discharged to impaired waterbodies[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2021: Set equal to 2012
$Percent_{NONIMP}$	Percent of wastewater discharged to nonimpaired waterbodies[a]	%	

[a] Value for this activity data varies over the Inventory time series.

Industrial Wastewater N_2O Emission Estimates

Nitrous oxide emission estimates from industrial wastewater are estimated according to the methodology described in the *2019 Refinement*. U.S. industry categories that are likely to produce significant N_2O emissions from wastewater treatment were identified based on whether they generate high volumes of wastewater, whether there is a high nitrogen wastewater load, and whether the wastewater is treated using methods that result in N_2O emissions. The top four industries that meet these criteria and were added to the inventory are meat and poultry processing; petroleum refining; pulp and paper manufacturing; and breweries (ERG 2021a). Wastewater treatment and discharge emissions for these sectors for 2021 are displayed in Table 7-36 below. Table 7-20 contains production data for these industries.

Table 7-36: Total Industrial Wastewater N_2O Emissions by Sector (2021, MMT CO_2 Eq. and Percent)

Industry	N_2O Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater N_2O
Meat & Poultry	0.2	47.7
Petroleum Refineries	0.1	29.8
Pulp & Paper	0.1	21.7
Breweries	+	0.8
Total	**0.5**	**100**

+ Does not exceed 0.5 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

More recent research has revealed that emissions from nitrification or nitrification-denitrification processes at wastewater treatment, previously judged to be a minor source, may in fact result in more substantial emissions (IPCC 2019). N_2O is generated as a by-product of nitrification, or as an intermediate product of denitrification. Therefore, N_2O emissions are primarily expected to occur from aerobic treatment systems. To estimate these emissions, the total nitrogen entering aerobic wastewater treatment for each industry must be calculated. Then, the emission factor provided by the *2019 Refinement* is applied to the portion of wastewater that undergoes aerobic treatment.

The total nitrogen that enters each industry's wastewater treatment system is a product of the total amount of industrial product produced, the wastewater generated per unit of product, and the nitrogen expected to be present in each meter cubed of wastewater (IPCC equation 6.13).

Equation 7-45: Total Nitrogen in Industrial Wastewater

$$TN_{INDi} = P_i \times W_i \times TN_i$$

where,

TN_{INDi} = total nitrogen in wastewater for industry *i* for inventory year, kg TN/year
i = industrial sector
P_i = total industrial product for industrial sector *i* for inventory year, t/year
W_i = wastewater generated per unit of production for industrial sector *i* for inventory year, m^3/t product
Tni = total nitrogen in untreated wastewater for industrial sector *i* for inventory year, kg TN/m^3

For the four industries of interest, the total production and the total volume of wastewater generated has already been calculated for CH_4 emissions. For these new N_2O emission estimates, the total nitrogen in the untreated wastewater was determined by multiplying the annual industry production, shown in Table 7-20, by the average wastewater outflow, shown in Table 7-23, and the nitrogen loading in the outflow shown in Table 7-37.

Table 7-37: U.S. Industrial Wastewater Nitrogen Data

Industry	Wastewater Total N (kg N/ m^3)	Source for Total N
Pulp and Paper	0.30[a]	Cabrera (2017)
Meat Processing	0.19	IPCC (2019), Table 6.12
Poultry Processing	0.19	IPCC (2019), Table 6.12
Petroleum Refining	0.051	Kenari et al. (2010)
Breweries – Craft	0.055	IPCC (2019), Table 6.12
Breweries – NonCraft	0.055	IPCC (2019), Table 6.12

[a] Units are kilograms N per air-dried metric ton of production.

Nitrous oxide emissions from industry wastewater treatment are calculated by applying an emission factor to the percent of wastewater (and therefore nitrogen) that undergoes aerobic treatment (IPCC Equation 6.11).

Equation 7-46: N_2O Emissions from Indsutrial Wastewater Treatment Plants

$$N_2O\ Plants_{IND} = \left[\sum_i \left(T_{i,j} \times EF_{i,j} \times TN_{INDi}\right)\right] \times \frac{44}{28}$$

where,

$N_2O\ Plants_{IND}$ = N_2O emissions from industrial wastewater treatment plants for inventory year, kg N_2O/year
TN_{INDi} = total nitrogen in wastewater from industry *i* for inventory year, kg N/year
$T_{i,j}$ = degree of utilization of treatment/discharge pathway or system *j*, for each industry *i* for inventory year
i = industrial sector
j = each treatment/discharge pathway or system
$EF_{i,j}$ = emission factor for treatment/discharge pathway or system j, kg N_2O-N/kg N. 0.015 kg N_2O-N/kg N (IPCC 2022)
44/28 = conversion of kg N_2O-N into kg N_2O

For each industry, the degree of utilization (Ti,j)–the percent of wastewater that undergoes each type of treatment–was previously determined for CH_4 emissions and presented in Table 7-22.

Emissions from Industrial Wastewater Treatment Effluent:

Nitrous oxide emissions from industrial wastewater treatment effluent are estimated by multiplying the total nitrogen content of the discharged wastewater effluent by an emission factor associated with the location of the discharge. Where wastewater is discharged to aquatic environments with nutrient-impacted/eutrophic conditions

(i.e., water bodies which are rich in nutrients and very productive in terms of aquatic animal and plant life), or environments where carbon accumulates in sediments such as lakes, reservoirs, and estuaries, the additional organic matter in the discharged wastewater is expected to increase emissions.

Equation 7-47: N_2O Emissions from Industrial Wastewater Treatment Effluent

$$N_2O\ Effluent_{IND} = N_{EFFLUENT,IND} \times EF_{EFFLUENT} \times 44/28$$

where,

$N_2O\ Effluent_{IND}$ = N_2O emissions from industrial wastewater discharge for inventory year (kg N_2O/year)
$N_{EFFLUENT,IND}$ = Total nitrogen in industry wastewater effluent discharged to aquatic environments for inventory year (kg N/year)
$EF_{EFFLUENT}$ = Tier 1 emission factor for wastewater discharged to aquatic environments (0.005 kg N_2O-N/kg N) (IPCC 2019)
44/28 = Conversion of kg N_2O-N into kg N_2O

The total N in treated effluent was determined through use of a nutrient estimation tool developed by EPA's Office of Water (EPA 2019). The Nutrient Tool uses known nutrient discharge data within defined industrial sectors or subsectors, as reported on Discharge Monitoring Reports, to estimate nutrient discharges for facilities within that sector or subsector that do not have reported nutrient discharges but are likely to discharge nutrients. The estimation considers, within each sector or subsector, elements such as the median nutrient concentration and flow, as well as the percent of facilities within the sector or subsector that have reported discharges. Data from 2018 are available for the pulp, paper, and paperboard, meat and poultry processing, and petroleum refining industries. To complete the time series, an industry-specific percent removal of nitrogen was calculated using the total nitrogen in untreated wastewater. See Table 7-38.

Because data for breweries was not available, the removal of nitrogen was assumed to be equivalent to secondary treatment, or 40 percent (IPCC 2019). The Tier 1 emission factor (0.005 kg N_2O/kg N) from IPCC (2019) was used.

Table 7-38: Industrial Wastewater Nitrogen Discharged in 2018 by Sector (kg N)

Industry	N $Effluent_{IND}$ (kg N)	Industry-Specific N Removal Factor
Meat & Poultry	12,078,919	0.082
Petroleum Refineries	1,698,953	0.045
Pulp & Paper	18,809,623	1.08
Breweries[a]	1,604,878	NA

[a] Nitrogen discharged by breweries was estimated as 60 percent of untreated wastewater nitrogen.
Source: ERG (2021a).

Uncertainty

The overall uncertainty associated with both the 2021 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (IPCC 2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, fruits and vegetable processing, ethanol production, petroleum refining, and breweries. Uncertainty associated with the parameters used to estimate N_2O emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, petroleum refining, and breweries. Uncertainty associated with centrally treated constructed wetlands parameters including U.S. population served by constructed wetlands, and emission and conversion factors are from IPCC (2014), whereas uncertainty associated

with POTW flow to constructed wetlands and influent BOD and nitrogen concentrations were based on expert judgment (ERG 2021b).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-39. For 2021, methane emissions from wastewater treatment were estimated to be between 15.1 and 27.8 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 29 percent below to 32 percent above the 2021 emissions estimate of 21.1 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 13.8 and 61.2 MMT CO_2 Eq., which indicates a range of approximately 34 percent below to 193 percent above the 2021 emissions estimate of 20.9 MMT CO_2 Eq.

Table 7-39: Approach 2 Quantitative Uncertainty Estimates for 2021 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2021 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**21.1**	**15.1**	**27.8**	**-29%**	**+32%**
Domestic	CH_4	13.9	9.2	19.7	-34%	+42%
Industrial	CH_4	7.2	4.2	11.3	-42%	+58%
Wastewater Treatment	**N_2O**	**20.9**	**13.8**	**61.2**	**-34%**	**+193%**
Domestic	N_2O	20.4	12.8	60.4	-37%	+195%
Industrial	N_2O	0.5	0.5	1.4	-0.4%	+202%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). This effort included a general or Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;
- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected trends of emission estimates; and
- Compared estimates to previous estimates to identify significant changes.

Calculation-related QC (category-specific, Tier 2) was performed for a portion of the domestic wastewater treatment discharges methodology, which included assessing available activity data to ensure the most complete publicly data set was used and checking historical trends in the data to assist determination of best methodology for filling in the time series for data that are not available annually.

All transcription errors identified were corrected and documented. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Population data were updated using the same and latest data sources as the state-level emissions Inventory to create consistency across inventory estimates. These changes affected the entire timeseries, except 2000. Protein data were updated to reflect available protein values available for 2011, 2013, and 2018 through 2020 (FAO 2022c). Pulp, paper, and paperboard production data were updated to reflect revised values for 2020 (FAO 2022a). Pulp, paper, and paperboard wastewater outflow data were updated to reflect new available values for 2020 which affected 2019 and 2020 (AF&PA 2022). Updated red meat production values for 2020, were updated based on revised data (USDA 2022a; USDA 2022c). Fruits and vegetables production values were updated for the time series (ERG 2022). Ethanol production values for 2015 and 2020 were based on revised data (RFA 2022a; RFA 2022b). Petroleum refining production values for 2020 were revised based on EIA (2022). In addition, EPA revised the domestic sludge generation methodology to estimate the sludge generation from U.S. Territories and update the time series to include new 2018 values (ERG 2022).

In addition, for the current Inventory, estimates of CO_2-equivalent total CH_4 and N_2O emissions from wastewater treatment and discharge have been revised to reflect the 100-year global warming potentials (GWPs) provided in the IPCC *Fifth Assessment Report* (AR5) (IPCC 2013). AR5 GWP values differ slightly from those presented in the IPCC *Fourth Assessment Report* (AR4) (IPCC 2007) (used in the previous Inventories). The GWP of CH_4 has increased from 25 to 28, leading to an overall increase in CO_2-equivalent CH_4 emissions while the GWP for N_2O decreased from 298 to 265 leading to a decrease in CO_2-equivalent N_2O emissions. The AR5 GWPs have been applied across the entire time series for consistency. Further discussion on this update and the overall impacts of updating the Inventory GWP values to reflect the IPCC *Fifth Assessment Report* can be found in Chapter 9, Recalculation and Improvements.

Compared to the previous Inventory which applied 100-year GWP values from AR4, the cumulative effect of all these recalculations had a minor impact on the overall wastewater treatment emission estimates:

- Domestic wastewater treatment and discharge CH_4 emissions increased on average 13.9 percent over the timeseries, with the smallest increase of 11.4 percent (1.7 MMT CO_2 Eq.) in 1995 and largest increase of 19.9 percent (2.3 MMT CO_2 Eq.) in 2019.
- Domestic wastewater treatment and discharge N_2O emissions decreased an average 11.0 percent over the timeseries, with the smallest decrease in 8.9 percent (2.0 MMT CO_2 Eq.) in 2019 to the largest decrease of 11.0 percent (2.6 MMT CO_2 Eq.) in 2020.
- Industrial wastewater treatment and discharge CH_4 emissions increased on average 12.1 percent over the timeseries, with the smallest increase of 11.3 percent (0.7 MMT CO_2 Eq.) in 2020 and largest increase of 12.3 percent (0.77 MMT CO_2 Eq.) in 2017.
- Industrial wastewater treatment and discharge N_2O emissions decreased an average 11.1 percent over the timeseries, with the smallest decrease of 11.1 percent (0.04 MMT CO_2 Eq.) in 1991 to the largest decrease of 11.5 percent (0.06 MMT CO_2 Eq.) in 2020.

Over the time series, the total emissions on average increased by 1.1 percent from the previous Inventory. The changes ranged from the smallest increase, 0.4 percent (0.2 MMT CO_2 Eq.), in 2004, to the largest decrease, 2.4 percent (1.0 MMT CO_2 Eq.), in 2019.

Planned Improvements

EPA notes the following improvements may be implemented or investigated within the next two or three inventory cycles pending time and resource constraints:

- Investigate anaerobic sludge digester and biogas data compiled by the Water Environment Federation (WEF) in collaboration with other entities *as a potential source of updated activity data;*

- *Due to lack of these data, the United States continues to use another method for estimating biogas produced. This method uses the standard 100 gallons/capita/day wastewater generation factor for the United States (Ten-State Standards). However, based on stakeholder input, some regions of the United States use markedly less water due to water conservation efforts so EPA plans to investigate updated sources for this method as well.*

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement them until data are available or identified:

- Investigate additional sources for estimating wastewater volume discharged and discharge location for both domestic and industrial sources. For domestic wastewater, the goal would be to provide additional data points along the time series, while the goal for industrial wastewater would be to update the Tier 1 discharge methodology to a Tier 2 methodology.
- Investigate additional sources for domestic wastewater treatment type in place data.
- Continue to review whether sufficient data exist to develop U.S.-specific CH_4 or N_2O emission factors for domestic wastewater treatment systems, including whether emissions should be differentiated for systems that incorporate biological nutrient removal operations; and
- Investigate additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems.
- Evaluate the use of POTW BOD effluent discharge data from ICIS-NPDES.[13] Currently only half of POTWs report organics as BOD_5 so EPA would need to determine a hierarchy of parameters to appropriately sum all loads. Using these data could potentially improve the current methane emission estimates from domestic discharge.
- Evaluate the use of POTW N effluent discharge data from ICIS-NPDES. Currently only about 80 percent of POTWs report a form of N so EPA would need to determine an appropriate method to scale to the total POTW population. EPA is aware of a method for industrial sources and plans to determine if this method is appropriate for domestic sources.

7.3 Composting (CRF Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Composting reduces the amount of methane-generating waste entering landfills, destroys pathogens in the waste, sequesters carbon, and provides a source of organic matter. Composting can also generate a saleable product and reduce the need for chemical fertilizers when the end product is used as a fertilizer or soil amendment. This source category assumes all composting facilities are commercial, large-scale anaerobic windrow composting facilities with yard trimmings as the main waste stream composted (BioCycle 2017). Facilities using aerobic composting methods (e.g., aerated static piles, in-vessel composting) are operational in the United States, however national estimates of the material processed by these facilities are not readily available and therefore not included. Residential backyard composting is also not included in this source category.

Composting naturally converts a large fraction of the degradable organic carbon in the waste material into carbon dioxide (CO_2) through aerobic processes without anthropogenic influence. With anthropogenic influences (e.g., at commercial or large on-site composting operations), anaerobic conditions can be created in sections of the compost pile when there is excessive moisture or inadequate aeration (or mixing) of the compost pile, resulting in the formation of methane (CH_4). Methane in aerobic sections of a windrow pile are generally oxidized by

[13] ICIS-NPDES refers to EPA's Integrated Compliance Information System – National Pollutant Discharge Elimination System.

microorganisms, which convert the CH_4 to CO_2 emissions. Even though CO_2 emissions are generated, they are not included in net greenhouse gas emissions for composting. Consistent with the *2006 IPCC Guidelines*, net CO_2 flux from carbon stock changes in waste material are estimated and reported under the LULUCF sector. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can also be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the thermophilic and secondary mesophilic stages of composting (Cornell 2007). Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

From 1990 to 2021, the amount of waste composted in the United States increased from 3,810 kt to 22,946 kt (see Table 7-42). There was some fluctuation in the amount of waste composted between 2006 to 2009 where a peak of 20,063 kt composted was observed in 2008, which decreased to 18,838 kt composted the following year, presumably driven by the economic crisis of 2009 (data not shown). Since 2009, the amount of waste composted has gradually increased, and when comparing 2010 to 2021, a 25 percent increase in waste composted is observed. Emissions of CH_4 and N_2O from composting from 2010 to 2021 have increased by the same percentage.

In 2021, CH_4 emissions from composting (see Table 7-40 and Table 7-41) were 2.6 MMT CO_2 Eq. (92 kt), and N_2O emissions from composting were 1.8 MMT CO_2 Eq. (7 kt), representing consistent emissions trends over the past several years. Composted material primarily includes yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include small-scale backyard composting and agricultural composting mainly due to the lack of consistent and comprehensive national data. Additionally, it is assumed that backyard composting tends to be a more naturally managed process with less chance of generating anaerobic conditions and CH_4 and N_2O emissions. Agricultural composting is accounted for in Volume 4, Chapter 5 (Cropland) of this Inventory, as most agricultural composting operations are assumed to land-apply the resultant compost to soils.

The growth in composting since the 1990s and specifically over the past decade may be attributable to the following factors: (1) the enactment of legislation by state and local governments that discouraged or banned the disposal of yard trimmings and/or food waste in landfills, (2) an increase in yard trimming collection and yard trimming drop off sites operated by local solid waste management districts/divisions, , (3) an increased awareness of the environmental benefits of composting, and (4) loans or grant programs to establish or expand composting infrastructure.

Most bans or diversion laws on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). California, for example, enacted a waste diversion law for organics including yard trimmings and food scraps in 1999 (AB939) that required jurisdictions to divert 50 percent of the waste stream by 2000, or be subjected to fines. Currently, 20 states representing up to 42 percent of the nation's population have enacted legislation banning yard waste from landfill disposal (U.S. Composting Council 2022). Additional initiatives at the metro and municipal level also exist across the United States. Roughly 4,713 composting facilities exist in the United States with most (57.2 percent) composting yard trimmings only (BioCycle 2017).

In the last decade, bans and diversions for food waste have also become more common. As of 2022, eight states (California, Connecticut, Massachusetts, New Jersey, New York, Orgon, Vermont, Washington) and seven local governments (Austin, TX; Boulder, CO; Hennepin County, MN; Portland, OR; New York City, NY; San Francisco, CA; Seattle, WA) had implemented organic waste bans or mandatory recycling laws to help reduce organic waste entering landfills, with most having taken effect after 2013 (U.S. Composting Council 2022). In most cases, organic waste reduction in landfills is accomplished by following recycling guidelines, donating excess food for human consumption, or by sending waste to organics processing facilities (Harvard Law School and CET 2019). An example of an organic waste ban as implemented by California is the California Mandatory Recycling Law (AB1826), which requires companies to comply with organic waste recycling procedures if they produce a certain amount of organic

waste and took effect on January 1, 2015 (Harvard Law School and CET 2019). In 2017, *BioCycle* released a report in which 27 of 43 states that responded to their organics recycling survey noted that food waste (collected residential, commercial, institutional, and industrial food waste) was recycled via anaerobic digestion and/or composting. These 27 states reported an estimated total of 1.8 million tons of food waste diverted from landfills in 2016 (BioCycle 2018b). A growing number of initiatives to encourage households and businesses to compost or beneficially reuse food waste also exist.

Table 7-40: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2017	2018	2019	2020	2021
CH_4	0.4	2.1	2.7	2.5	2.5	2.6	2.6
N_2O	0.3	1.5	1.9	1.8	1.8	1.8	1.8
Total	**0.7**	**3.6**	**4.7**	**4.3**	**4.3**	**4.4**	**4.4**

Note: Totals by gas may not sum due to independent rounding.

Table 7-41: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2017	2018	2019	2020	2021
CH_4	15	75	98	90	91	92	92
N_2O	1	6	7	7	7	7	7

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process.

The emissions shown in Table 7-40 and Table 7-41 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

Equation 7-48: Greenhouse Gas Emission Calculation for Composting

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, kt CH_4 or N_2O
M = mass of organic waste composted in kt
EF_i = emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006)
i = designates either CH_4 or N_2O

Per IPCC Tier 1 methodology defaults, the emission factors for CH_4 and N_2O assume a moisture content of 60 percent in the wet waste (IPCC 2006). While the moisture content of composting feedstock can vary significantly by type, composting as a process ideally proceeds between 40 to 65 percent moisture (University of Maine 2016; Cornell 1996).

Estimates of the quantity of waste composted (M, wet weight as generated) are presented in Table 7-42 for select years. Estimates of the quantity composted for 1990 and 2005 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2015 (EPA 2018); estimates of the quantities composted for 2017 to 2018 were taken from EPA's *Advancing Sustainable Materials Management: 2018 Tables and Figures* (EPA 2020a); the estimate of the quantity composted for 2019 to 2021 were extrapolated using the 2018 quantity composted and a ratio of the U.S. population growth between 2018 to 2019, 2019 to 2020, and 2020 to 2021, respectively (U.S. Census Bureau 2021 and U.S. Census Bureau 2022). Estimates of waste composted by commercial facilities in

Puerto Rico were provided for select years by EPA Region 2 (Kijanka 2020). This inventory includes waste composted in Puerto Rico for 2017, 2018, and/or 2019 from three facilities in Puerto Rico, ranging from approximately 1,200 kt to a high of 15,000 kt. The average waste composted for these years was used as the annual amount composted for the respective facility for years the facility was operational. The annual quantity of composted waste in Puerto Rico was forecasted for 2020 and 2021 using available data from prior years, assumed metro area population data near where each facility is located, and the Microsoft FORECAST function to obtain annual composting estimates. Puerto Rico waste composition estimates for 2020 and 2021. Efforts are made each inventory year to fill historical and current data gaps for Puerto Rico's waste composting estimates.

Table 7-42: U.S. Waste Composted (kt)

Activity	1990	2005	2017	2018	2019	2020	2021
Waste Composted	3,810	18,655	24,501	22,594	22,698	22,918	22,946

Uncertainty

The major uncertainty drivers are the assumption that all composting emissions come from commercial windrow facilities and the use of default emission factors (IPCC 2006) which is tied to a homogenous mixture of waste processed across the country (largely yard trimmings). Data presented by BioCycle (BioCycle 2017) confirm most composting operations use the windrow method and yard trimmings are the largest share of material composted across the country, but there are other composting methods used and waste characteristics will vary at a facility level. Additionally, there are composting operations in Puerto Rico and U.S. territories that are not explicitly included in the national quantity of material composted as reported in the EPA Sustainable Materials Management Reports because the methodological scope does not include Puerto Rico and U.S. territories. EPA took steps to include emissions from Puerto Rico and U.S. Territories beginning in the 1990 to 2020 inventory and will continue to seek out additional data in future Inventories.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±58 percent for the Tier 1 methodology and considers the individual emission factors applied to the default emission factors and activity data.

Emissions from composting in 2021 were estimated to range between 1.8 and 7.0 MMT CO_2 Eq., which indicates a range of 58 percent below to 58 percent above the 2021 emission estimate of each gas (see Table 7-43).

Table 7-43: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2021 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4	2.6	1.1	4.1	-58%	+58%
	N_2O	1.8	0.8	2.9	-58%	+58%
	Total	**4.4**	**1.8**	**7.0**	**-58%**	**+58%**

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current Inventory.

Recalculations Discussion

The U.S. population estimate for 2020 was revised with current U.S. Census Bureau data (U.S. Census Bureau 2022). Because the 2020 composting estimates are extrapolated based on population growth, this recalculation also resulted in a nominal increase (1 percent or 145 kt) in the quantity of material composted for 2020 compared to that in the 1990 to 2020 Inventory report.

In addition, for the current Inventory, CO_2-equivalent estimates of total CH_4 and N_2O emissions from composting have been revised to apply the 100-year global warming potentials (GWPs) provided in the IPCC *Fifth Assessment Report* (AR5) (IPCC 2013). AR5 GWP values differ slightly from those presented in the IPCC *Fourth Assessment Report* (AR4) (IPCC 2007) (used in the previous inventories). The AR5 GWPs have been applied across the entire time series for consistency. The GWP of CH_4 has increased from 25 to 28, leading to an overall increase in CO_2-equivalent CH_4 emissions while the GWP for N_2O decreased from 298 to 265 leading to a decrease in CO_2-equivalent N_2O emissions. Compared to the previous Inventory which applied 100-year GWP values from AR4, the change in CO_2-equivalent CH_4 emissions was a 12 percent increase for each year of the time series, while the change in CO_2-equivalent N_2O emissions was an 11 percent decrease for each year of the time series. Further discussion on this update and the overall impacts of updating the inventory GWPs to reflect the IPCC *Fifth Assessment Report* can be found in Chapter 9, Recalculations and Improvements. The net impact from these updates was an average annual 1 percent increase in composting emissions for the time series.

Planned Improvements

EPA recently completed a literature search on emission factors and composting systems and management techniques that were documented in a draft technical memorandum. The purpose of this literature review was to compile all published emission factors specific to various composting systems and composted materials in the United States to determine whether the emission factors used in the current methodology can be revised or expanded to account for geographical differences and/or differences in composting systems used. For example, outdoor composting processes in arid regions typically require the addition of moisture compared to similar composting processes in wetter climates. In general, there is a lack of facility-specific data on the management techniques and sum of material composted to enable the incorporate of different emission factors. EPA will continue to seek out more detailed data on composting facilities to enable this improvement in the future.

Relatedly, EPA has received comments during previous Inventory cycles recommending that calculations for the composting sector be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents. At this time, EPA is not aware of any available datasets which would enable estimations to be performed at this level of granularity. EPA will continue to search for data which could lead to the development of subcategory-specific composting emission factors to be used in future Inventory cycles.

EPA has put significant work into its Excess Food Opportunities Map dataset, including the compilation of composting facilities and feedstock accepted across the country. Additionally, the EPA's 2018 Wasted Food Report (EPA 2020b) includes estimates of composted waste for individual sectors (e.g., food and beverage manufacturing, restaurants/food services, hospitals, correctional facilities, office buildings). Estimates are provided for one year, 2018. The Inventory compilation team plans to review this report's estimates in comparison to the EPA's Facts and Figures report to identify sectors that are not duplicated in the Facts and Figures reports, and develop a methodology to generate estimates for all years in the Inventory time series (1990 through 2021).

EPA will also continue to seek out activity data including processing capacity and years of operation for commercial composting facilities in Puerto Rico (for additional years), Guam, and other U.S. Territories for inclusion in a future Inventory.

7.4 Anaerobic Digestion at Biogas Facilities (CRF Source Category 5B2)

Anaerobic digestion is a series of biological processes in the absence of oxygen in which microorganisms break down organic matter, producing biogas and digestate. The biogas primarily consists of CH_4, biogenic CO_2, and trace amounts of other gases such as N_2O (IPCC 2006) and is often combusted to produce heat and power, or further processed into renewable natural gas or for use as a transportation fuel. Digester gas contains approximately 65 percent CH_4 (a normal range is 55 percent to 65 percent) and approximately 35 percent CO_2 (WEF 2012; EPA 1993). Methane emissions may result from a fraction of the biogas that is lost during the process due to leakages and other unexpected events (0 to 10 percent of the amount of CH_4 generated, IPCC 2006), collected biogas that is not completely combusted, and entrained gas bubbles and residual gas potential in the digestate. Carbon dioxide emissions are biogenic in origin and should be reported as an informational item in the Energy Sector (IPCC 2006). Volume 5 Chapter 4 of the *2006 IPCC Guidelines* notes that at biogas plants where unintentional CH_4 emissions are flared, CH_4 emissions are likely to be close to zero.

Anaerobic digesters differ based on the operating temperature, feedstock type and moisture content, and mode of operation. The operating temperature dictates the microbial communities that live in the digester. Mesophilic microbes are present at temperatures ranging from 85 to 100 degrees Fahrenheit while thermophilic microbes thrive at temperatures ranging from 122 to 140 degrees Fahrenheit (WEF 2012). Digesters may process one or more types of feedstock, including food waste; municipal wastewater solids; livestock manure; industrial wastewater and residuals; fats, oils, and grease; and other types of organic waste streams. Co-digestion (multiple feedstocks) is employed to increase methane production in cases where an organic matter type does not break down easily. In co-digestion, various organic wastes are decomposed in a singular anaerobic digester by using a combination of wastewater solids or manure and food waste from restaurants or food processing industry, a combination of manure and waste from energy crops or crop residues (EPA 2016), or alternative combinations of feedstock. The moisture content of the feedstock (wet or dry) impacts the amount of biogas generation. Wet anaerobic digesters process feedstock with a solids content of less than 15 percent while dry anaerobic digesters process feedstock with a solids content greater than 15 percent (EPA 2020). Digesters may also operate in batch or continuous mode, which affects the feedstock loading and removal. Batch anaerobic digesters are manually loaded with feedstock all at once and then manually emptied while continuous anaerobic digesters are continuously loaded and emptied with feedstock (EPA 2020).

The three main categories of anaerobic digestion facilities included in national greenhouse gas inventories include the following:

- Anaerobic digestion at biogas facilities, or stand-alone digesters, can be industry-dedicated digesters that process waste from on industry or industrial facility (typically food of beverage waste from manufacturing), or multi-source digesters that process feedstocks from various sources (e.g., municipal food scraps, manure, food processing waste). Some stand-alone digesters also co-digest other organics such as yard waste.
- On-farm digesters manage organic matter and reduce odor generated by farm animals or crops. On-farm digesters are found mainly at dairy, swine, and poultry farms where there is the highest potential for methane production to energy conversion. On-farm digesters may also accept food waste as feedstock for co-digestion.
- Digesters at water resource recovery facilities (WRRF) produce biogas through the treatment and reduction of wastewater solids. Some WRRF facilities may also accept and co-digest food waste.

This section focuses on stand-alone anaerobic digestion at biogas facilities. Emissions from on-farm digesters are included Chapter 5 (Agriculture) and AD facilities at WRRFs are included in Section 7.2 (Wastewater Treatment).

From 1990 to 2021, the estimated amount of waste managed by stand-alone digesters in the United States increased from approximately 786 kt to 8,263 kt, an increase of 951 percent. As described in the Uncertainty section, no data sources present the annual amount of waste managed by these facilities prior to 2015 when the EPA began a comprehensive data collection survey. Thus, the emission estimates between 1990 and 2014, and for 2019 to 2021 are general estimates extrapolated from data collected for years 2015 to 2018. The steady increase in the amount of waste processed over the time series is likely driven by increasing interest in using waste as a renewable energy source and other organics diversion goals.

In 2021, emissions from stand-alone anaerobic digestion at biogas facilities were approximately 0.2 MMT CO_2 Eq. (6 kt) (see Table 7-44 and Table 7-45).

Table 7-44: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (MMT CO_2 Eq.) from 1990-2021

Activity	1990	2005	2017	2018	2019	2020	2021
CH_4 Generation	+	0.1	0.2	0.2	0.2	0.2	0.2
CH_4 Recovery	(+)	(+)	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions	**+**	**+**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Absolute value does not exceed 0.05 MMT.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 7-45: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (kt) from 1990-2021

Activity	1990	2005	2017	2018	2019	2020	2021
CH_4 Generation	1	2	7	7	7	7	7
CH_4 Recovery	(+)	(+)	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions	**1**	**2**	**6**	**6**	**6**	**6**	**6**

+ Does not exceed 0.5 kt.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Methodology

Methane emissions from anaerobic digestion depend on factors such as the type of waste managed, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the digestion process.

The emissions presented in Table 7-44 were estimated using the IPCC default (Tier 1) methodology (Volume 5, Chapter 4, IPCC 2006) given in Equation 7-49 below, which is the product of an emission factor and the mass of organic waste processed. Only CH_4 emissions are estimated because N_2O emissions are considered negligible (IPCC 2006). Some Tier 2 data are available (annual quantity of waste digested) for the later portion of the time series (2015 and later).

Equation 7-49: Methane Emissions Calculation for Anaerobic Digestion

$$CH_4\ Emissions = \sum_i (M_i \times EF_i) \times 10^{-3} - R$$

where,

CH_4 Emissions = total CH_4 emissions in inventory year, Gg CH_4

M_i = mass of organic waste treated by biological treatment type *i*, Gg, see Table 7-46

EF = emission factor for treatment *i*, g CH_4/kg waste treated, 0.8 Mg/Gg CH_4

i = anaerobic digestion

R = total amount of CH_4 recovered in inventory year, Gg CH_4

Equation 7-50: Recovered Methane Estimation for Anaerobic Digestion

$$R = Biogas \times 0.0283 \times \frac{minutes}{year} \times Biogas\ CH_4\ Density \times C_{CH4} \times \frac{1}{10^9} \times (1 - DE)$$

where,

Biogas	=	the annual amount of biogas produced, standard cubic feet per minute (scfm)
0.0283	=	conversion factor cubic meter/cubic feet
525,600	=	minutes per year
662	=	CH_4 density in biogas (EPA 1993), g CH_4/m^3 CH_4
65%	=	C_{CH4}, concentration of CH_4 in the biogas (WEF 2012; EPA 1993)
$1/10^9$	=	conversion factor, grams to kt
0.99	=	destruction efficiency for combustion unit

Per IPCC Tier 1 methodology defaults, the emission factor for CH_4 assumes a moisture content of 60 percent in the wet waste (IPCC 2006). Both liquid and solid wastes are processed by stand-alone digesters and the moisture content entering a digester may be higher. One emission factor recommended by the *2006 IPCC Guidelines* (0.8 Mg/Gg CH_4) is applied for the entire time series (IPCC 2006 Volume 5, Chapter 4, Table 4.1).

The annual quantity of waste digested is sourced from recent EPA surveys of anaerobic digestion facilities (EPA 2018, 2019, and 2021). The EPA was granted the authority to survey anaerobic digestion facilities that process food waste annually through an Information Collection Request (ICR No. 2533.01). The scope includes stand-alone and co-digestion facilities (on-farm and water resource recovery facilities [WRRF]). Three reports with survey results have been published to date:

- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results* (EPA 2018)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results* (EPA 2019)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in (2017 & 2018): Survey Results* (EPA 2021)

These reports present aggregated survey data including the annual quantity of waste processed by digester type (i.e., stand-alone, on-farm, and WRRF); waste types accepted; biogas generation and end use; and more. The aggregated data presented in the EPA reports are underestimates of the actual amount of processed waste and biogas produced because (1) surveys rarely achieve a 100 percent response rate and some fraction of facilities in each survey year did not respond to the survey; (2) EPA focused this survey on facilities that process food waste, and there may be additional operational digesters that are not located on farms or at wastewater treatment plants; and (3) EPA has done due diligence to identify all stand-alone digesters that process food waste but may not have identified all facilities across the United States and its territories. The amount of waste digested as reported in the survey reports were assumed to be in wet weight; the majority of stand-alone digesters were found to be wet and mesophilic (EPA 2019).

The annual quantity of waste digested at stand-alone digesters for 1990 to 2014 (only 1990 and 2005 are shown in Table 7-46) was estimated by multiplying the count of estimated operating facilities (as presented in Table 7-47) by the weighted average of waste digested in 2015 and 2016 collected through EPA's survey data (EPA 2018; EPA 2019). Masked survey responses of food and non-food waste processed were shared with the Inventory team by the EPA team leading the EPA AD Data Collection Surveys. This provided an accurate count of the number of facilities that provided annual quantities of digested waste, which matters for the weighted average. The weighted average applied to the current inventory is calculated as follows for 1990 to 2014:

Equation 7-51: Weighted Average of Waste Processed

$$Weighted\ Average\ Waste\ Processed = \frac{(W_{2016} \times Fac_{2016} + W_{2015} \times Fac_{2015})}{(Fac_{2016} + Fac_{2015})}$$

where,

W = total waste processed in the respective survey year, food and non-food waste (short tons).

Fac = the number of facilities that reported an amount of waste processed in the respective survey year. Note the number of facilities that provided an annual quantity of waste processed data was internally shared and differs from the total number of facilities that responded to the EPA surveys as presented in EPA (2018, 2019).

Estimates of the quantity of waste digested (M, wet weight as generated) are presented in for select years and the number of facilities that reported annual quantities of waste digested to the EPA survey were 45 and 44 in 2015 and 2016, respectively (using masked facility data provided by the EPA AD survey data collection team).

Estimates of the quantity of waste digested for 1990 to 2014 are calculated by multiplying the weighted average of waste digested from 2015 and 2016 survey data (216,494 short tons) by the count of operating facilities in each year. This calculation assumes that each facility operates continuously from the first year of operation for the remainder of the time series. Additional efforts will be made to quantify the number of operating facilities and estimates of the total waste digested by year for future Inventories as described in the Planned Improvements section. Estimates of the quantity digested for 2015 and 2016 were taken from EPA's AD survey data (EPA 2018; EPA 2019, respectively). The estimate of waste digested for 2019 through 2021 were extrapolated using the average of the waste digested from the 2017 and 2018 survey data (EPA 2021) as a proxy. The average did not include data from 2015 and 2016 because there is a drop in the amount of waste digested by nearly 1 million tons between 2016 and 2017. The quantities digested between 2015 and 2016 are similar, and quantities digested between 2017 and 2018 are similar. Estimates for 2019 to 2021 will be updated as future EPA survey reports are published.

Table 7-46: U.S. Waste Digested (kt) from 1990-2021

Activity	1990	2005	2017	2018	2019	2020	2021
Waste Digested[a]	786	2,357	8,206	8,320	8,263	8,263	8,263

[a] The amount of waste digested primarily consists of food waste. The amount processed for all years is likely an underestimate because the estimates were developed from survey data provided by operating facilities for 2015 to 2018 (EPA 2018; EPA 2019; EPA 2021). Facilities that did not respond to the EPA surveys are not included and all years except 2015 to 2018 are estimated using assumptions regarding the number of operating facilities and the weighted average of waste digested. Additionally, the liquid portion of the waste digested in 2015 and 2016 are not included due to limited information on the specific waste types to perform the unit conversion to kt. EPA converted liquid waste to tons for 2018 and 2019 using a conversion factor of 3.8 pounds per gallon (EPA 2021). The weighted average of waste digested in 2015 and 2016 (as reported in EPA 2018 and 2019) is used as the average for 1990 to 2014, and the average waste digested as reported in EPA (2021) is used as a proxy for years 2019 to 2021.

The estimated count of operating facilities is calculated by summing the count of digesters that began operating by year over the time series. The year a digester began operating is sourced from EPA (2021). This assumes all facilities are in operation from their first year of operation throughout the remainder of the time series, including facilities prior to 1990. This is likely an overestimate of facilities operating per year but does not necessarily translate to an overestimate in the amount of waste processed because a weighted average of waste processed for the surveyed facilities is applied to these years. The number of facilities in 1990 to 2014 are directly used in calculating the emissions, while the directly reported annual amount of waste processed from the survey data are used for 2015 to 2021.

Table 7-47: Estimated Number of Stand-Alone AD Facilities Operating[a] from 1990-2021

Year	1990	2005	2017	2018	2019	2020	2021
Estimated Count of Operational Facilities	4	12	68	68	68	68	68

[a] The count of operational facilities was visually estimated from Figure 5 in EPA (2021), which presents the count of the first year of digester operation. The number of operational facilities by year is assumed to be the cumulative total from the prior year. This method assumes all facilities are operating from 1990, or their first year of operation, to 2020. The number of facilities operating between 2015 to 2018 are equal to the number of facilities surveyed by EPA (EPA 2018, 2019, and 2021). The number of facilities operating in 2019 and 2020 are assumed to be the same as the last survey report data year, i.e., 2018 as reported in EPA (2021). These assumptions are further discussed in the Methodology and Time-Series Consistency section.

Activity data for the amount of biogas recovered (R in the emission calculation equation) is limited across the time series. Currently, there are only four data points (2015, 2016, 2017, and 2018) represented for the entire sector, as reported in the EPA AD Data Collection Survey reports (EPA 2018, 2019, and 2021). The total quantity of collected biogas from the survey respondents is reported in standard cubic feet per minute (scfm) as shown in Table 7-48. Volume 5, Chapter 4 of the *2006 IPCC Guidelines* notes that only emissions from flaring can be reported under the waste sector. The top three known uses of the biogas generated by stand-alone digesters are combined heat and power (CHP), the production of electricity that is sold to the grid, and using the biogas to fuel boilers and furnaces to heat the digestor and other facility spaces (EPA 2018; EPA 2019). Thus, no biogas is assumed to be flared.

Table 7-48: Estimated Biogas Produced and Methane Recovered from Anaerobic Digestion at Biogas Facilities Operating from 1990-2021[a]

Activity	1990	2005	2017	2018	2019	2020
Total Biogas Produced (scfm)[b]	767	2,301	6,402	7,282	6,842	6,842
R, recovered CH_4 from biogas (kt)[c]	(0.05)	(0.14)	(0.41)	(0.47)	(0.49)	(0.49)

[a] Total biogas produced in standard cubic feet per minute (scfm) was reported in aggregate in the EPA survey data (EPA 2018, 2019, 2021) for 20 2018. The quantities presented in this table are likely underestimates because not all operational facilities provided a survey response to the EP Data Collection Surveys.

[b] Data for all years in the time series except for 2015 and 2016 are extrapolated using the average of the total biogas collected between 2015 to divided by the average number of survey responses to generate a weighted average estimate of biogas collected per facility, which is then mult by the total facility count (as shown in Table 7-47).

[c] The quantity of CH_4 recovered from the biogas produced is estimated for all years except 2015 to 2018, which are taken from EPA (2018), EPA (and EPA (2021).

Note: Parentheses indicate negative values.

Uncertainty

The methodology applied for the 1990 to 2014 emissions estimates should be considered a starting point to build on in future years if additional historical data become available. Four years of facility-provided data are available (2015 to 2018) while the rest of the time series is estimated based on an assumption of facility counts and the 2015 and 2016 weighted average annual waste digested as calculated from survey data. The major limitations, and uncertainty drivers in the emissions estimates, are related to the uncertainty in assumptions to ensure completeness across the time series and the limitations in the EPA AD survey data, as described below:

1. The EPA AD survey (EPA 2018; EPA 2019; EPA 2021) did not receive a 100 percent response rate, meaning that the survey data represent a portion, albeit the majority, of stand-alone digesters, annual waste processed, and biogas recovered. The methodology applied here did not attempt to estimate waste digested by facilities that did not respond to the survey, which likely underestimates the quantity of waste digested and CH_4 emissions.

2. The EPA AD survey data (EPA 2018; EPA 2019) present both food and non-food waste digested. The non-food waste was reported as liquid (gallons) and solid (tons). The quantity of liquid waste managed is not included in the estimated quantity of annual waste digested for 2015 and 2016, which is used as a proxy for 1990 to 2014 because data on the waste types are not available to convert the quantity from gallons

to tons. This slightly underestimates the quantity of waste digested and CH_4 emissions. EPA (2021) did convert the liquid waste managed to tons for 2017 and 2018 using a general conversion factor.

3. The assumption required to estimate the activity data for 1990 to 2014 may overestimate the number of facilities in operation because it assumes that each facility operates from its start year for the entire time series (i.e. facility closures are not taken into account). This introduces a large amount of uncertainty in the estimates compared to years where there is directly reported survey data. It is unclear whether this under- or over-estimates the quantity of waste digested and CH_4 emissions.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±54 percent for the Approach 1 methodology.

Emissions from anaerobic digestion at stand-alone biogas facilities in 2021 were estimated to be between 0.1 and 0.3 MMT CO_2 Eq., which indicates a range of 54 percent below to 54 percent above the 2021 emission estimate of CH_4 (see Table 7-49). A ±20 percent uncertainty factor is applied to the annual amount of material digested (i.e., the activity data), which was developed with expert judgment (Bronstein 2021). A ±50 percent default uncertainty factor is applied to the CH_4 emission factor (IPCC 2006). Using the IPCC's error propagation equation (Equation 3.1 in IPCC 2006 Volume 1, Chapter 3), the combined uncertainty percentage is ±54 percent.

Table 7-49: Approach 1 Quantitative Uncertainty Estimates for Emissions from Anaerobic Digestion (MMT CO_2 Eq. and Percent)

Source	Gas	2021 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Anaerobic Digestion at Biogas Facilities	CH_4	0.2	0.1	0.3	-54%	+54%

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1, Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current Inventory.

Recalculations Discussion

For the current Inventory, estimates of CO_2-equivalent CH_4 emissions from anaerobic digestion at biogas facilities have been revised to reflect the 100-year global warming potentials (GWPs) provided in the IPCC *Fifth Assessment Report* (AR5) (IPCC 2013). AR5 GWP values differ slightly from those presented in the IPCC *Fourth Assessment Report* (AR4) (IPCC 2007) (used in previous Inventories). The AR5 GWPs have been applied across the entire time series for consistency. The GWP of CH_4 has increased from 25 to 28, leading to an overall increase in CO_2-equivalent CH_4 emissions. Compared to the previous Inventory which applied 100-year GWP values from AR4, the change in CO_2-equivalent CH_4 emissions was a 12 percent increase for each year of the time series. Further discussion on this update and the overall impacts of updating the Inventory GWPs to reflect the IPCC *Fifth Assessment Report* can be found in Chapter 9, Recalculations and Improvements.

Planned Improvements

EPA will continue to incorporate updated survey data from future EPA AD Data Collection Surveys when the survey data are published. These revisions will change the estimated emissions for 2019 to 2021.

EPA will also re-assess how best to estimate annual waste processed using proxy data for years between the EPA AD Data Collection Survey reports as needed (e.g., for 2019, 2020, 2021). The methodology described here assumes the same average amount of waste is processed each year for 2019 through 2021.

EPA continues to seek out data sources to confirm the estimated number of operational facilities by year prior to 2015 and consider how best to estimate the quantity of waste processed per year by these facilities with the goal of better estimating the annual quantity of waste digested between 1990 to 2014. Available data will also be compiled where available for facilities that did not directly respond to the EPA AD Data Collection surveys for completeness.

EPA will seek out data sources to confirm the amount of recovered biogas for years prior to 2015 (i.e., the years prior to the EPA AD Data Collection Surveys). Currently, partial data of recovered biogas are available between 2015 to 2018 from the EPA AD Data Collection Surveys. The primary purpose of this improvement will be to understand whether the range of recovered biogas from the survey data are reflective of earlier years in the time series.

7.5 Waste Incineration (CRF Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the combustion of waste are accounted for in the Energy sector rather than in the Waste sector because almost all combustion of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The combustion of waste in the United States in 2021 resulted in 12.8 MMT CO_2 Eq. of emissions. For more details on emissions from the combustion of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste combustion include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided.

An analysis of the likely level of medical waste incineration emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of Inventory reporting under the UNFCCC. More information on this analysis is provided in Annex 5.

Furthermore, an analysis was conducted on the likely level of sewage sludge incineration emissions based on the total amount of sewage sludge generated and assumed percent incineration. Based on assumed amount of sludge incinerated and non-CO_2 factors for solid biomass it was determined that annual greenhouse gas emissions for sewage sludge incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of Inventory reporting under the UNFCCC. More information on this analysis is provided in Annex 5.

7.6 Waste Sources of Precursor Greenhouse Gases–TO BE UPDATED FOR FINAL INVENTORY REPORT

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of precursors to greenhouse gases. The reporting requirements of the UNFCCC[14] request that information be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmosphere aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from waste sources for the years 1990 through 2021 are provided in Table 7-50.

Table 7-50: Emissions of NO_x, CO, NMVOC, and SO_2 from Waste (kt)

Gas/Source	1990	2005	2017	2018	2019	2020	2021
NO_x	**+**	**2**	**1**	**1**	**1**	**1**	**1**
Landfills	+	2	1	1	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous[a]	+	0	0	0	0	0	0
CO	**1**	**7**	**6**	**5**	**5**	**5**	**5**
Landfills	1	6	6	5	5	5	5
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	0	0	0	0	0	0
NMVOCs	**673**	**114**	**52**	**52**	**52**	**52**	**52**
Wastewater Treatment	57	50	25	22	22	22	22
Miscellaneous[a]	557	44	22	20	20	20	20
Landfills	58	22	11	10	10	10	10
SO_2	**+**	**1**	**1**	**1**	**1**	**1**	**1**
Landfills	+	1	1	1	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous[a]	+	0	0	0	0	0	0

+ Does not exceed 0.5 kt.

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals by gas may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2021 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2022a). For Table 7-50, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Tier 1/Tier 2 source categories to those more closely aligned with IPCC categories, based on EPA (2003).[15] NEI Tier 1 emission categories related to the IPCC waste sector include:

[14] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

[15] The NEI estimates and reports emissions from six criteria air pollutants (CAPS) and 187 hazardous air pollutants (HAPS) in support of National Ambient Air Quality Standards. Reported NEI emission estimates are grouped into 60 sectors and 15 Tier 1

Waste Disposal and Recycling (landfills; publicly owned treatment works; industrial wastewater; treatment, storage, and disposal facilities; and other). As described in detail in the NEI Technical Support Documentation (TSD) (EPA 2021), emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2021, which are described in detail in the NEI's TSD (EPA 2021). No quantitative estimates of uncertainty were calculated for this source category.

source categories, which broadly cover similar source categories to those presented in this chapter. For this report, EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI Tier 1/Tier 2 categories to better align with IPCC source categories, and to ensure consistency and completeness to the extent possible. [See Annex 6.X for more information on this mapping].