Solid Waste Management in Delhi

An environmental and social analysis

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Prepared for the Chintan Environmental Research and Action Group, New Delhi, India

April 2019

Disclaimer:
The author conducted this study as part of the program of professional education at the Frank Batten School of Leadership and Public Policy, University of Virginia. This paper is submitted in partial fulfillment of the course requirements for the Master of Public Policy degree. The judgments and conclusions are solely those of the author, and are not necessarily endorsed by the Batten School, the University, or any other agency

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Table of Contents

Key Terms

Municipality – Local governing body that handles solid waste management.

Municipal Solid Waste (MSW) – Waste generated by the public; typically, MSW is a catch-all for waste that is not construction and demolition (C&D) waste, electronic waste (E-waste), or medical waste. It includes biodegradable waste, dry waste, domestic hazardous waste, and non-biodegradable non-recyclable inert waste.

Material Recovery – The process of mining re-usable materials from waste stream, such as recyclables or biodegradable waste.

Centralized waste management – Waste is collected as mixed waste by private waste collection contractors, and transported to city-level processing centers for resource recovery or sent to landfills for disposal.

Decentralized waste management – Communities process waste through different strategies such as compost, recycling, or local landfilling. Waste is sorted by type to enhance recovery.

Informal Sector – Economic activities or exchanges that are outside the formal economy, thus excluded from tax or social services.

Wet waste – Biodegradable waste. Includes food, yard waste, wood.

Dry waste – Typically recyclable waste. Includes plastic, paper, metal, glass, etc.

Hazardous waste – Typically includes inert materials, diapers, paint drums, used batteries, chemicals, bulbs.

Waste Segregation – Separating municipal solid waste by waste type (wet, dry, hazardous) into bins at source of generation (usually a household or business).

Waste-to-Energy (WtE) Incineration – Waste-to-Energy combustion (WTE) converts combustible solid waste to an ash residue by incineration (burning). By-products include electricity and steam.

Aerobic and Anaerobic Compost – Compost converts decomposing biodegradable waste into useable products. Aerobic composting creates fertilizer, while anaerobic compost captures biogas (methane and carbon dioxide) to be used as fuel or electricity.

Abbreviations

GHG – Greenhouse gas

MSW – Municipal Solid Waste

INR – Indian Rupee

TPD – Metric Tonnes per day

USD – United States Dollar

WM – Waste Management

Client Description

Chintan Group is an environmental research and advocacy non-profit based in New Delhi, India. Their mission is to reduce India's ecological footprint and increase environmental justice through partnerships, grassroots programming, advocacy, and research. Chintan is interested in investigating the environmental, economic, and social implications of Delhi's waste management strategy and potential alternatives to inform their advocacy strategy. They currently support working towards a zero-waste, zero-landfill waste management system.

Executive Summary

Over the last twenty years, the city of Delhi has experienced rapid urbanization and economic growth. The absolute and per capita increase in waste generation has overwhelmed Delhi's solid waste management system, forcing municipalities to dump the majority of waste in unhygienic and exhausted landfills. Evidence suggests that the city's waste mis-management threatens both human and environmental health.

The city has implemented alternative strategies to landfilling, primarily through centralized resource recovery initiatives such as Waste-to-Energy (WtE) incineration and city compost. Centralized strategies collect mixed waste, and material recovery begins once waste is brought to centers within the city.

The city must choose between continuing to invest in centralized resource recovery or to uproot the existing system in favor of decentralized waste management. Fundamentally, decentralized waste management requires city leaders to reconceive of waste as a resource, instead of an inconvenience to be disposed of or burned. Decentralized waste management also depends participation from the public to process waste in their homes and communities by segregating waste at source, composting biodegradable waste, and forming relationships with recycling organizations. In this analysis, I consider and compare the costs and associated benefits of combinations of decentralized and centralized waste management strategies. I evaluate the changes in waste diversion from landfills, greenhouse gas emissions, health, and feasibility of implementation for the following scenarios:

- **Option 1: Status Quo** evaluates the current state of solid waste management as a baseline to measure changes in waste, emissions, and health associated with alternative strategies.

- **Option 2: Decentralized Waste Management** considers a scenario where waste segregation at source increases the system's capacity for sustainable waste processing through local and municipal compost, cooperative recycling,

and WtE incineration.

- **Option 3: Centralized Waste Management** proposes additional investment in centralized waste management practices, such as WtE and sanitary landfilling, to mitigate negative health and climate externalities associated with the status-quo.

- **Option 4: Zero-waste Waste Management** expands on Option 2 and increases material recovery through compost, recycling, and public awareness to further reduce need for landfilling in the waste management process.

Status quo waste management is centralized, meaning that mixed waste is collected from homes, businesses, and other establishments, and resource recovery is attempted within city facilities. Option 3 proposes supplementing existing centralized management practices with technology to improve effectiveness of processing, abate pollution, and alleviate risk to human health. Options 2 and 4 offer modified forms of decentralization strategies that prioritize diverting waste from landfills, and vary by cost and feasibility of implementation.

Ultimately, I recommend **Option 4: Develop a Zero- Landfill system.** Option 4 is an enhanced decentralized model that is cost effective, mitigates emissions, and reduces waste management's health risk to society. It is the strongest strategy across these criteria relative to the other options. Its major limitation is feasibility, but for the purposes of advocacy, the feasibility criteria are the least important. Going forward, I suggest comprehensive needs assessment to better understand public interest and administrative feasibility, and developing a long-term action plan for municipality leaders to structure localized approaches.

India and Waste Management

India is home to 1.3 billion people, forming over 17 percent of the world population (World Bank, 2018). The population of Delhi, one of India's largest and fastest growing regions, has increased at an accelerating rate, growing from 11.3 million in 2011 to approximately 19.5 million in 2018. From 1999 to 2016, the estimated total volume of municipal solid waste (MSW) produced in Delhi per day has outpaced its population growth. Rapid urbanization, accompanied by mass migration and economic growth, has greatly increased both absolute and per capita waste generation, overwhelming Delhi's solid waste management system and creating a waste crisis.

Overview of Delhi's Solid Waste Management System

In India, city municipalities are responsible for collecting, processing, and disposing of municipal solid waste A municipality is local governing body, and in Delhi, municipalities govern regions ranging from 140,000 to 6.4 million people (Municipal Corporation of Delhi, 2017). While national and state legislation provide waste management guidelines, the municipalities bear the brunt of determining how to process and accommodate increasing volumes of waste; Chart A.1 (see appendix) provides additional information on the structure and responsibility of government in waste management. The Municipal Corporation of Delhi (MCD) is formed by the North Delhi, South Delhi, East Delhi, New Delhi, and the Delhi Cantonment Board Municipals Corporations. The jurisdiction is extremely diverse. It includes urban areas and rural villages, informal settlements such as slums and squatter settlements, and commercial zones such as industrial areas and dairy colonies. Broadly, the waste is collected from homes and businesses, transported to local dumps, processing centers, or enters the informal recovery process, and eventually is transported to landfills, city compost centers, or Waste-to-Energy (WtE) plants. Table 1 provides an overview of each phase of waste management.

Table 1: Delhi's Solid Waste Management System

PHASE	**Description**
COLLECTION	*Formal*: In the formal system, a municipality corporation authorizes private companies or formally employs workers (swatcha karamcharis) to collect mixed waste from households, businesses, and community *dhalaos* (dump spaces). *Informal*: Informal sector workers (commonly referred to as 'rag pickers' [hereafter recyclists]) also collect waste from households, *dhalaos*, storage receptacles, collection centers, streets, etc. to recover materials to sell to waste dealers. Many localities, especially unauthorized colonies and squatter settlements, do not have formal collection services and resort to open dumping.
RECYCLING	Almost all recycling in India is undertaken by the informal sector (Annepu, 2012). Once waste is collected or dumped, recyclists mine for recyclable materials, such

	as plastic, paper, glass, and metals. The recyclables move through a series of waste dealers and finally sold to wholesalers, who then transport waste to recycling processing centers.
TRANSPORT	With a proportion of recyclables removed, waste is either informally transported by ‘open dumpers’ or formally transferred by covered trucks to Delhi’s three landfills, Okhla, Bhalswa, and Ghazipur.
LANDFILL	Upon arrival at the landfill, waste is processed. Biodegradable waste is separated for compositing or refuse fuel derivation (Narela plant only). Mixed-waste is then transferred to Waste-to-Energy (WtE) plant for incineration. Inert and biodegradable waste rejects are discarded in the landfill.
COMPOSTING	Biodegradable waste is composted through windrow anaerobic composting, which occurs at landfill sites. Compost is also sold on site;
WTE INCINERATION	Waste-to-Energy incineration is a controlled combustion process for mixed waste. Plants use thermal technology to breakdown combustible and biodegradable solid waste, producing an ash residue and gas. The thermal process can also generate electricity, steam, or other energy, which can be sold to generate revenue. Incoming mixed-waste must have high biodegradable content free from contaminants to ensure the burn is ‘safe.’

Composition of waste

Weight and composition are key to determining suitability of potential waste management strategies, as well as estimating greenhouse gas (GHG) emissions from waste decay and adverse public health effects. Using an average of several credible estimates, I estimate that the majority of MSW generated in Delhi is biodegradable, while the remaining waste is recyclable or inert (Table 2). Inert waste is defined as non-biodegradable, non-recyclable, and / or hazardous material for this analysis.

Table 2: Waste Composition in Indian Cities

Waste type	Weight (TPD)	Composition (%)
Biodegradable	7,842.25	63.5
Recyclable	2,408.25	19.5
Inert	2,099.50	17

How much waste?

Currently, Delhi generates about 12,350 tonnes of municipal solid waste per day (TPD). 87 percent (10,711 TPD) of waste generated is formally collected. Among waste that is collected, 34 percent (3,660 TPD) is successfully processed via WtE incineration and 7 percent (720 TPD) is composted, totaling 41 percent. The remaining 6,128 TPD of collected waste is disposed in landfills (Annepu, 2012; MCD, 2017).

However, these centralized technologies are capable of processing significantly more waste. WtE and compost centers have the capacity to process 57 percent of collected waste; however, evidence suggests that defunct machinery, unsafe burning, and contaminated mixed waste reduce their effectiveness. As a result, waste intended for processing ends up in landfills, in the form of contaminated compost or ground/fly ash (Shriram Institute, 2017).

The remaining 13 percent of waste generated is not technically collected, but a significant proportion is still recovered through informal material recovery systems. Chintan estimates that in Delhi, there are 300,00 to 400,000 'rag pickers' or recyclists who are responsible for recovering nearly 56 percent of all recyclable waste and 70 percent of plastic waste (CSE, 2016; Annepu, 2012). This amounts to recovery of an additional 1,348.6 TPD of recyclable waste.

In total, approximately 40 percent (5,008 TPD) of the total MSW generated is processed through formal centralized processing (WtE, compost) or informal recyclable waste recovery, while 60 percent (7,341 TPD) is disposed in landfills from formal collection or is never collected. Table 3 summarizes these figures below.

Table 3: MSW Generation, Collection, and Processing Per Day (2018)

Summary	Weight (TPD)	Total Waste Generated (%)
Total MSW sustainably processed	5,008.6	40
Total MSW dumped or landfilled	7,341.4	60
Total MSW generated	12,350	100
Total MSW formally collected	10,711	87

The Challenge: Reducing Dependence on Landfills

The rising volume of waste in Delhi has overwhelmed its existing solid waste management infrastructure. Delhi's three semi-controlled[1] landfills (Okhla, Gazipur, and Bhalswa) were deemed dangerously over capacity in 2010, and continued disposal threatens both environmental and human health. The landfills produce leachate that poisons ground water, expose nearby communities to harmful biological vectors, release trace amounts of carcinogenic volatile organic compounds, and emit dangerous greenhouse gases into the atmosphere (Siddiqui, 2013; Pradyumna, 2013; Ghosh et. al, 2015; CSE 2017). Despite significant harm, within its current waste management system Delhi must continue to dump.

[1] Semi-controlled landfills have limited capacity to segregate waste and are not engineered to manage leachate discharge or GHG emissions generated by decomposing waste.

There are several factors that prevent Delhi from diverting waste from its landfills. First, waste that is formally collected by municipalities is not segregated. 'Mixed' or unsegregated waste can complicate the material recovery process by contaminating biodegradable waste, rendering waste unfit for recovery through centralized compost or combustion in WtE incinerators.[2] Secondly, the city does not allocate resources towards recycling, relying on the informal sector alone to process recyclable waste.

Other externalities of mismanaged waste

In addition to landfill use, there are other harmful externalities associated with the current waste management system. Researchers from the Shriram Institute for Industrial Research, Delhi (2017) found that WtE incinerators currently burn waste that is 13.3 percent lower than the 1500 kcal/kg minimum for safe WtE incineration. The low energy content is not hot enough to safely combust all waste, and produces excessive fly and ground ash that may contain toxins. Burning mixed waste in WtE incinerators also releases harmful air pollutants into the atmosphere from combustion of recyclable (plastic) or hazardous material. Evidence suggests that Delhi's WtE incinerators do not comply with regulation to filter emissions, which can expose residents to harmful air pollutants.[3] Furthermore, mixed-waste compost contains heavy metals, causing it to fail basic fertilization standards (Saha et. al, 2010; Wang and Nie, 2001). Despite high subsidies, even usable compost sales are low. Unusable or unsellable compost is subsequently landfilled.

Secondly, relying on the informal sector to carry out recycling, while inexpensive to execute, exposes workers to extraordinarily unsanitary conditions while collecting waste without any stable compensation or health benefits. In a survey of informal workers, Annepu (2012) found that recyclists are more than seven times more likely to experience cardiovascular risk and more than three times as likely to experience lung infections than the general population.

In response to the continued dependence on landfills and harmful externalities of waste mismanagement, the Government of India has implored Delhi to take immediate action to curb current harm and reduce future harm. The following literature review identifies strategies for addressing the failures of the current waste management system and overcoming harmful externalities.

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[2] Approximately 60 percent of compost is landfilled due to high heavy metal content, while 40 percent of WtE waste is landfilled due to improper burning.

[3] In 2014, the Delhi Pollution Control Committee (DPCC) issued a 'show cause' notice to the Okhla WtE plant seeking an explanation for uncontrolled emission in violation of norms. It's unclear whether the necessary changes were made to meet safe standards (Millennium Post, 2014).

Strategies for Sustainable Solid Waste Management

To mitigate dependence on landfills and reduce informal dumping, the city of Delhi must formulate a functional, effective, and sustainable solid waste management system. The potential alternatives will consider sustainable practices in waste collection, waste recovery for recyclable, biodegradable, and inert wastes, and waste disposal (World Bank, 2018). In addition, the city must apply sustainable practices at the local and municipal level.

Waste Separation at Source

Waste collection and segregation is a crucial step in waste management for lower-middle income countries; in fact, Annepu (2012) suggests that waste segregation at source is the single-most important practice India can implement to establish sustainable solid waste management systems. The scheme requires waste generators to separate their waste into bins to prevent co-mingling and contamination. The Center for Science and Environment, a prominent environmental action think-tank based in Delhi, has suggested the city implement several polices to support segregation at source, including installing color-coded bins to separate wet (biodegradable) waste, dry (recyclable) waste, and hazardous or inert waste at community waste storage units, subsidizing or providing bins for households and businesses, charging a user-fee for waste collection to raise revenues, and levying fines on illegal dumping (CSE, 2017).

A woman deposits dry waste into a partitioned collection truck in Muzaffarpur. (*Photo by Swati Singh Sambyal, published by the Washington Post, July 2018*)

Several Indian cities have successfully implemented waste segregation programs. In 2017, the sub-metropolitan city of Muzaffarpur, Bihar, India launched an extensive waste segregation campaign to manage its landfills and informal dumpsites. In partnership with CSE and ITC Ltd,[4] the Muzaffarpur Municipal Corporation (MMC) launched the 'Well-being Out of Waste' initiative, which involved recruiting volunteers to implement a door-to-door education campaign on

[4] An Indian cigarette company, likely executing corporate social responsibility

the importance of segregating waste. The scheme provided all households and businesses with plastic bins for wet waste, dry waste, and hazardous waste. The MMC established an infrastructure for biodegradable waste management by equipping all collection vehicles with partitions for collection of separate dry and wet waste (pictured above) to reduce contamination, built municipal aerobic composting facilities, and set up composting pits communities for neighborhood and commercial use. The campaign achieved 80 percent segregation over the study period and eliminated waste burning and informal dumping (*Model Framework for Segregation*, CSE, 2018).

However, even cities in high-income countries interested in sustainable waste management struggle to implement waste segregation at the household and commercial level because it is inconvenient and time intensive. To overcome this barrier, Damghani et al. (2009) suggest extensive and repetitive environmental education campaigns using brochures, posters, and public information resources to raise awareness.

Informal Recycling

The vital role of the informal sector in solid waste management in developing countries is increasingly being recognized. Informal recycling workers are key to recovering resources from mixed waste and creating livelihood for poor and marginalized communities. Their services greatly reduce the volume of materials that end up in waste processing centers and landfills.

Research suggests that organizing the informal sector and promoting a formal process for material recovery is an effective way of extending recycling services in rapidly urbanizing areas (Devi and Satyanarayana, 2001; Annepu, 2012; CSE, 2017). Medina (2008) suggest that grassroots organizing is key to strengthening the bargaining position of recyclers. Waste picker organizations can enter into informal agreements or formal contracts with

BOX 1: COOPERATIVE RECYCLING IN PUNE, MAHARASHTRA

In 2006, a group of recyclists in Pune formed India's first member-owned and managed waste picker cooperative, Solid Waste Collection and Handling (SWaCH). In a unique formal-informal partnership, recyclists signed an MOU with the Pune Municipal Cooperation (PMC) authorizing them to provide door-to-door waste collection to city households.

The workers receive equipment, technical training for collection and composting, access to recyclables, and are granted the right to charge residents for collection. Workers enforce segregation at source by collecting only segregated recyclable and biodegradable waste. Once collected, recyclables enter the informal processing value chain and biodegradable waste is converted into compost instead of dumped in city landfills. Although the PMC incurs capital costs and supports health insurance for workers, its costs are significantly lower than prior contracts with private collection services. By 2008, SWaCH workers executed collection in 127 of 144 sub-units in all 14 administrative wards of Pune, servicing 200,000 residents. The cooperative has approximately 1,500 members (SWaCH, 2019).

businesses, industry, and neighborhood associations to gain access to recyclable materials or to sell materials or manufactured items. Medina also suggests that in the absence of government intervention, organizing cooperatives of workers creates opportunities for segregating at source, which greatly increases the value of recovered materials and the efficiency of informal recycling. Dias (2008) illustrates the value of organization through case studies from Columbia, Brazil, and Pune, India (see Box 1).

In a study evaluating the feasibility of integrating informal recycling into formal MSW systems in Asia, Bercegol et. al (2017) find that there are both economic and cultural barriers to formal integration. The incentive to formalize the informal sector is low, as informal recycling services are implemented without government coordination. Secondly, the authors find that even when municipal authorities in Asia recognize the formalizing the waste recycling economy has public interest potential, they are often unwilling to formally integrate these workers into the MSW system, instead preferring to “modernize” urban services.[5]

Biodegradable waste management: Composting

As over 50 percent of Delhi’s waste is biodegradable, composting and anaerobic digestion are feasible options for reducing landfill waste. Composting and anaerobic digestion convert decomposable organic materials into an organic fertilizer and/or collect biogas (see photo below). Fertilizer can be resold for agricultural use and biogas can be used as fuel. Composting activities are becoming increasingly common for waste management in other South Asian cities, and have been deployed through decentralized (community level) units and centralized (municipal and city level) units (Zurbrugg, 2003).

Smaller cities have successfully implemented both decentralized and centralized composting campaigns in India. Alappuzha, a small city in Kerala, India, earned recognition from the United Nations Environment Program as one of the top cities in the world executing sustainable waste management. Its system puts the responsibility of waste management onto citizens, who compost biodegradable waste and channel dry and inert waste to recycling channels. The city’s “Clean Home, Clean City” initiative provided nearly two years of training and education to citizens on waste segregation and compost, and subsidized up 90 percent of costs to provide households and businesses with biogas plants, pipe compost, and aerobic compost units (Dhanalakshmi, 2015; see photo below). Larger aerobic compost units were built throughout municipalities to ensure those who could not or would not

[5] Delhi, in particular, has exhibited preference for modernizing waste management by establishing 3-4 Waste-to-Energy plants

purchase units still were able to compost, and to deposit collected biodegradable waste. The system is self-sustaining and has not required additional collection investment since 2017.

A biogas unit in Kerala, India. (Photo by Ranjith Annepu)

Despite this success, many cities have struggled to establish a market and demand for the compost product, and to enforce compliance at the household level. Saha et. al (2010) conducted a study on the quality of compost in produced in India and found that many samples in mega-cities, including samples from Delhi, failed to meet adequate fertilizing and heavy metal parameters due to the use of mixed waste compost. Waste that was even partially segregated was significantly more likely to pass standards, suggesting that implementation of decentralized waste collection and separation can reduce contamination.

Biodegradable waste management: Waste-to-Energy Incineration & energy recovery

Highly biodegradable waste is generally suitable for combustion solutions. When operated effectively and held to environmentally sound standards, WtE incinerators are capable of reducing the volume of waste disposed in landfills, thereby reducing pollution (Word Bank, 2018). WtE has become an increasingly common energy recovery strategy in high-income countries such as the Gulf Cooperation Council (GCC), Europe, and developed countries in Asia such as Japan and Singapore (American Society of Mechanical Engineers, 2008).

However, WtE is becoming more realistic in developing countries. In China, WtE incineration has generally been successful. In an assessment of MSW management technology options, Cheng et. al (2010) found that WtE incineration reduced the total volume of waste requiring disposal by landfill by 90 percent. The plant has the capacity to handle mixed waste streams with mechanical-grate pollution control technology that treats flue gas and hazardous fly ash. The plants also significantly reduced transportation costs and contributed to fewer landfill-related GHG emissions.

The feasibility and effectiveness of WtE strategies in reducing pollution and recovering energy in other low-income countries, however, remains unclear. Cheng (2010) and Annepu (2012) report that WtE systems are extremely expensive to establish and require high operating and maintenance costs. Existing WtE plants in Delhi have come under intense scrutiny for releasing toxic air emissions and generating excessive fly ash.

Hazardous Waste collection and Local landfilling

Successful waste recovery is contingent on treatment and disposal of hazardous and / or inert wastes. Hazardous waste should be separated to prevent contamination or pollution, and treated in specialized facilities such as chemical processing plants, incinerators, and disassembly centers. In a true decentralized model, the CSE (2017) suggests that in addition to city-level or municipal level landfills, cities consider constructing community engineered landfills for inert wastes.

Sanitary Landfills

Another strategy involves converting landfills to sanitary landfills through landfill gas capture and liner replacement. It has been well-documented that landfills are a point source of GHG emissions. As waste decomposes, combination of chemical, thermal, and microbial reactions release gases (US Environmental Protection Agency, 1999). In India, emissions from waste are double the global average, due to a high proportion of biodegradables in waste streams and the warm, wet climate (Siddiqui, 2013). Landfills are the second largest source of methane in India, after coal mining (CSE, 2016).

Landfill gas (LFG) recovery has been implemented at seven landfills located in Delhi, Mumbai, Kolkata and Ahmadabad. Annepu (2012) estimates that these LFG recovery projects will reduce India's GHG production by 7.4 million tons of CO2 equivalents per year. Although this technology is expensive and difficult to maintain, countries can finance gas capture projects through international partnerships: for example, capture projects in Brazil were partially financed by selling emissions reductions through the World Bank's Carbon Partnership Facility (World Bank, 2014; 2018). It is feasible for Delhi to consider investing in LFG technology to continue convert its landfills to sanitary landfills.

Another source of pollution from landfills is contamination of ground water due to decay of leachate 'liners.' Leachate liners prevent landfill leachate (runoff of toxic chemicals from decomposing garbage) from contaminating ground water supply. Liners can be replaced with clay or other high-density material to prevent leachate runoff from affecting human health (US EPA, 2010).

Methodology

This literature reviewed several strategies for sustainable solid waste management that the city of Delhi has considered over the last several years. The analysis is structured to consider how implementation of combinations of these strategies will divert waste from landfills, offset Delhi's net greenhouse gas emission contribution, alleviate health costs, and assess the political and administrative feasibility of implementation, in order to inform the Client's future advocacy efforts in waste management. The following alternatives are considered for evaluation:

- **Option 1: Status Quo** evaluates the current state of solid waste management as a baseline to measure changes in waste, emissions, and health associated with the Options 2, 3, and 4.
- **Option 2: Decentralized Waste Management** considers a scenario where waste segregation at source increases the system's capacity for sustainable waste processing through local and municipal compost, cooperative recycling, and WtE incineration.
- **Option 3: Centralized Waste Management** proposes additional investment in centralized waste management practices, such as WtE and sanitary landfilling, to mitigate negative health and climate externalities associated with the status-quo.
- **Option 4: Zero-waste Waste Management** expands on Option 2 and increases material recovery through compost, recycling, and public awareness to further reduce need for landfilling in the waste management process.

Criteria for Evaluation

To evaluate the options, I will consider the following five criteria associated with each policy option, listed in order of importance to the Client:

- **Cost effectiveness** as the share of waste diverted from landfills per crore of rupee (INR) investment
- **Climate change** as the option's net contribution to greenhouse gas emissions
- **Health risk** as the option's impact on health of informal workers and communities adversely affected by landfills
- **Political feasibility** as explicit local, state, national, and / or public support for the option
- **Administrative feasibility** as the complexity of coordination and implementation for each option.

Because waste management requires immediate action and restructuring, the criteria will only consider the short-term (3 year) costs, revenues, and implications of the alternatives. To measure cost effectiveness, I map out each option's proposed waste management system and measure the volume of waste processed for all phases and waste types. I then calculate the share of waste diverted per crore of INR investment. For climate change, I convert the change in landfill waste deposition to the associated reduction in carbon-dioxide equivalent emissions to quantify the change in net GHG emissions associated with each option. Finally, I use a low-to-high scale to measure the health risk, political, and administrative feasibility associated with each option. I rely on health data from communities living and working within proximity of the landfill for the health criterion, and assess current waste management legislation and complexity of implementation to determine feasibility.

Cost-effectiveness: Waste Reduction

Delhi's most pressing priority is to reduce waste deposition in landfills. This criterion will evaluate the cost-effectiveness of each option with respect to waste reduction. The waste cost-effective metric will estimate the change in tons per day of waste generated relative to cost. To measure the change in waste, I estimate the total volume of waste processed at several inflection points. I include:

- Waste collected from households and businesses
- Waste recovered by recyclists
- Waste processed in local and centralized composting units
- Waste processed in local and municipal hazardous and inert waste centers
- Waste incinerated by WtE plants
- Waste deposited in landfills

The total volume of waste generated per alternative will be divided by the cost of the alternative, so that waste cost-effectiveness can be compared across alternatives. To calculate net cost, I estimate the implementation costs of each alternative relative to the baseline 'status quo' alternative using comparable waste management programs from India, China, Croatia, and the United States.[6] I also estimate revenues associated with each alternative, and subtract them from costs to determine net cost.

Climate Change

The background and literature review report important information on the harmful environmental consequences of unsanitary landfills, so it is essential to measure the greenhouse gas emissions associated with each alternative. I will measure the net change in greenhouse gas emissions by multiplying the weight of waste dumped by the carbon dioxide equivalent associated with the biodegradable content per ton of waste dumped. To accommodate for varying degrees of enforcement, I include estimates for full-compliance and partial-compliance (10% leakage in waste collected).

Health Risk

Evidence suggests that Delhi's current waste management system is detrimental to human health, in particular marginalized informal recyclists who implement the bulk of material recovery and citizens living in proximity of landfills and WtE incineration plants. This

[6] I adjust costs to account for inflation by converting units to 2017 crore rupees.

criterion will estimate how changes in waste management will affect human health, and rank each alternative from low-risk to high-risk to human health. An alternative earns a 'high risk' ranking if its tenants do not improve the status-quo health risk associated with waste management. The option earns a 'medium risk' ranking if health outcomes could improve for some community members and / or informal workers, but does not take direct action to change health outcomes for informal workers. The option earns a 'high risk' ranking if the alternative could significantly improve health outcomes for the community and directly affect health outcomes of informal workers.

Political feasibility

This criterion will assess government and public support for each alternative at the local, state, and national level. I rank each option from low to high. An alternative earns a 'low' ranking if it violates existing legislation and / or has little to no public support. To receive a 'moderate' ranking, the option must earn explicit support from a local, state, or national governing body (see Chart A.1 for structure of Delhi governance) and have explicit public support. To receive a 'high' ranking, the alternative must earn support from legislation, explicit support from national, state, and local government, and have explicit public support.

Administrative feasibility

Administrative feasibility considers the difficulty of implementation and enforcement of each alternative. I rank each option from low to high. The option earns a low administrative feasibility ranking if it requires drastic, complex, and system-wide changes to the current waste management system to coordinate or implement, a moderate ranking if it requires moderately challenging system-wide changes to coordinate and implement, and a high ranking if the option is within the municipalities' current capacity to coordinate and implement.

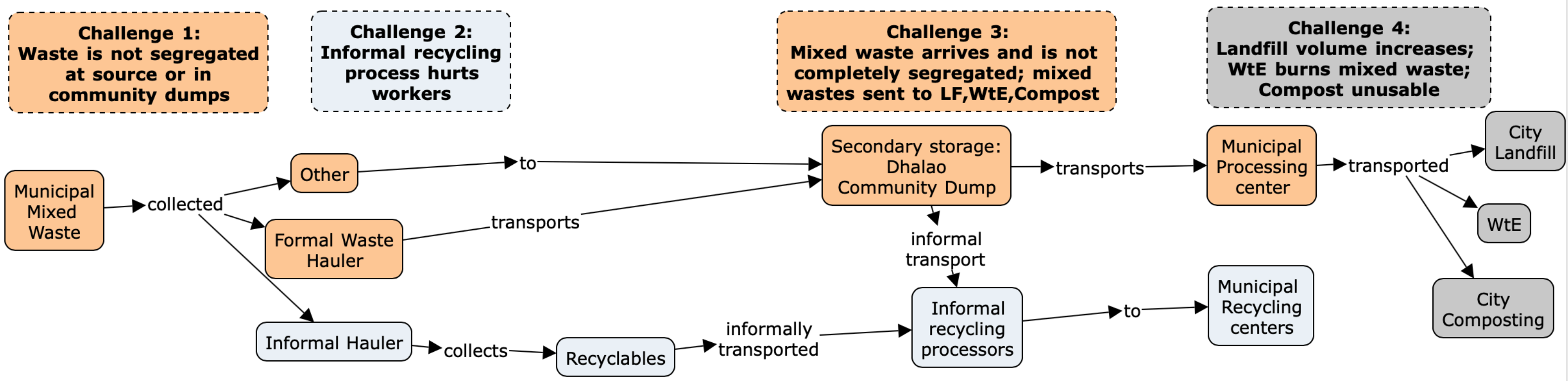
Policy Options and Evaluation

This section describes each option, accompanying policy, and evaluation per the criteria.

Option 1: Status Quo

The first option represents the 'status quo' municipal solid waste management process. Table 2 outlines a comprehensive review of this process, and the accompanying flowchart (Chart 1) illustrates the flow of waste and identifies procedural challenges from the background and literature. In this system, a sizeable proportion of MSW accumulates in Delhi's unhygienic landfills. Processing centers do not have the capacity to segregate such high volumes of mixed waste, and as a result, mixed waste that includes hazardous chemicals, metals, and plastics is both incinerated and composted. Incinerating mixed waste reduces combustion efficiency, which in turn releases harmful emissions and generates additional bottom and fly ash that ends up in landfills. Composting mixed waste decreases compost quality to unusable levels, and unsold compost is often landfilled. Furthermore, informal recyclers work in unsanitary conditions without compensation, and communities living within the vicinity of landfills and WtE incinerators are exposed to pollutants and contamination.

Chart 1: Current MSW System, Challenges Identified



Cost Effectiveness: **Zero.**
In this option, there is no change in waste diverted from landfills. Table A.2 reports the collection and processing capacity of the current system.

Climate Change: **4,178** tonnes of CO2 equivalent per landfilled tonne of MSW.
According to Annepu (2012), within the current waste management structure approximately 0.57 tonnes of carbon dioxide equivalent are generated per ton of waste dumped or landfilled per day in India. Currently, the city dumps about 7,341 TPD of waste, which is associated with 4,178 tonnes of carbon dioxide equivalent generated per day from Delhi's three landfills.

Health Risk: **High-risk** to human health.
Communities surrounding landfills and informal recyclers incur high health costs associated with landfill gasses, WtE combustion of contaminated mixed waste, and unsanitary working conditions in the informal sector. In the status quo, communities surrounding the landfill and recyclists both experience adverse health consequences; thus, the option earns a 'high' health risk ranking.

Political Feasibility: **Low.**

The status quo violates national waste management regulation. In 2016, the Ministry of Environment, Forest and Climate Change notified the Solid Waste Management Rules.[7] The Rules prohibit mixed-waste dumping, order landfill operators to convert unhygienic landfills to sanitary landfills, and include "emphasis on decentralised processing to make use of all components…so as to minimise the burden on landfills" (Ministry of Environment, Forest, and Climate Change, 2016).

To increase compliance with the SWM Rules, in January 2018, the Lieutenant Governor of Delhi, Anil Baijal, notified the Solid Waste Management By-Laws 2018 for the National Capital Territory of Delhi (NCT). These by-laws were intended to provide legislative 'teeth' to improve enforcement of decentralized waste management policies at the local level. The status-quo system directly violates both pieces of legislation by depending on unhygienic landfilling and mixed-waste dumping, and currently has made no provision for local waste recovery. Furthermore, citizens of Delhi are generally unsatisfied with current waste management and continued landfill use due to the health risks imposed and unsanitary conditions in the city (*Times of India, 2019; Hindustan Times, 2019; Delhi Greens, 2019; The Hindu, 2018; Down to Earth, 2017; 2018; 2019*). Thus, the status quo earns a 'low' political feasibility ranking, because it violates existing legislation and public interest.

Administrative Feasibility: **High.**
Administrative feasibility for the status quo system is high, because no systematic change is required.

Option 2: Decentralize Waste Collection, Separation, and Recovery

This option proposes radical changes to solid waste management collection and recovery by decentralizing biodegradable processing and increasing capacity for recycling. Its tenants are based on SWM strategies identified by recent national solid waste standards, the 2018 Solid Waste Management By-Laws, which suggest establishing infrastructure for decentralized waste processing. The option emphasizes the waste generator's responsibility to segregate at source into biodegradable (wet waste), non-biodegradable (dry waste), and domestic hazardous waste, recognizes services of the informal sector, and advises stricter penalties for failing to segregate mixed and dumping. Improving segregation will reduce contamination, allow for additional material recovery through recycling, and improve quality of waste that reaches centralized processing units such as WtE plants and city composting. Chart A.3 displays the intervention for each phase of waste processing by waste type.

[7] 'Rules' are equivalent to legislation in the United States.

I consider the following decentralized policies to inform the analysis.

- Enforcing collection fees to equip municipality to collect segregated waste: Municipalities levy fines on households and businesses that illegally dump wastes and charge user fees for waste management services to raise revenue. With nearly 3.58 million households, I estimate that charging 140 INR per household with 60 percent compliance will generate 108.4 crore INR over three years. With these funds, the municipality equips collection vehicles (tippers, tricycles, tractors, trucks, etc.) with containers to keep biodegradable, recyclable, and hazardous waste separate.

- Installing community composting and municipality composting centers: Pending needs assessment, municipalities install composting pits or facilities and operating staff for processing biodegradable waste at the community and municipality level. At least one facility per municipality and 15 community pits per ward (approximately 2,000 households) are installed and maintained. I estimate that investing 82 crore INR in start-up and operation costs for community and municipal compost will process approximately 18 percent of total biodegradable waste. I estimate that sales from compost will generate approximately 376 crore INR over three years.

- Providing color coded bins to households and install bins at secondary storage units: To encourage separation, municipalities provide bins to households and commercial entities: green for wet (biodegradable) waste, blue for dry (recyclable) waste, and black for hazardous waste. For households and businesses without formal collection, the municipalities install bins at community-level waste units. I estimate collection equipment and maintenance will cost 511.6 crore INR.

- Strengthening informal recycling cooperatives: Municipalities sign a Memorandum of Understanding (MOU) with existing recycling unions (for example, Safai Sena). The agreement could coordinate collection efforts, material recovery for each waste type, and establish compliance with waste segregation. The MOU could also allocate resources to existing recycling cooperatives to formalize their organizational capacity, strengthen their bargaining power, and enable them to provide workers access to health services. I estimate that 4.5 crore INR investment in recycling cooperatives will increase recycling capacity by 10 percent relative to the status quo recycling capacity.

- Installing community inert and / or hazardous waste processing: The MCD collaborates with municipal hazardous waste processing centers to determine suitable locations for installing community-level centers to receive hazardous waste, and installs small landfills for non-compostable, non-recoverable waste. I estimate that investing 43.5 crore INR in inert waste processing will divert 18 percent of inert waste from disposal in city landfills.

Cost Effectiveness: **6.3 - 18.4 tonnes of waste diverted** per day per INR crore investment
In this option, I consider two variations of decentralization: full implementation with 100 percent waste collected, and partial implementation with 10 percent leakage where 90 percent of waste is collected.

Under full implementation of this option, I estimate that proposed changes in segregation, collection, biodegradable waste recovery (compost, WtE), and recycling cooperatives are capable of processing approximately 64 percent (7,903 TPD) of the total municipal solid waste generated, while 36 percent (4,447 TPD) is landfilled or dumped. The option increases waste recovery by 56 percent relative to the status quo, or an additional 2,894 TPD diverted from landfills. Table 4 displays these summary results, while the accompanying Table A.4 reports the estimated capacity of waste recovery for each intervention by waste type.

I estimate the total cost of implementation of this option, including equipment and three years of operation, to be approximately 641.8 crore INR (2017), and benefits from compost sales and user fees to be approximately 484.5 crore INR (2017). The cost-effectiveness, or the total waste diverted divided by the net cost, is approximately 18.4 tonnes of waste diverted per day per INR crore investment.

With partial implementation, I estimate that approximately 54 percent of total waste generated is sustainably processed (6,001 TPD) while 56 percent is landfilled or dumped (6,348.9 TPD). The option increases waste recovery by 20 percent relative to the status quo, or an additional 992.6 TPD diverted from landfills. Using the same net cost assumptions from full implementation, the cost-effectiveness is 6.3 tonnes of waste diverted per day per crore investment.

Table 4: Summary of Waste Outcome, Decentralized WM Model

	Summary	Weight (TPD)	Share of Total (%)
Full compliance	Total sustainably processed	7,903	64
	Total dumped or landfilled	4,447	36
	Total MSW generated	12,350	100
10% leakage	Total sustainably processed	6,001.2	49
	Total dumped or landfilled	6,348.8	51
	Total MSW generated	12,350	100

Climate Change: **46 - 74% decrease in carbon dioxide equivalent**

In the decentralized option, nearly 77 percent of biodegradable waste is processed. Because biodegradable wastes are the primary source of GHG emissions in landfills, the increase in processing yields a lower estimate for tonnes of carbon dioxide (CO_2) equivalence per tonne of waste dumped per day. By reducing the biodegradable content of the 4,447 TPD of waste landfilled or dumped, the option generates approximately 1,089.5 tonnes of CO_2 equivalent per day and decreases current CO_2 equivalent emissions by 74 percent.

With partial implementation, the option collects 90 percent of waste and recovers approximately 67 percent of biodegradable waste. The CO_2 equivalent per ton of waste dumped increases to 0.35, generating approximately 2,235.55 tonnes of CO2 equivalent. The option decreases current CO_2 equivalent emissions by 46 percent

Health Risk: **Medium-risk** to human health**.**

This option affects health by reducing the harmful emissions generated by WtE and by encouraging municipalities to set up formal partnerships with informal recycling unions. By enforcing waste segregation, municipalities will greatly reduce the contamination of biodegradable waste that is burned in WtE incineration. This will reduce pollutants generated by emissions from WtE. By investing in the informal sector, municipalities equip cooperatives to take additional health considerations to offset detrimental health outcomes, but the option does not directly prioritize improving the health conditions of recyclists. Without direct action to mitigate health outcomes for recyclists, this option earns a 'medium' health risk rank.

Political feasibility: **Moderate.**

This option is politically feasible. As mentioned, the Government of Delhi has explicitly stated support for improving compliance and enforcement of decentralized waste management policies through its 2018 by-laws. However, regulation issued in 2016 included similar provisions emphasizing a decentralized approach, and did not result in tangible change. The will to implement the decentralized approach rests with the municipalities, who often lack capacity or funding to do so. However, public support for decentralization has increased in light of controversy surrounding WtE pollution and failed compost (*Down to Earth*, April 2019). This support is essential to this option, which requires the public to process (via compost) 8 percent of biodegradable waste in their communities. Thus, with explicit state and national support, the option is moderately political feasibility but would require stated support from municipalities to be highly feasible.

Administrative feasibility: **Moderate.**
Administratively, this policy is moderately challenging to implement. It relies on municipalities to create spaces for local compost (approximately 2,000 households), community compost (approximately 10,000 households), and community landfills for inert waste. As Delhi is already incredibly crowded, finding land would be challenging, but not impossible. Another administrative limitation is the sensitivity of organic compost, which requires skill-intensive training to execute properly. However, other Indian cities, such as Pune, have successfully implemented wide-scale segregation and localized processing, which could provide a template for Delhi to surmount these administrative obstacles (CSE, 2016). With moderately challenging system-wide change required for implementation, the option earns a 'moderate' administrative feasibility rank.

Option 3: Invest in Centralized Waste Disposal

In the absence of waste segregation, the city Government of Delhi must also consider undertaking investment to improve its existing centralizing processing systems: WtE incineration and landfilling. Whereas the implementing responsibility of Option 2 rests with municipal bodies, Option 3 relies on enforcement and coordination of state and municipal agencies. This option requires state-level agencies or private companies to invest in sanitizing landfills, increase monitoring of WtE and composting units, improve hazardous waste separation, and dis-incentivize deposition of bulky, unseparated waste at landfills and central processing units. The policies include:

- <u>Converting all landfills to sanitary landfills:</u> The city will install leachate liners in landfills and restrict the content of waste disposed to only non-biodegradable, inert waste, and other appropriately stabilized biological waste. I estimate the conversion will cost 124 crore INR in capital and maintenance costs.

- <u>Install Landfill Gas (LFG) capture:</u> Require landfill operators to install and maintain gas capture systems, to protect surrounding communities from toxic gases and to capture methane for energy production. I estimate that installation and maintenance will cost 39 crore INR for all three landfills, and that revenues from sale of landfill gas for energy or electricity will total 118 crore INR over three years.

- <u>Reduce contaminated burning and composting:</u> The city will monitor the composition of mixed-waste processed by privately-operated WtE units and municipal composting units to ensure hazardous materials and recyclable materials are removed. This will ensure a 'clean burn' and improve usability of compost. The increase in monitoring will increase the volume of biodegradable waste processed by 17 percent to meet minimum standards (70 percent biodegradable, 30 percent inert).

- <u>Comply with pollution control equipment standards:</u> WtE incinerators are already required to control air pollution and monitor fly-ash content, yet evidence suggests this equipment is defunct or not well-maintained. The city will enforce fines for non-compliance with existing legislation and invest in mechanical-grate technology for cleaning emissions and by-products. I estimate the additional investment will cost approximately 2,730 crore INR.

- <u>Outlaw tipping fees</u>: To disincentive transporting heavy waste to waste processing centers, the city will ensure landfills do not pay waste transporters for heavy waste.

Cost Effectiveness: **0.16 tonnes of waste diverted** per day per INR crore investment
Under full implementation of this option, I estimate that the changes in centralized landfilling and WtE incineration will not drastically alter the city's ability to process waste or reduce the flow of waste that is dumped or landfilled, yielding a very low cost-effectiveness. The alternative makes no change to the 'status quo' mixed waste collection; instead, it equips WtE to safely burn mixed waste. This increases the city's capacity to process waste by 4 percentage points, and represents a 10 percent increase in waste recovery; however, 55 percent or 6,851.38 TPD of MSW are landfilled or dumped. Table 5 displays these results, while the accompanying Table A.5 reports detailed changes in estimated processing capacity.

I estimate the total net cost of implementation, including equipment and three years of operation, to be approximately 2,893.09 crore INR and benefits from sale of LFG capture for three years to be approximately 117.6 crore INR. The cost-effectiveness, or the total waste diverted divided by the net cost, is approximately 0.16 tonnes of waste diverted per day per INR crore investment.

Table 5: Summary of Waste Outcome, Centralized WM

Summary	**Weight (TPD)**	**Share of Total (%)**
Total sustainably processed	5,498.62	45
Total dumped or landfilled	6,851.38	55
Total MSW generated	12,350	100

Climate Change: **83% decrease in carbon dioxide equivalent**
Under a centralized model, landfill gas capture technology captures the bulk of carbon-dioxide equivalent generated by decomposing biodegradable waste. With a functioning LFG capture system, I estimate the carbon-dioxide equivalent per tonne of waste landfilled is 0.11, and with 6,851.4 TPD of waste landfilled, will generate 730 tonnes of carbon-dioxide equivalent per day. The option reduces the status-quo CO_2 production by 83 percent.

Health Risk: **Medium-risk** to human health**.**
This option greatly reduces exposure to air pollution from landfills and WtE incineration, but does not address disproportionate health costs borne by informal waste workers. By capturing landfill gas and investing in technology to clean WtE emissions and by-products, the alternative addresses concerns brought forth by environmentalists and advocates to prevent further harm to community health. However, by failing to recognize or allocate resources to informal recycling cooperatives, the option does not impact health outcomes of informal workers. Thus, by lowering the burden experienced by communities and not directly improving the burden experienced by workers, the centralized option is a 'medium' health risk.

Political feasibility: **Moderate.**
The centralized option is moderately politically feasible. In July 2018, the South Delhi Municipal Corporation (SDMC) brought a lawsuit to the state court to authorize the construction of an additional landfill and WtE incineration plant in the Delhi Ridge (*Down to Earth*, 2018). The SDMC is the wealthiest municipality in Delhi. Although this legislative action is not conclusive evidence of total deviation from the national or state policy outlook, or that other municipalities are following suit, it does suggest that municipalities do have the agency to defer from national recommendations with support from private landfill or WtE operators. However, this legislative action has prompted widespread protests in South Delhi, including a major protest on March 23th, 2019, with a turnout of over 3,000 people (*Times of India, 2019; Hindustan Times, 2019; Delhi Greens, 2019; The Hindu, 2018; Down to Earth, April 2019)*. This suggests that the option lacks public support

In addition, municipalities have tested landfill gas capture projects, further suggesting interest in centralized strategies. A pilot LFG capture system was installed at the Ghazipur landfill in 2017 and considered a success; LFG-capture systems have not yet been established in the other two landfills, but this is evidence that the technology is already being considered (Nandakumar, 2017). Despite the show of local government interest, without support from state and national agencies or the public the option is only moderately feasible.

Administrative feasibility: **Low.**
Evidence from the status-quo suggests that implementing clean centralized technologies is not administratively feasible. Despite existing regulation, WtE technology is implemented improperly and landfills remain unsanitary. Because landfills and WtE incinerators are privately operated, this suggests that the state government may not have the capacity to hold operators accountable for compliance with regulation. Non-compliance may be due to the significant investment required to increase compliance with regulatory legislation (approximately 3,000 crore INR or $400 million USD), but there are likely other factors at play as well.

Option 4: Develop a Zero- Landfill system

In this strategy, Delhi moves towards eliminating landfill disposal from its solid waste management system. In an ideal 'zero-waste' system, material flow is circular: 100 percent of waste is reused, recycled, repaired, or redistributed. While a completely 'zero-waste' system is not feasible in Delhi over the next three years, this alternative considers increasing biodegradable, recyclable, and inert waste processing to close the city's landfills. The alternative increases processing by adding household composting, introduces more formal collection agreements with recyclists, and increases inert processing capacity.

- Total implementation of Option 2: The municipality implements all components of Option 2 (Decentralized WM) and recovers 64 percent of total waste generated.

- Launch awareness campaign for household compost: The plan will educate and sensitize waste generators to the importance of segregation at source, subsidies for composting equipment, and penalties for non-compliance. It will launch a Delhi-version of the India-wide mobile application "I Got Garbage" to inform citizens of collection schedules, source-separation guidelines, and fees. I estimate that household compost will process an additional 4 percent of biodegradable waste, cost 70 crore INR for awareness campaigns and subsidized equipment, and generate an additional 32 crore INR in revenue.

- Employ informal recyclers: In addition to strengthening cooperatives, municipalities will uptake a rights-based approach by hiring recycling cooperatives to executive collection in underserved wards. The municipality will also train and hire informal workers to operate community composting facilities. I estimate the additional integration will increase recyclable waste recovery by 30 percent relative to the status quo and cost 6 crore INR.

- Invest in community bio-gas composting: In addition to anaerobic compost, the MCD could support mobile and fixed community and household bio-gas composting units. Biogas composting units capture emissions released from decay of compost, which can be used for cooking in households and businesses. The additional investment in compost could increase municipal and community compost capacity by 11 percentage points and cost 200 crore INR.

Cost Effectiveness: **6.38 – 10.35 tonnes of waste diverted** per day per INR crore investment
In this option, I consider two variations of the option: full implementation with 100 percent waste collected, and partial implementation with 10 percent leakage where 90 percent of waste is collected.

Under full implementation of this option, I estimate that the changes in segregation, collection, biodegradable waste recovery (compost, WtE), recycling infrastructure, and compliance are capable of processing approximately 87 percent (10,700 TPD) of the total municipal solid waste generated, while 13 percent (1,650 TPD) is landfilled or dumped. This option increases resource recovery by 114 percent relative to the status quo, or an additional 5,691 TPD diverted from landfills. Table 6 reports these results, while the accompanying Table A.6 reports the estimates of processing capacity for each waste intervention by waste type.

I estimate the total cost of implementation, including equipment and three years of operation, to be approximately 1,066 crore INR (2017), and benefits from compost sales and user fees to be approximately 517 crore INR (2017). The cost-effectiveness, or the total waste diverted divided by the net cost, is approximately 10.35 tonnes of waste diverted per day per INR crore investment.

With partial implementation, I estimate that approximately 69 percent of total waste generated is sustainably processed (8,518 TPD) while 21 percent is landfilled or dumped (3,831.6 TPD). This option increases resource recovery by 70 percent relative to the status quo, or an additional 3,509.76 TPD diverted from landfills. Using the same net cost assumptions from full implementation, the cost-effectiveness is 6.4 tonnes of waste diverted per day per INR crore investment.

Table 6: Summary of Waste Outcome, Zero-Waste WM Model

	Summary	Weight (TPD)	Share of Total (%)
Full compliance	Total sustainably processed	10,699.9	87
	Total dumped or landfilled	1,650.3	13
	Total MSW generated	12,350	100

	Total sustainably processed	8,518.4	69
10% leakage	Total dumped or landfilled	3,831.6	31
	Total MSW generated	12,350	100

Climate Change: **82 - 97% decrease in carbon dioxide equivalent**
In the zero-waste option, nearly 92 percent of biodegradable waste is processed. Because biodegradable wastes are the primary source of GHG emissions in landfills, the increase in processing yields a lower estimate for carbon dioxide equivalence per tonne of waste dumped per day (0.09 CO_2). By reducing waste landfilled or dumped to 1,650 TPD, the zero-waste option generates approximately 142 CO_2 equivalent per day, a 97 percent reduction.

With partial implementation, the option collects 90 percent of waste and recovers approximately 82 percent of biodegradable waste. The CO_2 equivalent per ton of waste dumped increases to 0.19, generating approximately 736 tonnes of CO_2equivalent. This is an 82 percent decrease in CO_2 equivalent production relative to the status quo.

Health Risk: **Low-risk** to human health**.**
The zero-waste option further reduces risk to human health by expanding on the benefits outlined in Option 2 (Decentralization). It increases compliance with segregation to further reduce the contamination of biodegradable waste in WtE incineration and pollution, which reduces pollution exposure to communities surrounding landfills and WtE incinerators. The option also holds municipalities accountable for improving working conditions for informal workers by integrating them into the formal system. With this additional investment in segregation, compliance, and accountability for the informal sector, the zero-waste option is considered low-risk to human health.

Political feasibility: **Low.**
Additional research is required to determine if this option is politically feasible. As with Option 2, there is both state and national support for decentralization. However, municipalities face low incentive comply with formal integration of the informal sector into waste collection and compost because they currently reap the benefits of recycling recovery at little to no operating or capital cost. Furthermore, the public would be responsible for processing nearly 14 percent of biodegradable waste in their homes and communities. Stakeholder analysis is required to assess public support for this option. Without explicit public, national, state, or municipal support for zero-waste, political feasibility is low.

Administrative feasibility: **Low.**
Administratively, this option faces the same challenges as Option 2 and requires additional compliance from households and businesses to completely restructure waste collection to include the informal sector. To achieve desired results, it requires high compliance and

drastic system-wide change to ensure all waste types are sustainably processed. Thus, administratively this option would be challenging to execute.

Analysis of Policy Options

The above analysis is consolidated into a table of outcomes, using estimates from the partial implementation (10% leakage) of decentralized waste management and zero-waste waste management (Table 7). The partial implementation estimates are used to allow for expected variation compliance and implementation. There are significant tradeoffs among the options, and the final recommendation rests on the relative importance between criteria: waste diverted and cost effective are most important, followed by climate change and health risk to society, and finally political and administrative feasibility.

Table 7: Outcomes Matrix of Waste Management (WM) Strategies

Option	Waste diverted (%)	Cost effectiveness*	Change in CO_2 (%)	Health Risk	Political Feasibility	Administrative Feasibility
Status Quo	41	0	0	High	Low	High
Decentralize WM	49	44	46	Medium	Moderate	Moderate
Centralize WM	45	1.2	83	Medium	Moderate	Low
Zero-Waste WM	69	45	82	Low	Low	Low

**cost reported in millions of USD*

Delhi's top priority is to increase its capacity to recover waste and divert waste from exhausted landfills. When allowing for a realistic 10 percent leakage in segregation of waste in Option 2 (Decentralized WM) the proportion of waste diverted is within a few percentage points of Option 1 (Status quo) and Option 3 (Centralized WM). However, Option 2 is still significantly less expensive than Option 3 and is 36 times more cost effective. Option 4 (Zero-waste) is equally cost effective to Option 2, but aims to recover significantly more biodegradable, recyclable, and inert waste than Option 2 while incurring proportional increases in cost and revenues. Charts 2, 3, and 4 provide a visual comparison of the changing proportion of processed and landfilled waste for each management option, revealing that Option 4 is capable of sustainably processing the largest volume of waste and therefore diverts the most waste from landfills.

Chart 2: Decentralized Solid Waste Management by Waste Type

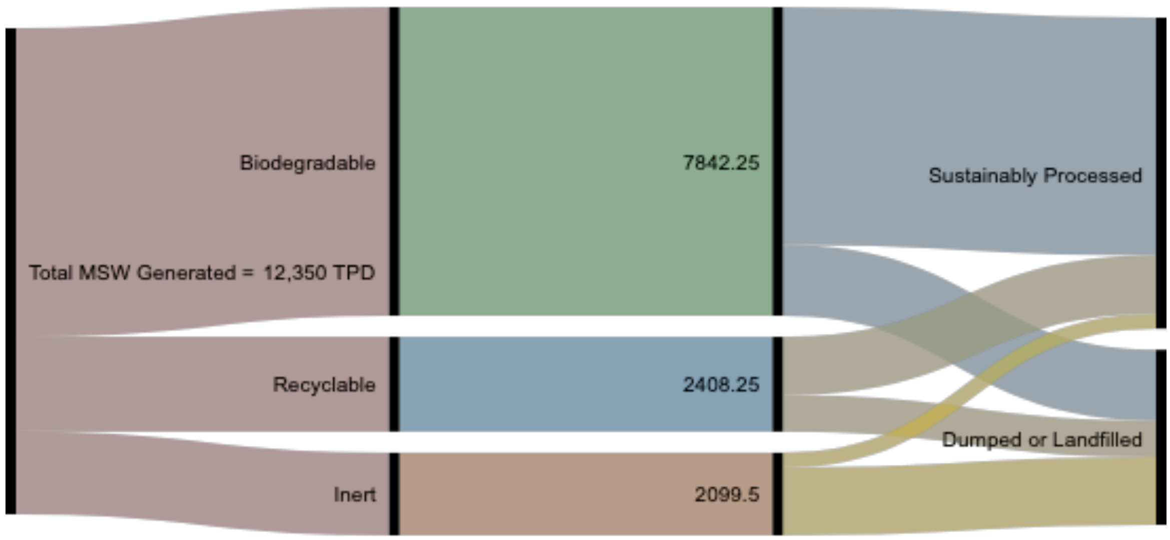


Chart 3: Centralized Solid Waste Management by Waste Type

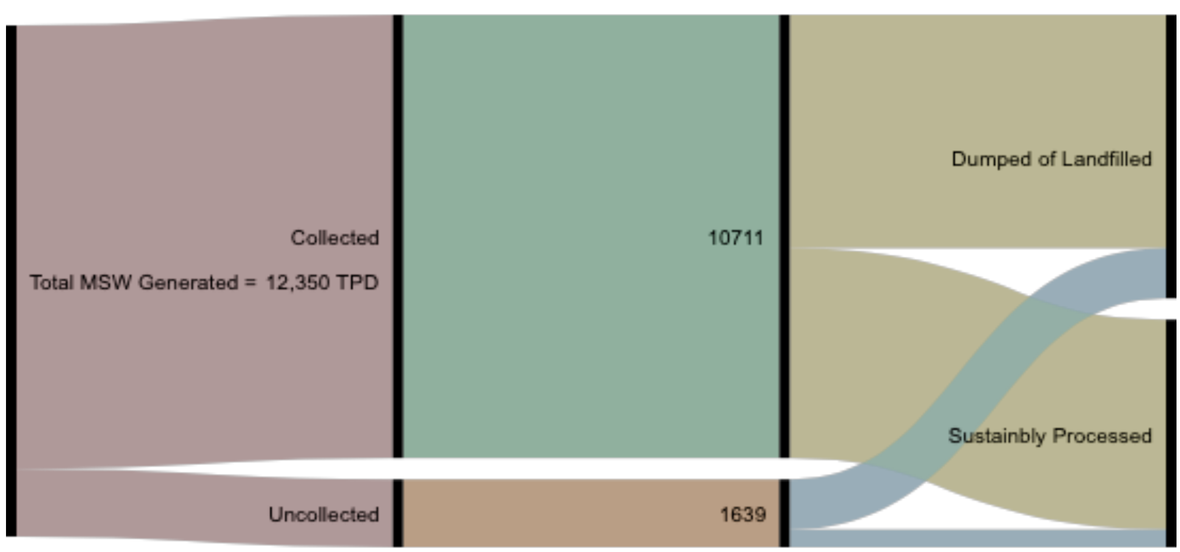
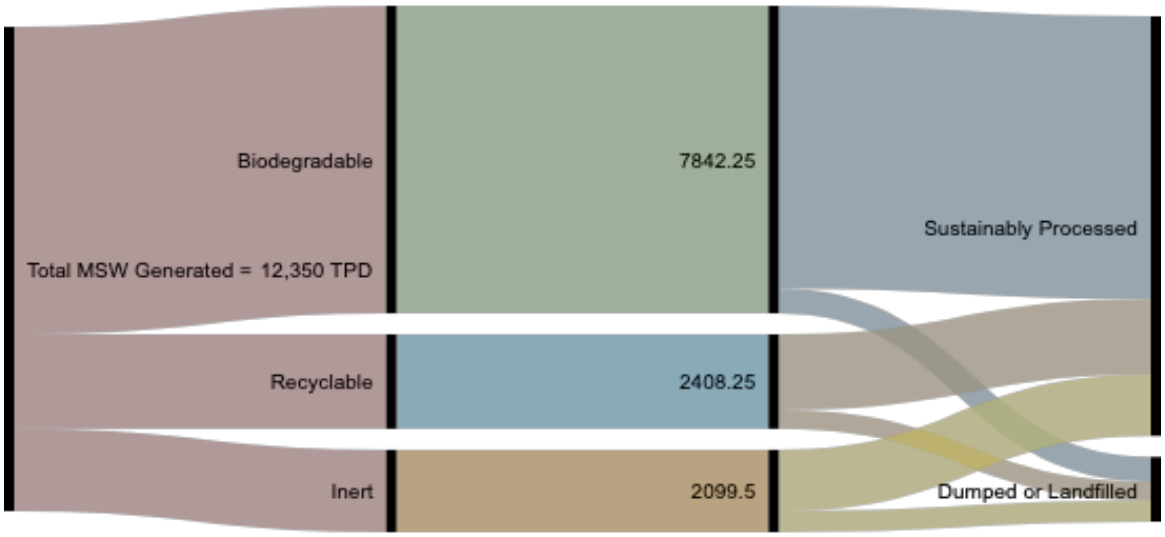


Chart 4: Zero-Waste Solid Waste Management by Waste Type



The climate change and health risk criteria are equally important. Options 3 and 4 are both highly effective in reducing net greenhouse gas emissions. Option 3 relies on centralized technologies for emissions capture, while Option 4 optimizes recovery of biodegradable waste. Option 2 still significantly decreases emissions, but is about half as effective as the other options.

Neither Option 2 nor Option 3 include specific provision for recyclists, but both provide protection for communities; Option 2 reduces contaminated waste in landfills and WtE while Option 3 cleans contaminated emissions. Option 4 has the lowest health risk because it provides additional provision for health care to informal workers, and with higher levels of segregation of waste, nearly eliminates contaminates from WtE incineration and landfilled wastes that would affect the health of surrounding communities. Therefore, it has the lowest health risk to society at large.

The final tier of criteria is political and administrative feasibility. Option 1 and Option 4 are both politically infeasible, but for different reasons. All tiers of government have voiced interest, through legislation or commentary, for improving quo waste management, and citizens have expressed discontent with the status quo through protest and advocacy. While no stakeholders have voiced opposition to Option 4, further assessment is required to determine if communities are willing to compost and the feasibility of informal sector integration. Options 2 and 3 are moderately feasible as different stakeholders have expressed support, but ultimately Option 2 has stronger explicit support. Option 2 is endorsed by national legislation ordering it to take effect, as well as enthusiastic support from the public, environmentalists, and advocates. Option 3 appears to be the system of choice for the wealthiest municipality in Delhi, which may suggest influence from private operators can prevent municipalities from decentralizing despite national law. However, it lacks support from the public, weakening its position against Option 2.

In terms of administrative feasibility, Option 1 is the most feasible because no further action is required to implement it. Option 2 is moderately difficult to administer as it requires changes in systematic waste management, but many cities in India have successfully decentralized formerly centralized management systems, so it remains administratively feasible. Option 3 and Option 4 have low administrative feasibility. For Option 3, it is unlikely that massive investment and / or changes in centralized waste management technologies are capable of being enforced, as current protections are neither enforced nor implemented for reasons unknown to the author. Option 4 is the most difficult to implement as it requires widespread system change to execute and attain the desired impact.

Recommendation

I recommend **Option 4: Develop a Zero- Landfill system.** Option 4 is an enhanced decentralized model that is cost effective, mitigates emissions, and reduces waste management's health risk to society. Its major limitation is feasibility, but for the purposes of advocacy, the feasibility criteria are the least important. If the municipalities are incapable of forming informal-formal partnerships and / or implementing widespread biodegradable waste recovery, the model will resemble Option 2. Relative to Option 3, Option 2 is still highly cost effective and moderately feasible.

Caveats

This analysis makes several assumptions, limiting the scope of its generalizability. The estimates for waste generation and waste content are averages of several sources outlined in Tables A.7 and A.8. The volume of daily waste generated is not regularly collected in Delhi, so I used estimates for India's per-capita waste generation and multiplied by the estimated population of Delhi. For waste content, I took the average of two primary sources that estimate waste content of Delhi in 2012 and 2006. I cross-checked these averages with World Bank estimates on waste content in South Asia, and found the estimates were within five percentage points of their range. I did not include the South Asia estimates into the average because the region is extremely diverse and India estimates, though dated, were more relevant.

For cost-effectiveness, the analysis relies on existing cost analyses conducted on decentralized waste management strategies (for example, waste segregation initiatives, awareness campaigns, compost pits, etc.) In a city the size of Delhi, these costs may undergo economies of scale, and thus overstate their true cost of implementation. Options 2 and 4 also incorporate compost sales to off-set initially high start-up costs. While I use the market rate for compost and account for selling 80 percent of compost generated, if quality control metrics are not enforced its possible compost will not generate the necessary revenue to offset these costs. On the other hand, if compost sales are greater than 80 percent, revenues would outweigh costs in the three-year time period.

To measure emissions, I multiplied the tonnes of carbon-dioxide equivalent emissions per tonne of biodegradable waste by the change in biodegradable landfill deposit for each option. This estimate came from Annepu (2012) which collected primary data on landfill emissions in India. While this figure captures an important source of emissions generated from landfills, it does not consider the change in emissions associated with changes in waste collection or burned waste. The estimate is also from 2012, and it's possible that the change in waste composition over the seven years could alter emissions generation. Furthermore, compost may also contribute to emissions, but in many systems these emissions are captured. However, it is possible that compost could release emissions if systems are mismanaged.

Option 3 suggests improvements to centralized waste management systems, such as WtE and hygienic landfilling, to mitigate concerns about health risks and emissions. Because WtE and landfill operations are privatized, I rely on evidence from watch-dog organizations (Down to Earth, Shriram Institute) and waste management experts in the United States for suggestions on improving their processing. Ultimately, without primary data, it's impossible to verify if these policy suggestions are feasible with the current WtE and landfill system.

Finally, with respect to feasibility, administrative and political feasibility fail to account for extra-governmental forces such as private market interests, acquiring sources of investment, and corruption.

Implementation

While Chintan, as an advocacy and research group, cannot directly change policy, I recommend the following avenues for implementation.

- **Continue to advocate for zero-waste sustainable solid waste management** as the ideal waste management strategy for Delhi, and support this advocacy strategy by highlighting the net reduction of greenhouse gasses, reduction in health burden, and cost-effectiveness benefits associated with zero-waste.

- **Conduct needs assessment** to assess suitable localized biodegradable and inert waste management strategies, considering pit composting, biogas capture, vermicomposting, and local landfilling for each municipality.

- **Partner with the Center for Science and Environment (CSE) to develop a Model Framework for Segregation for Delhi** with concrete strategies for implementation of segregation and resource recovery. Suggest a waste management plan and timeline for all five municipalities, and enlist support and input across sectors and disciplines by including community members, activists, environmental scientists, architects, and other experts.

- **Approach officials in State-level organizations** to push for accountability to laws and funding to support decentralization, such as subsidies for bins for segregation and support for recycling cooperatives. Specifically focus advocacy efforts on reaching officials in the Delhi Development Authority (DDA) such as Chairman Anil Baijal or Vice Chairman Tarun, or Urban Development Department (UDD) Secretary Raajiv Yaduvanshi or Secretary Sanjay Goel.

- **Consider extra-governmental approaches** to waste management by facilitating training for volunteers to coordinate waste segregation, partnerships with recycling cooperatives, and composting in their own communities. This program could be funded by collecting user fees from neighbors, similar to "neighborhood watch" programs.

Appendix

Chart A.1: Hierarchy in Solid Waste Management[8]

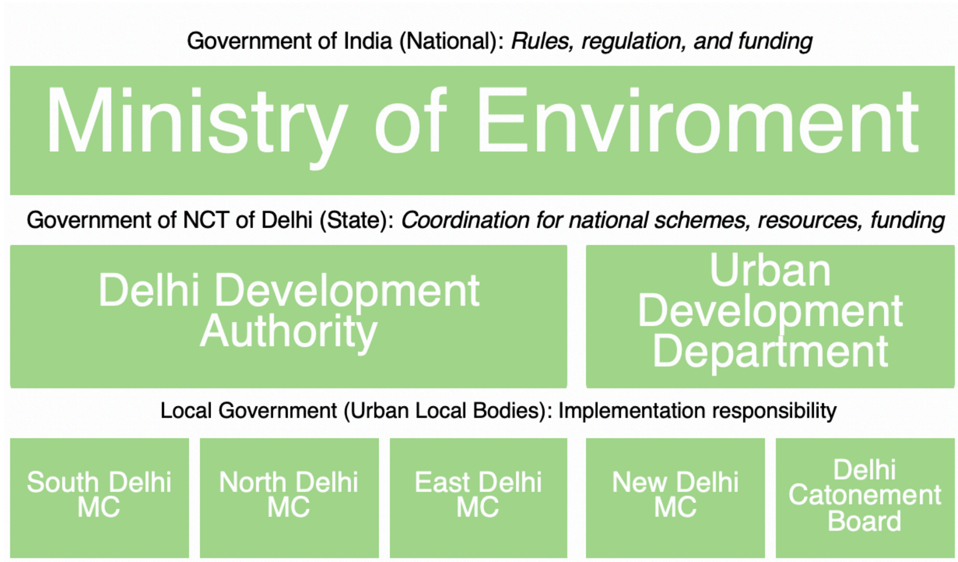


Table A.2: Estimate of Waste Processing Capacity, Option 1 (Status Quo)

Total MSW collected	**Waste type**	**Composition**	**Destination**	**Weight (TPD)**	**Processed (TPD)**	**Landfill (TPD)**
10,711.00	Mixed	Biodegradable, recyclable, non-biodegradable, non-recyclable, hazardous	City compost	1,200.00	720.00	480.00
			WtE	4,900.00	2,940.00	1,960.00
			Landfill or Dump	4,611.00	922.20	3,688.80
Total MSW uncollected	**Waste type**	**Composition**	**Destination**	**Weight (TPD)**	**Processed (TPD)***	**Landfill (TPD)**
1,639.00	Mixed	Biodegradable, recyclable, non-biodegradable, non-recyclable, hazardous	Landfill or dump	1,639.00	426.42	1,212.58

[8] *Adapted from Framework of Municipal Solid Waste in India, India Urban Development Gateway, 2017*

Chart A.3: Flowchart of Decentralized Waste Management: Destination, Intervention, and Waste Type

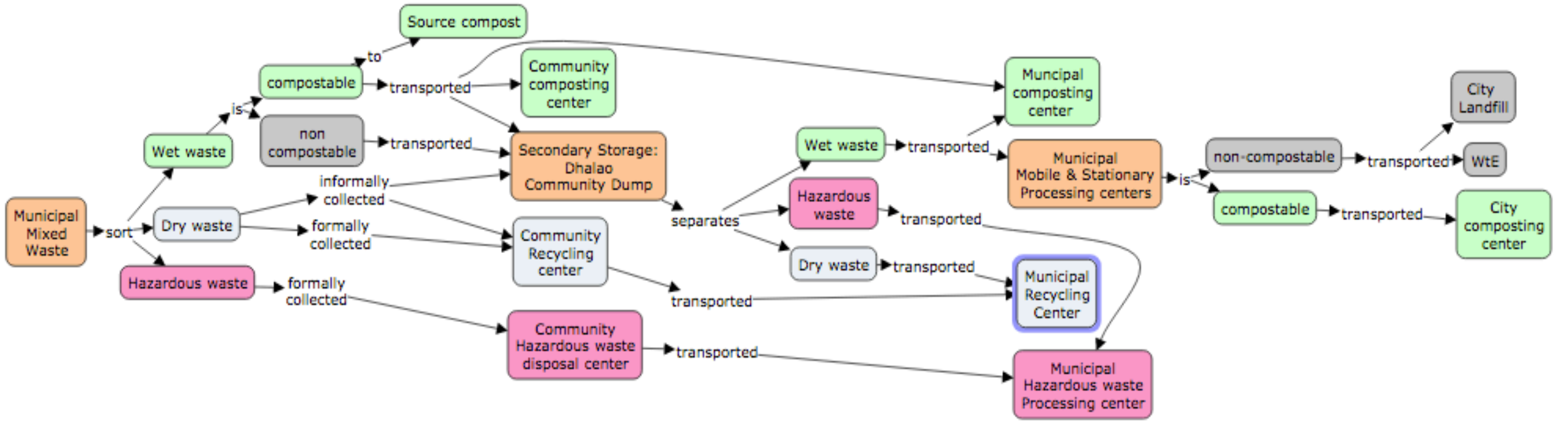


Table A.4: Estimate of Waste Processing Capacity, Option 2 (Decentralized WM)

Total biodegradable waste generated (TPD)	**Destination**	**Volume (TPD)**	**Processed (TPD)**	**Landfill (TPD)**
	Community compost	627.38	627.38	0
	Municipality compost	784.23	784.23	0
7,842.25	City compost	1,200.00	1,200.00	0
	WtE	3,430.00	3,430.00	0
	Wastage	1,800.65	0	1,800.65
Total recyclable waste generated (TPD)	**Destination**	**Volume (TPD)**	**Processed (TPD)**	**Landfill (TPD)**
2,408.25	Informal recycling value chain	1,483.48	1,483.48	0
	Wastage	924.77	0	924.77
Total NBNRHM* generated (TPD)	**Destination**	**Volume (TPD)**	**Processed (TPD)**	**Landfill (TPD)**
	Community processing	167.96	167.96	0
2,099.50	Municipal processing	209.95	209.95	0
	WtE	1,470.00	0	1,470.00
	wastage	251.59	0	251.59

Table A.5: Estimate of Waste Processing Capacity, Option 3 (Centralized WM)

Total MSW collected	**Waste type**	**Composition**	**Destination**	**Weight (TPD)**	**Processed (TPD)**	**Landfill (TPD)**
10,711.00	Mixed	Biodegradable, recyclable, non-biodegradable, non-recyclable, hazardous	City compost	1,200.00	720.00	480.00
			WtE	4,900.00	3,430.00	1,470.00
			Landfill or Dump	4,611.00	922.20	3,688.80
Total MSW uncollected	**Waste type**	**Composition**	**Destination**	**Weight (TPD)**	**Processed (TPD)***	**Landfill (TPD)**
1,639.00	Mixed	Biodegradable, recyclable, non-biodegradable, non-recyclable, hazardous	Landfill or dump	1,639.00	426.42	1,212.58

Table A.6: Estimate of Waste Processing Capacity, Option 2 (Zero-Waste WM)

Total biodegradable waste generated (TPD)	**Destination**	**Volume (TPD)**	**Processed (TPD)**	**Landfill (TPD)**
7,842.25	Household compost	313.69	313.69	0
	Community compost	784.23	784.23	0
	Municipality compost	1,481.40	1,481.40	0
	City Compost	1,200.00	1,200.00	0
	WtE	3,430.00	3,430.00	0
	Wastage	632.93	0	632.93
Total recyclable waste generated (TPD)	**Destination**	**Volume (TPD)**	**Processed (TPD)**	**Landfill (TPD)**
2,408.25	formal collection by 'informal' sector	445.04	445.04	0
	Informal recycling value chain	1,483.48	1,483.48	0
	wastage	479.72	0	479.72
Total NBNRHM* generated (TPD)	**Destination**	**Volume (TPD)**	**Processed (TPD)**	**Landfill (TPD)**

	Community processing	167.96	167.96	0
2,099.50	Municipal processing	209.95	209.95	0
	WtE	1,470*	0	1,470
	wastage	251.59	0	251.59

Table A.7: Estimates of MSW Generation in Delhi, 2019

Per capita MSW generation	**Estimate**	**Unit**	**Source**
Per-capita (India)	0.00057	tonnes of per day per capita	World Bank, 2018
*Per-capita (India)***	0.00065	tonnes per day per capita	Annepu, 2012; World Bank, 2016; CSE, 2017
Per capita (Delhi)	0.00060-0.00069	tonnes per day per capita	Delhi Development Authority, 2000
Per capita (Delhi)	0.000596	tonnes per day per capita	Municipal Corporation of Delhi (MCD), 2017
Population of Delhi	**Estimate**	**Unit**	**Source**
*High estimate***	19,000,000.00	million people	India Census 2011 (scaled up to 2019)
Low estimate	17,950,000.00	million people	MCD, 2017
Total MSW generated	**Estimate**	**Unit**	**Source**
*High estimate***	12,350.00	tonnes generated per day	MCD 2017; Census data
Low estimate	11,667.50	tonnes generated per day	MCD 2017; Census data

Table A.8: Estimates of Waste Content in Delhi

MSW Composition	**Estimate from Annepu (2012)**	**Estimate from East Delhi MC (2005)**	**Average****	**Check: WB South Asia Estimate (2018)**
Biodegradable	0.51	0.76	0.635	0.57
Recyclable	0.18	0.21	0.195	0.25
Inert	0.31	0.03	0.17	0.18

**Estimate used in final analysis

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Pledge and Signature

On my honor as a student, I have neither given nor received aid on this assignment.
Signed,

Jacqueline Jane Hammaker