Best Practices for Solid Waste Management

A Guide for Decision-Makers in Developing Countries

Solid Waste Management and Climate Change

July 2023
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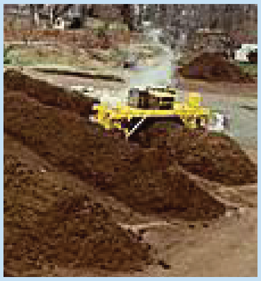

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United States Environmental Protection Agency
Office of Resource Conservation and Recovery

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Acronyms and Abbreviations

CCAC	Climate and Clean Air Coalition
CCBO	Clean Cities Blue Ocean
CIEL	Center for International Environmental Law
EPR	Extended Producer Responsibility
EU	European Union
GHG	Greenhouse Gas
GMI	Global Methane Initiative
IEA	International Energy Agency
LFG	Landfill Gas
MRV	Measurement, Reporting, and Verification
NAPA	National Adaptation Programme of Action
OECD	Organisation for Economic Co-operation and Development
PAYT	Pay-As-You-Throw
SWEET	Solid Waste Emissions Estimation Tool
UNEP	United Nations Environment Programme
UNDP	United Nations Development Program
U.S. EPA	United States Environmental Protection Agency
USAID	U.S. Agency for International Development
WHO	World Health Organization

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SOLID WASTE MANAGEMENT AND CLIMATE CHANGE

Key Resources

- Best Practices for Solid Waste Management: A Guide for Decision-Makers in Developing Countries (U.S. EPA 2020)
- Waste and Climate Change - Global Trends and Strategy Framework (UNEP 2010)
- Waste Reduction Model (WARM) (U.S. EPA 2022)
- Solid Waste Emissions Estimation Tool (SWEET) (GMI 2022)
- Waste Management Planning to Mitigate the Impact of Climate Change (U.S. EPA 2022)
- Climate and Clean Air Coalition Waste [CCAC Undated(a)]
- Toolkit for Building Coalitions for Resilience (Climate Links 2017)
- Potential Impacts of Climate Change on Waste Management (Bebb, J. and Kersey, J. 2003)
- Zero Waste to Zero Emissions (GAIA 2022)
- Guide to Climate Change Adaptation in Cities (The World Bank Group 2011)

Section 1

Introduction

The solid waste sector is a major source of pollutants that contribute to climate change, including methane and black carbon. At the same time, solid waste collection, transportation, recycling, treatment, and disposal services and infrastructure are highly vulnerable to climate stressors, such as extreme weather events. As such, improving how cities manage solid waste can simultaneously mitigate climate change and enhance local resilience to climate change impacts.

Solid Waste Management and Climate Change is part of the United States Environmental Protection Agency's **Best Practices for Solid Waste Management in Developing Countries Toolkit**. The Toolkit serves as a free resource for decision-makers implementing solid waste management programs. The Toolkit includes e-learning modules, communication materials, webinar materials, videos, and the **Best Practices Guide for Solid Waste Management in Developing Countries** (the Guide). The **Guide** describes key aspects of solid waste management and identifies best practices that can be implemented in medium and large cities in developing countries. **Solid Waste Management and Climate Change** is a companion chapter to the **Guide**.

This companion chapter is divided into two sections. The first section provides an overview of how solid waste contributes to climate change and best practices to reduce emissions from the sector. The second section includes a discussion of the impacts of climate change on solid waste management and best practices to build a climate-resilient solid waste management system.

This companion chapter is not intended to be a step-by-step implementation manual, but it highlights resources that local authorities and decision-makers can refer to for more detailed technical guidance. Approaches that may be successful in one city or region may not function everywhere, so the chapter presents decision-makers with the information and resources to improve equity in solid waste management within the context of their given situation.

Section 2

How Does the Solid Waste Sector Contribute to Climate Change?

The solid waste sector is a major source of emissions that contribute to climate change, especially methane and black carbon. Methane and black carbon are short-lived climate pollutants that remain in the atmosphere for a shorter time than carbon dioxide but have substantially higher global warming potential. According to some estimates, the waste sector accounts for 11 percent of global anthropogenic methane emissions (GMI 2015) and 5 percent of global black carbon emissions [CCAC Undated(a)]. In terms of their total contribution to climate change, these emissions equate to roughly 2 percent of all greenhouse gas (GHG) emissions globally (Climate Watch 2019).

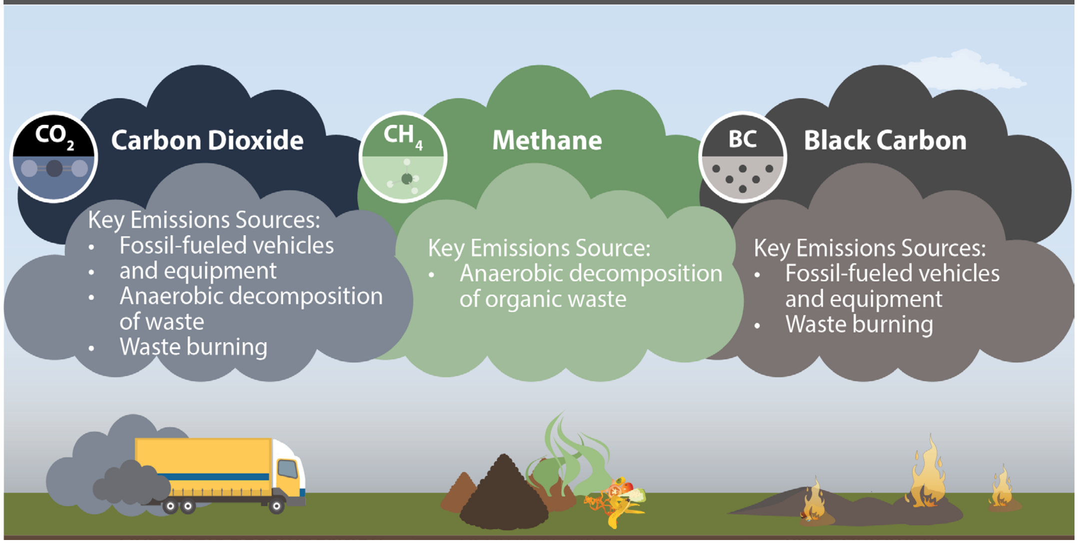
The three major pollutants from the solid waste sector – in terms of their contribution to climate change – are:

- **Carbon dioxide**, a GHG, has an atmospheric lifetime of hundreds of years. Carbon dioxide emissions from the solid waste sector come from the use of fossil-fueled vehicles and equipment, anaerobic decomposition of waste, and burning of waste.
- **Methane**, a potent GHG with a lifetime of 12 years that is 27-30 times more powerful than carbon dioxide at trapping heat in the atmosphere over a 100-year time period (EPA Undated). Methane emissions in the solid waste sector come from the anaerobic (oxygen-free) decomposition of organic waste.
- **Black carbon,** a component of particulate matter that is formed by the incomplete combustion of fossil fuels, biofuels, and biomass. It has an atmospheric lifetime of days to weeks. Although it is not a GHG, it still has a substantial effect on climate, with a warming impact of 500 to 1,500 times that of carbon dioxide by mass [CCAC Undated(b)]. Black carbon is released from fossil-fueled vehicles and equipment and by burning waste.

Exhibit 1 identifies the emissions of GHGs and black carbon associated with solid waste management. Emissions contributing to climate change come from various sources throughout the different stages of solid waste management, including:

- **Collection.** In low-income countries, waste collection coverage is less than 40 percent—compared to 96 percent in high-income countries (World Bank 2018). Residents who receive infrequent waste collection often resort to informal means of disposal such as open burning—resulting in black carbon and carbon dioxide emissions—or open dumping by roadsides or unused areas—generating methane from the decomposing organic waste.
- **Transportation.** Waste is often transported from collection sites to treatment and disposal sites by diesel-fueled trucks and tractors, which results in black carbon and carbon dioxide emissions.
- **Recycling.** Informal sector workers play a critical role in collecting and recycling waste in developing countries. However, these workers sometimes resort to the burning of waste—which produces black carbon and carbon dioxide—to extract and collect valuable raw materials in waste (e.g., copper, aluminum). Furthermore, some informal recyclers may not be aware of best practices to handle waste containing refrigerants, such as air conditioners (AC) and refrigerators. Mishandling of such waste could lead to the

Exhibit 1. The Contribution of the Solid Waste Sector to Climate Change



release of fluorinated gases with global warming potentials thousands of times higher than carbon dioxide (Castro et al. 2021).

- **Organic waste treatment.** While the treatment of organic waste—through composting or anaerobic digestion—has the potential to reduce methane emissions, methane leakages may occur when treatment facilities are not routinely maintained. Furthermore, some treatment facilities may have inadequate capacity to handle large volumes of organic waste. The accumulation and decomposition of organic waste at such treatment facilities prior to treatment could lead to methane emissions.
- **Disposal.** Landfill gas, which primarily consists of methane and carbon dioxide, is generated at disposal sites from the anaerobic decomposition of organic waste. When waste is disposed of at improperly managed landfills and dumpsites, methane and carbon dioxide are not captured at all; therefore, substantially greater amounts are released into the atmosphere. Even well-managed landfills with landfill gas (LFG) capture systems typically capture 60 to 90 percent of the methane created by the landfill during its lifetime (U.S. EPA 2021). Additionally, black carbon and carbon dioxide are released due to fires. Accidental fires can be caused by spontaneous combustions, where waste material is heated by chemical oxidation and biological decomposition and the heat causes the material to ignite, or from hot surfaces encountering methane releases. Intentional fires are sometimes started to reduce the volume of waste or to recover metals from the waste. The presence of methane in decomposing solid waste can exacerbate the risk and severity of fires. Compactors and tractors (Exhibit 2) used at landfills and dumpsites are often powered by diesel fuel and thus emit black carbon and carbon dioxide.

Exhibit 2. Landfill tractor in Dhaka, Bangladesh

KEY POINT

Recycling Can Mitigate the Contribution of Plastics to Climate Change

GHG emissions from the plastics lifecycle have serious implications for climate change. Globally, emissions from plastic production and incineration are projected to reach 1.34 gigatonnes of carbon dioxide per year by 2030—equivalent to the emissions of roughly 295 new 500-megawatt coal plants (CIEL 2019). By 2040, plastics are estimated to account for up to 20 percent of total GHG emissions globally (Pew Charitable Trusts 2020). Through a **local systems approach**, cities can create effective strategies for circularity (reusing and recycling resources rather than wasting) to reduce plastic waste and associated emissions (USAID 2022a). A systems approach could:

- **Incorporate data** to develop effective strategies and regulations. For example, policymakers may determine that plastic bags comprise a large portion of the waste stream and can implement fees on plastic bags as a deterrent.
- **Engage stakeholders** to understand local needs and prioritize inclusivity. Through engagement, decision-makers can learn how policies may affect certain populations and whether or not the policies would place a higher, disproportionate burden on some stakeholders.
- **Incorporate the "Three Rs"** (reduce, reuse, recycle) into the plastic lifecycle. By considering the entire lifecycle, products can be designed for reuse, which can decrease virgin plastic products as well as the amount that is incinerated or disposed at landfills and dumpsites.

CASE IN POINT

Replacing a Dumpsite with a Sanitary Landfill in Brasília

In Brasília, the capital of Brazil, the Estrutural landfill received more than 2,700 metric tonnes of municipal waste each day by 2018. Proper landfill management practices such as daily cover and compaction were not implemented, and waste was typically burned, resulting in black carbon emissions. The lack of gas capture systems also resulted in methane emissions.

A replacement recycling facility and a sanitary landfill that began operating in 2018 were estimated to result in avoiding 70 percent of the 1.4 million metric tonnes of carbon dioxide equivalent that would have been emitted by 2050 if the Estrutural dumpsite had continued operations.

For more information, visit UNEP's website.

Section 3

Best Practices for Improving Solid Waste Management and Reducing Emissions

The best practices discussed in this section can improve solid waste management and reduce emissions at the generation, collection, recycling, treatment, and disposal stages of solid waste management. Some of the best practices discussed—including bans on open burning or disposal of organics and recyclables in landfills—may require strict enforcement to be effective. Tracking the emissions and emissions reductions at each stage of the solid waste management process may be helpful to monitor the implementation progress and effectiveness of best practices.

3.1 Understanding the Waste Stream and Preventing Waste

Source reduction and material reuse are the most preferred steps in the solid waste management hierarchy (U.S. EPA 2022a). When products are reused or made with secondary (recycled) materials, less energy will be needed to extract, transport, and process raw materials. Lower energy demand means reducing the use of fossil fuels and the resulting GHGs and other air pollutants emitted into the atmosphere.

Decision-makers can consider the following suggested actions for reducing waste, thereby reducing emissions related to waste management that contribute to climate change:

- **Characterizing waste**. Waste characterization helps decision-makers understand where to target efforts to minimize and prevent waste. For example, decision-makers can use the results from waste characterization studies to identify non-recyclable materials that should be a target for waste prevention strategies.

  For more information on conducting waste characterizations and their uses in solid waste management planning, see **Section 7 – Waste Characterization** of the Guide.

- **Engaging stakeholders**. Stakeholder engagement is critical for implementing strategies to reduce waste generation. This may include communication and outreach to the public about waste minimization through reducing consumption, recycling, and home composting. For more information on stakeholder engagement, see **Section 4 – Stakeholder Engagement** of the Guide.

- **Promoting home treatment of organic waste**. Yard waste and food waste resulting from food preparation and leftovers of cooked food can be treated at home instead of contributing to the solid waste to be managed by local government. The type of technology and the amount of waste that can be treated are based on a number of considerations, including space availability. Household composting can range from vermicomposting (worm composting) in a small bin in the kitchen to composting in large piles in the yard (GIZ 2022). Organic waste can even be processed in small anaerobic digesters with the gas being used for cooking and the digestate used as soil amendment in the garden.

- **Implementing strategies to reduce packaging waste**. Packaging waste represents a significant portion of the waste mix. Strategies like bulk vending of commodities and refilling of containers can be encouraged for certain products (e.g., nuts, grains, milk, oil, detergent) to reduce the amount of packaging waste. Bulk vending is a practice employed in many countries in the past prior to moving to the convenience of packaged goods. These strategies offer consumers an opportunity to move away from disposable packaging and help suppliers reduce their carbon footprint.

- **Imposing bans and fees on specific items**. Bans and fees on certain products have been shown to discourage consumer use and eliminate waste. For example, small fees for plastic bags at grocery stores can reduce the consumption of single-use plastic bags and encourage shoppers to bring their own reusable bags. Bans on certain types of single-use plastic items (e.g., bags, cutlery, straws) have been implemented in many countries, including Tanzania, Kenya, Rwanda, European Union (EU) countries, the United Kingdom, and parts of India and China.
- **Requiring standardization to increase reuse and prevent waste**. The use of different types of accessories such as chargers and earphones for consumer electronics contributes to increasing waste. Several countries (e.g., EU) are beginning to require standardized chargers to reduce this waste.

EXHIBIT 3 CASE STUDY

Improving Collection Route Efficiency

In 2021, the Clean Cities Blue Ocean Program (CCBO) evaluated waste collection and sweeping systems in Pisco City, Peru, by seeking input from the city's technical and operational personnel and representatives of the communities served, and monitoring vehicles and routes. Based on their evaluation, CCBO developed a Routing Manual for Pisco and other cities to use to improve waste collection and routing efficiencies. The CCBO-optimized routes are expected to expand solid waste collection coverage in Pisco from 35,550 residents to at least 42,820 residents. Increasing collection coverage reduces open dumping and burning both of which result in emissions contributing to climate change. Increasing collection coverage reduces open dumping and burning both of which result in emissions contributing to climate change.

For more information, see the CCBO Report.

EXHIBIT 4 CASE STUDY

Using SWEET to Estimate Emissions from Solid Waste Management in Accra, Ghana

The World Health Organization (WHO) conducted a study on the health and climate impacts of solid waste management in Accra, Ghana. WHO used SWEET, an Excel-based tool developed by the United States Environmental Protection Agency under the auspices of the Global Methane Initiative, to estimate baseline climate pollutant emissions. WHO also used SWEET to estimate emissions for three alternative scenarios: ceasing open burning, increasing composting and recycling, and capturing methane from landfills. The results of the study provided WHO with evidence to prioritize the ban of waste burning and increase in waste collection capacity to avoid public health impacts.

For more information, read GMI's case study.

3.2 Separation, Collection, and Transportation

Best practices for mitigating climate pollutant emissions during waste collection and transportation include the following:

- **Segregating waste at the source**. This can enable better recycling and cleaner feedstock for organic waste treatment. Source segregation programs are more effective when accompanied by education and outreach campaigns to both waste generators and collections staff. Local governments may also need to provide the infrastructure (e.g., bins or receptacles for the different waste categories) for these programs to be implemented successfully. For more information, see **Section 9 – Separation, Collection, and Transportation** of the Guide.

- **Imposing collection fees**. Collection fees can incentivize generators to reduce the amount of waste they create, while increasing revenue to cover local governments' waste collection costs. For example, Pay-As-You-Throw (PAYT) programs charge residents a collection fee based on the quantity of waste generated. To reduce the risks of improper disposal, decision-makers may need to account for residents' ability to pay collection fees; for example, by charging different fee amounts based on income.

- **Increasing collection coverage** to underserved areas and communities will help to reduce illegal dumping where decomposition of organic waste can generate methane and burning of waste which produces black carbon and carbon dioxide emissions. Some communities are underserved due to access issues, including narrow roads and congestion. Pedal tricycles can be deployed for collection in such areas to increase collection coverage.

- **Banning open burning of waste** can reduce black carbon and other harmful toxic pollutants that impact air quality and human health. However, such bans require that appropriate infrastructure be in place for collection, as waste generators often resort to burning waste due to inadequate collection services.

- **Optimizing collection routes** ensures that vehicles use the most efficient path and timing to gather waste, eliminating overlapping waste collection routes and decreasing the number of instances when vehicles are traveling with less-than-full loads (Exhibit 3). For more information on optimizing collection routes, see **Section 9 – Separation, Collection, and Transportation** of the Guide.

- **Deploying cleaner fleets,** such as electric vehicles and pedal tricycles, for waste collection can reduce emissions of carbon dioxide and black carbon. Compressed natural gas from LFG is used by some cities (e.g., Hyderabad in India, Rio de Janeiro in Brazil) as an alternative to fossil fuels such as diesel and petrol.

3.3 Recycling

Recycling—by collecting and separating recyclable materials from the waste stream—reduces the consumption of fossil fuels and virgin materials to create new products and thus mitigates upstream climate pollutants. Best practices to improve recycling include the following:

- **Integrating the informal recycling sector**. Informal recyclers heavily rely on recovering and selling valuable materials from waste as a source of income. Without the proper training and equipment that is typically provided to recyclers in the formal sector, informal recyclers may resort to practices such as waste burning to extract recyclable metals. To prevent improper recycling and increase recycling capacity, decision-makers may consider integrating informal recycling workers into formal employment by promoting their legal recognition and offering formal workplace training. If informal sector workers are reluctant to enter the formal workplace, decision-makers could conduct outreach to ensure that waste is not burned for materials recovery. For more information on integrating the informal recycling sector, see the **Equity and Solid Waste Management companion chapter** to the Guide.

- **Requiring the use of recyclable material**. Reducing the amount of virgin natural resources required to produce a certain level of output and recycling post-consumption waste material back into the manufacturing process can reduce energy consumption and avoid emissions. Laws, regulations, or policies can be initiated that require a certain amount of post-consumer plastic in new plastic packaging or a certain percentage of recycled paper in manufacturing new paper products. In the absence of such initiatives, government agencies could also adopt sustainable purchasing procurement processes where their purchases require the use of recycled material when appropriate.

- **Establishing Extended Producer Responsibility (EPR) policies**. EPR policies place a shared responsibility for end-of-life product management on producers and other entities in the product chain as opposed to requiring consumers to pay for waste disposal. Voluntary EPR policies are typically undertaken by industries, while mandatory EPR policies are mandated by law and implemented through government regulations. EPR policies can target various points in a product's lifecycle. For example, material taxes incentivize producers to use environmentally friendly or recyclable materials to create end products. Deposit-refund schemes, sometimes considered the earliest form of EPR, promote recycling by requiring buyers to pay a deposit that could be refunded if they return the product for recycling or disposal. For more information on EPR policies, see **Section 6 – Economic Considerations** of the **Guide**.

- **Instituting programs to improve recycling**. PAYT programs create an incentive for residents and businesses to recycle more as they reduce the quantity of waste to minimize collection fees. These types of programs can be designed in concert with incentive programs that reward people for depositing recycled materials (e.g., glass, plastic bottles) at central collection points [C40 Knowledge Hub Undated]. The development of recycling markets, including the development of online platforms to connect sellers and buyers, can also help increase recycling.

3.4 Treatment

When selecting waste treatment technologies, decision-makers can consider potential emissions reductions along with other technical and financial factors. Best practices to lower emissions from waste treatment include:

- **Sizing treatment facilities appropriately**. Undersized facilities may have inadequate capacity to handle waste, leading to the accumulation of organic waste off-site that could decompose and generate methane. On the other hand, oversized facilities may not be cost-efficient as they may be running under capacity and wasting energy. Waste characterization is necessary to understand the quantity and type of waste to be managed currently. For proper sizing of facilities, it is important to consider population projections and changing consumer habits along with waste characterization.

- **Improving operations and maintenance**. Lack of training often results in poor operation and maintenance of treatment facilities, leading to problems such as gas leaks at anaerobic digestion facilities or leachate at composting facilities. Decision-makers may consider providing facility workers training on best practices to maintain and operate treatment facilities.

- **Developing an emissions measurement, reporting, and verification (MRV) system**. Measuring and tracking emissions and emissions reductions from solid waste projects can help decision-makers implement appropriate emissions control solutions (Exhibit 4). Decision-makers can use the Global Methane Initiative's *Policy Maker's Handbook for Measurement, Reporting, and Verification in the Biogas Sector* to implement best practices for project-level MRV (GMI 2022).

3.5 Disposal

Open dumpsites and landfills are significant sources of black carbon and methane emissions. Best practices to mitigate emissions from solid waste disposal include:

- **Remediating or closing existing dumpsites**. Open dumpsites are differentiated from sanitary landfills in that the latter include an engineered design, consisting of a variety of systems for controlling the impacts of land disposal on human health, safety, and the environment. Site assessments help determine if a dumpsite needs to be closed or is suitable for conversion into a controlled dumpsite where some management practices, such as leachate collection, soil cover, and gas collection systems can be instituted. Following an initial assessment, a site will need preparation, including site leveling, drainage construction, fencing installation, and leachate and gas collection systems. Controlled sites may be monitored regularly to understand their waste composition and methane production. Dumpsites could be closed with LFG collection systems to avoid methane emissions. Landfill fires with resulting black carbon emissions can also be avoided by remediation and closure of dumpsites. For more information on dumpsite management, see **Section 12 - Dumpsite Management** of the **Guide**.

- **Diverting organic waste from dumpsites and landfills**. Governments can ban the disposal of organic waste at open dumpsites and landfills. Through source separation during the collection process and better treatment processes, organic materials can be disposed of through composting or anaerobic digestion. Composting and anaerobic digestion can reduce the emission of methane into the atmosphere, with the latter allowing for the use of methane as a renewable fuel. For more information, see **Section 10 - Organic Waste Management** of the **Guide**.

- **Imposing landfill fees and bans**. Decision-makers can charge users fees for the waste that ends up in the landfill. Most low-income countries have low or no tipping fees for disposal at landfills. Tipping fees will incentivize recycling and treatment of organic waste to minimize the cost of disposal. Decision-makers may also impose landfill bans to prohibit certain materials or items from being disposed of at landfills. However, before implementing landfill bans, decision-makers should assess and evaluate the suitability of this approach. Landfill bans may increase the risks of open dumping or other improper waste disposal methods in areas with limited capacity for waste recycling and treatment.

- **Recovering energy from landfills**. LFG can be used as an energy source, reducing local methane emissions. It is estimated that an LFG energy system will capture roughly 60 to 90 percent of the methane emitted from the landfill, depending on system design and effectiveness (U.S. EPA 2022b). Producing energy from LFG offsets the use of fossil fuels to produce the same amount of energy and further reduces the amount of GHGs released to the atmosphere. It should be noted that these systems need to be monitored to detect and repair leaks.

Questions for Decision-Makers

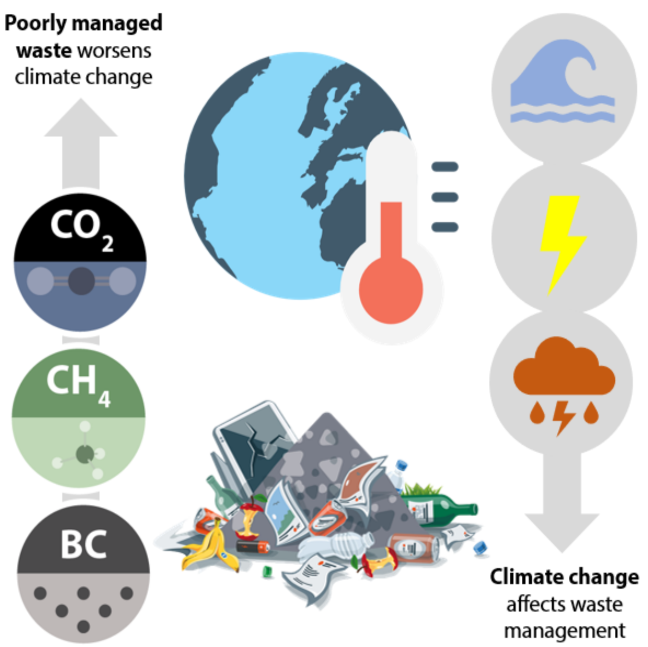
- Are waste collection services provided comprehensively and regularly?
- Are collection routes efficient?
- Is organic waste separated and treated?
- Is the waste disposed of at sanitary landfills or dumpsites?
- Are emissions of climate pollutants (e.g., methane, black carbon, carbon dioxide) from waste collection, recycling, treatment, and disposal being monitored?

Section 4

How Does Climate Change Impact Solid Waste Management?

Climate change can disrupt solid waste management operations and damage infrastructure. Exhibit 5 summarizes the relationship between the solid waste sector and climate change.

Exhibit 5. Solid Waste Sector and Climate Change Relationship



Rising surface temperatures, heavier rainfall, sea-level rise, and extreme weather events—such as cyclones, hurricanes, and strong winds—could affect the generation, collection, recycling, treatment, and disposal of waste (USAID 2011). In developing countries, climate impacts on the solid waste sector often disproportionately affect the poor and marginalized populations who reside in close proximity to waste treatment sites or disposal sites and those that work in the waste sector.

This section discusses the impacts of climate change on every stage of solid waste management (summarized in Exhibit 6), including:

- **Generation.** Longer and more frequent hot days could increase the production and consumption of cooling technologies, such as AC systems and fans (IEA 2018). As advanced cooling technologies become more widely available, older, less efficient technologies will be replaced, increasing waste generation. In addition, extreme weather events, including storms and sea-level rise, can result in debris from damages to physical infrastructure to be managed as waste, and can also damage waste recycling and treatment equipment and infrastructure.

- **Collection**. Higher temperatures increase the need for more frequent waste collection due to quicker organic waste decomposition. Decomposing organic waste causes odors, insect and pest infestations, and bioaerosol releases that are harmful to human health and the environment (Bebb and Kersey 2003). Extreme heat could lead to heat-related illnesses among waste sector workers, particularly those in the informal sector, who often lack personal protective equipment and a covered space in which to work. Increased precipitation could flood roads; disrupt waste collection routes and schedules; and wash uncollected waste into streets, waterways, and drains, exacerbating flooding. Rising sea levels could submerge coastal areas and make roads inaccessible to waste collection vehicles (Gichamo and Gokcekus 2019).

- **Recycling and treatment**. Extreme heat could damage equipment, reduce worker productivity due to heat stress and heat-related illnesses, and increase demand for space-cooling equipment, impacting the operation and efficiency of waste treatment and recycling facilities. Hot and humid conditions could increase organic waste decomposition rates, affecting anaerobic digestion and composting processes (Bebb and Kersey 2003). Increased precipitation and storms could inundate and damage waste recycling and treatment infrastructure and equipment. Sea-level rise could also inundate and damage waste recycling and treatment equipment and infrastructure along the coast (Gichamo and Gokcekus 2019).
- **Disposal**. Higher temperatures can increase the temperature of landfill sites, triggering a series of detrimental health and environmental impacts. For example, combustible waste materials at landfill sites could catch fire in extreme heat. Extreme heat and humidity could also speed up waste decomposition, which could increase the production of LFG, bad odors, and leachate that pollute the air and water of surrounding communities (Walker 2018). Heavy rainfall and storms increase the risks of leachate and gas migration off-site. They can also contribute to slope failures that sometimes result in fatalities among onsite workers and people in proximity to the landfill. By contrast, the lack of rainfall could lead to droughts that may increase the risks of dust emissions and dispersion. Sea-level rise could increase flooding and erosion of coastal landfills, leading to the uncontrolled release of solid waste into coastal waters (Nichols et al. 2021).

CASE IN POINT

Waste from Super Typhoon Haiyan

In 2013, Super Typhoon Haiyan swept across the Philippines and destroyed 1.1 million homes and 33 million coconut trees. In the city of Tacloban, the typhoon generated a million cubic yards of debris—equivalent to 30 feet of waste to cover 10 American football fields (The New Humanitarian 2013). Two months after the typhoon hit, the United Nations Development Programme (UNDP) launched the cash-for-work program, which compensates locals for collecting the debris waste left by the typhoon. The program not only helped clear up debris waste, but also helped typhoon survivors get back on their feet (UNDP 2015).

For more information, see the UNDP case study.

CASE IN POINT

Landfill Fire at the Bhalswa Landfill in New Delhi, India

In April 2022, a massive fire broke out at the Bhalswa Landfill—the fourth large-scale fire at a Delhi landfill that month (the three others were at the Ghazipur Landfill). Under extreme heat, methane gas generated by decaying organic matter spontaneously ignites, causing frequent landfill fires. After this incident, the Delhi Fire Services urged the responsible government agencies to dump sand or construction waste after every layer of freshly dumped waste to serve as a barrier against fires (Hindustan Times 2022).

For more information, see the Hindustan Times article.

Exhibit 6. Summary of Potential Climate Change Impacts on Different Stages of Solid Waste Management

	Rising Temperature	Changes in Precipitation	Extreme Weather	Sea-Level Rise
Generation	• Increased generation of waste from the replacement of old cooling technologies	• Waste from damaged equipment and infrastructure as a result of flooding from increased precipitation	• Debris from strong winds, cyclones, and hurricanes	• Waste from damaged waste recycling and treatment equipment and infrastructure as a result of flooding
Collection	• Reduced waste worker productivity due to heat-related illnesses and heat stress • Increased frequency of collection due to organic waste decomposition	• Disruptions to waste collection routes and schedules from flooded roads worsened by increased precipitation	• Disruptions to waste collection routes and schedules from strong winds, cyclones, and hurricanes	• Submerged coastal areas making roads inaccessible for waste collection and transportation
Recycling and Treatment	• Damaged recycling and treatment equipment, reduced worker productivity, and increased demand for space-cooling • Increased organic waste decomposition rate, impacting biological waste treatment	• Damaged recycling and treatment infrastructure and equipment as a result of flooding from increased precipitation	• Damaged recycling and treatment infrastructure and equipment as a result of strong winds, heavy rainfall, or heat waves	• Damaged coastal recycling and treatment infrastructure and equipment
Disposal	• Increased risks of landfill fires • Faster organic waste decomposition leading to increased production of LFG, odors, and leachate	• Increased leachate and gas migration off-site as a result of flooded landfills • Increased dust emissions and dispersion from drought as a result of decreased precipitation • Landfill slope failures, potentially resulting in fatalities, with excessive rainfall	• Blowing of waste off-site from strong winds • Flooded landfill sites that increase risks of leachate and gas migration off-site	• Increased flooding and erosion of coastal landfills, leading to uncontrolled release of solid waste into coastal waters

Section 5

Best Practices for Improving the Climate Resilience of Solid Waste Management

A climate-resilient solid waste management system is one that can anticipate, prepare for, and respond to climate change and minimize disruption and damage. Climate-resilient strategies achieve equity goals when vulnerable populations have adequate resources needed to adapt to climate change. A process that cities can use to improve climate resilience in the solid waste sector includes the following actions:

- **Identify impacts of climate change**. Cities need to understand the potential scenarios of climate change at their location. While some areas may be affected by extreme heat, others may face more frequent storms, and yet others may face both. These scenarios have varying impacts on the waste sector as described in the previous section.
- **Conduct a risk and vulnerabilities assessment on solid waste management**. Cities may find it helpful to conduct assessments to identify specific risks and vulnerabilities to their solid waste management system and the alternative approaches for building resilience.
- **Develop and implement a climate resilience plan**. After identifying strategies to reduce climate impacts, cities can develop and implement a climate resilience plan to ensure that their solid waste management system can respond to climate change and continue to operate seamlessly. Cities can actively seek input from key stakeholders in developing the plan. They can align their plans with national climate and development goals, policies, and programs to bring secondary benefits such as improving public health, creating jobs, and preventing environmental damage. Many countries have developed national adaptation plans, and it is important to integrate the waste management sector into these plans. For example, adaptation initiatives to address marginalized communities in flood-prone areas should also consider the provision of waste collection services to these areas.
- **Monitor progress and modify as needed**. Cities need to measure the effectiveness of a climate resilience plan and modify it as needed. Climate resilience plans should be flexible and may be changed as cities experience climate change events and find vulnerabilities in their plans.

5.1 Stakeholder Engagement

Engaging stakeholders across the solid waste management system is critical to building resilience. Stakeholders include those who receive and provide waste management services in the public and private sectors, and especially marginalized populations such as informal sector workers and those who live in proximity to waste treatment and disposal facilities.

Cities can raise awareness of the impacts of climate change on solid waste management and best practices to reduce these impacts. Stakeholders can also collaborate with cities to prepare for and respond to hazardous climate events. Decision-makers can consider the following best practices when creating a stakeholder engagement plan for climate resilience:

- **Identifying stakeholders with an equity lens**. Marginalized groups—including women, informal sector workers, residents of informal settlements, indigenous groups, and ethnic minorities—may face economic, political, social, and cultural barriers that inhibit their ability to interact with government bodies and participate in decision-making. These groups are often the most vulnerable to climate impacts because of their low socioeconomic status. For more information on equity in solid waste management, see the **Equity and Solid Waste Management companion chapter**.

- **Assessing the risks and vulnerabilities of each stakeholder group**. Each stakeholder group may be impacted by climate-related hazards in a different way. For example, informal recycling workers may be more vulnerable to climate-related hazards than formal ones because of their limited access to shelter and proper health and safety equipment.

- **Informing stakeholders about climate risks**. Stakeholders should be frequently informed about climate risks to enable them to prepare and react to these risks. Decision-makers can establish a platform or campaign to regularly inform stakeholders on climate change impacts and adaptation activities. This can come in the form of newsletters, social media posts, website updates, public service announcements on radio and television, texts, and emails.

- **Actively involving stakeholders in resilience planning**. Decision-makers may consider creating a community engagement plan to understand community needs. The engagement plan could be focused on the high-priority climate risks the community is facing and could involve holding regular public meetings.

5.2 Solid Waste Management Integration into Resilience Planning

The solid waste sector is highly dependent on the energy, water, and transportation sectors. The systematic linkages of solid waste management with other economic sectors require its integration into broader climate resilience planning (UN-Habitat 2011). Disruptions to other economic sectors can have a ripple effect on solid waste management. For example, power system failures because of storms may impact operations at waste processing sites.

Transportation infrastructure such as roads or bridges can be blocked by floods or landslides, disrupting the transport of waste from waste collection, recycling, or treatment sites. Poor waste collection can also affect other sectors, as plastics and other wastes can block drains and further exacerbate flooding in cities. Best practices for integrating solid waste management into climate resilience planning include:

- **Reviewing national-level climate resilience plans**. An understanding of existing national-level policies on climate change mitigation and adaptation can help decision-makers identify linkages and opportunities to align solid waste sector resilience strategies. Decision-makers can start by compiling and reviewing national-level climate change policies, including Nationally Determined Contributions and National Adaptation Plans (OECD 2021). Methane mitigation from improved solid waste management practices can be included in Nationally Determined Contributions. Enhancements to solid waste infrastructure, including landfills and treatment facilities, can be addressed in National Adaptation Plans (World Bank 2011).

- **Establishing linkages between solid waste sector resilience plans and national plans (Exhibit 7)**. Infrastructure development is one of the main components of national and local economic development plans. Decision-makers may benefit from creating an inventory of solid waste infrastructure and assets at risk of climate impacts. Such an inventory can help national and subnational governments identify facilities at risk and determine priorities for climate-resilient investments (Hallegatte, Rentschler, and Rozenberg 2020).

- **Engaging with sectoral government entities and relevant non-state actors.** Coherence between solid waste sector policies and national and subnational development goals involve careful coordination across government agencies at both the national and local level. Decision-makers responsible for solid waste management can engage with other government agencies and relevant non-state actors to determine policy objectives and priority actions for climate resilience and assign responsibilities for overseeing and implementing the actions (OECD 2021).

EXHIBIT 7 CASE STUDY

Solid Waste Management in the Solomon Islands' National Adaptation Programme of Action (NAPA)

In the Solomon Islands, solid waste management adaptation strategies have historically been implemented under various legislations and by-laws. In 2008, the Solomon Islands established solid waste management as a priority in its NAPA. Through the NAPA, the Solomon Islands developed an integrated climate resilience plan for solid waste management that would enable better coordination across all relevant departments and organizations.

For more information, see the Solomon Islands National Adaptation Programme of Action.

5.3 Disaster Solid Waste Management Planning

Large-scale natural disasters may generate more disaster waste than many communities can handle. Recovering and recycling some of the waste left behind after a natural disaster—including building debris and vegetation, such as downed trees and plants or leaves—can help communities with overall waste reduction and materials management. Best practices for creating a disaster plan for solid waste management include the following:

- **Improve disaster waste management preparedness (Exhibit 8)**, which may involve:
  - Conducting risk and vulnerability assessments of existing waste infrastructure
  - Identifying potential waste streams that a disaster might generate in a community
  - Evaluating the capacity of existing reuse and recycling programs to handle disaster waste
  - Considering post-disaster waste collection and transportation strategies
  - Determining and selecting potential waste management sites and facilities
  - Involving public and private actors and identifying their roles in post-disaster waste collection and disposal
- **Create an early warning system**, which commences once a climate-related hazard (e.g., flood or cyclone) is announced. Following this warning, the disaster preparedness plan can be activated, directing responsible decision-makers to begin identifying potential locations for waste removal. Temporary solid waste management sites can be established to prepare for the safe storage of disaster waste that it may not be possible to transport to regulated landfills.
- **Implement an emergency response plan**, which involves a rapid assessment of the type, scale, and location of disaster waste.
- **Implement a disaster waste recovery plan**, which involves restoring, resuming, and reconstructing all affected waste services and facilities. Trained field operators can be deployed to collect, recycle, and remove disaster waste based on the recovery plan.
- **Create a plan for managing waste from reconstruction operations**, which will likely involve rehabilitation of any damaged solid waste management facilities.

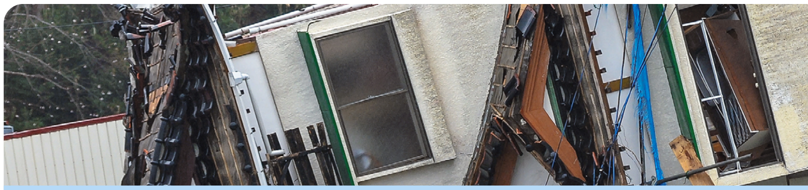


EXHIBIT 8 CASE STUDY

Managing Disaster Waste in Japan

Japan is one of the most disaster-prepared countries in the world. After the Tōhoku earthquake and tsunami in March 2011, Japan's Ministry of Environment established a task force—consisting of more than 100 experts from government agencies, research institutions, academia, and industry—to manage the waste generated from the disaster. The Ministry of Environment created guidelines for municipalities to manage disaster waste, including guidelines for maximizing the recycling of disaster debris and relying on local employment for waste recovery.

For more information about managing disaster waste in Japan, see the World Bank's What a Waste 2.0 report.

5.4 Climate-Resilient Solid Waste Infrastructure and Operations

Climate stressors can impact both solid waste infrastructure and operations. Exhibit 9 provides a list of established measures for minimizing climate-related damages to solid waste infrastructure and operations at each stage of the solid waste management process.

Exhibit 9. Measures for Improving Resilience in Solid Waste Management

Solid Waste Management Stages	Measures for Improving Resilience
Generation	• Promoting the reduction of waste through awareness-raising activities • Implementing at-source waste segregation • Developing protocols for managing disaster waste
Collection	• Ensuring waste collection bins and vehicles are adequately secured and covered to prevent the blowing of waste and bins from strong winds • Rescheduling waste collection during extreme weather conditions (e.g., heat, cold, storms) to reduce worker health risks • Increasing waste collection frequency to prevent waste build-up
Recycling and Treatment	• Developing defenses against sea-level rise • Improving the siting of recycling and treatment facilities away from flood plains (e.g., low-lying areas near rivers or coastal areas)
Disposal	• Implementing landfill leachate control systems to reduce leachate migration off-site • Diverting organic waste from landfill through segregated organics collection to reduce the likelihood of landfill fires from extreme heat • Managing disposal sites to prevent slope failures during heavy rainfall because they can be fatal to residents near the site and informal sector workers on site • Developing defenses against sea-level rise • Implementing fire prevention practices during extreme heat (e.g., the application of daily landfill cover with inert waste) • Inspecting and monitoring the risk of landslides and groundwater contamination • Siting landfills away from drinking water supplies • Compacting waste at disposal sites daily to prevent landslides

Questions for Decision-Makers

- What are potential local extreme weather changes due to global climate change (e.g., increased precipitation, increased frequency of storms)?
- What are the current infrastructure assets for solid waste management, and how might potential extreme climate events impact them?
- Are solid waste collection and transportation systems designed to operate in changing climactic scenarios?
- Are waste management treatment and disposal sites designed to minimize the impacts of floods or other climate risks?

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