REDUCING METHANE EMISSIONS FROM THE SOLID WASTE SECTOR: Lessons from California's Experiences

March 2023

BERKELEY LAB

Berkeley Law | California-China Climate Institute

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About the California-China Climate Institute

The California-China Climate Institute was launched in September 2019 and is a University of California-wide initiative housed jointly at UC Berkeley's School of Law (through its Center for Law, Energy, and the Environment) and the Rausser College of Natural Resources. It is chaired by Jerry Brown, former Governor of the State of California, and vice-chaired by the former Chair of the California Air Resources Board Mary Nichols. The Institute also works closely with other University of California campuses, departments, and leaders. Through joint research, training, and dialogue in and between California and China, this Institute aims to inform policymakers, foster cooperation and partnership, and drive climate solutions at all levels.

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Acknowledgments

This report and analysis were led by the California-China Climate Institute (CCCI) at the University of California, Berkeley, along with support from the Lawrence Berkeley National Laboratory (LBNL). We appreciate the financial support from the Institute for Governance & Sustainable Development (IGSD).

We would like to thank members from the California Air Resources Board (CARB), California Department of Resources Recycling and Recovery (CalRecycle), Los Angeles County Sanitation Districts (LACSD), Institute for Governance & Sustainable Development (IGSD), University of Maryland (UMD), and Center for Law, Energy & the Environment (CLEE) at the University of California, Berkeley for providing additional information and answering questions.

In addition, we would like to gratefully acknowledge helpful comments from the following reviewers of this report: Anthy Alexiades (CARB), Mary Jane Coombs (CARB), Kyle Pogue (CalRecycle), Timothy Hall (CalRecycle), Brian Stalker (CalRecycle), Danielle Osborne (CalRecycle), Michelle Dewey (CalRecycle), Cara Morgan (CalRecycle), Sue Vang (CalRecycle), Gil Damon (CLEE), Ken Alex (CLEE), Caitlan Frederick (IGSD), Gabrielle Dreyfus (IGSD), Dung Kong (LACSD) and Mengye Zhu (UMD).

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SUMMARY FOR POLICYMAKERS

Methane is a short-lived greenhouse gas with more than 80 times the global warming impact of carbon dioxide over 20 years in the atmosphere. Therefore, reducing methane emissions is key to slowing climate change in the near term. Currently, solid waste landfills account for 20% of global anthropogenic methane emissions and are the third largest source of anthropogenic methane emissions in the United States.

Reducing methane emissions from solid waste landfills is a challenge because it requires a dramatic reduction of waste generation, effective enforcement of regulations, and large amounts of investment in infrastructure. However, the benefits of addressing this issue are huge: mitigating solid waste methane emissions will significantly slow climate change in the near term, as well as contribute to improving clean energy adoption and reducing food insecurity.

Within the U.S., California stands out as the first state to develop comprehensive reduction strategies for solid waste methane. In California, the solid waste sector is a key source of methane emissions, contributing 22% of the state's total methane emissions of 38.85 million metric tons of carbon dioxide equivalent (MMT CO_2e) in 2020. In recognition of the importance of reducing solid waste methane emissions, California first introduced its Landfill Methane Regulation in 2010. Since then, policies and programs have been developed and implemented to reduce methane emissions from municipal solid waste landfills.

Policies and programs have focused on two main approaches to reducing methane emissions from municipal solid waste landfills: (1) diverting organic waste from landfills, and (2) reducing methane emissions from existing landfills.

Policies, regulations, and financial incentives have been created to support this dual approach to reducing methane emissions. While California has made significant progress in landfill methane reduction, it is still behind in meeting its goals. This paper analyzes policies and programs, implementation mechanisms, and lessons learned from California in reducing methane emissions from the solid waste sector. California's lessons and experiences help provide insights for other regions on best practices that could be adopted, as well as existing challenges and gaps to achieve methane reductions.

DIVERTING ORGANIC WASTE FROM LANDFILLS

Diverting organic waste from landfills is a strategy California has implemented to avoid and reduce landfill methane generation in the first place, as landfill organic waste is converted to methane through biological decomposition. California's regulations on organic waste diversion started with mandatory municipal solid waste recycling as early as 2008, followed by mandatory recycling of organic waste beginning in 2014. In September 2016, California passed Senate Bill 1383, which aimed to reduce the disposal of organic waste in landfills by 50% of 2014 levels in 2020 and by 75% in 2025, and to recover at least 20% of disposed edible food by 2025. With this important legislation, California established a comprehensive regulatory system with clear targets supported by various financial approaches, including procurement programs, fees, credits, and market expansion, to reduce the disposal of organic waste.

Although California has taken a series of actions to divert organic waste from landfills, it still has not achieved the 2020 goals required by law (Table SPM-1). This slow progress could lead to annual methane emissions being higher through 2030 than originally anticipated by the latest Short-Lived Climate Pollutant Reduction Strategy published in 2017.

Table SPM-1 | Overall progress of California's organic waste diversion		
Criteria	**Goal**	**Progress**
Solid Waste Recycling Rate	75% by 2020	42% in 2020
Organic Waste Disposal Reduction Rate	50% by 2020 (compared to 2014 baseline)	11% in 2021 (compared to 2014 baseline)

The failure to achieve these 2020 targets is mainly because regulations under SB 1383 were not adopted until fall of 2020, they were prohibited from taking effect until January 2022, and local jurisdictions cannot enforce them until January 2024. In fact, state agencies relied on voluntary and incentive-based mechanisms to achieve the 2020 targets in the early years of SB 1383 implementation.

Despite the slow enforcement timeline, California has made significant progress in expanding organic waste processing infrastructure and the market for recovered organic waste products as a result of actions undertaken in support of SB 1383. Organic waste processing infrastructure has been expanding, meaning that more organic waste can be diverted from landfills in the future. Organic waste processing capacity has increased by about 400,000 tons in the past few years, and it is estimated that by 2025, California will be able to process 10 million tons of organic waste currently disposed of in landfills. At the same time, markets for recovered organic waste products, such as compost and biomethane, are growing.

However, key challenges still exist for achieving a level of organic waste diversion sufficient to meet California's future goals. Those challenges include slow progress in establishing waste collection and recycling services, a lack of and insufficient organic waste collection and processing infrastructure to meet anticipated needs,[1] and limits to market development for compost and biomethane (Table SPM-2).

REDUCING METHANE EMISSIONS FROM EXISTING LANDFILLS

Reducing methane emissions from existing landfills is also important since landfill methane will escape and become fugitive emissions if not effectively controlled. Since the Landfill Methane Regulation was issued in 2010, California has developed a holistic policy framework for reducing methane emissions from existing municipal solid waste landfills. Three types of measures are adopted to reduce methane from landfills:

- **Regulations:** The Landfill Methane Regulation sets standards for installing and operating gas collection and control systems, surface methane concentrations and component leak monitoring, emission exceedances correction, information reporting, and recordkeeping.
- **Financial Mechanisms:** Financial incentives and grants, enforcement equipment loans, and fees are adopted in California to encourage landfill gas recovery projects and support local enforcement agencies.
- **Quantifying and Understanding Landfill Methane Emissions:** Model estimation, methane hotspot research using a "tiered observation system" of remote sensing and ground verification, and regional inventory analysis are used to measure methane emissions at different scales and identify emission sources.

There is mixed progress in controlling landfill methane emissions. On the one hand, landfill methane emissions in California have increased slightly from 7.79 MMT CO_2e in 2010 to 8.44 MMT CO_2e in 2020. On the other hand, landfill methane emissions per ton of municipal solid waste in California shows a decreasing trend, despite the increasing amount of municipal solid waste disposal, which

[1] Approximately 18 million additional tons of organic waste will need to be processed at compost, anaerobic digestion, chip-and-grind, or other organic waste processing facilities in 2025 to meet the SB 1383 targets. However, based on current capacity projections, California's infrastructure will be able to process only about 10 million tons of the 18 million additional tons.

Table SPM-2 | Summary of key challenges to organic waste diversion		
Measures	**Key Challenges**	**Underlying Causes**
Establish Waste Collection and Recycling Services	Slow progress	• Regulations under SB 1383 did not take effect until January 2022
Infrastructure Expansion	Lack of organic waste processing infrastructure to meet anticipated needs	• Lack of funding • Lack of long-term feedstock contracts • Competition from lower-priced disposal alternatives • Increased environmental regulatory cost for facility development • Increased costs from contaminated feedstock
Recovered Organic Waste Product Market Development	Limits to compost market expansion	• Farmers in California might not have access to agricultural compost • Contaminated feedstock
	Limits to biomethane market expansion	• High capital expenses for distribution and connection • Market uncertainty for biogas projects • Ineffective pricing mechanism

is a sign of significant progress (Figure SPM-1). This progress can be attributed to the fact that a significant proportion of landfills in California have installed landfill gas collection and control systems. In addition, advanced technologies were utilized to monitor significant methane sources across the state and ensure compliance with the Landfill Methane Regulation.

However, despite California's progress, challenges still exist in quantifying and incentivizing greater reductions in landfill methane emissions. Technical factors responsible for these challenges include a lack of continuous methane leakage monitoring, simplified estimation models with limited validation of emission estimates, and the slow pace of technology innovation in improving landfill methane emission control.

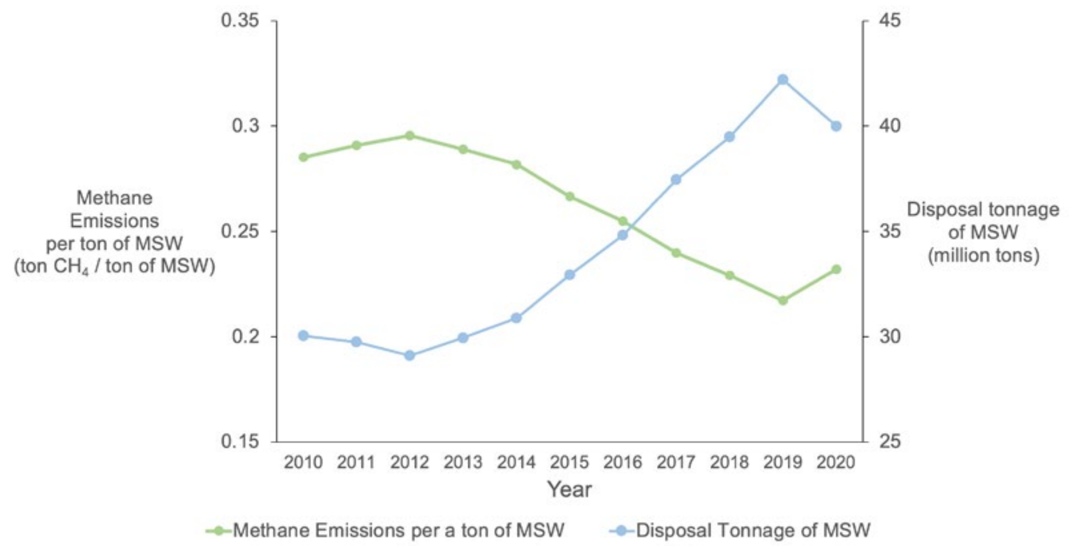
POLICY RECOMMENDATIONS

In support of the greenhouse gas reduction goals set in California's plan to reach carbon neutrality by 2045, more emphasis on landfill waste methane reduction will be needed. Existing policies and programs have resulted in some progress in organic waste diversion and limiting landfill methane emissions, but key targets for the solid waste sector remain unmet.

To effectively divert organic waste from landfills, the state government should focus on improving local jurisdictions' waste management systems and increase grant funding through CARB or CalRecycle programs to support infrastructure expansion. Local jurisdictions can consider organic waste treatment options beyond composting and anaerobic digestion. Education and outreach programs should be conducted widely because such programs can change people's behavior, which is important for reducing food waste and lowering the cost of organic waste diversion. The development of recovered organic waste product markets is also important for infrastructure expansion because higher demand for recovered organic waste products can drive production and will encourage infrastructure expansion.

In addition to the expansion of organic waste treatment facilities, more work needs to be done to effectively control methane emissions from existing landfills. These efforts will increase the collection of landfill methane as well as the supply of clean electricity. Currently, the cost

Figure SPM-1 | California Annual Municipal Solid Waste Disposal and Landfill Methane Emissions per Ton of Municipal Solid Waste[1]



[1] CARB, 2022a; Department of Resources Recycling and Recovery, n.d.-g

of inspection, equipment installment, landfill methane estimation model inaccuracy, and slow progress in methane control technology innovation are major barriers to landfill methane control. More financial support from the state government is necessary to develop new tools for field inspection. More research on landfill methane capture and collection technologies is needed to stimulate innovation and lower the cost of landfill methane control.

As the first state to develop comprehensive methane reduction strategies for the solid waste sector, California is uniquely positioned to spearhead global efforts to address the significant climate impacts of the solid waste sector. California's comprehensive landfill methane reduction framework, consisting of regulation, financial incentives, and many other policy instruments, provides a possible template for achieving solid waste methane reduction in other jurisdictions worldwide. Challenges that California is currently facing should be considered and addressed in the future when other jurisdictions devise policies to reduce solid waste methane.

Below are five policy recommendations for other jurisdictions based on lessons and experiences from California:

- A comprehensive methane policy package should include policy, regulations, financial incentives, and behavioral change-focused programs.
- Organic waste recycling and edible food recovery are critical components of solid waste methane mitigation strategies, as they reduce the overall financial and infrastructural burden on waste management systems while reducing potential methane emissions.
- As organic waste continues to increase, more infrastructure capacity is necessary to divert waste from landfills. It is important for subnational governments to consider and address the negative impacts of some organic waste treatment options (such as compost and anaerobic digestion) through available technologies and to explore new treatment options.
- Advanced monitoring systems, accurate inventory models, and financial support for technology innovation are needed to track and reduce methane emissions from existing landfills.
- Given the role of municipalities in waste management in many subnational jurisdictions (such as states and provinces), enforcing local compliance with state or national regulations is essential to implement methane reduction strategies.

Abbreviations and Acronyms

AB	Assembly Bill
BioMAT	Bioenergy Market Adjusting Tariff
C&D	Construction and Demolition
CALMIM	California Landfill Methane Inventory Model
CAP	Corrective Action Plan
CARB	California Air Resources Board
CEC	California Energy Commission
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CH4	Methane
CO_2	Carbon Dioxide
CPUC	California Public Utilities Commission
GCCS	Gas Collection and Control Systems
GHG	Greenhouse Gases
GWP	Global Warming Potential
IOUs	Investor-Owned Utilities
IPCC	Intergovernmental Panel on Climate Change
JPL	Jet Propulsion Laboratory
LCFS	Low Carbon Fuel Standard
LEA	Local Enforcement Agency
LMOP	Landfill Methane Outreach Program
LMR	Landfill Methane Regulation
MMBtu	Million British Thermal Units
MMT	Million Metric Tons
MOU	Memoranda of Understanding
MSW	Municipal Solid Waste
NOV	Notice of Violation
ppmv	Parts per Million Volume
RDRS	Recycling and Disposal Reporting System
RNG	Renewable Natural Gas
SB	Senate Bill
SCAQMD	South Coast Air Quality Management District
SLCP	Short-Lived Climate Pollutant
U.S. EPA	U.S. Environmental Protection Agency
VOC	Volatile Organic Compound

INTRODUCTION

Reducing methane emissions is key to slowing climate change in the near term. Methane (CH4) is about 80 times as potent as carbon dioxide (CO_2) at warming the planet over a 20-year period.[2] Since 1850, methane emissions from human activity—primarily from agriculture, energy production, and waste—have contributed about 0.5°C to the net current warming of 1.1°C.[3] Methane is also short-lived, with a lifetime of about 12 years, which means that cutting methane emissions has an almost immediate impact on warming. Therefore, reducing the impact of methane emissions, especially in the near term, is essential to achieve the 1.5°C Paris Agreement targets.[4]

Taking targeted action on reducing methane could avoid nearly 0.3°C of global warming by the 2040s.[5] Reducing methane can also complement decarbonization strategies and help to achieve net-zero CO_2 by 2050, further mitigating the effects of climate change. Over the next few decades, measures that reduce methane can cut warming more quickly and more significantly than those that reduce CO_2 emissions in the near term. Compared to methane, reducing CO_2 emissions alone ultimately have less impact on mitigating warming in the first 20 to 30 years due in part to the unmasking effect of cooling aerosols that are co-emitted with fossil fuel burning.[6] Additionally, because methane emissions contribute to ozone pollution and other negative co-pollutants that lead to adverse effects on human health and agricultural productivity, their reduction can provide co-benefits in improved air quality, better health conditions, and increased crop yields.[7]

The United States, along with the European Union, is leading the Global Methane Pledge, which aims to reduce global human-related methane emissions by at least 30% below 2020 levels by 2030.[8] Currently, solid waste landfills account for 20% of global anthropogenic methane emissions and are the third largest source of anthropogenic methane emissions in the United States, following those in the agricultural and energy sectors.[9] Key mitigation measures for the solid waste sector have an estimated global reduction potential of 29–36 million metric tons of methane per year[10] (MMT CH4/yr). Those measures include the reduction of food and solid wastes, diversion of organic waste from landfills, capture and use of landfill gas, and controlling and flaring landfill emissions that cannot be captured and used.[11]

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2 IPCC, 2021
3 IPCC, 2021
4 IPCC, 2022
5 UNEP & CCAC, 2021
6 Dreyfus et al., 2022
7 UNEP & CCAC, 2021
8 The White House, 2021
9 UNEP & CCAC, 2021
10 UNEP & CCAC, 2021
11 UNEP & CCAC, 2021

In the 2021 U.S. Methane Emissions Reduction Action Plan published by the White House Office of Domestic Climate Policy, the U.S. set a national goal of a 70% methane emissions capture and flare rate for all landfills across the country.[12] However, waste management often falls under the jurisdiction of subnational authorities within the U.S., and there is currently no specific national guidance on policies or programs for achieving landfill methane reductions. This gap provides an opportunity for states and subnational authorities to play an active role in defining their own methane reduction goals and taking mitigation actions in the solid waste sector.

Within the U.S., California stands out as one of the first subnational jurisdictions to have developed comprehensive short-lived climate pollutant (SLCP) reduction strategies across greenhouse gases (GHGs) and source sectors, especially on methane in the solid waste sector. Building on the state's overall target of a GHG emissions reduction of 40% below 1990 levels by 2030, California adopted 2030 targets for reducing black carbon by 50%, methane by 40%, and hydrofluorocarbons by 40% against a 2013 baseline.[13] For methane, solid waste landfills are a key source of emissions, contributing 22% of California's total methane emissions of 38.85 MMT of carbon dioxide equivalent (CO_2e)[14] in 2020, according to the latest inventory.[15] In recognition of the importance of reducing methane emissions from solid waste landfills, the California Air Resources Board (CARB) first introduced its Landfill Methane Regulation (LMR) in 2010. Since then, a series of policies and programs have been introduced and implemented to specifically reduce methane emissions from municipal solid waste landfills.

Using California as an example, this paper analyzes policies and programs, implementation mechanisms, and lessons learned from California in reducing methane emissions from the solid waste sector. Comprehensive assessments of policies and programs adopted in California can provide insights into some best practices that could be adopted by other regions and in understanding existing challenges and gaps to achieve methane reductions in the solid waste sector.

The rest of this report contains two major sections: (1) a summary of California's policies, implementation mechanisms, and lessons in reducing solid waste methane emissions, as well as a summary of the progress and challenges in organic waste diversion and reducing methane from existing landfills, and (2) a conclusion and discussion, which summarizes policy gaps and policy recommendations.

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[12] The White House, 2021

[13] Senate Bill 1383, 2016

[14] This number is calculated using 100-year global warming potential (GWP) of methane based on IPCC AR4 (CARB, 2022a). The 20-year GWP of methane is about 80 and better captures the near-term warming impact of methane and urgency of limiting overshoot of 1.5°C guardrail (Abernethy & Jackson, 2022).

[15] CARB, 2022a

BEST PRACTICES OF CALIFORNIA POLICIES, PROGRAMS, AND APPROACHES

As stated in California's Global Warming Solutions Act, Assembly Bill 32, CARB was charged with reducing statewide GHG emissions to the 1990 level by 2020.[16] Since methane is an important greenhouse gas, California has published a series of policies and conducted some projects to reduce methane emissions from municipal solid waste landfills. Those policies and projects could be categorized into two main approaches: (1) diverting organic waste from landfills[17] and (2) reducing and capturing methane emissions from existing landfills.

DIVERTING ORGANIC WASTE FROM LANDFILLS

Landfill organic waste is converted to landfill methane through a process called anaerobic breakdown.[18] If not fully controlled, this landfill methane escapes and becomes fugitive emissions. Since organic waste accounts for a significant portion of California's disposed waste stream (44%)[19] and the methane generated (20%),[20] it is necessary to construct a holistic framework to effectively divert organic waste from landfills.

Various measures could be adopted to divert organic waste from landfills; these include source reduction,[21] recycling, food recovery,[22] composting,[23] and anaerobic digestion.[24] These measures can provide a variety of environmental and economic benefits. For example, food recovery programs can effectively reduce the amount of organic waste disposal and provide healthy foods; composting can return nutrients to soils and make them more productive. Anaerobic digestion of diverted organic waste concentrates and captures methane, which can then be used to generate electricity and help California to achieve the goal of obtaining 60% of its electricity from renewable sources by 2030 and 100% from renewable and zero-carbon resources by

16 AB 32, 2006

17 For more information about California's policies in managing other types of waste, please refer to the website of California's Department of Resources Recycling and Recovery: https://calrecycle.ca.gov/.

18 Anaerobic breakdown of organic waste occurs when anaerobic bacteria digest biomass and produce biogas such as methane under anaerobic conditions.

19 Organic waste is defined in CCR Title 14 Section 18982(a)(46) as "solid wastes containing material originated from living organisms and their metabolic waste products including, but not limited to, food, green material, landscape and pruning waste, organic textiles and carpets, lumber, wood, paper products, printing and writing paper, manure, biosolids, digestate, and sludges." Therefore, even though paper and organic are two types of waste in the latest California waste characterization study, they are both organic waste according to the law.

20 Department of Resources Recycling and Recovery, 2020b, 2020a

21 Source reduction, also known as waste prevention or pollution prevention, is the elimination of waste before it is created. According to the U.S. Environmental Protection Agency (EPA), this method is the most preferred option in food recovery hierarchy (U.S. EPA, 2022a).

22 Food recovery means collecting edible food that would otherwise go to waste and redistributing it to feed people in need.

23 Composting is a controlled, aerobic process that converts organic materials into a nutrient-rich soil amendment or mulch through natural decomposition.

24 Anaerobic digestion is a process through which bacteria break down organic matter in the absence of oxygen (CARB, 2017a).

Table 1 | Summary of goals and requirements of California's organic waste diversion regulations	
Policy	**Goals and Requirements**

Assembly Bill 341 (2011)	• Goals:
	  ○ No less than 75% of solid waste generated be source reduced, recycled, or composted by 2020
	• Requirements:
	  ○ Businesses that generate four cubic yards or more of commercial solid waste per week should arrange for recycling services.
	  ○ Local jurisdictions should implement recycling programs and report the progress to CalRecycle.

Assembly Bill 1826 (2014)	• Requirements:
	  ○ Businesses that generate eight cubic yards or more of organic waste per week should arrange recycling services specifically for organic waste
	  ○ The threshold amount of waste per week above which businesses should recycle organic waste will be gradually tightened.[1]

Senate Bill 1383 (2016)	• Goals:
	  ○ Reducing the disposal of organic waste by 50% of 2014 levels in 2020 and by 75% in 2025.
	  ○ At least 20% of disposed edible food should be recovered by 2025.

1 The threshold was last revised in 2020 to two cubic yards per week for businesses.

2045.[25] Methane produced from anaerobic digestion can also be utilized as renewable natural gas (RNG) in hard-to-decarbonize sectors such as transportation and industrial manufacturing.

To promote the adoption of these measures, California has issued a series of regulations and financial policies and conducted some programs to encourage the diversion of organic waste from landfills. Multiple state agencies and stakeholders are involved.

Standards and Regulations

California's regulation on organic waste diversion started with mandatory recycling. According to the 2008 Assembly Bill (AB) 32 Scoping Plan, mandatory recycling was one measure to reduce GHG emissions[26] as required by AB 32. In 2011, California passed AB 341, declaring that "not less than 75% of solid waste generated be source reduced, recycled, or composted by 2020."[27] This bill requires a business that generates four cubic yards or more of commercial solid waste per week to arrange for recycling services and also asks local jurisdictions to implement a commercial solid waste recycling program that consists of education, outreach, and monitoring of business.[28] Each jurisdiction is also required to report the progress of the recycling program to the Department of Resources Recycling and Recovery.

Mandatory recycling of organic waste was the next step to divert organic waste from landfills and achieve California's recycling goal, as organic waste is a key component of the waste stream,[29] and most of it could be used for compost, mulch, or anaerobic digestion. Starting from 2016, AB 1826 required businesses that generate eight cubic yards or more of organic waste per week to

25 Senate Bill 100, 2018
26 CARB, 2008a
27 AB 341, 2011
28 Department of Resources Recycling and Recovery, n.d.-a
29 Department of Resources Recycling and Recovery, 2020a

arrange recycling services specifically for organic waste.[30] Requirements for local jurisdictions were similar to those in AB 341. However, unlike AB 341, AB 1826 gradually lowers the threshold amount of waste above which businesses should recycle organic waste. In September 2020, CalRecycle reduced the threshold to two cubic yards of solid waste per week.

In September 2016, California passed Senate Bill (SB) 1383, which set a goal of reducing the disposal of organic waste by 50% of 2014 levels in 2020 and 75% in 2025. In addition, the law established a specific target for food recovery: "at least 20% of disposed edible food should be recovered by 2025."[31] That goal was set because food waste alone accounts for approximately 13.5% of California's total disposal waste stream, and about 2.9% of the waste stream is potentially donatable food.[32] Preventing food waste and rescuing edible food could effectively reduce methane emissions from landfills and address food shortage issues. Table 1 summarizes the goals and requirements for the state's organic waste diversion regulations.

Organic waste reduction regulations under SB 1383 are now the major policies that regulate organic waste reduction in California, as regulations under the bill started taking effect on January 1, 2022. There are eight major components of organic waste reduction regulation: collection and recycling, procurement requirements, food recovery, capacity planning, enforcement, recordkeeping requirements, waivers and exemptions, and reporting.[33] Table 2 summarizes the main contents of each category.

To ensure compliance with regulations under SB 1383, both local jurisdictions and CalRecycle have the discretion to enforce regulations and impose penalties. Since January 1, 2022, local jurisdictions have been required to conduct annual route reviews[34] and to inspect regulated entities to determine overall compliance. A jurisdiction may impose penalties if an organic waste generator[35] is found to be violating the regulations. For CalRecycle, the SB 1383 enforcement structure allows CalRecycle to focus on compliance assistance[36] first and dedicate enforcement efforts to serious offenders. If compliance issues cannot be addressed through compliance assistance, CalRecycle has the discretion to issue a Notice of Violation (NOV) to trigger the enforcement process and can decide whether to place a jurisdiction on a Corrective Action Plan (CAP), which will extend compliance timelines. If compliance actions fail, CalRecycle can impose administrative civil penalties.[37]

Financial Mechanisms

Besides standards and regulations, various measures have been taken to align financial incentives with organic waste diversion. These measures include procurement programs, fees, credits, and market expansion.

Procurement of biomethane produced from organic waste is an important financial mechanism adopted by California to encourage the use of renewable gas and organic waste diversion, as it could effectively reduce otherwise uncontrolled methane emissions in landfills. Moreover, methane from organic waste could displace some of the fossil fuel natural gas, thus decarbonizing California's transportation sector and supporting the development of a more sustainable energy system. Recognizing the benefits of utilizing methane from organic waste, California has taken action to promote its use through procurement programs. In 2012, SB 1122 required investor-owned utilities (IOUs) to offer contracts and tariffs

30 AB 1826, 2014

31 SB 1383, 2016

32 Department of Resources Recycling and Recovery, 2020a

33 Department of Resources Recycling and Recovery, n.d.-b

34 SB 1383 establishes route review requirements for all three-plus, three, and two-container waste collection systems. All waste hauler routes must be evaluated annually for prohibited container contaminants (see 14 CCR Chapter 12, Article 3, Section 18984.5(b)).

35 Regulations under SB 1383 define an organic waste generator as a person or entity that is responsible for the initial creation of organic waste (see Title 14, CCR, Article 1 section 18982).

36 Including implementation checklists, training, and model implementation tools.

37 SB 1383, 2016

Table 2 | Summary of organic waste reduction regulations under SB 1383	
Organic Waste Reduction Regulation Components	**Main Contents**
Collection and Recycling	• Requires every jurisdiction to provide mandatory organic waste collection services to all residents and businesses. • Collection and recycling requirements for residents, businesses, schools, state agencies, etc. • Requirement for transfer/processing facility and operation
Procurement Requirements	• Requires cities and counties to procure a certain amount of recovered organic waste products[1] annually.
Food Recovery	• Requires jurisdictions to establish food recovery programs and strengthen food recovery networks through capacity planning. • Requires certain food businesses to establish contracts with food recovery organizations and provide excess edible food to them.
Capacity Planning	• Requires counties and jurisdictions to identify existing capacity and estimate necessary new capacity for organic waste recycling and edible food recovery.
Enforcement	• Requires jurisdictions to implement an annual inspection and enforcement program to ensure compliance. • Requires CalRecycle to conduct compliance evaluations for jurisdictions, non-local entities, and local education agencies
Recordkeeping Requirements	• Recordkeeping requirements for jurisdictions, self-haulers of organic waste, commercial edible food generators, food recovery organizations/services, and waste transfer/processing facilities.
Waivers and Exemptions	• Exemption conditions for certain jurisdictions, non-local entities, and local education agencies.
Reporting	• Requires jurisdictions to report on program implementation and capacity planning to CalRecycle. • Requires facilities to submit information to the Recycling and Disposal Reporting System (RDRS).

1 Jurisdictions can fulfill their target by procuring any combination of the following recovered organic waste products: compost, mulch, and renewable energy (transportation fuel, heat, and electricity) from anaerobic digestion and electricity from biomass conversion.

to procure an additional 250 megawatts of electricity generated from bioenergy facilities, including organic waste diversion facilities.[38] In 2018, SB 1440 authorized the California Public Utilities Commission (CPUC) to adopt biomethane procurement targets[39] for gas providers in California. Under SB 1440, the CPUC passed a decision in February 2022, establishing both short-term and medium-term procurement goals for biomethane to help divert eight million tons of organic waste from landfills annually.[40]

As part of their SB 1383 organic waste reduction regulations, CalRecycle also adopted requirements for cities and counties to procure recovered organic waste products, including biomethane, compost, and mulch, to encourage organic waste diversion from landfills and help build markets for these products. These products can benefit local communities, as well as help to improve soil and air quality. From the state's perspective, the procurement of such products

38 SB 1122, 2012

39 SB 1440, 2018

40 CPUC, 2022

Table 3 | Financial mechanisms used to promote organic waste diversion

Financial Mechanisms	Specific Actions

Procurement Requirement	• Procurement of biomethane:
	  ○ Senate Bill 1122 required IOUs to procure an additional 250 megawatts of electricity generated from bioenergy facilities.
	  ○ The CPUC established procurement goals for biomethane to divert eight million tons of organic waste from landfills annually.
	• Procurement of recovered organic waste products:
	  ○ Senate Bill 1383 set annual procurement targets for cities and counties.

Incentive Programs	• Awarded funding through the Healthy Soils Program to promote the use of compost on agricultural lands. • Awarded tradable credits to fuel suppliers through the LCFS program to increase supply of low carbon transportation fuel. • CEC invested in renewable fuel through the Clean Transportation Program. • CalRecycle funded food recovery projects through the Food Waste Prevention and Rescue Grant Program and the Edible Food Recovery Grant Program.
Fees	• Integrated waste management fees are collected to promote the waste management programs. • Senate Bill 1383 authorizes local jurisdictions to charge and collect fees to recover the costs.

will help strengthen California's green economy, stimulate investment in organic waste diversion infrastructure, and create new jobs.[41]

Beginning in January 2022, organic waste reduction regulations under SB 1383 set an annual procurement target for cities and counties in California based on population. It requires them to procure a certain amount of recovered organic waste products[42] every year for 5 years (from 2022 to 2026). After that, the procurement target for each city and county is updated every 5 years to account for changes in jurisdiction populations[43]. Through mandatory governmental procurement, the demand for recovered organic waste products is increased, providing a demand side incentive.

Expanding the market for recovered organic waste products could also increase the demand for such products and can foster organic waste diversion from the demand side. To expand markets for recovered organic waste products, CalRecycle provides compost market resources to compost producers in California by offering free online advertising. CalRecycle also collaborates with the California Department of Food and Agriculture to award funding to projects through the Healthy Soils Program that support agricultural practices that sequester carbon and are most often awarded to projects to apply compost on agricultural lands in support of the Healthy Soils Initiative.[44]

In addition, CARB approved the Low Carbon Fuel Standard (LCFS) Regulation in 2010 to decrease the carbon intensity of California's transportation fuel pool and promote the use of low-carbon transportation fuels, such as upgraded biomethane as RNG, by awarding tradable credits to suppliers of transportation fuels to reduce the carbon intensity of the fuels they supply.[45] The California Energy Commission (CEC) has conducted the Clean Transportation Program and invested up to $100 million to encourage the use of renewable transportation fuel, including biofuel recovered from

[41] Department of Resources Recycling and Recovery, 2019; Department of Resources Recycling and Recovery, 2020b

[42] Types of recovered organic waste products include: compost, mulch, renewable energy (transportation fuel, heat, and electricity) from anaerobic digestion and electricity from biomass conversion.

[43] Department of Resources Recycling and Recovery, 2022a

[44] Department of Food and Agriculture, n.d.

[45] CARB, n.d.-a

organic waste.[46] Moreover, CalRecycle has multiple programs including the Food Waste Prevention and Rescue Grant Program and the Edible Food Recovery Grant Program to fund projects that prevent food waste or rescue edible food that would otherwise be landfilled.[47] Since 2016, CalRecycle has awarded over 100 projects through the Food Waste Prevention and Rescue Grant Program and the Edible Food Recovery Grant Program, resulting in nearly 154 million pounds of edible food from being landfilled, equivalent to more than 128 million meals (as of June 2022).[48] CalRecycle also conducts the Organics Grant Program, which provides grant funding to composting and anaerobic digestion projects in California that will reduce the amount of California-generated organic waste being sent to landfills.[49]

Last but not least, fees are adopted to recover the cost of organic waste diversion from landfills. promote waste management programs, including solid waste reduction and composting.[50] Moreover, SB 1383 authorizes local jurisdictions to charge and collect fees to recover the costs For example, California has been collecting integrated waste management fees at the rate of $1.40 per ton of material disposed of at landfills to support CalRecycle's expenditure and incurred in reducing organic waste disposal in landfills.[51] Table 3 summarizes California's major financial mechanisms to promote organic waste diversion.

Progress and Challenges

Progress

Since the release of AB 32 in 2008, California has established a comprehensive regulatory system with clear targets and utilized various financial approaches to reduce the disposal of organic waste. Although California has taken a series of actions to divert organic waste from landfills through measures such as recycling, composting, and anaerobic digestion, it still has failed to achieve the 2020 goals required by law. For example, according to the report State of Disposal and Recycling in California, although California's recycling rate had increased from 37% to 42% in 2020, the 2020 goal was actually 75%.[52]

Table 4: Overall progress of California's organic waste diversion

Criteria	Goal	Progress
Solid Waste Recycling Rate	75% by 2020	42% in 2020
Organic Waste Disposal Reduction Rate	50% by 2020 (compared to 2014 baseline)	11% in 2021[1] (compared to 2014 baseline)

1 The amount of organic waste disposed of in landfills has increased between 2014 and 2021. The calculation was based on CalRecycle's data of landfill waste disposal and percentage of organic waste in the disposed waste stream.

Moreover, California failed to achieve the goal of reducing its organic waste disposal in landfills by 50% below 2014 levels by 2020, as established by SB 1383[53]. Additionally, according to CalRecycle's internal calculation, the amount of organic waste disposed of in landfills decreased by only 11% between 2014 and 2021. This slow progress of organic waste disposal reduction could lead to annual methane emissions being higher through 2030 than originally anticipated by the latest Short-Lived Climate Pollutant Reduction Strategy published in 2017.[54] Table 4 shows the progress California has made in meeting its organic waste diversion goals.

46 California Energy Commission, n.d.

47 For more information about CalRecycle's Greenhouse Gas Reduction Grant and Loan Programs, please refer to https://calrecycle.ca.gov/climate/grantsloans/.

48 Department of Resources Recycling and Recovery, n.d.-d

49 Department of Resources Recycling and Recovery, 2023

50 Department of Tax and Fee Administration, n.d.

51 SB 1383, 2016

52 Department of Resources Recycling and Recovery, 2021

53 Department of Resources Recycling and Recovery, 2020b

54 CARB, 2022b

The failure to achieve these 2020 targets is mainly because regulations under SB 1383 were not adopted until fall of 2020 and were prohibited from taking effect until January 2022. Additionally, local jurisdictions cannot enforce those regulations until January 2024. In fact, according to the latest AB 32 Climate Change Scoping Plan published in 2022, state agencies relied on voluntary and incentive-based mechanisms to achieve the 2020 targets in the early years of SB 1383 implementation. Under this strategy, incentives are replaced with requirements as the solutions become increasingly feasible and cost-effective.[55]

Despite the failure to achieve these 2020 targets, California did make significant progress in expanding its organic waste processing infrastructure. According to CalRecycle, organic waste processing capacity has increased by more than 400,000 tons in the past few years. Specifically, new and expanded compost facilities brought about 200,000 additional tons of organic waste processing capacity from 2018 to 2020, and two new anaerobic digestion facilities have been established to provide 90,000 tons of capacity from 2017 to 2020. Six wastewater treatment plants are anticipated to start co-digesting[56] food waste and will bring an additional 140,000 tons of capacity online by 2025, supporting the organic waste diversion targets set in SB 1383.[57]

Granting funds is an important measure California utilizes to encourage infrastructure expansion. By 2020, California has provided roughly $140 million to help local governments and private facility operators increase organic waste processing infrastructure. In particular, since 2014, CalRecycle has awarded $72.5 million to 16 compost and 9 anaerobic digestion infrastructure projects, as well as $20 million to 64 food prevention and rescue projects.[58] Meanwhile, it is estimated that 14 new compost facilities and 8 anaerobic digestion facilities will begin operating in the next few years and increase the organic waste processing capacity by approximately 1.85 million tons.[59] In 2020, CalRecycle estimated that, by 2025, California will be able to process 10 million tons of organic waste currently disposed of in landfills, among which 5.3 million tons will be composted and about 1 million tons will be anaerobically digested, should the existing processing capacity and anticipated capacity be fully utilized.[60]

Education and outreach programs also support better waste management practices. For example, San Diego is now operating one of the largest composting facilities in California—the Miramar Greenery. The key to its success is the customer training program. According to the program, customers are required to be educated about the contamination in the waste they dump, and the percentage of their waste will be evaluated. This training program effectively reduces contamination in the waste and reduces the facility's operating costs. After the training program's launch, the Miramar Greenery expanded in 2008 and won an Organics Infrastructure Grant from CalRecycle to expand capacity and improve its facilities.[61]

However, there is still a lack of organic waste processing capacity in California, despite the anticipated capacity increase by 2025. Figure 1 shows that the anticipated capacity of composting, anaerobic digestion, and co-digestion in 2025 is significantly less than the capacity needed for fulfilling the 75% organic waste disposal reduction goal in SB 1383.[62]

In addition to infrastructure expansion, California has made some progress in strengthening the markets for recovered organic waste products. Specifically, California has been setting annual procurement goals for local jurisdictions to establish and strengthen the market for two major types of products: compost and biomethane.

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[55] CARB, 2022b

[56] Municipal wastewater treatment plants (WWTPs) are identified as one measure of organic waste diversion by accepting food waste diverted from landfills and co-digesting it with sewage sludge. Through co-digestion, municipal WWTPs can produce, capture, and make beneficial use of biogas, which is a renewable source of methane.

[57] Department of Resources Recycling and Recovery, 2020b

[58] CARB, 2020a

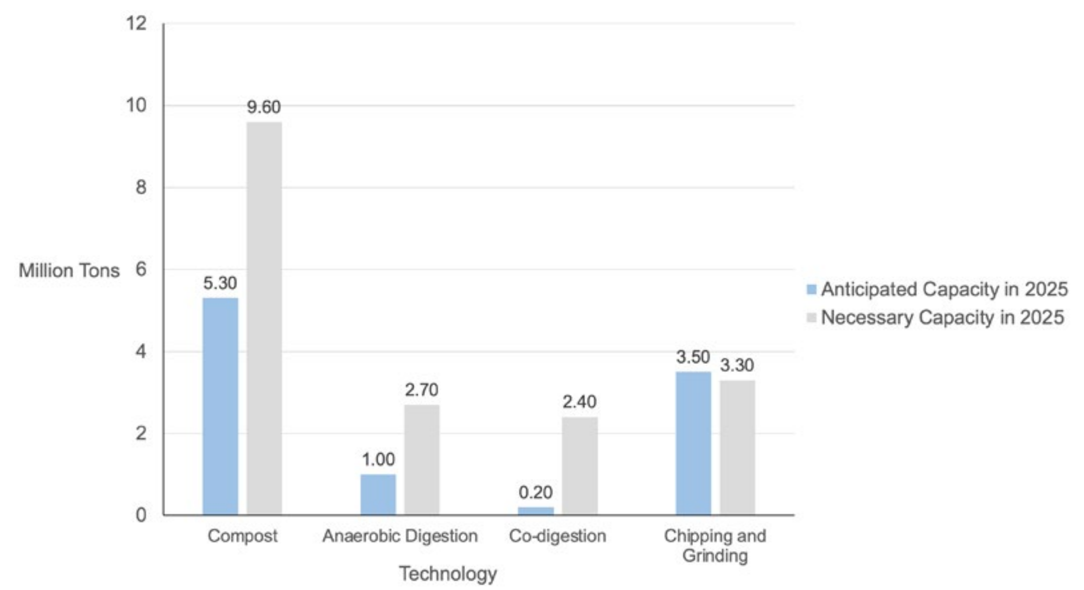
[59] Department of Resources Recycling and Recovery, 2020b

[60] Department of Resources Recycling and Recovery, 2020b

[61] Department of Resources Recycling and Recovery, n.d.-i.

[62] Department of Resources Recycling and Recovery, 2020b

Figure 1 | California's Existing, Anticipated, and Necessary Organic Waste Capacity[1]



1 Department of Resources Recycling and Recovery, 2020b

Compost

For compost, the markets and demand are currently strong and mature.[63] Nearly 170 businesses in California produce compost and mulch.[64] Agriculture is the largest market for compost; about 65% of the compost produced was sold to this sector in 2017, according to a survey.[65] About 40% of composting facilities in California receive organic certification from the Department of Food and Agriculture's Organic Input Material Program and Organic Material Review Institute's compost registration program. The compost produced by these facilities was adopted in organic farming production in California.[66] The California Healthy Soils Program also boosted the compost market. As part of the state's climate initiatives, the program provides financial incentives and demonstration project funding for practices that improve soil health, including compost application.[67]

There are also other important markets for compost, including nurseries, landscaping companies, the California Department of Transportation, and local municipal programs. California's Model Water Efficient Landscape Ordinance requires compost application at a rate of four cubic yards per 1,000 square feet for all planted areas for new or remodeled landscapes, unless the landscape has greater than 6% organic matter in the top 6 inches of soil.[68] The Department of Transportation applied about 80,000 tons of compost in 2016 along highways for landscaping, seeding, and erosion control purposes,[69] and the use of compost by the Department of Transportation accounted for 5% of the compost produced in California in 2017, which is a much larger market share compared to that estimated in 2010.[70] Municipal programs consumed 3% of compost in 2017, and as procurement programs are implemented, the demand for compost is expected to increase.

Biomethane

Biomethane is a renewable natural gas (RNG) produced from decaying organic matter. It has the potential to replace the use of fossil natural gas in the industrial and manufacturing sectors. For

63 Department of Resources Recycling and Recovery, 2020b
64 Department of Resources Recycling and Recovery, n.d.-c
65 Department of Resources Recycling and Recovery, 2019
66 Department of Resources Recycling and Recovery, 2020b
67 Coker & Ziegenbein, 2018
68 Department of Water Resources, 2020
69 Department of Resources Recycling and Recovery, n.d.-h; Department of Resources Recycling and Recovery, 2020b
70 Department of Resources Recycling and Recovery 2019

biomethane, there are three primary markets: (1) vehicle fuel, (2) general use, including heating, and (3) electricity generation. The strength of these three markets varies.

The market for upgraded biomethane as RNG for use in vehicles is currently robust. On the demand side, according to CARB, about 98% of compressed natural gas and liquefied natural gas demand for transportation was met by RNG in 2021.[71] Meanwhile, the procurement requirements under the CalRecycle SB 1383 organic waste reduction regulations and the Clean Transportation Program established by AB 118[72] could also increase the demand for RNG. On the supply side, the implementation of SB 1383 will increase supply. Two credit markets (Federal Renewable Fuel Standard and the California Low Carbon Fuel Standard) can help offset the high cost of producing RNG and encourage RNG fuel utilization.

The markets for biomethane as a heating or electricity source are relatively weak. Currently, only three municipal solid waste anaerobic digestion facilities and one waste water co-digestion facility in California injects biomethane into the pipeline.[73] In 2021, the percentage of electricity generated from biomethane in California was less than 2.77% in California.[74]

However, California has adopted a series of policies to boost these two markets and has made some progress. In 2012, SB 1122 established the Bioenergy Market Adjusting Tariff (BioMAT) program. As a feed-in tariff program, the BioMAT required California's major electrical IOUs[75] to procure biogas from renewable sources such as organic waste diversion.[76] In 2015, the CPUC funded $40 million for an incentive program to support anaerobic digestion facilities to transfer biomethane through pipelines to IOUs. Most municipal solid waste anaerobic digestion facilities in California are also generating electricity from biogas onsite and sending it to the grid.[77]

Challenges

An important reason why California has not yet achieved its targets is the slow progress that has been made toward waste collection and recycling services. For example, although jurisdictions in California were required by CalRecycle to provide organic waste collection and recycling services to residents and businesses, many residents, businesses, and waste haulers still have not heard about the program and have not been trained to separate organic waste from the daily waste stream.[78] This is mainly because the regulations under SB 1383 did not take effect until January 2022, and many cities did not provide waste collection and recycling services until the summer of 2022. Moreover, many cities, especially small ones that have not had robust organics-collection systems in place historically, find it difficult to raise enough funding for collection and recycling services due to the lack of state funding and the negative impact on the economy from the COVID-19 pandemic. This gap could limit the supply of organic waste feedstock, thus limiting infrastructure expansion. To address this gap, some jurisdictions have been given extensions, waivers, and exemptions because of the challenges they face.[79] In the near future, collection and recycling services are supposed to be in place, and residents and businesses will be required to start separating organic waste.

There is also a lack of organic waste processing facilities. According to CalRecycle, although organic waste processing capacity has increased by about 400,000 tons in the past few years, the amount of organic waste disposed of in landfills has increased by more than 2 million tons between 2014 and 2018. CalRecycle also estimated that approximately 27 million additional tons of organic material will need to be redirected from landfills in 2025 to meet the SB 1383 reduction goal, including 18 million additional tons of organic waste will need to be processed at compost,

71 CARB, 2022d
72 AB 118, 2007
73 Department of Resources Recycling and Recovery, 2020b
74 CEC, 2021
75 San Diego Gas & Electric, Pacific Gas and Electric, and Southern California Edison
76 SB 1122, 2012
77 Department of Resources Recycling and Recovery, 2020b
78 Brooke, 2022
79 Moran, 2021

Table 5 | Estimated composting, anaerobic digestion, and chip-and-grind capacity in 2025 (Million Tons)[1]			
Technology	Estimated Anticipated Additional Capacity, 2025[2] (Million Tons)	Estimated Needed Additional Capacity, 2025 (Million Tons)	Difference (Million Tons)
Compost	5.3	9.6	-4.3
Anaerobic Digestion	1.0	2.7	-1.7
Co-Digestion	0.2	2.4	-2.2
Chipping and Grinding	3.5	3.3	0.2
Total	10.0	18.0	-8.0

1 Department of Resources Recycling and Recovery, 2020b

2 Estimated anticipated capacity to divert additional tons from landfills to compost, anaerobic digestion, and chip and grind

anaerobic digestion, chip-and-grind, or other organic waste processing facilities. However, based on current capacity projections, California's infrastructure will be able to process only about 10 million tons of the 18 million additional tons by 2025.[80]

In other words, while organic waste processing capacity has been growing, significant infrastructure expansion beyond what is anticipated is necessary for California to achieve the SB 1383 reduction goal. Specifically, the expansion of composting, anaerobic digestion, and co-digestion capacity are very important since there are significant differences between the anticipated and needed capacity in 2025 (Table 5).

Several issues such as lack of funding, lack of long-term contracts, increased regulatory costs, contaminated feedstock, and potential negative environmental impact could also limit the expansion of the organic waste collection and recycling infrastructure capacity.

Low funding levels for infrastructure investment has made it difficult for cities in California to establish organic waste management systems. As is estimated by CalRecycle, it will cost approximately $20.9 billion between 2019 and 2030, with up to 100 new facilities, to fully implement SB 1383 regulations.[81] What is worse, there has been a cap of the integrated waste management fees at $1.40 per ton of MSW disposed of at landfills since 2002.[82] In other words, the fees are not modernized, limiting the funding available for CalRecycle to conduct waste management programs.[83]

The lack of long-term feedstock contracts and competition from lower-priced disposal alternatives could be two other economic barriers to infrastructure expansion. According to a survey conducted by CalRecycle, the perceived availability of feedstock materials was the biggest factor driving facility expansion. However, due to the lack of long-term feedstock contracts, many composting and anaerobic digestion facilities did not plan to expand since it would be risky and costly for facilities to develop new processing capacity without a dedicated contract for feedstock.[84] Besides the contract issue, organic waste processing facilities were also facing competition from lower-priced disposal alternatives, including direct land application[85] and alternative daily cover.[86] Even though the issues of contracts and competition are likely no longer a problem in California now that SB 1383 is being implemented and more organics are being collected, other states and countries should pay attention to those two issues if they wish to apply California's experiences.

80 Department of Resources Recycling and Recovery, 2020b

81 California State Association of Counties, 2018; Department of Resources Recycling and Recovery, 2020b; Moran, 2021

82 Department of Tax and Fee Administration, n.d.

83 Department of Resources Recycling and Recovery, 2020b

84 Department of Resources Recycling and Recovery, 2019

85 Direct land application is the final deposition of compostable material on any land, including land zoned only for agricultural uses.

86 Alternative daily cover (ADC) means cover material other than earthen material placed on the surface of the active face of a municipal solid waste landfill at the end of each operating day to control vectors, fires, odors, blowing litter, and scavenging (Department of Resources Recycling and Recovery, 2020b).

Increased regulatory cost for facility development is another challenge that facility operators have to face. Even though organic waste diversion options such as composting and anaerobic digestion are regarded as important measures to reduce landfill organic waste disposal, their negative environmental impacts, such as air pollution and water pollution, cannot be ignored.[87] Therefore, additional pollution mitigation measures need to be adopted, which will increase diversion facilities' financial burden. In other words, compliance costs associated with new requirements and regulations may be a limiting factor when existing facilities are considering expansion. For example, the San Joaquin Air Pollution Control District and the South Coast Air Quality Management District both developed restriction rules for composting facilities based on limiting volatile organic compound (VOC) emissions. As a result, although some facilities may have permitted capacity to process more organic waste, they need to seek new or adjusted air district permits to accommodate increased air pollution emissions from facilities, which would limit the ability to process additional organic material.[88]

Challenges also exist for recovered organic waste product market development. CalRecycle estimates that the amount of recovered organic waste products will increase significantly should SB 1383 be fully implemented. Specifically, an additional 5.5 million tons of compost and more than 14 billion cubic feet of biomethane will be produced by 2025.[89] As such, strong end-use markets need to be established to absorb the increase in recovered organic waste products production.

However, there are some major challenges for the markets of compost and biomethane to develop. For compost, expanding its biggest market—agriculture—remains challenging. One challenge is that farmers in California might not have access to agricultural compost.[90] Even though a study showed there would be enough agricultural land for compost to be fully distributed in California,[91] the cost of compost and the related transportation cost is often too high for many farmers to apply that compost to their lands.[92] In other words, there are additional untapped agricultural markets for compost. More financial incentives and compost delivery systems between cities and farms could increase compost use on agricultural lands.

For biomethane, the challenges to market expansion include the high cost of injecting biomethane into pipelines, market uncertainty, and pricing mechanisms.[93] Due to high capital expenses, anaerobic facilities that generate biomethane often rely on revenue from renewable energy incentives to make production economically viable and are more vulnerable to cost increases and uncertainty about markets and financial incentives.

The high cost of injecting biomethane into pipelines is a major difficulty in expanding the market of biomethane. Although injecting biomethane into pipelines is an effective way to distribute it, the cost of connecting municipal solid waste anaerobic facilities to common carrier pipelines could be very expensive. Pacific Gas and Electric estimates that the cost of connection per project could be from $2 million to $5 million and could take up to 24 months[94]—in addition to the costs of preliminary engineering studies, monitoring, and testing. As a result, only three municipal solid waste anaerobic digestion facilities and one waste water co-digestion facility in California injects biomethane into the pipeline

Market uncertainty and pricing mechanisms also limit the market for electricity generated from biogas. The participation rate in the BioMAT has been "minimal," especially for "Category 1 Biogas,"[95] which includes biogas from "wastewater treatment, municipal organic waste diversion, food processing, and co-digestion."[96] One reason for this phenomenon is market uncertainty. Currently, projects are required to complete a costly interconnection study before joining the BioMAT. Those projects will stay in the queue until both project developers and IOUs agree on a

[87] Gittelson et al., 2022
[88] Department of Resources Recycling and Recovery, 2019
[89] Department of Resources Recycling and Recovery 2020b
[90] Khalsa & Brown, 2017
[91] Harrison et al., 2020
[92] Wozniacka, 2022
[93] Department of Resources Recycling and Recovery, 2020b
[94] Pacific Gas and Electric, n.d.
[95] Department of Resources Recycling and Recovery, 2020b
[96] CPUC, 2017

Table 6 | Summary of key challenges to organic waste diversion		
Measures	**Key Challenges**	**Underlying Causes**
Establish Waste Collection and Recycling Services	Slow progress	• Regulations under SB 1383 did not take effect until January 2022
Infrastructure Expansion	Lack of organic waste processing infrastructure to meet anticipated needs	• Lack of funding • Lack of long-term feedstock contracts • Competition from lower-priced disposal alternatives • Increased environmental regulatory cost for facility development • Increased costs from contaminated feedstock
Recovered Organic Waste Product Markets Development	Limits to compost markets expansion	• Farmers in California might not have access to agricultural compost • Contaminated feedstock
	Limits to biomethane markets expansion	• High capital expenses for distribution and connection • Market uncertainty for biogas projects • Ineffective pricing mechanism

contract price. In other words, projects have to pay for an interconnection study before signing a contract. In this case, uncertainty about the contract increases economic risks and can result in procurement termination. Another reason is the pricing mechanism for electricity covered in the BioMAT—it requires that "after at least one of three projects has accepted a contract price, at least five additional applicants are needed to trigger another price adjustment."[97] Due to the low participation rate in the BioMAT, the contract price of biomethane electricity remains at the lowest level, significantly limiting the supply of biogas electricity.

Last but not least, contamination is a challenge hampering both infrastructure expansion and recovered organic waste products market expansion. With the mandatory goal of food recovery in SB 1383 and the rise of food scrap collection programs, the amount of contamination,[98] especially plastic contamination, in feedstocks is on the rise statewide.[99] Even though a part of the plastic in food scrape is bioplastic, which is compostable, composting facilities generally cannot differentiate fossil-based plastic from bioplastic, so they screen these out and send them to a landfill.

This has two impacts. On the one hand, contaminated feedstocks will make infrastructure expansion difficult. This is because contamination in feedstock makes running organic waste treatment facilities less economically attractive since it is costly to remove contamination from feedstock and from recovered organic waste products. For example, a 2017 survey found that many facilities in California do not have plans to expand processing capacity for food waste in the near future, as contamination is more common in feedstock that contains food waste. As a result, even though California has a robust infrastructure to process wood and green waste, the infrastructure for food scraps is still in early development, and less than 50% of composting facilities accept food scraps.[100] The limitation of food scrap processing capacity would hamper SB 1383 implementation since food waste alone accounts for about 13.5% of California's total waste stream.

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97 Department of Resources Recycling and Recovery, 2020b

98 Common types of contaminants in organic waste feedstock include heavy metals, herbicides, pesticides, plastics, glass and ceramics.

99 Department of Resources Recycling and Recovery, 2019

100 Department of Resources Recycling and Recovery, 2020b

On the other hand, contamination impacts product marketability. As mentioned before, it is costly to remove contaminants from the final compost products.[101] Therefore, the demand for high-quality compost, especially in agricultural lands, will drive compost prices up as the amount of contamination in feedstock is increasing, thus limiting its application. There are also concerns that, as the cost of contaminant removal is high, contaminated or even uncomposted waste will be directed to agricultural lands, which will impair land productivity and food safety. In that case, distrust between compost producers and consumers will prevent compost markets from developing.[102] Table 6 summarizes some challenges to organic waste diversion and the underlying causes of those challenges.

REDUCING METHANE EMISSIONS FROM EXISTING LANDFILLS

Since the promulgation of the LMR in 2010, California has developed a holistic policy framework for reducing methane emissions from existing municipal solid waste landfill. Multiple state agencies and stakeholders are involved in this framework, and three types of measures are adopted: (1) standards and regulations, (2) financial mechanisms, and (3) quantifying and understanding landfill methane emissions.

Standards and Regulations

Pursuant to the GHG reduction goal in AB 32, CARB approved the LMR in 2010 to reduce emissions of methane from municipal solid waste landfills. This regulation was one of the first regulations put in place in response to AB 32, and it is also the current regulation.

The LMR consists of standards for installing and operating gas collection and control systems (GCCS), surface methane concentrations and component leak monitoring, emission exceedances correction, information reporting, and recordkeeping.[103] Proper enforcement of these regulations is key to identifying landfill methane sources and preventing landfill methane leakage. Major provisions of the regulation are summarized in Table 7.

The standards and thresholds in the LMR were determined based on experience and existing data. For example, the landfill gas heat input capacity threshold for a GCCS installation, 3.0 million British thermal units per hour (MMBtu/hr), was determined based on the least amount of landfill methane necessary for a GCCS to run.

Another example is the surface emissions standard for instantaneous surface monitoring. The 500 ppmv surface emissions standard was set based on experience from the South Coast Air Quality Management District (SCAQMD), as well as a balance between methane reduction and safety. The SCAQMD had a rule similar to the LMR before 2010, and the surface emissions standard in that rule was 500 ppmv for instantaneous surface monitoring. It was found that the 500 ppmv standard was exceeded a little more than half of the time during its implementation period, meaning that 500 ppmv could be a good threshold.[104] Meanwhile, during the rulemaking process in 2008, stakeholders suggested that the 200 ppmv standard initially proposed by CARB could be too stringent and could increase landfill fire risk, decrease the ability to meet federal wellhead monitoring limits for oxygen and nitrogen, and interfere with landfill gas-to-energy projects. Considering these facts, CARB finally decided to use 500 ppmv as the surface emissions standard for instantaneous surface monitoring. It requires reporting of instantaneous surface monitoring measurements of 200 ppmv or greater to collect additional data to (1) help determine the range of surface methane emissions levels at landfills in which landfill fires are reported, and (2) help determine the feasibility of a lower surface emissions standard.[105]

Note that no quantitative targets for landfill methane capture rate were set in the LMR. This is because methane generation varies by many factors, such as season, precipitation, soil type, and

[101] Department of Resources Recycling and Recovery, 2019; Department of Resources Recycling and Recovery, 2020b
[102] Wozniacka, 2022
[103] CARB, 2010
[104] CARB, 2008b
[105] CARB, 2009

Table 7 | Summary of major provisions in the LMR

Component	Major Provisions
Applicability to Municipal Solid Waste (MSW) Landfills	• Applies to all MSW landfills that received waste after 1/1/1977 • No requirements for closed, uncontrolled MSW landfills having < 450,000 tons of waste • MSW landfills having ≥ 450,000 tons of waste must comply with the requirements of the regulation unless all exemption requirements are met
Exemptions	• Hazardous waste landfills, landfills regulated under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA); construction and demolition (C&D) landfills; and closed MSW landfills having < 450,000 tons of waste
Surface Emission Standards	• 500 parts per million volume (ppmv) methane standard for instantaneous surface monitoring or • 25 ppmv methane standard for averaged methane concentration limit based on integrated monitoring
Emission Control Requirements	• Corrective action must be initiated within ten calendar days of identifying a surface or component emissions exceedance, and within five days of any positive wellhead pressure reading
Control Device Requirements	• 99% methane destruction efficiency for most control devices • Annual source testing (triennial if certain conditions are met)
Monitoring Requirements	• Quarterly monitoring for surface concentrations and component leaks (Annual monitoring if certain conditions are met) • Monthly monitoring of gauge pressure within gas extraction wells • Continuous monitoring of control equipment temperature and gas flow rates
Recordkeeping Requirements	• Records that must be kept include • GCCS design • GCCS monitoring data • Performance test data of GCCS • Emission-related data
Reporting Requirements	• Reports that must be submitted include Waste-in-Place Report, Landfill Gas Heat Input Capacity Report, Design Plan, and Annual Report • Annual Reports (for controlled landfills) include all instantaneous surface monitoring measurements of 200 ppmv or greater, component leaks, mitigation actions, periods of positive well pressure, GCCS downtime, and combustion device temperature excursions
Implementation and Compliance	• Agreements between CARB and local air districts • Local air districts can collect fees to recover implementation costs • Penalties provisions for non-compliant landfills

others, which makes it difficult to accurately calculate the methane generation, as well as the landfill methane capture efficiency.[106] Therefore, using landfill methane capture rates as the target may not be reliable and may not be the most effective way to reduce emissions.

The LMR also allows California's air districts to voluntarily enter into memoranda of understanding (MOU) with CARB to enforce and implement the regulation. This is because some air districts

106 Yeşiller et al., 2022

have been implementing and enforcing federal and local requirements for municipal solid waste landfills since the early 1980s. Through MOUs, CARB and the air districts see an opportunity to ensure that CARB can retain oversight authority while air districts that have the will, resources, and especially the experience with regulating landfills can implement the LMR. By signing MOUs, CARB designates authority to local air management districts instead of directly regulating local landfill owners, thus reducing burdens on those who have been regulated. Therefore, MOUs were developed between CARB and local air districts, especially the larger local air districts, to help implement the LMR.[107] For smaller air districts, CARB implements the LMR directly. As of 2020, 23 of California's 35 air districts in California had entered into an MOU with CARB to enforce the LMR at 174 landfill facilities. CARB directly enforces the regulation at 17 landfills.[108]

Since 2012, CARB has been conducting landfill inspections annually in cooperation with local air quality management districts to ensure compliance with the LMR. In 2021, CARB conducted 15 landfill inspections and found that 9 of them had methane levels higher than that allowed by the LMR. Approximately 12% of the inspected gas wells in those 15 landfills had methane readings above the 500 ppmv standard set by the regulation.[109] Once exceedances are found, landfills are required to take corrective action within 10 days. CARB follows up on exceedances in the non-MOU districts. CARB is also in the process of developing new tools to make landfill inspections more efficient.[110]

In 2017, the LMR was submitted to the U.S. Environmental Protection Agency (U.S. EPA) as California's plan to implement the U.S. EPA's Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills (Emission Guidelines).[111] Overall, the LMR was more stringent than the EPA's Emission Guidelines. For example, compared to the 2,750,000 tons of waste threshold of GCCS installment in the Emission Guidelines (40 CFR § 60, 2016), the threshold in the LMR is ≥ 450,000 tons of waste and gas heat input capacity ≥ 3.0 MMBtu/hr, meaning that the LMR applies to smaller landfills and regulates more municipal solid waste. However, the EPA partially approved and partially disapproved California's state plan because the state plan omitted some operational, monitoring, recordkeeping, and corrective action requirements related to temperature, oxygen, or nitrogen.[112] Therefore, some landfill owners or operators have to report additional information to EPA besides that required by the LMR.

Financial Mechanisms

Different types of financial mechanisms are adopted in California to encourage landfill gas recovery projects, reduce methane emissions from municipal solid waste landfills, and recover the cost of methane regulation implementation. Among those policies, various state agencies and stakeholders are involved.

CalRecycle has long been providing financial incentives, in consultation with CARB, CEC, and the CPUC, to support landfill gas recovery projects. It has awarded grants totaling $1 million to support commercial-scale productions of liquified renewable natural gas from landfill gas. It also has provided funding to some landfill-based anaerobic digestion compost pilot projects, with the aim of assessing the capability and cost-effectiveness of in-situ landfill-based anaerobic digester technologies designed to generate electricity and produce quality compost.[113]

CalRecycle also developed an equipment loan program to support local enforcement agencies (LEA) in California. Once certified by CalRecycle, these LEAs are designated by the local government to implement waste-related policies. The program aims to help LEAs with the financial and technical difficulties in monitoring landfill gas by loaning gas monitoring equipment, providing technical assistance for loaned equipment, and repairing equipment for LEAs.[114]

107 CARB, 2016a
108 CARB, 2020b
109 CARB, 2021b
110 CARB, 2021b
111 CARB, 2017b
112 U.S. EPA, 2020
113 Department of Resources Recycling and Recovery, n.d.-e
114 Department of Resources Recycling and Recovery, n.d.-f

Besides grants and loans, fees are also used to recover the cost of implementing the LMR and reduce methane emissions from existing municipal solid waste landfills. Landfill owners or operators are required to pay fees assessed by air districts.[115]

Quantifying and Understanding Landfill Methane Emissions

California is also taking action to identify the sources and calculate the amount of methane emissions since this data is essential to policymaking.

The primary method California has adopted to quantify landfill methane emissions is model estimations. After the LMR took effect in 2010, CARB designed a Landfill Gas Tool to calculate the landfill methane emissions as part of the broader GHG emissions inventory, as well as to assist solid waste landfill owners and operators in calculating the heat input capacity, expected landfill gas methane recovery, and methane emissions. This tool is based on the first-order decay model used in the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines on solid waste disposal.[116] It adopts some default indexes such as methane oxidation rate (10%), the percentage of methane captured by landfill GCCS (75%), the anaerobically degradable organic carbon content of each component of landfill waste, and decay rates from the U.S. EPA, 2006 IPCC Guidelines, and other sources. Data inputs to the model, such as site-specific landfill gas collection data, landfill waste amount (waste-in-place) data, and waste composition, are collected from landfill gas collection surveys conducted by CARB and CalRecycle, the U.S. EPA greenhouse gas reporting program, and the Disposal Reporting System of CalRecycle.[117]

However, the Landfill Gas Tool mentioned above has some shortcomings. For example, this model assumes a generalized instead of a season-specific climate effect on methane generation, and it neglects the effect of landfill cover on gas transport and oxidation.[118] To better understand methane emissions in California, the CEC initiated a project in cooperation with CalRecycle to develop the process-based California Landfill Methane Inventory Model (CALMIM) for landfill operators to estimate landfill methane emissions.[119] Unlike the model based on 2006 IPCC guidelines, CALMIM does not rely on first-order kinetic models for theoretical methane generation; it allows the use of site-specific indexes, and it has a higher certainty in estimating landfill methane emissions compared to previous inventory models.[120] After CALMIM was published in 2012, it was field-validated at 10 California sites and was used to estimate the 2010 annual landfill methane emissions in California for comparison to the state's official GHG inventory.[121]

Another effort to identify major sources and amounts of methane emissions was statewide methane hotspot research pursuant to AB 1496. In 2015, AB 1496 began requiring CARB to "Undertake monitoring and measurements of high emission methane 'hot spots.'"[122] To meet the requirement, CARB, together with CEC, funded a large-scale statewide aerial methane survey conducted by NASA's Jet Propulsion Laboratory (JPL). CARB also implemented a "Tiered Observation System" (Table 8) and used various technologies, including remote sensing, ground verification, and inventory analysis, to measure methane emissions at different scales and identify emission sources.[123] One of the research efforts, the California statewide methane survey, imaged about 59,000 square kilometers and surveyed about 272,000 methane-emitting infrastructure elements at oil and gas facilities, waste facilities, and dairies. Five campaigns were conducted over several months from 2016 to 2018, resulting in the detection, geolocation, and quantification of 564 strong methane point sources. Of the 436 solid waste disposal sites surveyed, methane plumes were found at 32 facilities, and plumes

115 CARB, 2010, p. 24
116 CARB, 2021a
117 CARB, 2016b
118 Jain et al., 2021; Spokas et al., 2021
119 Department of Resources Recycling and Recovery, n.d.-e
120 Spokas et al., 2011
121 Spokas et al., 2015; Spokas et al., 2021
122 AB 1496, 2015
123 CARB, n.d.-b

Table 8 | California's "Tiered Observation System"	
Emission Identification Methods	**Function**
Satellite-based Remote Sensing	Provide broad identification of high-methane-concentration regions and methane emission point sources.
Aircraft-based Remote Sensing	Identify individual methane plumes (point sources) and quantify methane flux by using methane and meteorological monitors.
Ground Verification	Identify local methane point sources and measure methane flux with mobile monitors and infrared cameras.
Regional Inventory Analysis	Evaluate ambient concentration of methane based on CARB's statewide GHG monitoring network.

detected at landfills tended to have higher emission rates than plumes found in other sectors.[124] Starting in late 2023, this type of remote sensing monitoring of landfills is expected to be available routinely from satellites. All seven GHG monitoring stations operated by CARB helped to measure ambient methane concentrations and identify sources based on inverse modeling, augmenting the effectiveness of remote sensing.[125] This represented a major advance in the combination of remote sensing and ground verification to assess methane point sources over large areas.

California also takes action to improve methane emission measurement and modeling. CARB collaborated with Scientific Aviation to perform airborne quantification of facility-level methane emissions fluxes from important methane sources, including some solid waste landfills.[126] This information complements the JPL imaging research, collectively helped quantify emission reduction rates from landfills, and detected malfunctions in landfill GCCS, enabling timely repairs.

Moreover, the California state government is now collaborating with a nonprofit organization, Carbon Mapper, to initiate a new program and launch two satellites in 2023. These two satellites are supposed to provide regular, complete, and precise measurements of methane and CO_2 emissions using remote sensing technologies.[127]

Progress and Challenges

Progress

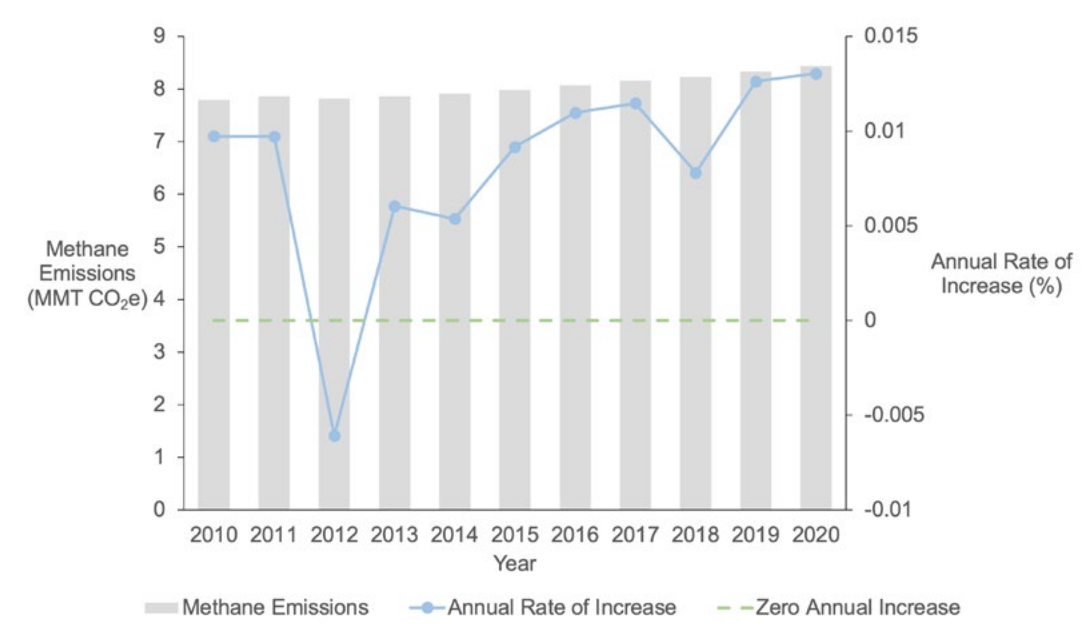
California has adopted a series of measures to control landfill methane since it established its LMR in 2010. Generally, California has achieved some reductions in landfill methane emissions. According to the 2021 Climate Action Team Report Card, California's landfill methane emissions have been reduced by 0.5–1.9 MMT CO_2e compared to what the emissions would have been without the implementation of the LMR.[128]

However, landfill methane emissions in California have been increasing slowly since 2010. Figure 2 shows the increasing trend of landfill methane emissions from 2010 to 2020, based on data from the California Greenhouse Gas Emission Inventory.[129]

As shown in Figure 2, landfill methane emissions in California have increased almost every year since 2010, except in 2012. Moreover, it is estimated that annual methane emissions will be higher through 2030 than originally anticipated, and the annual landfill methane emissions in 2030 will be just below the 2013 level even if the 75% organic waste disposal reduction goal of SB 1383 is

[124] Duren et al., 2020
[125] CARB, 2022c
[126] CARB, n.d.-b
[127] CARB, n.d.-c
[128] California Environmental Protection Agency, 2021
[129] CARB, 2022a

Figure 2 | California Annual Landfill Methane Emissions and Increases[1]



[1] CARB, 2022a

achieved.[130] One reason for this trend is that organic waste reduction regulations under SB 1383 are prohibited from taking effect until 2022. As a result, emissions have continued to increase. Another reason is that the amount of solid waste disposal, as well as organic waste disposal in landfills, has continued to increase beyond infrastructure capacity limits, especially in the past few years (Figure 3). During this time, California failed to achieve reductions in organic waste disposal of 50% below the 2014 levels goal by 2020.[131]

According to CARB's latest landfill methane emissions projection, achieving the 75% organic waste disposal reduction goal of SB 1383 would reduce annual landfill methane emissions just below the 2013 level (7.9 MMTCO_2e) by 2030.[132] If an additional 10% reduction in landfill methane emissions through improvements to direct methane control can be realized by 2030, the 2013 baseline could be reached five years sooner, achieving a reduction of 10% below 2013 levels by 2030 (7.2 MMTCO_2e).[133]

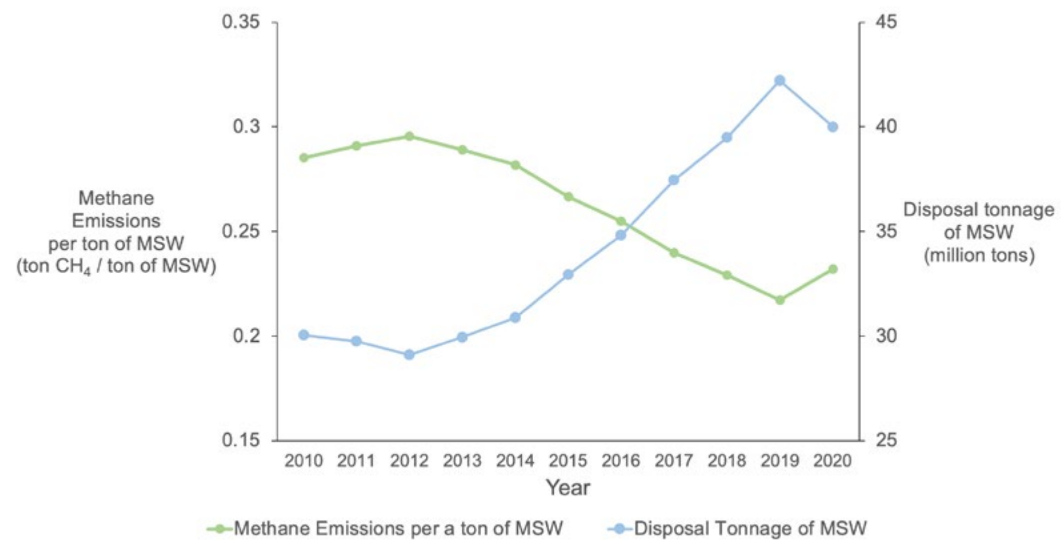
Despite the increasing trend in landfill methane emissions, California still has made some progress in controlling those emissions, as well as in updating the landfill methane inventory since the LMR took effect in 2010.

Although landfill methane emissions in California have been increasing (Figure 2), landfill methane emissions per ton of MSW show a decreasing trend, as is demonstrated in Figure 3.[134] This result substantiates the previous point that increasing solid waste disposal is to be blamed for the increase in landfill methane emissions in California.

The decreasing trend of landfill methane emissions per ton of MSW can be attributed to the fact that a significant proportion of landfills in California have installed landfill GCCS, and these landfills are the destination of most of the waste disposed of in California today. According to the U.S. EPA's Landfill Methane Outreach Program (LMOP) database, which covers a majority of landfills in California, among 300 landfills that have either accepted municipal solid waste or closed in the

[130] CARB, 2022b
[131] CARB, 2022b; Department of Resources Recycling and Recovery, n.d.-a
[132] CARB, 2022b
[133] CARB, 2022b
[134] Department of Resources Recycling and Recovery, n.d.-g

Figure 3 | California Annual MSW Disposal and Landfill Methane Emissions per ton of MSW[1]



1 CARB, 2022a; Department of Resources Recycling and Recovery, n.d.-g

past few decades, 197 of them (66%) have active landfill GCCS. Approximately 95% of the waste disposed of in California has been deposited in a landfill with GCCS, which could not be possible without the implementation of the LMR.[135] California also has the most operational landfill gas energy projects[136] among the U.S. states. There were 56 landfill gas energy projects in California in 2022, which accounts for 10.4% of all operational landfill gas energy projects in the U.S. and reduces 11.7 MMT CO_2e of landfill methane emissions.[137]

Challenges

Despite California's progress, challenges still exist in quantifying and supporting greater reductions in landfill methane emissions.

There is no continuous methane leakage monitoring. As required by the LMR, landfill owners or operators only need to conduct instantaneous and integrated landfill surface methane monitoring quarterly, and the surface methane emissions standards are based on methane concentrations instead of flux.[138] One reason for that is the high cost of landfill methane monitoring and inspection. Sometimes landfills can cover hundreds of acres, including hundreds of gas collection wells that need to be monitored during an inspection, which limits CARB's capacity to monitor landfill directly and continuously, resulting in only a few landfill inspections being conducted annually.

Although some campaigns, such as the California Methane Survey, were conducted to identify large landfill methane sources, these efforts only provide snapshots of emissions. These are not enough for accurate measurement because landfill methane emissions vary spatially and temporally and are affected by many factors such as cover type, meteorology, soil characteristics, and more.[139]

The scarcity of landfill methane emissions data presents a challenge to modeling landfill methane emissions. As mentioned, the current methodology for California landfill methane inventory relies on the first-order decay model, and the method used in the model has not been updated since

135 CARB, 2022b

136 There are three types of landfill gas energy projects: electricity production, thermal uses of landfill gas, and renewable natural gas production (U.S. EPA, 2017).

137 U.S. EPA, 2022b

138 CARB, 2010

139 National Academies of Sciences, 2018, p. 9; Yeşiller et al., 2022

2006.[140] However, research shows that the model will still either overestimate or underestimate the landfill methane emissions since some indexes used in the model could be significantly different from reality.[141] Even though some field campaigns and process-based model development have occurred in the past decade, providing important results and new methodologies, the lack of continuous monitoring data limited the validity of these models, and they have not been incorporated into California landfill methane emission inventories. Moreover, CARB currently uses a 100-year global warming potential (GWP) to calculate the CO_2 equivalence of landfill methane emissions in California. This could underestimate the warming impact of methane.

Another challenge is that there has not been a significant technological improvement in landfill waste management and methane control in the past decade. The latest version of technology and management guidance for reducing landfill methane was published in 2008. As the amount of organic waste and landfill methane is still increasing in California, measures included in the 2008 guidance might not be sufficient to effectively reduce landfill methane emissions. Research is needed to develop innovative technologies such as automated landfill gas collection,[142] biocovers,[143] and mechanical-biological treatment,[144] and resources should be diverted to support research and encourage the application of these technologies. If these innovative technologies can be applied at scale, landfills could be a clean option for organic waste treatment, thus lowering the cost of organic waste treatment[145], since landfill disposal is inexpensive compared to composting and anaerobic digestion. As a result, the synergy between landfill methane control and organic waste treatment capacity expansion could be achieved.

[140] The parameters used in that model have been updated frequently.

[141] K. A. Spokas et al., 2021; Walker et al., 2014; Yeşiller et al., 2022

[142] Automated landfill gas collection technology uses real-time data, automated valve adjustments, and cloud-connected control software to better control landfill methane emissions.

[143] A biocover is a porous material layer laid on top of a landfill, which is then covered by an oxidizing layer of mature compost. Fugitive landfill methane filters through the cover and is oxidized.

[144] A mechanical biological treatment system is a waste processing facility that combines a waste sorting facility with biological treatment methods such as anaerobic digestion and composting.

[145] Kong et al., 2012

CONCLUSION AND DISCUSSION

BEST PRACTICES IN CALIFORNIA

California has adopted a series of measures to reduce methane emissions from the solid waste sector, either by diverting organic waste from landfills or by reducing methane emissions from existing municipal solid waste landfills. Although the 2020 goal of reducing organic waste disposal set by SB 1383 has not been achieved, and the amount of landfill methane has kept increasing, California has made great progress, especially in expanding the organic waste processing infrastructure, promoting markets for recovered organic waste products, and ensuring that landfills control and minimize methane emissions. Moreover, as the regulations under SB 1383 started taking effect in 2022, more actions are planned to be taken in the future to divert organic waste, and if so, the 2025 goals in SB 1383 are more likely to be fulfilled.

Valuable knowledge has been learned in California's efforts to reduce solid waste methane emissions, and it is worth summarizing and applying its experiences to other regions to address their waste methane emissions.

There are many good practices for diverting organic waste from landfills. California has adopted both laws and programs to encourage solid waste reduction. Mandatory laws requiring recycling services for solid waste have helped increase the solid waste recycling rate and reduce the amount of organic waste disposed of in landfills. Moreover, the statewide 2025 edible food recovery target and the projects pursuant to it provide an effective method and an organized system for food waste reduction while at the same time addressing environmental justice and poverty issues.

Grants were allocated to organic waste processing facilities to encourage infrastructure expansion. It is estimated that 14 new compost facilities and 8 anaerobic digestion facilities will begin operating in the next few years and increase the organic waste processing capacity by approximately 1.85 million tons. In addition, California has become the first state that will ban single-use, non-compostable pre-checkout bags in stores.[146] This will reduce the amount of contaminated waste feedstock and reduce facilities' costs to remove contamination.

Market expansion of recovered organic waste products increased the demand for those products, thus increasing the revenue of waste processing facilities and helping to expand necessary infrastructure. Annual mandatory recovered organic waste products procurement targets were established for every city and county in California. Programs such as the LCFS, BioMAT, and Healthy Soils Program stimulated demand for compost and upgraded biomethane as a transportation fuel or electricity source.

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[146] Peyton, 2022

There also are good practices for controlling methane emissions from existing landfills. Collaboration between CARB and the local air management districts helped to implement the LMR. Memoranda of understanding provide a mechanism that can be adopted to help simplify and streamline the implementation of the regulation. The annual landfill methane inspections conducted by CARB help to ensure local landfill compliance with the regulation.

Various financial incentives, including grants for commercial biomethane production, funding for research and pilot projects, equipment loans, and implementation fees, are used in California to encourage landfill gas recovery projects, reduce methane emissions from municipal solid waste landfills, and recover the cost of methane regulation implementation.

The ability to identify methane sources is critical in landfill methane control, and California has made great progress. California uses a "tiered observation system" to systematically identify methane sources and estimate methane emissions flux. It also launched a project to develop a better model for landfill methane generation estimation based on field validation data. California's experience shows that both systematic monitoring and better landfill methane emissions modeling should be emphasized to support reducing landfill waste methane.

CHALLENGES AND SOLUTIONS

Although California has taken actions to reduce methane emissions from the solid waste sector and has made important progress, its goals for methane reduction are far from being achieved. For organic waste diversion, California failed to fulfill its goal of reducing the organic waste disposal rate by 50% by 2020, as California relied on voluntary mechanisms to implement SB 1383 in the early years. Regarding landfill methane control, California's GHG emissions inventory shows that landfill methane emissions have actually increased by 6 percent over the past decade. Challenges still remain for California to achieve its ambitious goals, and gaps in current policies need to be addressed.

California still faces challenges to provide waste collection and recycling services, as the regulations under SB 1383 did not take effect until January 2022, and many cities did not provide waste collection and recycling services until the summer of 2022. In the near future, collection and recycling services are supposed to be in place, and residents and businesses will be required to start separating organic waste. Meanwhile, according to the current capacity projection, the organic waste processing capacity is still not enough compared to the amount of organic waste anticipated in 2025.

To address the lack of infrastructure, several problems, such as lack of funding, lack of long-term contracts, and regulatory costs for facility development, need to be solved. The state government should put more effort toward improving organic waste diversion from landfills and grant more funding through CARB or CalRecycle programs to support infrastructure expansion. The integrated management fee should be modernized to provide CalRecycle with enough financial support. As municipal organic waste collection services are gradually established, local governments could sign long-term feedstock provision contracts with organic waste treatment facilities to ensure the availability of feedstock. In addition, financial instruments such as insurance could be utilized to further lower the financial risk. Regulatory costs could be reduced by accelerating the permission-acquiring process and prioritizing the infrastructure expansion requests from compost and anaerobic digestion facilities. However, the potential negative environmental impacts of some organic waste diversion options, such as composting and anaerobic digestion, should not be ignored. Existing air and water quality standards for composting and anaerobic digestion operations need to be fully enforced to maximize their climate mitigation benefits and minimize adverse impacts.

Besides infrastructure expansion, local jurisdictions should take action to reduce food waste, as food waste in organic waste feedstocks can be easily contaminated, making organic waste diversion less financially attractive. Local jurisdictions also can consider organic waste treatment options other than compost and anaerobic digestion. Given that the State Water Board report estimated that statewide wastewater treatment plants have a digester capacity for at least 2.4 million tons of food waste,[147] local jurisdictions should consider working with these facilities.

Education program requirements under SB 1383 should also be further enforced. Such programs can change people's behavior, leading to reduced food waste and lower costs of organic waste diversion. Through education programs, residents and businesses will reduce the amount of solid waste they produce, and waste haulers will be more likely to separate organic waste from waste streams correctly and avoid contamination in the organic waste. These behavioral changes could significantly reduce organic waste collection costs, making it easier for cities to provide organic waste collection services and relieving the pressure to expand the organic waste processing infrastructure. These changes also can increase the supply of high-quality organic waste feedstock to waste treatment facilities as more people participate in organic waste separation, which will lower the financial burden of running waste treatment facilities and make organic waste treatment more economically feasible.

The development of recovered organic waste product markets is also important for supporting infrastructure expansion. As the demand for recovered organic waste products goes up, facilities will have stronger economic incentives to increase production and expand infrastructure capacity. To better develop the market, more financial resources are needed to improve market infrastructures such as biomethane pipelines and compost delivery systems, as these are important to connect the supply and fulfill demand but are costly to build. Second, organic waste procurement programs such as the BioMAT need to be simplified to address regulatory barriers and reduce market uncertainty. Last, new markets for recovered organic waste products need to be explored. For example, compost, which is mostly used in agricultural lands, could also be used in rangeland and urban greening projects, as well as to help address food justice issues. Local cities could distribute the compost to urban farming projects and food banks or send it to smaller and mid-size and disadvantaged farmers who usually cannot afford compost.

Besides the expansion of organic waste recycling facilities, more attention should be paid to understanding and controlling methane emissions from existing landfills. This will increase the collection of landfill methane emissions as well as the supply of clean energy. Currently, the cost of inspection, lack of continuous monitoring data and model inaccuracies, and slow technology innovation are major barriers to improved landfill methane control. More financial and technical support is necessary to develop new and low-cost tools for field inspection, which could make landfill inspection more efficient. The landfill methane emission estimations model used by CARB should be improved to incorporate more flexibility regarding the specific characteristics of different landfills. More research on advanced landfill methane control technologies is needed to stimulate innovation and lower costs. The synergy between landfill methane control and organic waste treatment capacity expansion could be achieved if innovative technologies can be applied at scale.

As the first subnational jurisdictions to have developed comprehensive methane reduction strategies for the solid waste sector, California is uniquely positioned to spearhead global efforts to address the significant climate impacts of the solid waste sector. California's comprehensive landfill methane reduction framework, consisting of regulation, financial mechanisms, and many other instruments, provides a possible template for achieving solid waste methane reduction in other jurisdictions around the world. Challenges that California is currently facing should be considered and addressed in the future when other jurisdictions devise policies to reduce solid waste methane emissions.

Below are five policy recommendations for other jurisdictions to consider based on lessons and experiences from California:

[147] Department of Resources Recycling and Recovery, 2020b; California State Water Resources Control Board, 2019

- A comprehensive methane policy package should include policy, regulations, financial incentives, and behavioral change-focused programs.
- Organic waste recycling and edible food recovery are critical components of solid waste methane mitigation strategies, as they reduce the overall financial and infrastructural burden on waste management systems while reducing potential methane emissions.
- As organic waste continues to increase, more infrastructure capacity is necessary to divert waste from landfills. It is important for subnational governments to consider and address the negative impacts of some organic waste treatment options (such as compost and anaerobic digestion) through available technologies and to explore new treatment options.
- Advanced monitoring systems, accurate inventory models, and financial support for technology innovation are needed to track and reduce methane emissions from existing landfills.
- Given the role of municipalities in waste management in many subnational jurisdictions (such as states and provinces), enforcing local compliance with state or national regulations is essential to implement methane reduction strategies.

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