

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 17.4 percent of total U.S. anthropogenic methane (CH₄) emissions in 2019, the third largest contribution of any CH₄ source in the United States. Additionally, wastewater treatment and discharge, composting of organic waste, and stand-alone anaerobic digestion accounted for approximately 2.8 percent, 0.3 percent, and less than 0.1 percent of U.S. CH₄ emissions, respectively. Nitrous oxide (N₂O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N₂O emissions from the treatment process itself. Nitrous oxide emissions from composting were also estimated. Together, these waste activities account for 6.2 percent of total U.S. N₂O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH₄ 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.

Figure 7-1: 2019 Waste Chapter Greenhouse Gas Sources

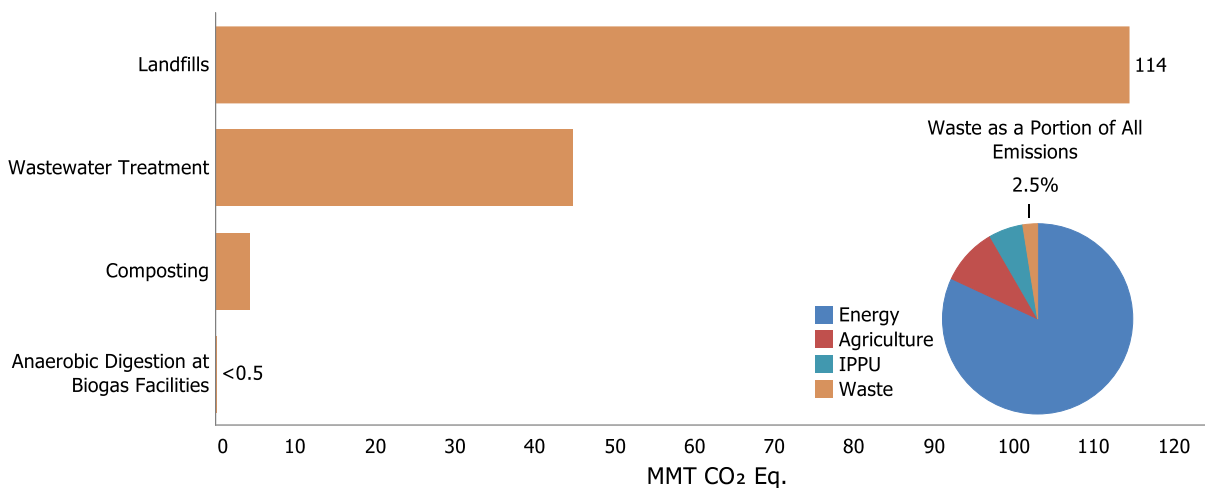
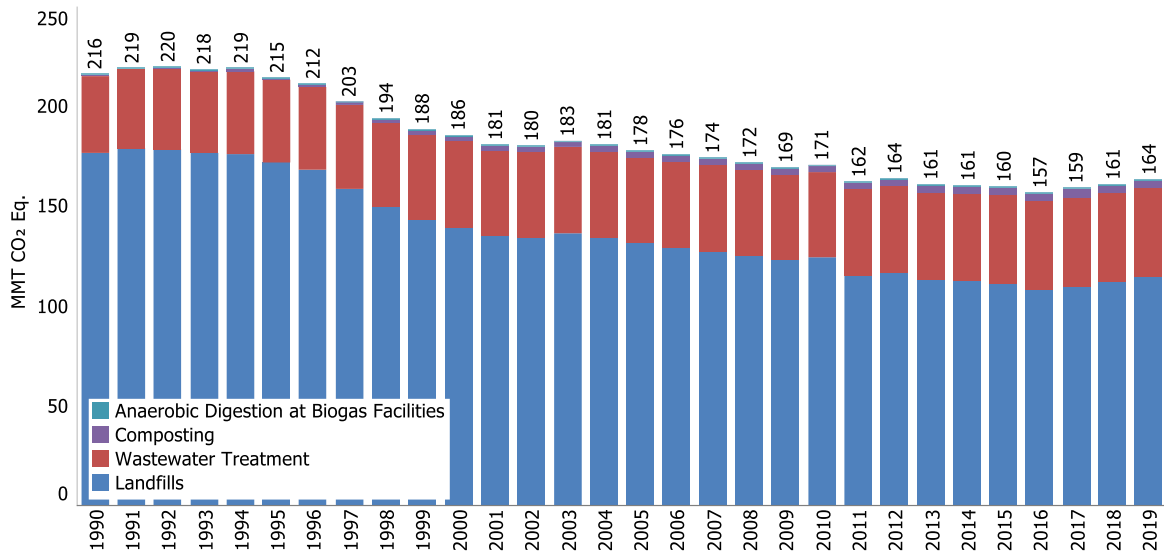


Figure 7-2: Trends in Waste Chapter Greenhouse Gas Sources



Overall, in 2019, waste activities generated emissions of 163.7 MMT CO₂ Eq., or 2.5 percent of total U.S. greenhouse gas emissions.

Table 7-1: Emissions from Waste (MMT CO₂ Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CH₄	197.1	153.4	132.5	129.2	130.5	132.9	135.3
Landfills	176.6	131.4	111.4	108.0	109.4	112.1	114.5
Wastewater Treatment	20.2	20.1	18.8	18.7	18.5	18.4	18.4
Composting	0.4	1.9	2.1	2.3	2.4	2.3	2.3
Anaerobic Digestion at Biogas Facilities	+	0.1	0.2	0.2	0.2	0.2	0.2
N₂O	19.0	24.6	27.3	27.9	28.6	28.2	28.4
Wastewater Treatment	18.7	23.0	25.4	25.9	26.4	26.1	26.4
Composting	0.3	1.7	1.9	2.0	2.2	2.0	2.0
Total	216.2	178.0	159.8	157.1	159.0	161.1	163.7

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CH₄	7,885	6,135	5,301	5,166	5,218	5,317	5,414
Landfills	7,063	5,255	4,456	4,321	4,375	4,482	4,580
Wastewater Treatment	806	803	753	747	739	737	736
Composting	15	75	85	91	98	90	91
Anaerobic Digestion at Biogas Facilities	1	2	7	7	7	7	7
N₂O	64	83	91	94	96	94	95
Wastewater Treatment	63	77	85	87	89	88	88
Composting	1	6	6	7	7	7	7

Note: Totals may not sum due to independent rounding.

Carbon dioxide (CO₂), CH₄, and N₂O 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 2019 resulted in 11.8 MMT CO₂ 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.

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 2018) to ensure that the trend is accurate. Based on the availability of updated methodological guidance from *2019 Refinement* (IPCC 2019), EPA revised the methodologies used to estimate CH₄ and N₂O emissions from domestic wastewater treatment as well as the methodology used to estimate CH₄ emissions from industrial wastewater treatment. EPA also added N₂O emission estimates from industrial wastewater treatment using a methodology based on the *2019 Refinement* (IPCC 2019). EPA also added emissions estimates from stand-alone anaerobic digestion to the Waste Chapter. For more information on specific methodological updates, please see the Recalculations 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 CH₄ flared at composting sites. Emissions reported in the Waste chapter for landfills, wastewater treatment, and stand-alone anaerobic digestion include those from all 50 states, including Hawaii and Alaska, as well as from the District of Columbia. Emissions from wastewater treatment include most U.S. Territories except for Pacific Islands. Those emissions are likely insignificant as those Pacific Islands have no permanent population. Emissions for composting include all 50 states, including Hawaii and Alaska, but not U.S. Territories. Composting emissions from U.S. Territories are assumed to be small. Similarly, we are not aware of any anaerobic 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 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 CO₂ 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 CO₂ 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 CH₄ emissions from MSW landfills for the years 2010 to 2019 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 or 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 (CH₄) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO₂) and 50 percent CH₄, 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.¹ Additionally, state and tribal requirements may exist.

Methane and CO₂ are the primary constituents of landfill gas generation and emissions. However, the *2006 IPCC Guidelines* set an international convention to not report biogenic CO₂ from activities in the Waste sector (IPCC 2006). Net carbon dioxide flux from carbon stock changes in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this Inventory). Additionally, emissions of NMOC and VOC are not estimated because they are emitted in trace amounts. Nitrous oxide (N₂O) 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 N₂O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N₂O emissions from solid waste disposal sites “because they are not significant.” Therefore, only CH₄ 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 CH₄ that is recovered and either flared or used for energy purposes; and (4) the amount of CH₄ 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, 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 60 years or longer as the degradable waste decomposes over time.

In 2019, landfill CH₄ emissions were approximately 114.5 MMT CO₂ Eq. (4,580 kt), representing the third largest source of CH₄ emissions in the United States, behind enteric fermentation and natural gas systems. Emissions from MSW landfills accounted for approximately 87 percent of total landfill emissions (99.4 MMT CO₂ Eq.), while industrial waste landfills accounted for the remainder (15.1 MMT CO₂ Eq). Estimates of operational MSW landfills in the United States have ranged from 1,700 to 2,000 facilities (EPA 2019a; EPA 2019c; Waste Business Journal [WBJ] 2016; WBJ 2010). More recently, 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 2019a; WBJ 2010). While the number of active MSW landfills has decreased

¹ For more information regarding federal MSW landfill regulations, see <http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm>.

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 (EREF 2016; EPA 2019b; BioCycle 2010). Regarding industrial waste landfills, the WBJ database (WBJ 2016) 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) of EPA’s Greenhouse Gas Reporting Program (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.

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 and then decreased by 5.7 percent to 213 MMT in 2019 (see Annex 3.14, Table A-221). The total amount of MSW generated is expected to increase as the U.S. population continues to grow, but the percentage of waste landfilled may decline due to increased recycling and composting practices. Net CH₄ 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 10.3 MMT in 2019 (see Annex 3.14, Table A-221). CH₄ emissions from industrial waste landfills have also remained at similar levels recently, ranging from 14.4 MMT CO₂ Eq. in 2005 to 15.1 MMT CO₂ Eq. in 2019 when accounting for both CH₄ generation and oxidation.

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 project and technical database contains certain information on the gas collection and control systems in place at landfills that are a part of the program, which can include the amount of landfill gas collected and flared. In 2020, LMOP identified 9 new landfill gas-to-energy (LFGTE) projects (EPA 2020a) that began operation. While the amount of landfill gas collected and combusted continues to increase, the rate of increase in collection and combustion no longer exceeds the rate of additional CH₄ generation from the amount of organic MSW landfilled as the U.S. population grows (EPA 2020b).

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: CH₄ Emissions from Landfills (MMT CO₂ Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
MSW CH ₄ Generation ^a	205.3	-	-	-	-	-	-
Industrial CH ₄ Generation	12.1	16.0	16.6	16.6	16.7	16.7	16.7
MSW CH ₄ Recovered	(21.3)	-	-	-	-	-	-
MSW CH ₄ Oxidized	(18.4)	-	-	-	-	-	-
Industrial CH ₄ Oxidized	(1.2)	(1.6)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
MSW net CH ₄ Emissions (GHGRP)	-	117.0	96.4	93.1	94.4	97.0	99.4
Industrial CH ₄ Emissions ^b	10.9	14.4	15.0	15.0	15.0	15.0	15.1
Total	176.6	131.4	111.4	108.0	109.4	112.1	114.5

^a MSW CH₄ generation is not estimated after 2005 because the directly reported net CH₄ emissions from the GHGRP are used.

^b Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 169 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2019 (EPA 2020b).

“-” Not applicable due to methodology change.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values. 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 2019, directly reported net CH₄ 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. These data incorporate CH₄ recovered and oxidized for MSW landfills. As such, CH₄ generation and CH₄ recovery are not calculated separately. See the Time-Series Consistency section of this chapter for more information.

Table 7-4: CH₄ Emissions from Landfills (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
MSW CH ₄ Generation ^a	8,214	-	-	-	-	-	-
Industrial CH ₄ Generation	484	638	665	666	667	668	669
MSW CH ₄ Recovered	(851)	-	-	-	-	-	-
MSW CH ₄ Oxidized	(736)	-	-	-	-	-	-
Industrial CH ₄ Oxidized	(48)	(64)	(66)	(67)	(67)	(67)	(67)
MSW net CH ₄ Emissions (GHGRP)	-	4,681	3,858	3,722	3,775	3,881	3,978
Industrial net CH ₄ Emissions ^b	436	575	598	599	600	601	602
Total	7,063	5,255	4,456	4,321	4,375	4,482	4,580

^a MSW CH₄ generation is not estimated after 2005 because the directly reported net CH₄ emissions from the GHGRP are used.

^b Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 169 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2019 (EPA 2020b).

“-” Not applicable due to methodology change.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values. 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 2019, directly reported net CH₄ 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. These data incorporate CH₄ recovered and oxidized for MSW landfills. As such, CH₄ generation and CH₄ recovery are not calculated separately. See the Time-Series Consistency section of this chapter for more information.

Methodology

Methodology Applied for MSW Landfills

A combination of IPCC Tier 2 and 3 approaches (IPCC 2006) are used to calculate emissions from MSW Landfills.

Methane emissions from landfills are estimated using two primary methods. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH₄ generation. The amount of CH₄ recovered and combusted from MSW landfills is subtracted from the CH₄ generation and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH₄ in a landfill that is oxidized to CO₂ 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.

$$CH_{4,MSW} = (G_{CH_4} - \sum_{n=1}^N R_n) * (1 - OX)$$

where,

$CH_{4,MSW}$	= Net CH_4 emissions from solid waste
$G_{CH_4,MSW}$	= 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.

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

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)

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.

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

	Annex Steps 1-3	Annex Step 4	Annex Step 5	Annex Step 6
Method	US-specific first-order decay (FOD) model	Back-casted EPA GHGRP reported net methane emissions	EPA GHGRP reported net methane emissions	EPA GHGRP reported net methane emissions
	1990 - 2004	2005 - 2009	2010 - 2016	2017 - Present
Parameters	IPCC 2006 Emission Factors: <ul style="list-style-type: none"> • DOC = 0.20 • MCF = 1 • $DOC_f = 0.5$ • OX = 0.10 • DE = 0.99 Activity Data: <ul style="list-style-type: none"> • National waste generation data multiplied by the national disposal factor 	<ul style="list-style-type: none"> • Back-casted GHGRP emissions from 2010 to the current reporting year^{1, 2} • 9% scale-up factor applied to GHGRP emissions 	<ul style="list-style-type: none"> • Net GHGRP emissions² • 9% scale-up factor applied to GHGRP emissions 	<ul style="list-style-type: none"> • Net GHGRP emissions² • 11% scale-up factor applied to GHGRP emissions

¹ The back-casted emissions are calculated using directly reported net methane emissions for GHGRP reporting years 2010 to 2019 (the current reporting year). The back-casted emissions are subject to change in each Inventory based on new reporting year reports and re-submitted greenhouse gas reports for previous years. This method is compatible with the IPCC 2006 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 IPCC 2006 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 IPCC 2006 Guidelines.

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 CH₄ 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., CH₄ 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 the Time Series Consistency section of this chapter, Annex 3.14, and a technical memorandum (RTI 2017).

A summary of the methodology used to generate the current 1990 through 2018 Inventory estimates for MSW landfills is as follows and is also illustrated in Annex Figure A-18:

- **1940 through 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 CH₄ generation, estimates for those years were included in the FOD model for completeness in accounting for CH₄ 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 CH₄ 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 through 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 CH₄ generation. Landfill-specific CH₄ recovery amounts were then subtracted from CH₄ 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 through 2009:** Emissions for these years are estimated using net CH₄ 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. 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. A single oxidation factor is not applied to the annual CH₄ 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 CH₄ flux rate. The average oxidation factor from the GHGRP facilities is 19.5 percent (from reporting years 2011 to 2017). 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 through 2016:** Net CH₄ 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 CH₄ 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. As noted above, GHGRP facilities use a variety of oxidation factors. The average oxidation factor from the GHGRP facilities is 19.5 percent. A detailed explanation of the methods used to develop the revised scale-up factor are presented in Annex 3.14 Step 5.
- **2017 through 2019:** 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 current (1990 to 2019) Inventory to incorporate facilities that have stopped reporting to the GHGRP, new additions to the 2020 LMOP Database (EPA 2020a), and corrections to the underlying database of non-reporting landfills used to develop the 9 percent scale-up factor that were identified. For 2017 to 2019, a scale-up factor of 11 percent is applied annually to the GHGRP net reported CH₄ emissions. A detailed explanation of the methods used to develop the revised scale-up factor are presented in Annex 3.14 Step 6.

Supporting information, including details on the techniques used to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in the Time-Series Consistency section of this chapter and 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 2020) 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 IPCC 2006 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:

$$CH_{4,IND} = (G_{CH_4} - \sum_{n=1}^N R_n) * (1 - OX)$$

where,

$CH_{4,Solid\ Waste}$	= Net CH_4 emissions from solid waste
$G_{CH_4,Ind}$	= 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 IPCC 2006 Guideline 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 in 2020 to investigate other sources of industrial food waste, which is briefly described in the Planned Improvements section, and decided to maintain the currently used methodology for the 1990-2019 Inventory due to questions around data availability across the 1990 to 2019 time series, the completeness and representativeness of other estimates and methodologies, and the level of effort required to reproduce and/or merge estimates across the 1990 to 2019 time series.

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. Data collected through EPA's GHGRP for industrial waste landfills (Subpart TT) show that only one of the 168 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2020b). 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 CH₄ oxidized by the landfill cover at industrial waste landfills was assumed to be 10 percent of the CH₄ 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 (and later land applied), 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, 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:

- 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* reports use a materials flow methodology, commonly referred to as a 'top-down' methodology, which relies heavily on a mass balance approach. Data are gathered from industry associations, key businesses, similar industry sources, and government agencies (e.g., the Department of Commerce and the U.S. Census Bureau) and are used to estimate tons of materials and products generated, recycled, combusted with energy recovery, other food management pathways, or landfilled nationwide. The amount of MSW generated is estimated by estimating production and then adjusting these values by addressing the imports and exports of produced materials to other countries. 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 (U.S. EPA 2020) uses a methodology that expanded the number of management pathways to include: animal feed; bio-based materials/biochemical processing (i.e., rendering); codigestion/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 and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH₄ 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 CH₄ generation potential (L₀) and the rate of decay that produces CH₄ from MSW, as determined from several studies of CH₄ 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 under-estimate CH₄ 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 CH₄ 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 2019, 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 2019. This methodology does not factor in annual landfill to landfill changes in landfill CH₄ 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.

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). This chapter, however, recommends against back-casting emissions back to 1990 with a limited set of data and instead provides guidance on techniques to splice, or join methodologies together. 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 the GHGRP data for MSW landfills, where directly reported CH₄ 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.

Aside from the uncertainty in estimating landfill CH₄ 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 CH₄ 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 CH₄ recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the Inventory's CH₄ recovery databases (used for years 1990 to 2004). Four CH₄ recovery databases are used to estimate nationwide CH₄ recovery for MSW landfills for 1990 to 2004; whereas directly reported CH₄ emissions, which accounts for CH₄ recovery, is used for facilities reporting to the GHGRP for years 2005 to 2018. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 through 2013 Inventory report (two years before the full GHGRP data set started being used for net CH₄ 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. Additionally, 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 CH₄ recovered.

The LFGE database was updated annually until 2015. The flare database was populated annually until 2015 by the voluntary sharing of flare sales data by select vendors, which likely underestimated recovery for landfills not included in the three other recovery databases used by the Inventory. The EIA database has not been updated since 2006 and has, for the most part, been replaced by the GHGRP MSW landfills database. To avoid double counting and to use the most relevant estimate of CH₄ 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 CH₄ 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 CH₄ 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 CH₄ 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 CH₄ 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 CH₄ generation

estimates for industrial waste landfills and carries the same amount of uncertainty as with the factor applied to CH₄ 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 CH₄ Emissions from Landfills (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission				
		Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	CH₄	114.5	88.0	140.0	-22%	+23%
MSW	CH ₄	99.4	74.1	124.5	-25%	+25%
Industrial	CH ₄	15.1	10.4	18.9	-31%	+25%

^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 CH₄ 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.² 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. 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.

For the current (1990 to 2019) Inventory, the scale-up factor was revised from 9 percent to 11 percent resulting from additional QC checks performed on the underlying 2016 Non-Reporting Landfills Database used to develop the 9 percent scale-up factor, the addition of the total waste-in-place for the 194 landfills no longer reporting to Subpart HH, changes to the waste-in-place for some landfills in the 2020 LMOP Database, and the increase in estimated annual waste disposed between 2016 and 2018 for all non-reporting landfills in the database. Overall, the estimated waste-in-place for non-reporting landfills increased by approximately 274 million MT. The estimates of waste-in-place for the non-reporting landfills should be considered best estimates based on available data from the 2020 LMOP Database (EPA 2020a) and the 2016 WBJ Directory (WBJ 2016). No efforts were made in developing the 2018 Non-Reporting Landfills Database to contact facilities to verify the information included in either source database.

Additional QC checks on the 2016 Non-Reporting Landfills Database increased the total waste-in-place estimated for 2016 by 38 million MT. Specifically, QC checks and corrections made to the underlying 2016 Non-Reporting Landfills Database resulted in an increase of 38 million tons of waste-in-place resulting from a formula error that under-estimated the waste-in-place for some landfills with a permitted end year after 2016, especially for those landfills that had reported closure dates in 2030 or later. The year that the waste-in-place data were from in the 2017 LMOP Database, a primary source used, was not pulled into the 2016 Non-Reporting Landfills Database, thus the methodology assumed that all waste-in-place data were from 2016. The waste-in-place year is now included in the 2018 Non-Reporting Landfills Database, allowing for a more realistic waste-in-place value to be estimated by landfill.

Several quality control checks were performed on the 2018 Non-Reporting Landfills Database used to calculate the 11 percent scale-up factor. Specific checks included a 10 percent check of the data carried over from the 2016 WBJ Directory and the LMOP Databases, randomly checking formula calculations, comparing the 2017 and 2020 LMOP Databases for changes in waste-in-place, and sorting the estimated waste-in-place column from largest to smallest to identify errors in the larger landfills.

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 CH₄ emissions for MSW landfills. These recalculations increased net emissions for MSW landfills from 2005 to 2015 by less than 0.5 percent when compared to the previous Inventory report. 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

² See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

annual greenhouse gas reports resubmitted for 2015 to 2018 slightly increased or decreased total Subpart HH reported net emissions by +/- 0.3 percent in the years the Subpart HH data are applied (i.e., 2005 to 2019). No Subpart HH reports were resubmitted for the 2010 to 2014 reporting years that resulted in net emission changes. These changes resulted in changes to the net Inventory emissions ranging from -0.03 percent to +0.06 percent. A change in net Subpart HH reported emissions results in the same percentage change in the Inventory emissions for that year.

The scale-up factor was also reassessed as a planned improvement for the current (1990 to 2019) Inventory. Results from this effort increased the scale-up factor from 9 percent to 11 percent. The scale-up factor increased because of the inclusion of 194 GHGRP Subpart HH facilities that have off-ramped, a calculation error identified for some non-reporting landfills when developing the 9 percent scale-up factor in 2016, and changes to the estimated waste-in-place for all non-reporting landfills since 2016. The 9 percent scale-up factor is being retained and used for 2005-2016 and the 11 percent is being used for 2017 to 2019.

Using the 11 percent scale-up factor, in addition to revisions to the previously submitted GHGRP reports between 2015 to 2018 ultimately increased net CH₄ emissions by 1.6 percent in 2017 (1.7 MMT CO₂ Eq.) and 1.4 percent in 2018 (1.5 MMT CO₂ Eq.) compared to the previous (1990 to 2018) Inventory.

Planned Improvements

EPA has received recommendations from industry stakeholders regarding the DOC values and decay rates (k value) required to be used in the GHGRP calculations based on recent trends in the composition of waste disposed in MSW landfills. Stakeholders have suggested that newer, more up-to-date default values for both k and DOC in the GHGRP could then be reflected in the 2005 and later years of the Inventory. In response, EPA is developing 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 future GHGRP rulemaking 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.

EPA is investigating the k values for the three climate types (dry, moderate, and wet) against new data and other landfill gas models, and how they are applied to the percentage of the population assigned to these climate types. EPA will also assess the uncertainty factor applied to these k values in the Waste Model.

With respect to the scale-up factor, EPA will periodically assess the impact to the waste-in-place and emissions data from 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 CO₂ equivalent emissions for 3 consecutive years or less than 25,000 metric tons of CO₂ equivalent emissions for 5 consecutive years). As was the case with this Inventory, if warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the Inventory. The methodology applied to develop the scale-up factor will be reviewed for the 1990 to 2020 inventory cycle to determine whether the total waste-in-place for all landfills in the Non-Reporting Landfills Database should be factored into the scale-up factor, or a subset of years (e.g., 25, 30, 50) depending on the duration of operation.

EPA began investigating the prevalence of food-related waste deposited into industrial waste landfills in 2020 and will record the findings from this exercise in a memorandum. The resources identified with the most relevant data for the Inventory include the EPA’s 2020 Wasted Food Measurement Methodology Scoping Memo (EPA 2020c); the Food Waste Reduction Alliance survey reports on the industrial food manufacturing sector conducted to date for 2012 (BSR 2013), 2013 (BSR 2014), and 2015 (FWRA 2016); and one peer-reviewed journal article entitled, Assessing U.S. food wastage and opportunities for reduction (Dou et al. 2016). EPA’s wasted food measurement methodology includes estimates for industrial food waste based on others’ research estimates, but industrial food waste estimates will not be incorporated into the EPA’s Advancing Sustainable Materials reports because industrial waste is beyond the scope of these reports. Dou et al. (2016) primarily used findings from the Food Waste Reduction Alliance surveys, which received survey data from a handful of facilities and may not be representative

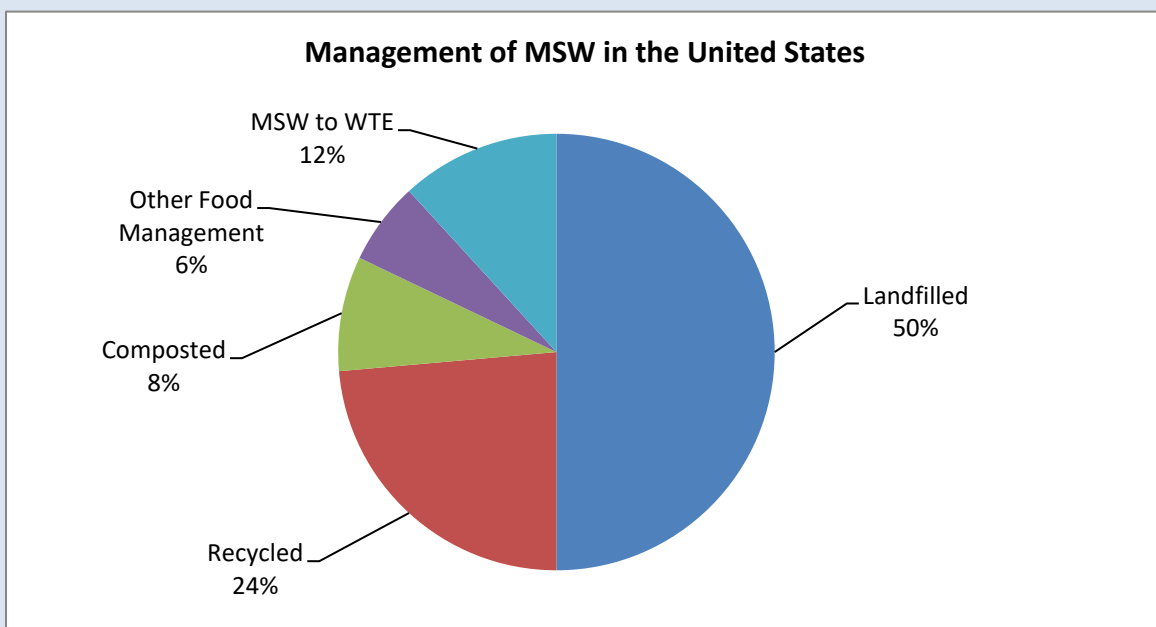
of the entire U.S. food and beverage sector. EPA has decided to maintain the currently applied methodology to estimate emissions from the industrial food and beverage sector for the current Inventory cycle.

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 2020) 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.

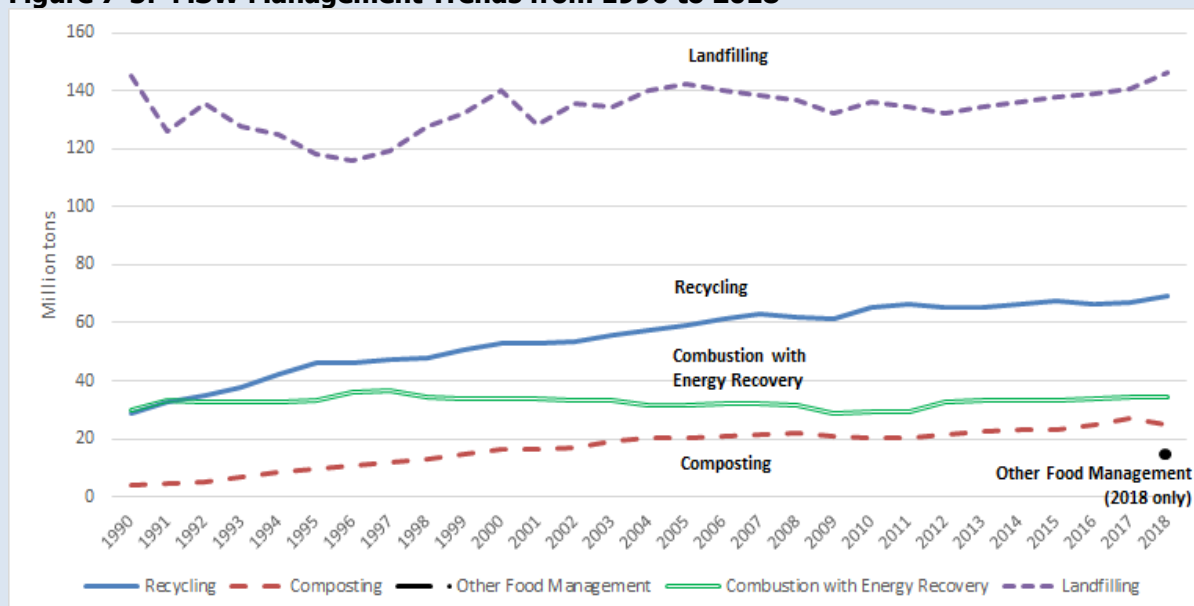
Figure 7-4: Management of Municipal Solid Waste in the United States, 2018



Source: EPA (2020d)

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).

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



Source: EPA (2020d). 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 2020d for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA 2019c 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 < <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management>>. Note: 2018 is the latest year of available data. Only one year of data (2018) is available for the ‘Other Food Management’ category.

Table 7-6 presents a typical composition of waste disposed of at a typical MSW landfill 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. Due to China’s recent ban on accepting certain kinds of solid waste by the end of 2017 (WTO 2017), inclusive of some paper and paperboard waste, plastic waste, and other miscellaneous inorganic wastes, there has been a slight increase in the disposal of paper and paperboard and plastic wastes since 2017 (Table 7-6). EPA expects these numbers to continue increasing until new markets for recycling of these goods are identified.

Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH₄ 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 CH₄ generation potential and CH₄ 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.

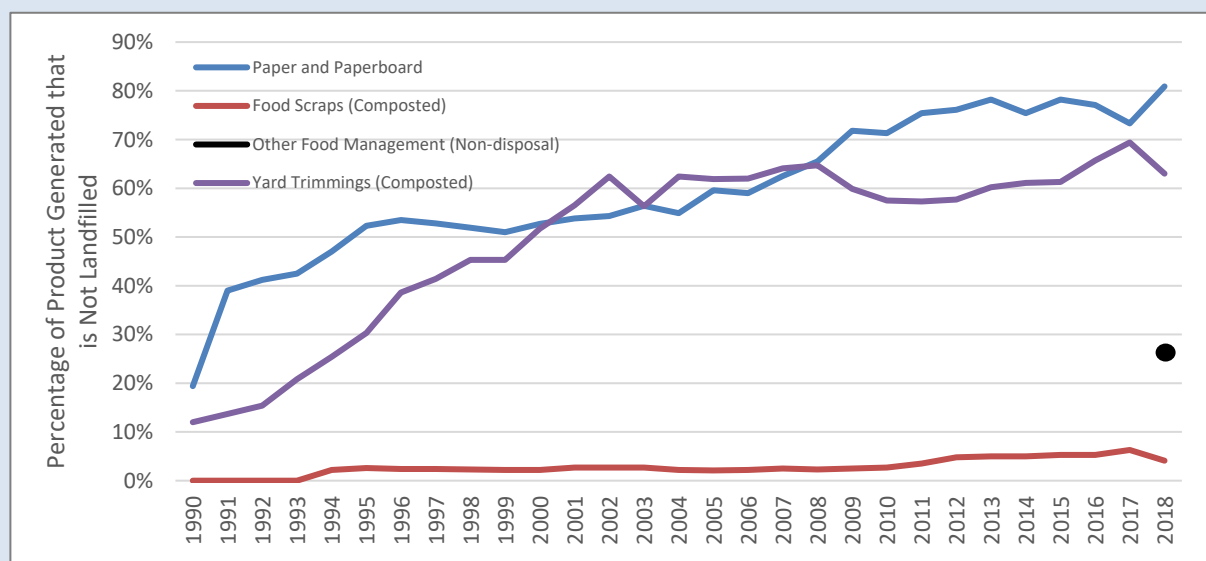
Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2018 (Percent)

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 (2020d)

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



Source: EPA (2020d). 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 2020d for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA 2019c 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 web site <<https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management>>.

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% of the food waste generated was beneficially reused or managed using a method that was not landfilling, recycling, or composting).

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

Wastewater treatment and discharge processes are sources of anthropogenic methane (CH₄) and nitrous oxide (N₂O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter,

suspended solids, nutrients, pathogenic organisms, and chemical contaminants.³ 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 18 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 2017). 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 CH₄, 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 CH₄ formed within the collection system enters the centralized system where it contributes to CH₄ 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.

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 CH₄. 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 it 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 N₂O 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 (NO₃) 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 (N₂). Nitrous oxide is generated as a by-product of nitrification, or as an intermediate product of denitrification. No matter where N₂O 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 CH₄ and biogenic CO₂) rises to the liquid surface and is typically released through vents. The gas produced in the effluent dispersal system (mainly N₂O and biogenic CO₂) is released through the soil.

³ Throughout the Inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

Discharge. Dissolved CH₄ and N₂O 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 addition of organic matter or nitrogen from wastewater discharges is generally expected to increase CH₄ and N₂O emissions from these environments. Where organic matter is released to slow-moving aquatic systems, such as lakes, estuaries, and reservoirs, CH₄ emissions are expected to be higher. Similarly, in the case of discharge to nutrient-impacted or hypoxic waters, N₂O emissions can be significantly higher.

The principal factor in determining the CH₄ 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 CH₄ 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 BOD₅. Throughout the rest of this chapter, the term “BOD” refers to BOD₅. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH₄ production, since CH₄ is produced only in anaerobic conditions. Where present, biogas recovery and flaring operations reduce the amount of CH₄ generated that is actually emitted. The principal factor in determining the N₂O 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 N₂O generation potential.

In 2019, CH₄ emissions from domestic wastewater treatment and discharge were estimated to be 10.3 MMT CO₂ Eq. (410 kt CH₄) and 1.8 MMT CO₂ Eq. (72 kt CH₄), respectively. 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 2017). In 2019, CH₄ emissions from industrial wastewater treatment and discharge were estimated to be 6.4 MMT CO₂ Eq. (254 kt CH₄). Industrial emission sources have generally increased across the time series through 1994 and then fluctuated up and down with production changes associated with the treatment of wastewater 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 seen an uptick since 2017. Table 7-7 and Table 7-8 provide CH₄ emission estimates from domestic and industrial wastewater treatment.

With respect to N₂O, emissions from domestic wastewater treatment and discharge in 2019 were estimated to be 20.5 MMT CO₂ Eq. (69 kt N₂O) and 5.3 MMT CO₂ Eq. (18 kt N₂O), respectively. Total N₂O emissions from domestic wastewater were estimated to be 25.8 MMT CO₂ Eq. (87 kt N₂O). Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption. In 2019, N₂O emissions from industrial wastewater treatment were estimated to be 0.6 MMT CO₂ Eq. (2 kt N₂O). 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 N₂O emission estimates from domestic wastewater treatment.

Table 7-7: CH₄ and N₂O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO₂ Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
CH₄	20.2	20.1	18.8	18.7	18.5	18.4	18.4
Domestic Treatment	13.5	13.0	11.2	10.9	10.5	10.4	10.3
Domestic Effluent	1.2	1.2	1.8	1.8	1.8	1.8	1.8
Industrial ^a Treatment	4.9	5.4	5.4	5.6	5.7	5.8	5.9
Industrial ^a Effluent	0.5	0.5	0.4	0.4	0.4	0.4	0.4
N₂O	18.7	23.0	25.4	25.9	26.4	26.1	26.4

Domestic Treatment	13.6	17.7	19.5	19.9	20.4	20.3	20.6
Domestic Effluent	4.7	4.8	5.4	5.4	5.4	5.3	5.3
Industrial ^b Treatment	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Industrial ^b Effluent	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	38.9	43.1	44.2	44.6	44.9	44.5	44.8

Note: Totals may not sum due to independent rounding.

^a Industrial activity for CH₄ 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 N₂O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

Table 7-8: CH₄ and N₂O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
CH₄	806	803	753	747	739	737	736
Domestic Treatment	540	518	447	434	421	416	410
Domestic Effluent	49	49	71	72	72	72	72
Industrial ^a Treatment	196	215	217	223	228	232	236
Industrial ^a Effluent	21	19	18	18	18	18	18
N₂O	63	77	85	87	89	88	88
Domestic Treatment	46	59	65	67	69	68	69
Domestic Effluent	16	16	18	18	18	18	18
Industrial ^b Treatment	1	1	2	2	2	2	2
Industrial ^b Effluent	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

^a Industrial activity for CH₄ 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 N₂O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

Methodology

The methodologies presented in IPCC (2019) form the basis of the CH₄ and N₂O emission estimates for both domestic and industrial wastewater treatment and discharge. Domestic wastewater treatment follows the IPCC Tier 1 methodology, while domestic wastewater discharge follows IPCC Tier 2 discharge methodology and emission factors. Industrial wastewater treatment and discharge follow IPCC Tier 1 methodologies.

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 previously estimated, such as N₂O emissions from industrial wastewater treatment, and to improve emission estimates for other sources, such as emissions from wastewater discharge and centralized wastewater treatment.

Domestic Wastewater CH₄ Emission Estimates

Domestic wastewater CH₄ emissions originate from both septic systems and from centralized treatment systems. Within these centralized systems, CH₄ emissions can arise from aerobic systems that liberate dissolved CH₄ 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);
- 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 CH₄ emissions are estimated as follows:

$$\text{Total Domestic CH}_4 \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D + E$$

Table 7-9 presents domestic wastewater CH₄ emissions for both septic and centralized systems, including anaerobic sludge digesters and emissions from centralized wastewater treatment effluent, in 2019.

Table 7-9: Domestic Wastewater CH₄ Emissions from Septic and Centralized Systems (2019, kt, MMT CO₂ Eq. and Percent)

	CH ₄ Emissions (kt)	CH ₄ Emissions (MMT CO ₂ Eq.)	% of Domestic Wastewater CH ₄
Septic Systems (A)	232	5.8	48.1
Centrally-Treated Aerobic Systems (B)	36	0.9	7.5
Centrally-Treated Anaerobic Systems (C)	134	3.3	27.7
Anaerobic Sludge Digesters (D)	8.1	0.2	1.7
Centrally-Treated Wastewater Effluent (E)	72	1.8	15.0
Total	482	12.1	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 18 percent in 2019; U.S. Census Bureau 2017) and an emission factor and then converting the result to kt/year.

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2020) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. Table 7-12 presents U.S. population for 1990 through 2019. 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 2017). Methane emissions for septic systems are estimated as follows:

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

Table 7-10: Variables and Data Sources for CH₄ Emissions from Septic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US _{POP}	U.S. population ^a	Persons	1990-2019: U.S. Census Bureau (2020)
T _{SEPTIC}	Percent treated in septic systems ^a	%	Odd years from 1989 through 2017: U.S. Census Bureau (2017)

Variable	Variable Description	Units	Inventory Years: Source of Value
			Data for intervening years obtained by linear interpolation 2018 and 2019: Forecasted from the rest of the time series
EF _{SEPTIC}	Methane emission factor – septic systems (10.7)	g CH ₄ /capita/day	1990-2019: 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 total BOD₅ produced (also referred to as the total organically degradable material in wastewater or TOW) for 1990 through 2019. The BOD₅ production rate 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:

$$\text{Total wastewater BOD}_5 \text{ produced per capita (U.S. Specific (ERG 2018a), kg/capita/day)}$$

$$\text{BOD}_{\text{gen rate}} = \text{BOD}_{\text{without scrap}} \times (1 - \% \text{disposal}) + \text{BOD}_{\text{with scraps}} \times (\% \text{disposal})$$

$$\text{Total organically degradable material in domestic wastewater (IPCC 2019 (Eq. 6.3), Gg/year)}$$

$$\text{TOW} = \text{US}_{\text{POP}} \times \text{BOD}_{\text{gen rate}} \times 365.25$$

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	1990-2019: Calculated
BOD _{without scrap}	Wastewater BOD produced per capita without kitchen scraps ^a	kg/capita/day	1990-2003: Metcalf & Eddy (2003)
BOD _{with scraps}	Wastewater BOD produced per capita with kitchen scraps ^a	kg/capita/day	2004-2013: Linear interpolation 2014-2019: Metcalf & Eddy (2014)
% disposal	Percent of housing units with kitchen disposal ^a	%	1990-2013: U.S. Census Bureau (2013) 2014-2019: Forecasted from the rest of the time series
TOW	Total wastewater BOD Produced per Capita ^a	Gg BOD/year	1990-2019: Calculated, ERG (2018a)
US _{POP}	U.S. population ^a	Persons	1990-2019: U.S. Census Bureau (2020)
365.25	Conversion factor	Days in a year	Standard conversion

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

Table 7-12: U.S. Population (Millions) and Domestic Wastewater BOD₅ Produced (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
Population	253	300	325	327	329	331	334
TOW	8,131	9,624	9,736	9,820	9,896	9,971	10,079

Sources: U.S. Census Bureau (2020); ERG (2018a).

Methane emissions from POTWs were estimated by multiplying the total organics in centrally treated wastewater (total BOD₅) produced per capita in the United States by the percent of wastewater treated centrally, or percent collected (about 82 percent in 2019), 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 factor⁴ 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 sludge⁵ 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 methodology (IPCC 2019) 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 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 CH₄ recovered or flared from both aerobic and anaerobic wastewater treatment were set equal to the IPCC default of zero.

The methodological equations for CH₄ emissions from aerobic and anaerobic systems are:

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

where,

$$\text{Total organics in centralized wastewater treatment (IPCC 2019 (Eq. 6.3A), Gg BOD/year)}$$

$$TOW_{CENTRALIZED} = TOW \times T_{CENTRALIZED} \times I_{COLLECTED}$$

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	Gg BOD/year	1990-2019: Calculated
TOW	Total wastewater BOD Produced per Capita ^a	Gg BOD/year	1990-2019: Calculated, ERG (2018a)
T _{CENTRALIZED}	Percent collected ^a	%	1990-2017: U.S. Census Bureau (2017) Data for intervening years obtained by linear interpolation

⁴ Emission factors are calculated by multiplying the maximum CH₄-producing capacity of domestic wastewater (B₀, 0.6 kg CH₄/kg BOD) and the appropriate methane correction factors (MCF) for aerobic (0.03) and anaerobic (0.8) systems (IPCC 2019) and constructed wetlands (0.4) (IPCC 2014).

⁵ 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.

			2018-2019: Forecasted from the rest of the time series
I _{COLLECTED}	Correction factor for additional industrial BOD discharged (1.25)	No units	1990-2019: IPCC (2019)

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

Organic component removed from aerobic wastewater treatment (IPCC 2019 (Eq. 6.3B), Gg/year)

$$S_{\text{aerobic}} = S_{\text{mass}} \times [(\% \text{ aerobic w/primary} \times K_{\text{rem,aer_prim}}) + (\% \text{ aerobic w/out primary} \times K_{\text{rem,aer_noprim}}) + (\% \text{ aerobic+digestion} \times K_{\text{rem,aer_digest}})] \times 1000$$

Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 (Eq. 6.1),

$$\text{kt CH}_4/\text{year} = B1 = [(TOW_{\text{CENTRALIZED}}) \times (\% \text{ aerobic}_{\text{COTCW}}) - S_{\text{aerobic}}] \times EF_{\text{aerobic}} - R_{\text{aerobic}}$$

Table 7-14: Variables and Data Sources for CH₄ Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
<i>Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt CH₄/year)</i>			
S _{aerobic}	Organic component removed from aerobic wastewater treatment	Gg BOD/year	1990-2019: Calculated
S _{mass}	Raw sludge removed from wastewater treatment as dry mass ^a	Tg dry weight/year	1988: EPA (1993c); EPA (1999) 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 2005-2019: Forecasted from the rest of the time series
% aerobic _{COTCW}	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. 2005-2019: 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	%	
%aerobic+digestion	Percent of aerobic systems with primary and anaerobic sludge digestion	%	
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	1990-2019: IPCC (2019)
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	
1000	Conversion factor	metric tons to kilograms	
EF _{aerobic}	Emission factor – aerobic systems (0.018)	kg CH ₄ /kg BOD	

Variable	Variable Description	Units	Inventory Years: Source of Value
R _{aerobic}	Amount CH ₄ recovered or flared from aerobic wastewater treatment (0)	kg CH ₄ /year	

^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 BOD₅ concentration of 30 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. These standards are based on plants generally utilizing simple settling and biological treatment (EPA 2013). Constructed wetlands do not have secondary sludge removal.

$$\begin{aligned} & \text{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) (IPCC 2014 (Eq. 6.1), kt} \\ & \text{CH}_4\text{/year)} = B2 \\ & = [(TOW_{CENTRALIZED}) \times (\%aerobic_{CW})] \times (EF_{CW}) \end{aligned}$$

$$\begin{aligned} & \text{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S.} \\ & \text{Specific, kt CH}_4\text{/year)} = B3 \\ & = [(POTW_flow_CW) \times (BOD_{CW,INF}) \times 3.785 \times (EF_{CW})] \times 1/10^6 \times 365.25 \end{aligned}$$

Table 7-15: Variables and Data Sources for CH₄ Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
<i>Emissions from Constructed Wetlands Only (kt CH₄/year)</i>			
TOW _{CENTRALIZED}	Total organics in centralized wastewater treatment	Gg BOD/year	1990-2019: Calculated
% aerobic _{CW}	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs.	%	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. 2013-2019: Forecasted from the rest of the time series
EF _{CW}	Emission factor for constructed wetlands	kg CH ₄ /kg BOD	1990-2019: IPCC (2014)
<i>Emissions from Constructed Wetlands used as Tertiary Treatment (kt CH₄/year)</i>			
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.

Variable	Variable Description	Units	Inventory Years: Source of Value
			2013-2019: Forecasted from the rest of the time series
BOD _{CW,INF}	BOD concentration in wastewater entering the constructed wetland (30)	mg/L	1990-2019: 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	1990-2019: IPCC (2014)
1/10 ⁶	Conversion factor	kg to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

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

$$\begin{aligned} \text{Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 (Eq. 6.1), kt CH}_4\text{/year)} &= C \\ &= [(TOW_{\text{CENTRALIZED}}) \times (\% \text{ anaerobic}) - S_{\text{anaerobic}}] \times EF_{\text{anaerobic}} - R_{\text{anaerobic}} \end{aligned}$$

Table 7-16: Variables and Data Sources for CH₄ Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems (kt CH₄/year)			
TOW _{CENTRALIZED}	Total organics in centralized wastewater treatment	Gg BOD/year	1990-2019: 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. 2005-2019: Forecasted from the rest of the time series
S _{anaerobic}	Organic component removed from anaerobic wastewater treatment (0)	Gg/year	1990-2019: IPCC (2019)
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	

Emissions from Anaerobic Sludge Digesters:

Total CH₄ 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 CH₄ in biogas, the density of CH₄, one minus the destruction efficiency from burning the biogas in an energy/thermal device and then converting the results to kt/year.

$$\begin{aligned} \text{Emissions from Anaerobic Sludge Digesters (U.S. Specific, kt CH}_4\text{/year)} &= D \\ &= [(POTW_flow_AD) \times (\text{biogas gen})/(100)] \times 0.0283 \times (\text{FRAC_CH}_4) \times 365.25 \times (662) \times (1-DE) \times 1/10^9 \end{aligned}$$

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

Variable	Variable Description	Units	Inventory years: Source of Value
<i>Emissions from Anaerobic Sludge Digesters (kt CH₄/year)</i>			
POTW_flow_AD	POTW Flow to Facilities with Anaerobic Sludge Digesters	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. 2005-2019: Forecasted from the rest of the time series
biogas gen	Gas Generation Rate (1.0)	ft ³ /capita/day	1990-2019: Metcalf & Eddy (2014)
100	Per Capita POTW Flow (100)	gal/capita/day	1990-2019: 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	1990-2019: 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	1990-2019: EPA (1993a)
DE	Destruction Efficiency (99% converted to fraction)	No units	1990-2019: EPA (1998); CAR (2011); Sullivan (2007); Sullivan (2010); and UNFCCC (2012)
1/10 ⁹	Conversion factor	g to kt	Standard conversion

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).

$$\begin{aligned} \text{Emissions from Centrally Treated Systems Discharge (U.S. Specific, kt CH}_4\text{/year)} &= E \\ &= (\text{TOW}_{\text{RLE}} \times \text{EF}_{\text{RLE}}) + (\text{TOW}_{\text{Other}} \times \text{EF}_{\text{Other}}) \end{aligned}$$

where,

$$\begin{aligned} \text{Total organics in centralized treatment effluent (IPCC 2019 (Eq. 6.3D), Gg BOD/year)} &= \text{TOW}_{\text{EFFtreat,CENTRALIZED}} \\ &= [\text{TOW}_{\text{CENTRALIZED}} \times \% \text{ primary} \times (1 - \text{TOW}_{\text{rem,PRIMARY}})] + [\text{TOW}_{\text{CENTRALIZED}} \times \% \text{ secondary} \times (1 - \\ &\quad \text{TOW}_{\text{rem,SECONDARY}})] + [\text{TOW}_{\text{CENTRALIZED}} \times \% \text{ tertiary} \times (1 - \text{TOW}_{\text{rem,TERTIARY}})] \end{aligned}$$

$$\begin{aligned} \text{Total organics in effluent discharged to reservoirs, lakes, or estuaries (U.S. Specific, Gg BOD/year)} &= \text{TOW}_{\text{RLE}} \\ &= \text{TOW}_{\text{EFFtreat,CENTRALIZED}} \times \text{Percent}_{\text{RLE}} \end{aligned}$$

$$\begin{aligned} \text{Total organics in effluent discharged to other waterbodies (U.S. Specific, Gg BOD/year)} &= \text{TOW}_{\text{Other}} \\ &= \text{TOW}_{\text{EFFtreat,CENTRALIZED}} \times \text{Percent}_{\text{Other}} \end{aligned}$$

Table 7-18: Variables and Data Sources for CH₄ Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
TOW _{EFFtreat,CENTRALIZED}	Total organics in centralized treatment effluent	Gg BOD/year	1990-2019: Calculated
TOW _{CENTRALIZED}	Total organics in centralized wastewater treatment	Gg BOD/year	1990-2019: Calculated
% primary	Percent of primary domestic centralized treatment	%	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. 2013-2019: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment	%	
% tertiary	Percent of tertiary domestic centralized treatment	%	
TOW _{rem,PRIMARY}	Fraction of organics removed from primary domestic centralized treatment	No units	1990-2019: IPCC (2019)
TOW _{rem,SECONDARY}	Fraction of organics removed from secondary domestic centralized treatment	No units	
TOW _{rem,TERTIARY}	Fraction of organics removed from tertiary domestic centralized treatment	No units	
TOW _{RLE}	Total organics in effluent discharged to reservoirs, lakes, and estuaries	Gg BOD/year	1990-2019: Calculated
TOW _{Other}	Total organics in effluent discharge to other waterbodies	Gg BOD/year	
EF _{RLE}	Emission factor (discharge to reservoirs/lakes/estuaries)	kg CH ₄ /kg BOD	1990-2019: IPCC (2019)
EF _{Other}	Emission factor (discharge to other waterbodies)	kg CH ₄ /kg BOD	
Percent _{RLE}	% discharged to reservoirs, lakes, and estuaries	%	1990-2010: Set equal to 2010 2010: ERG (2021) 2011: Obtained by linear interpolation 2012: ERG (2021) 2013-2019: Set equal to 2012
Percent _{Other}	% discharged to other waterbodies	%	

Industrial Wastewater CH₄ Emission Estimates

Industrial wastewater CH₄ 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 CH₄ 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 CH₄ emissions from wastewater treatment were identified and included in the Inventory. The main criteria used to identify U.S. industries likely to generate CH₄ are whether they generate high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH₄ 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 2019 are displayed in Table 7-19 below. Further discussion of wastewater treatment for each industry is included below.

Table 7-19: Total Industrial Wastewater CH₄ Emissions by Sector (2019, MMT CO₂ Eq. and Percent)

Industry	CH ₄ Emissions (MMT CO ₂ Eq.)	% of Industrial Wastewater CH ₄
Meat & Poultry	5.0	78.5
Pulp & Paper	0.7	11.4
Fruit & Vegetables	0.2	3.6
Ethanol Refineries	0.2	2.5
Breweries	0.1	2.2
Petroleum Refineries	0.1	1.8
Total	6.4	100

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

The general IPCC equation to estimate methane emissions from each type of treatment system used for each industrial category is:

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

where,

- CH₄ (industrial sector) = Total CH₄ 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 CH₄/kg COD)
- R_i = Methane recovered for industrial sector *i* (kg CH₄/year)

The general IPCC equation to estimate the total organics in wastewater (TOW) for each industrial category is:

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

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 (m³/t product)
- COD_i = Chemical oxygen demand (industrial degradable organic component in wastewater) (kg COD/m³)

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 (2021). For CH₄ 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).

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

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 (%)

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

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

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

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 factors⁶ 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	38.7	2.5	23.9	702.4
2005	92.4	31.4	25.1	42.9	11.7	23.1	818.6
2015	80.9	32.8	27.7	44.6	44.2	22.4	914.5
2016	79.9	34.2	28.3	43.5	45.8	22.3	926.0
2017	80.3	35.4	28.9	42.9	47.2	21.8	933.5
2018	79.4	36.4	29.4	42.6	48.0	21.5	951.4
2019	78.8	37.4	30.1	43.1	47.2	21.1	940.2

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

Sources: Pulp and Paper - FAO (2020a) and FAO (2020b); Meat, Poultry, and Vegetables - USDA (2020a and 2020c); Ethanol - Cooper (2018) and RFA (2020a and 2020b); Breweries - Beer Institute (2011) and TTB (2020); Petroleum Refining - EIA (2020).

Table 7-21: U.S. Industrial Wastewater Characteristics Data (2019)

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).

⁶ Emission factors are calculated by multiplying the maximum CH₄-producing capacity of wastewater (B₀, 0.25 kg CH₄/kg COD) and the appropriate methane correction factors (MCF) for aerobic (0), partially anaerobic (0.2), and anaerobic (0.8) systems (IPCC 2019).

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	60	5.2	75.9	38.5	37.4
Meat Processing	33	33 ¹	33	0	33
Poultry Processing	25	25 ¹	25	0	25
Fruit/Vegetable Processing	11	0	11	5.5	5.5
Ethanol Production – Wet Mill	33.3	33.3	0	0	0
Ethanol Production – Dry Mill	75	75	0	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

¹ Wastewater is pretreated in anaerobic lagoons prior to aerobic treatment.

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 (2021).

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).

Emissions from Discharge of Industrial Wastewater Treatment Effluent:

Methane emissions from discharge of industrial wastewater treatment effluent are estimated by multiplying the total organic content of the discharged wastewater effluent by an emission factor associated with the discharge:

$$\text{CH}_4 \text{ Effluent}_{\text{IND}} = \text{TOW}_{\text{EFFLUENT,IND}} \times \text{EF}_{\text{EFFLUENT}}$$

where,

- CH₄ Effluent_{IND} = CH₄ emissions from industrial wastewater discharge for inventory year (kg CH₄/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 CH₄/kg COD or 0.068 kg CH₄/kg BOD) (IPCC 2019)

The COD or BOD in industrial treated effluent ($TOW_{\text{EFFLUENT,industry}}$) 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.

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

where,

$TOW_{\text{EFFLUENT,IND}}$	= 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 (kg COD/year)
$\%_{\text{onsite}}$	= 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 and Paper. Wastewater treatment for the 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 CH₄ emissions for 1990 through 2019 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 2018. 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 2020a). 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 2019 was forecasted from the rest of the time series. A time series of the overall wastewater outflow 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 intervening years were obtained by linear interpolation, while 2017 to 2019 were forecasted from the rest of the time series. The average BOD concentrations 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 2019 (EPA 1997b; EPA 1993b; World Bank 1999; Malmberg 2018). Data for intervening years were obtained by linear interpolation.

Table 7-25: Wastewater Outflow (m³/ton) for Pulp, Paper, and Paperboard Mills

Year	Wastewater Outflow (m ³ /ton)
1990	68
2005	43
2015	40
2016	40
2017	39
2018	38
2019	38

Sources: ERG (2013a), AF&PA (2014), AF&PA (2016), AF&PA (2018).

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 CH₄/kg COD for anaerobic lagoons were used to estimate the CH₄ 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 CH₄/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 (m³/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

Commodity	Wastewater Outflow (m ³ /ton)	Organic Content in Untreated Wastewater (g BOD/L)
Other Vegetables	9.93	0.755
Fruit		
Apples	9.09	8.17
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 CH₄/kg COD for anaerobic treatment was used to estimate the CH₄ produced from these on-site treatment systems. The amount of CH₄ 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 CH₄ emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.⁷ 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 CH₄/kg COD. In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product, or 0.8 m³/ton (ERG 2013b).

⁷ Available online at <<https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector>>.

Breweries. Since 2010, the number of breweries has increased from less than 2,000 to more than 7,000 (Brewers Association 2020). 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 CH₄ emissions from anaerobic wastewater treatment. However, because many breweries recover their CH₄, 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 2020). 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 2019.

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 CH₄ 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 CH₄/kg COD for anaerobic treatment and 0 for aerobic treatment were used to estimate the CH₄ produced from these on-site treatment systems (IPCC 2006). The amount of CH₄ 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 N₂O Emission Estimates

Domestic wastewater N₂O emissions originate from both septic systems and POTWs. Within these centralized systems, N₂O 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 N₂O emissions are estimated as follows:

$$\text{Total Domestic N}_2\text{O Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D$$

Table 7-27 presents domestic wastewater N₂O emissions for both septic and centralized systems, including emissions from centralized wastewater treatment effluent, in 2019.

Table 7-27: Domestic Wastewater N₂O Emissions from Septic and Centralized Systems (2019, kt, MMT CO₂ Eq. and Percent)

	N ₂ O Emissions (kt)	N ₂ O Emissions (MMT CO ₂ Eq.)	% of Domestic Wastewater N ₂ O
Septic Systems	3	0.9	3.5
Centrally-Treated Aerobic Systems	66	19.6	76.1
Centrally-Treated Anaerobic Systems	0	0.0	0
Centrally-Treated Wastewater Effluent	18	5.3	20.4
Total	87	25.8	100

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:

$$\begin{aligned} \text{Annual per capita protein supply (U.S. Specific, kg/person/year)} &= \text{Protein}_{\text{SUPPLY}} \\ &= \text{Protein}_{\text{per capita}} / 1000 \times 365.25 \end{aligned}$$

$$\begin{aligned} \text{Consumed Protein (IPCC 2019 (Eq. 6.10A), kg/person/year)} &= \text{Protein} \\ &= \text{Protein}_{\text{SUPPLY}} \times \text{FPC} \end{aligned}$$

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

Variable	Variable Description	Units	Inventory Years: Source of Value
Protein			
Protein _{SUPPLY}	Annual per capita protein supply	kg/person/year	1990-2019: Calculated
Protein _{per capita}	Daily per capita protein supply ^a	g/person/day	1990-2019: USDA (2020b)
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 (2020b) 2011-2017: FAO (2020c) and scaling factor 2018, 2019: 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 18 percent in 2019; U.S. Census Bureau 2017), 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 the U.S. Census Bureau International Database (U.S. Census Bureau 2020) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. 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 2017). The methodological equations are:

$$\begin{aligned} \text{Total nitrogen entering septic systems (IPCC 2019 (Eq. 10), kg N/year)} &= \text{TN}_{\text{DOM_SEPTIC}} \\ &= (\text{USPOP} \times \text{T}_{\text{SEPTIC}}) \times \text{Protein} \times \text{FNPR} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON_septic}} \times \text{F}_{\text{IND-COM_septic}} \end{aligned}$$

$$\begin{aligned} \text{Emissions from Septic Systems (IPCC 2019 (Eq. 6.9))} &= A \\ &= \text{TN}_{\text{DOM_SEPTIC}} \times (\text{EF}_{\text{SEPTIC}}) \times 44/28 \times 1/10^6 \end{aligned}$$

Table 7-29: Variables and Data Sources for N₂O 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	1990-2019: Calculated
US _{POP}	U.S. population ^a	Persons	1990-2019: U.S. Census Bureau (2020)
T _{SEPTIC}	Percent treated in septic systems ^a	%	Odd years from 1989 through 2017: U.S. Census Bureau (2017) Data for intervening years obtained by linear interpolation 2018 and 2019: Forecasted from the rest of the time series
F _{NPR}	Fraction of nitrogen in protein (0.016)	kg N/kg protein	1990-2019: IPCC (2019)
N _{HH}	Additional nitrogen from household products (1.17)	No units	
F _{IND-COM_septic}	Factor for Industrial and Commercial Co-Discharged Protein, septic systems (1)	No units	
F _{NON-CON_septic}	Factor for Non-Consumed Protein Added to Wastewater (1.13)	No units	
EF _{SEPTIC}	Emission factor, septic systems (0.0045)	kg N ₂ O-N/kg N	
44/28	Conversion factor	Molecular weight ratio of N ₂ O 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 82 percent in 2019), 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.

Non-consumed protein in centralized wastewater treatment for the U.S. was determined by dividing the per capita total Kjeldahl nitrogen (TKN) loading (estimated by multiplying the influent nitrogen concentration by the wastewater flow to centralized wastewater treatment divided by the population using centralized wastewater treatment) by the nitrogen from protein (estimated by multiplying the fraction of N in protein [IPCC 2019] by the annual per capita protein supply [FAO 2020c]).

$$\begin{aligned} \text{Factor for Non-Consumed Protein (U.S. Specific)} &= F_{\text{NON-CON}} \\ &= [(N_{\text{INF}} \times \text{Flow}_{\text{US}} \times 3.785 \times 365.25) / (\text{US}_{\text{POP}} \times T_{\text{CENTRALIZED}})] / (\text{Protein}_{\text{SUPPLY}} \times F_{\text{NPR}}) \end{aligned}$$

$$\begin{aligned} \text{Total nitrogen entering centralized systems (IPCC 2019 (Eq. 10), kg N/year)} &= \text{TN}_{\text{DOM_CENTRAL}} \\ &= (\text{US}_{\text{POP}} \times T_{\text{CENTRALIZED}}) \times \text{Protein} \times F_{\text{NPR}} \times N_{\text{HH}} \times F_{\text{NON-CON}} \times F_{\text{IND-COM}} \end{aligned}$$

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
$F_{\text{NON-CON}}$	Factor for U.S. specific non-consumed protein	No units	1990-2019: Calculated
N_{INF}	Influent Nitrogen Concentration (40)	mg/L	1990-2019: Metcalf & Eddy (2014)
Flow_{US}	Wastewater Flow to Centralized Wastewater Treatment ^a	MGD	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 2013-2019: Forecasted from the rest of the time series
3.785	Conversion factor	liters to gallons	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
US_{POP}	U.S. population ^a	Persons	1990-2019: U.S. Census Bureau (2020)
$T_{\text{CENTRALIZED}}$	Percent collected ^a	%	Odd years from 1989 through 2017: U.S. Census Bureau (2017) Data for intervening years obtained by linear interpolation 2018 and 2019: Forecasted from the rest of the time series
$\text{Protein}_{\text{SUPPLY}}$	Annual per capita protein supply ^a	kg/person/year	1990-2019: Calculated
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2019: IPCC (2019)
$TN_{\text{DOM_CENTRAL}}$	Total nitrogen entering centralized systems	kg N/year	1990-2019: Calculated
Protein	Consumed protein per capita ^a	kg/person/year	1990-2019: Calculated
N_{HH}	Factor for additional nitrogen from household products (1.17)	No units	1990-2019: IPCC (2019)
$F_{\text{IND-COM}}$	Factor for Industrial and Commercial Co-Discharged Protein (1.25)	No units	

^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:

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

where,

$$\begin{aligned} \text{Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)} & \text{ (IPCC 2019 (Eq. 6.9),} \\ & \text{kt N}_2\text{O/year) = B1} \\ & = [(\text{TN}_{\text{DOM_CENTRAL}}) \times (\% \text{ aerobic}_{\text{COTCW}})] \times \text{EF}_{\text{aerobic}} \times 44/28 \times 1/10^6 \end{aligned}$$

Table 7-31: Variables and Data Sources for N₂O 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 N₂O/year)			
TN _{DOM_CENTRAL}	Total nitrogen entering centralized systems	kg N/year	1990-2019: Calculated
% aerobic _{COTCW}	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. 2005-2019: Forecasted from the rest of the time series
EF _{aerobic}	Emission factor – aerobic systems (0.016)	kg N ₂ O-N/kg N	1990-2019: IPCC (2019)
44/28	Conversion factor	Molecular weight ratio of N ₂ O 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.

$$\begin{aligned} \text{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)} & \text{ (IPCC 2014 (Eq. 6.9), kt} \\ & \text{N}_2\text{O/year) = B2} \\ & = [(\text{TN}_{\text{DOM_CENTRAL}}) \times (\% \text{ aerobic}_{\text{CW}})] \times \text{EF}_{\text{CW}} \times 44/28 \times 1/10^6 \end{aligned}$$

$$\begin{aligned} \text{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)} & \text{ (U.S.} \\ & \text{Specific, kt N}_2\text{O/year) = B3} \\ & = [(\text{POTW_flow_CW}) \times (\text{N}_{\text{CW_INF}}) \times 3.785 \times (\text{EF}_{\text{CW}})] \times 1/10^6 \times 365.25 \end{aligned}$$

Table 7-32: Variables and Data Sources for N₂O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt N₂O/year)			
TN _{DOM_CENTRAL}	Total nitrogen entering centralized treatment	kg N/year	1990-2019: 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,

Variable	Variable Description	Units	Inventory Years: Source of Value
			1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2019: Forecasted from the rest of the time series
EF _{CW}	Emission factor for constructed wetlands (0.0013)	kg N ₂ O-N/kg N	1990-2019: IPCC (2014)
44/28	Conversion factor	Molecular weight ratio of N ₂ O to N ₂	Standard conversion
1/10 ⁶	Conversion factor	kg to kt	Standard conversion
<i>Emissions from Constructed Wetlands used as Tertiary Treatment (kt N₂O/year)</i>			
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. 2013-2019: Forecasted from the rest of the time series
N _{CW,INF}	BOD concentration in wastewater entering the constructed wetland (25)	mg/L	1990-2019: Metcalf & Eddy (2014)
3.785	Conversion factor	liters to gallons	Standard conversion
EF _{CW}	Emission factor for constructed wetlands (0.0013)	kg N ₂ O-N/kg N	1990-2019: IPCC (2014)
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.

$$\begin{aligned} \text{Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 (Eq. 6.9), kt N}_2\text{O/year)} &= C \\ &= [(\text{TN}_{\text{DOM_CENTRAL}}) \times (\% \text{ anaerobic})] \times \text{EF}_{\text{anaerobic}} \times 44/28 \times 1/10^6 \end{aligned}$$

Table 7-33: Variables and Data Sources for N₂O Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
<i>Emissions from Centrally Treated Anaerobic Systems</i>			
TN _{DOM_CENTRAL}	Total nitrogen entering centralized treatment	kg N/year	1990-2019: 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. 2005-2019: Forecasted from the rest of the time series
EF _{anaerobic}	Emission factor for anaerobic reactors/deep lagoons (0)	kg N ₂ O-N/kg N	1990-2019: IPCC (2019)
44/28	Conversion factor	Molecular weight ratio of N ₂ O 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	Centralized WWT			
	Population	Population (%)	Protein Supply	Protein Consumed
1990	253	75.6	43.1	33.2
2005	300	78.8	44.9	34.7
2015	325	80.1	44.3	34.2
2016	327	81.1	44.7	34.4
2017	329	82.1	44.9	34.6
2018	331	82.0	44.4	34.2
2019	334	82.2	44.4	34.2

Sources: Population - U.S. Census Bureau (2020); WWTP Population - U.S. Census Bureau (2017); Available Protein - USDA (2020b); Protein Consumed - FAO (2020c).

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 2021) and emission factors for discharge to impaired waterbodies and other waterbodies from IPCC (2019). The methodological equations are:

$$\begin{aligned} \text{Emissions from Centrally Treated Systems Discharge (U.S. Specific)} &= D \\ &= [(N_{\text{EFFLUENT,IMP}} \times EF_{\text{IMP}}) + (N_{\text{EFFLUENT,NONIMP}} \times EF_{\text{NONIMP}})] \times 44/28 \times 1/10^6 \end{aligned}$$

where,

$$\begin{aligned} \text{Total organics in centralized treatment effluent (IPCC 2019 (Eq. 6.8), kg N/year)} &= N_{\text{EFFLUENT,DOM}} \\ &= [\text{TN}_{\text{DOM,CENTRAL}}^8 \times \% \text{ primary} \times (1 - N_{\text{rem,PRIMARY}})] + [\text{TN}_{\text{DOM,CENTRAL}} \times \% \text{ secondary} \times (1 - N_{\text{rem,SECONDARY}})] + \\ &\quad [\text{TN}_{\text{DOM,CENTRAL}} \times \% \text{ tertiary} \times (1 - N_{\text{rem,TERTIARY}})] \end{aligned}$$

$$\begin{aligned} \text{Total nitrogen in effluent discharged to impaired waterbodies (U.S. Specific, kg N/year)} &= N_{\text{EFFLUENT,IMP}} \\ &= (N_{\text{EFFLUENT,DOM}} \times \text{Percent}_{\text{IMP}}) / 1000 \end{aligned}$$

$$\text{Total nitrogen in effluent discharged to nonimpaired waterbodies (U.S. Specific, kg N year)} = N_{\text{EFFLUENT,NONIMP}}$$

⁸ See emissions from centrally treated aerobic and anaerobic systems for methodological equation calculating TN_{DOM,CENTRAL}.

$$= (N_{\text{EFFLUENT,DOM}} \times \text{Percent}_{\text{NONIMP}}) / 1000$$

Table 7-35: Variables and Data Sources for N₂O Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$N_{\text{EFFLUENT,DOM}}$	Total organics in centralized treatment effluent	kg N/year	1990-2019: Calculated
44/28	Conversion factor	Molecular weight ratio of N ₂ O to N ₂	Standard conversion
1/10 ⁶	Conversion factor	kg to kt	Standard conversion
$TN_{\text{DOM,CENTRAL}}$	Total nitrogen entering centralized treatment	kg N/year	1990-2019: 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. 2013-2019: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment ^a	%	
% tertiary	Percent of tertiary domestic centralized treatment ^a	%	
$N_{\text{rem,PRIMARY}}$	Fraction of nitrogen removed from primary domestic centralized treatment (0.1)	No units	1990-2019: IPCC (2019)
$N_{\text{rem,SECONDARY}}$	Fraction of nitrogen removed from secondary domestic centralized treatment (0.4)	No units	
$N_{\text{rem,TERTIARY}}$	Fraction of nitrogen removed from tertiary domestic centralized treatment (0.9)	No units	
$N_{\text{EFFLUENT,IMP}}$	Total nitrogen in effluent discharged to impaired waterbodies	kg N/year	1990-2019: Calculated
$N_{\text{EFFLUENT,NONIMP}}$	Total nitrogen in effluent discharged to nonimpaired waterbodies	kg N/year	
EF_{IMP}	EF (discharge to reservoirs/lakes/estuaries) (0.19)	kg N ₂ O-N/kg N	1990-2019: IPCC (2019)
EF_{NONIMP}	EF (discharge to other waterbodies) (0.005)	kg N ₂ O-N/kg N	
Percent _{IMP}	Percent of wastewater discharged to impaired waterbodies ^a	%	1990-2010: Set equal to 2010 2010: ERG (2021) 2011: Obtained by linear interpolation 2012: ERG (2021) 2013-2019: 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 N₂O Emission Estimates

Nitrous oxide emission estimates from industrial wastewater were added to the inventory for the first time and developed according to the methodology described in the *2019 Refinement*. U.S. industry categories that are likely

to produce significant N₂O 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 N₂O 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 2021). Wastewater treatment and discharge emissions for these sectors for 2019 are displayed in Table 7-36 below. Table 7-20 contains production data for these industries.

Table 7-36: Total Industrial Wastewater N₂O Emissions by Sector (2019, MMT CO₂ Eq. and Percent)

Industry	N ₂ O Emissions	
	(MMT CO ₂ Eq.)	% of Industrial Wastewater N ₂ O
Meat & Poultry	0.3	47.3
Petroleum Refineries	0.2	33.2
Pulp & Paper	0.1	19.0
Breweries	+	0.5
Total	0.5	100

+ Does not exceed 0.5 kt.

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). N₂O is generated as a by-product of nitrification, or as an intermediate product of denitrification. Therefore, N₂O 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).

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

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, m³/t product.
- TN_{*i*} = total nitrogen in untreated wastewater for industrial sector *i* for inventory year, kg TN/m³.

For the four industries of interest, the total production and the total volume of wastewater generated has already been calculated for CH₄ emissions. For these new N₂O 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	0.22 ^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).

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

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. Table 6.8a in the <i>2019 Refinement</i> provides 0.016 kg N_2O -N/kg N as a default IPCC value for aerobic treatment systems.
$44/28$	= conversion of kg N_2O -N into kg N_2O .

For each industry, the degree of utilization ($T_{i,j}$)—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.

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

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 (kg N_2O -N/kg N)
$44/28$	= 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 N₂O/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	8,773,308	0.082
Petroleum Refineries	1,698,953	0.045
Pulp & Paper	18,809,623	1.08
Breweries	1,069,919	NA

^a Nitrogen discharged by breweries was estimated as 60 percent of untreated wastewater nitrogen.

Sources: ERG (2021)

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2019 CH₄ and N₂O 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 CH₄ 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 N₂O 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.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-39 and Table 7-40. For 2019, methane emissions from wastewater treatment were estimated to be between 13.3 and 25.4 MMT CO₂ Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 28 percent below to 38 percent above the 2019 emissions estimate of 18.4 MMT CO₂ Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 16.7 and 81.6 MMT CO₂ Eq., which indicates a range of approximately 37 percent below to 209 percent above the 2019 emissions estimate of 26.4 MMT CO₂ Eq.

For 1990, methane emissions from wastewater treatment were estimated to be between 14.8 and 27.5 MMT CO₂ Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 27 percent below to 37 percent above the 1990 emissions estimate of 20.2 MMT CO₂ Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 12.9 and 60.1 MMT CO₂ Eq., which indicates a range of approximately 31 percent below to 218 percent above the 1990 emissions estimate of 18.7 MMT CO₂ Eq.

Table 7-39: Approach 2 Quantitative Uncertainty Estimates for 2019 Emissions from Wastewater Treatment (MMT CO₂ Eq. and Percent)

Source	Gas	2019 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	CH₄	18.4	13.3	25.4	-28%	+38%
Domestic	CH ₄	12.1	7.9	17.7	-35%	+47%
Industrial	CH ₄	6.4	3.8	10.3	-41%	+62%
Wastewater Treatment	N₂O	26.4	16.7	81.6	-37%	+209%
Domestic	N ₂ O	25.8	15.7	80.5	-39%	+212%
Industrial	N ₂ O	0.6	0.6	1.7	-2%	197%

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

Table 7-40: Approach 2 Quantitative Uncertainty Estimates for 1990 Emissions from Wastewater Treatment (MMT CO₂ Eq. and Percent)

Source	Gas	1990 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	CH₄	20.2	14.8	27.5	-27%	+37%
Domestic	CH ₄	14.7	10.1	21.6	-31%	+46%
Industrial	CH ₄	5.4	3.3	8.4	-40%	+52%
Wastewater Treatment	N₂O	18.7	12.9	60.1	-31%	+221%
Domestic	N ₂ O	18.3	12.0	59.3	-34%	+224%
Industrial	N ₂ O	0.4	0.4	1.3	2%	218%

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

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above and Recalculations section below.

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 *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.

EPA conducted early engagement and communication with stakeholders on updates prior to the expert review cycle of the current Inventory. EPA held stakeholder meetings in August of 2020 where EPA provided a presentation detailing updates made to both domestic wastewater and a portion of industrial wastewater treatment and requested stakeholder feedback. Stakeholder feedback received is discussed in the Recalculations Discussion and Planned Improvements sections.

Recalculations Discussion

Population data were updated to reflect revised U.S. Census Bureau datasets which resulted in changes to 2010 through 2018 values (U.S. Census Bureau 2020). Protein data were updated to reflect available protein values available for 2014 through 2017 (FAO 2020c). Pulp, paper, and paperboard production data were updated to reflect revised values for 2018 (FAO 2020a). Updated red meat production 2017 and 2018 data, as well as fruits and vegetables processing production 2016 through 2018 data, were based on revised values (USDA 2020a; USDA 2020c).

EPA revised the domestic wastewater CH₄ methodology based on the *2019 Refinement* (IPCC 2019): added a correction factor to account for organics from industrial and commercial contributions to POTWs (1.25); updated the emission factor for centralized aerobic systems which accounts for loss of dissolved methane formed with in the collection system (from 0 to 0.018 kg CH₄/kg BOD); revised the estimate of organics removed with sludge from POTWs; added emission estimates from discharge of domestic wastewater to aquatic environments based on type of receiving water (e.g., reservoir, lake, estuaries); and updated wastewater treatment activity data to align with the updates to organics removed and emissions from discharge to aquatic environments (ERG 2021). All of these changes affected the time series from 1990 through 2018. Domestic wastewater treatment and discharge CH₄ emissions increased an average of 43 percent over the time series, with the smallest increase of 39.6 percent (4.2 MMT CO₂ Eq.) in 1997 and largest increase of 48.0 percent (4.3 MMT CO₂ Eq.) in 2012.

EPA revised the domestic wastewater N₂O methodology based on the *2019 Refinement* (IPCC 2019): added emission estimates from septic systems; added a correction factor to account for nitrogen from household products to POTWs and septic systems (1.17); revised the methodology for treatment plants to account for aerobic and anaerobic treatment systems; updated the emission factor for centralized aerobic systems (from 0 to 0.016 kg N₂O-N/kg N); and revised emission estimates from discharge of domestic wastewater to aquatic environments to account for the condition of the receiving waterbody (i.e., nutrient-impacted/eutrophic conditions, or not impacted) (ERG 2021). All of these changes affected the time series from 1990 through 2018. Domestic wastewater treatment and discharge N₂O emissions increased an average 423 percent over the time series, with the smallest increase of 410 percent (15 MMT CO₂ Eq.) in 2010 and largest increase of 441 percent (14.9 MMT CO₂ Eq.) in 1990.

EPA revised the industrial wastewater CH₄ methodology based on the *2019 Refinement* (IPCC 2019): revised the estimate of organics removed with sludge; added emission estimates from discharge of industrial wastewater to aquatic environments using a Tier 1 methodology and default emission factor; and updated wastewater treatment activity data to align with the updates to emission factor categories (ERG 2021). All of these changes affected the time series from 1990 through 2018. Industrial wastewater treatment and discharge CH₄ emissions increased an average of 7.7 percent over the time series, with the smallest increase of 5.9 percent (0.3 MMT CO₂ Eq.) in 2017 and largest increase of 10.2 percent (0.5 MMT CO₂ Eq.) in 1990.

EPA added industrial wastewater N₂O emissions for the first time based on the *2019 Refinement* (IPCC 2019) methodology. EPA identified four categories with the largest potential contribution to include and added estimates

associated with treatment plant emissions as well as emissions from the discharge of wastewater. These additions affected the entire time series.

The cumulative effect of these recalculations had a large impact on the overall wastewater treatment emission estimates. Over the time series, the average total emissions increased by 118 percent from the previous Inventory. The changes ranged from the smallest increase, 108 percent (20.1 MMT CO₂ Eq.), in 1990, to the largest increase, 135 percent (25.8 MMT CO₂ Eq.), in 2017.

Planned Improvements

EPA implemented revisions based on the *2019 Refinement* but notes the following continued improvements:

- Evaluate the use of POTW BOD effluent discharge data from ICIS-NPDES.⁹ Currently only half of POTWs report organics as BOD₅ 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.
- 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 data.
- Investigate research on methane and nitrous oxide emissions released from domestic treatment processes, as time and resources allow. This would include a 2012 Water Environment Research Foundation study depicting a calculation-based method of potential interest.
- 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.*
- Review whether sufficient data exist to develop U.S.-specific CH₄ or N₂O 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.
- Consider updating the non-consumed protein factor ($F_{\text{NON-CON}}$) for centralized treatment to the default value in IPCC (2019). The current U.S.-specific factor is likely overestimating the non-consumed protein as it is based on influent nitrogen (which includes other sources of nitrogen) (i.e., IPCC 2019).

⁹ ICIS-NPDES refers to EPA's Integrated Compliance Information System – National Pollutant Discharge Elimination System.

- EPA will continue to look for methods to improve the transparency of the fate of sludge produced in wastewater treatment.

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. If the end product is of lesser quality, it can be disposed of in a landfill.

Composting naturally converts a large fraction of the degradable organic carbon in the waste material into carbon dioxide (CO₂) 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 (CH₄). This CH₄ is then oxidized to a large extent in the aerobic sections of the compost. The estimated CH₄ 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 (N₂O) emissions can also be produced. The formation of N₂O 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 N₂O than, for example, yard waste, however data are limited.

Even though CO₂ emissions are generated, they are not included in net greenhouse gas emissions for composting because they are considered biogenic, or natural occurring. In accordance with the *2006 IPCC Guidelines*, only anthropogenic emissions are included in the emission estimates for composting.

From 1990 to 2019, the amount of waste composted in the United States increased from 3,810 kt to 22,687 kt. There was some fluctuation in the amount of waste composted between 2006 to 2009 where a peak of 20,049 kt composted was observed in 2008, which decreased to 18,824 kt composted the following year, presumably driven by the economic crisis of 2009. Between 2009 and 2017, the amount of waste composted gradually increased by approximately 7 percent each year. Emissions of CH₄ and N₂O from composting from 2010 to 2017 have increased by the same percentage. The past two years (2017 and 2018) are similar to 2016 in the amount of material composted and emissions, leading one to conclude that 2017 may be a minor outlier.

In 2019, CH₄ emissions from composting (see Table 7-41 and Table 7-42) were 2.3 MMT CO₂ Eq. (90.7 kt), and N₂O emissions from composting were 2.0 MMT CO₂ Eq. (6.8 kt). Emissions have increased steadily from 2010 and have exhibited a decreasing trend the past two years. The wastes composted primarily include 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 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 CH₄ and N₂O emissions. Agricultural composting is accounted for in Volume 4, Chapter 5 (Cropland) of this Inventory, as most agricultural composting operations are assumed to then land-apply the resultant compost to soils.

The growth in composting since the 1990s and specifically over the past decade is attributable primarily to the following factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings and food waste in landfills, (2) yard trimming collection and yard trimming drop off sites provided 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, 22 states representing about 44 percent of the nation’s population have enacted such legislation (NERC 2020). There are many more initiatives at the metro and municipal level 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 April 2019, six states (California, Connecticut, New York, Massachusetts, Rhode Island, Vermont) and seven municipalities (Austin, TX; Boulder, CO; Hennepin County, MN; Metro, 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, most having taken effect after 2013 (Harvard Law School and CET 2019). 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). There are a growing number of initiatives to encourage households and businesses to compost or beneficially reuse food waste, although many states and municipalities currently have limited resources to address this directly.

Estimates for excess food and food waste at a national scale have been limited, but EPA has recently filled this gap. EPA completed a thorough mass balance analysis of all management pathways for food waste and excess food in the *Advancing Sustainable Materials Management: 2018* report (EPA 2020d, commonly referred to as the Facts and Figures reports) using a methodology that expanded the number of management pathways for excess food and food waste to include:

- animal feed;
- bio-based materials/biochemical processing (i.e., rendering);
- codigestion/anaerobic digestion;
- composting/aerobic processes;
- combustion;
- donation;
- land application;
- landfill; and
- sewer/wastewater treatment.

Approximately 18 million tons of food was diverted from landfills in 2018 (EPA 2020d).

Table 7-41: CH₄ and N₂O Emissions from Composting (MMT CO₂ Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
CH ₄	0.4	1.9	2.1	2.3	2.4	2.3	2.3
N ₂ O	0.3	1.7	1.9	2.0	2.2	2.0	2.0
Total	0.7	3.6	4.0	4.3	4.6	4.3	4.3

Note: Totals may not sum due to independent rounding.

Table 7-42: CH₄ and N₂O Emissions from Composting (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
CH ₄	15.2	74.6	84.9	91.1	97.9	90.3	90.7
N ₂ O	1.1	5.6	6.4	6.8	7.3	6.8	6.8

Methodology

Methane and N₂O 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 methodology assumes all material composted is done so at commercial or industrial composting facilities with windrow piles (widely used because they are cost-effective). Data for small-scale, or household composting or other non-windrow type composting operations are not documented in the national estimates. The methodology assumes the material composted primarily consists of yard trimmings, food waste, and some paper products.

The emissions shown in Table 7-41 and Table 7-42 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 CH₄ recovery is expected to occur at composting operations in the emission estimates presented):

$$E_i = M \times EF_i$$

where,

E_i	= CH ₄ or N ₂ O emissions from composting, kt CH ₄ or N ₂ O,
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 ₂ O/kt of waste treated (wet basis) (IPCC 2006), and
i	= designates either CH ₄ or N ₂ O.

Per IPCC Tier 1 methodology defaults, the emission factors for CH₄ and N₂O 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 Composting 1996).

Estimates of the quantity of waste composted (M , wet weight as generated) are presented in Table 7-43 for select years. Estimates of the quantity composted for 1990, 2005, and 2015 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures 2015* (EPA 2018); the estimates of the quantities composted for 2016 and 2017 were taken from EPA's *Advancing Sustainable Materials Management: 2016 and 2017 Tables and Figures* (EPA 2019); the estimate of the quantity composted for 2018 was taken from Table 35 of EPA's *Advancing Sustainable Materials Management: Facts and Figures 2015* (EPA 2020); and the estimate for 2019 was extrapolated using the 2018 quantity composted and a ratio of the U.S. population growth between 2018 to 2019, respectively (U.S. Census Bureau 2019). Note that the EPA's *Advancing Sustainable Materials Management: Facts and Figures* reports present quantity of material composted in short tons and the quantities are converted to metric tons to perform the emission calculations under the IPCC framework. The quantity of waste composted in the Facts and Figures reports are developed to provide national coverage, but commercial/industrial composting facilities in Puerto Rico and U.S. territories may not be explicitly included in the mass balance approach used in the reports. This is a planned improvement as noted below.

Table 7-43: U.S. Waste Composted (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
Waste Composted	3,810	18,643	21,219	22,780	24,485	22,580	22,687

Uncertainty and Time-Series Consistency

Uncertainty is the difference between a true value and the measured value. Two uncertainty drivers in the composting emission estimates include the activity data and the emission factors used.

With respect to the activity data used for the composting emission estimates, a true value is fuzzy because data sources presenting facility-specific data are lacking. The methodology applied for the 1990 to 2019 emissions estimates uses annually modeled estimates of waste composted sourced from EPA’s Advancing Sustainable Materials Management: Facts and Figures reports. The EPA’s Facts and Figures reports uses, at a national level, a modeled materials flow methodology, which relies on a mass balance approach. Models use a number of parameters, which themselves may have varying degrees of uncertainty. No facility-specific or direct state data on commercial composting facilities are used when calculating annual estimates for national quantities of waste composted. EPA collects data from industrial associations, key businesses and industry sources, the Department of Commerce and U.S. Census Bureau. This data is then imported into the materials flow model to estimate tonnage of materials generated, recycled, composted, sent to combustion facilities, beneficially reused, and finally, landfilled. Using estimates from a modeled materials flow approach introduces uncertainty.

The second large area of uncertainty lies with the emission factors themselves. A variety of different organic wastes may be composted at the same facility such as yard waste, animal manure, food waste. One emission factor for methane and nitrous oxide, respectively, are used regardless of the type of waste composted and the composting method. The estimated uncertainty from the *2006 IPCC Guidelines* is ± 50 percent for the Tier 1 methodology.

Emissions from composting in 2019 were estimated to be between 2.1 and 6.4 MMT CO₂ Eq., which indicates a range of 50 percent below to 50 percent above the 2019 emission estimate (see Table 7-44).

Table 7-44: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO ₂ Eq.)			
			Lower Bound	Upper Bound	Lower Bound (%)	Upper Bound (%)
Composting	CH ₄	2.3	1.1	3.4	-50%	+50%
	N ₂ O	2.0	1.0	3.0	-50%	+50%
	Total	4.3	2.1	6.4	-50%	+50%

The same methodological approaches (e.g., one data source for the quantity of mass composted, the same emission factors) were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

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 *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current Inventory.

Recalculations Discussion

The quantity of material composted for 2018 was updated with the publication of the EPA’s Advancing Sustainable Materials Management Report (EPA 2020). The quantity of material composted decreased from 24.59 million tons in the previous Inventory report to 22.6 million tons (or 8.19 percent) for 2018 in the current Inventory report. Relatedly, total emissions decreased by 8.19 percent or 0.38 MMT CO₂ Eq. for 2018.

Planned Improvements

In 2017, EPA completed a literature search on emission factors and composting systems and management techniques that will be documented in a technical memorandum for the next (1990 to 2019) Inventory. 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 incorporation 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.

Efforts are also being made to improve the completeness of the composting Inventory by incorporating composted waste from U.S. territories. In 2016, EPA conducted a desk-based investigation into industrial/commercial composting facilities in the U.S. territories and identified facilities in Puerto Rico. Three facilities are currently operational, and some operational data and quantities of material composted are available for the past three years. Additional efforts are being made to collect additional historical information to estimate of the quantity of waste composted and/or approximate the population (or households) these facilities serve. This data may be incorporated into the current or future Inventories as a methodological improvement.

7.4 Stand-Alone Anaerobic Digestion (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 soil amendments (e.g., compost). The biogas primarily consists of CH₄, biogenic CO₂, and trace amounts of other gases such as N₂O (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 CH₄ (a normal range is 55 percent to 65 percent) and approximately 35 percent CO₂ (WEF 2012). 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 CH₄ generated, IPCC 2006), collected biogas that is not completely combusted, and entrained gas bubbles and residual gas potential in the digested sludge. 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 IPCC 2006 Guidelines notes that at biogas plants where unintentional CH₄ emissions are flared, CH₄ 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 manure and food waste from restaurants or food processing industry, or a combination of manure and waste from energy crops or crop residues (EPA 2016). The moisture content of the feedstock (wet or dry) impacts the amount of biogas generation. Wet anaerobic digesters process feedstock with a solids content 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:

- Stand-alone digesters typically manage food waste from different sources, including food and beverage processing industries. Some stand-alone digesters also co-digest other organics such as yard waste.
- On-farm digesters that 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 also accept food waste as feedstock for co-digestion.
- Digesters at water resource recovery facilities (WRRF) to 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 AD 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 2019, the estimated amount of waste managed by stand-alone digesters in the United States increased from approximately 866 kt to 10,620 kt, an increase of 92 percent. As described in the Uncertainty and Time-Series Consistency 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 in the early part of the time series are general estimates, extrapolated from data collected later in the time series (i.e., 2015 and later). 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.

In 2019, emissions from stand-alone anaerobic digestion facilities were approximately 0.2 MMT CO₂ Eq. (7 kt) (see Table 7-45 and Table 7-46).

Table 7-45: CH₄ Emissions from Stand-Alone Anaerobic Digestion (MMT CO₂ Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
CH ₄ Generation	+	0.1	0.2	0.2	0.2	0.2	0.2
CH ₄ Recovered	(+)	(+)	(+)	(+)	(+)	(+)	(+)
CH₄ Emissions	+	0.1	0.2	0.2	0.2	0.2	0.2

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

+ Does not exceed 0.05 MMT CO₂ Eq.

Table 7-46: CH₄ Emissions from Stand-Alone Anaerobic Digestion (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
CH ₄ Generation	1	3	8	7	8	8	8
CH ₄ Recovered	(+)	(+)	(0.6)	(0.7)	(0.6)	(0.6)	(0.6)
CH₄ Emissions	1	2	7	7	7	7	7

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

+ Does not exceed 0.5 kt.

Methodology

Methane 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 7-45 were estimated largely using the IPCC default (Tier 1) methodology given in Equation 4.1 below (Volume 5, Chapter 4, IPCC 2006), which is the product of an emission factor and the mass of organic waste processed. Only CH₄ emissions are estimated because N₂O 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).

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

where,

CH₄ Emissions = total CH₄ emissions in inventory year, Gg CH₄

M_i = mass of organic waste treated by biological treatment type *i*, Gg, see Table 7-29

EF = emission factor for treatment *i*, g CH₄/kg waste treated, 0.8 Mg/Gg CH₄

i = anaerobic digestion

R = total amount of CH₄ recovered in inventory year, Gg CH₄

= Biogas x 0.0283 x minutes/year x biogas CH₄ density x C_{CH₄} x 1/10⁹ x (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 = CH₄ density in biogas (EPA 1993), g CH₄/m³ CH₄

65% = C_{CH₄}, concentration of CH₄ in the biogas

1/10⁹ = conversion factor, grams to kt

0.99 = destruction efficiency for combustion unit

Per IPCC Tier 1 methodology defaults, the emission factor for CH₄ 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 IPCC 2006 Guidelines (0.8 Mg/Gg CH₄) 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 (US EPA 2018 and 2019). 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]). Two reports with survey results have been published to date (the third is expected in late 2021):

- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results* (US EPA, 2018)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results* (US EPA, 2019).

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 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 (US EPA 2019).

The annual quantity of waste digested for 1990 to 2014 (only 1990 and 2005 are shown) 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 1990 to 2019 inventory is calculated as follows:

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

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 and 2019.

Estimates of the quantity of waste digested (M, wet weight as generated) are presented in Table 7-47 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 (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 2017 to 2019 were extrapolated using the average of the waste digested from the 2015 and 2016 surveys as a proxy. Planned updates to the waste digested for 2017 to 2019 are described in the Planned Improvements section.

Table 7-47: U.S. Waste Digested (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
Waste Digested ¹	786	3,142	9,963	9,305	9,634	9,634	9,634

¹ 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 and 2016 (EPA 2018; EPA 2019). Facilities that did not respond to the EPA surveys are not included and all years except 2015 and 2016 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. The average waste digested as reported in EPA 2018 and 2019 is used as a proxy for years 2017 to 2019.

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 2019. This assumes all facilities are in operation from their first year of operation throughout the remainder of the time series. 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 2017.

Table 7-48: Estimated Number of Stand-Alone AD Facilities Operating from 1990-2019¹

Year	1990	2005	2015	2016	2017	2018	2019
Estimated Count of Operational Facilities	4	16	56	58	58	60	60

¹ The count of operational facilities was visually estimated from Figure 5 in EPA 2020, 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 2019. This is further discussed in the Uncertainty and Time Series 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 two data points (2015 and 2016) represented for the entire sector, as reported in the EPA AD Data Collection Survey reports (EPA 2018 and 2019). The total quantity of collected biogas from the survey respondents for 2015 and 2016 is reported in standard cubic feet per minute (scfm) as shown in Table 7-49. 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 generation for stand-alone digesters are for 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 digester and other facility spaces (EPA 2018; EPA 2019). Thus, no biogas is assumed to be flared.

Table 7-49: Estimated Biogas Produced and Methane Recovered from Stand-Alone AD Facilities Operating from 1990-2019¹

Activity	1990	2005	2015	2016	2017	2018	2019
Total Biogas Produced (scfm) ²	820	3,279	9,176	10,498	11,886	12,296	12,296
R, recovered CH ₄ from biogas (kt) ³	0.05	0.21	0.59	0.67	0.63	0.63	0.63

¹ Total biogas produced in standard cubic feet per minute (scfm) was reported in aggregate in the EPA survey data (EPA 2018 and 2019) for 2015 and 2016. The quantities presented in this table are likely underestimates because not all operational facilities provided a survey response to the EPA AD Data Collection Surveys.

² Data for all years in the time series except for 2015 and 2016 are extrapolated using the average of the total biogas collected in 2015 and 2016, divided by the average number of survey responses to generate an average estimate of biogas collected per facility, which is then multiplied by the total facility count (as shown in Table 7-30).

³ The quantity of CH₄ recovered from the biogas produced is estimated for all years except 2015 and 2016, which are taken from EPA (2018) and (2019).

Uncertainty and Time-Series Consistency

The methodology applied for the 1990 to 2019 emissions estimates should be considered a starting point to build on in future years. Two years of facility-provided data are available (2015 and 2016) while the rest of the time series is estimated based off an assumption of facility counts and a weighted average annual waste processed developed from the two years of 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) 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 CH₄ 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 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 CH₄ emissions.
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 CH₄ emissions.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Tier 1 methodology.

Emissions from stand alone anaerobic digesters in 2019 were estimated to be between 0.1 and 0.3 MMT CO₂ Eq., which indicates a range of 50 percent below to 50 percent above the 2019 emission estimate of each gas (see Table 7-50).

Table 7-50: Tier 1 Quantitative Uncertainty Estimates for Emissions from Digestion (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate			
			(MMT CO ₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stand-alone Anaerobic Digestion	CH ₄	0.2	0.1	0.3	-50%	+50%

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 *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current Inventory.

Recalculations Discussion

This is a new source category included for the current (1990 to 2019) Inventory; thus, no recalculations have been made.

Planned Improvements

Several potential improvements will be investigated for inclusion in future inventory years with the intent of reducing the uncertainties described in the Uncertainty and Time-Series Consistency section. First, EPA plans to incorporate survey data from future EPA AD Data Collection Surveys when the survey data are published. The next report for 2017 is expected to be published in 2021. This addition will change the estimated emissions for 2017 and potentially the weighted average applied to the 1990 to 2014 time series. EPA will pull in survey data for future years when published. This revision will change emissions estimates for 2018 and 2019.

Second, EPA will re-assess how best to estimate annual waste processed using proxy data for years between the EPA AD Data Collection Survey reports as needed. The initial methodology described here assumes the same amount of waste is processed each year from 2017 to 2019.

Third, EPA will conduct additional research to confirm the number of operational facilities by year prior to 2015 and 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 for facilities that did not directly respond to the EPA AD Data Collection surveys for completeness.

Fourth, EPA will investigate the amount of recovered biogas for years prior to 2015 (i.e., the years prior to the EPA AD Data Collection Surveys). Currently, only two years of data of recovered biogas are available and the primary purpose will be to understand whether the range of recovered biogas from the 2015 and 2016 survey data are reflective of earlier years.

Fifth, the uncertainty assessment will be further reviewed to confirm the appropriateness of the uncertainty factor(s) to be applied.

7.5 Waste Incineration (CRF Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) 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 2019 resulted in 11.8 MMT CO₂ Eq. of emissions, over half of which (6.6 MMT CO₂ Eq.) is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste incineration 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 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 CO₂ 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

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of precursor gases. The reporting requirements of the UNFCCC¹⁰ request that information be provided on precursor greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-CH₄ volatile organic compounds (NMVOCs), and sulfur dioxide (SO₂). These gases are not direct greenhouse gases, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO₂, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse

¹⁰ See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

gases. Total emissions of NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2019 are provided in Table 7-51. Sulfur dioxide emissions are presented in Section 2.3 of the Trends chapter and Annex 6.3.

Table 7-51: Emissions of NO_x, CO, and NMVOC from Waste (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
NO_x	+	2	2	1	1	1	1
Landfills	+	2	2	1	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous ^a	+	0	0	0	0	0	0
CO	1	7	7	6	5	5	5
Landfills	1	6	7	6	5	5	5
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous ^a	+	0	0	0	0	0	0
NMVOCs	673	114	63	57	52	52	52
Wastewater Treatment	57	49	27	25	22	22	22
Miscellaneous ^a	557	43	24	22	20	20	20
Landfills	58	22	12	11	10	10	10

Note: Totals may not sum due to independent rounding.

+ 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.

Methodology

Emission estimates for 1990 through 2019 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2020) and disaggregated based on EPA (2003). Emission estimates of these gases were provided by sector, using a “top down” estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Uncertainty and Time-Series Consistency

No quantitative estimates of uncertainty were calculated for this source category. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.