Identifying Sustainable Organic Waste Management Systems in Urban India: Case Study of Pune, India

by

Rachel Martha Katims Perlman

B.S. Science of Natural and Environmental Systems
Cornell University, 2012

SUBMITTED TO THE INSTITUTE FOR DATA, SYSTEMS, AND SOCIETY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2015

Signature of Author Signature redacted
Rachel Martha Katims Perlman
Technology and Policy Program
August 7, 2015

Certified by Signature redacted
Randolph E. Kirchain, Jr.
Principal Research Scientist, Engineering Systems
Thesis Supervisor

Accepted by Signature redacted
Munther A. Dahleh
William A. Coolidge Professor of Electrical Engineering and Computer Science
Director, Institute for Data, Systems, and Society
Acting Director, Technology and Policy Program

Identifying Sustainable Organic Management Systems in Urban India: Case Study of Pune, India

by Rachel Martha Katims Perlman

Submitted to the Institute for Data, Systems, and Society on August 7, 2015 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in Technology and Policy
Thesis Supervisor: Randolph E. Kirchain, Jr., Principal Research Scientist, Engineering Systems

ABSTRACT:

With increasing population and per-capita capita waste generation, cities in India and other developing countries are seeking alternative strategies to manage the organic fraction of municipal solid waste in an effort to improve efficiency, reduce costs, and increase environmental performance. This thesis aims to explore the tradeoffs of various organic waste management strategies in the urban Indian context, specifically using a case study analysis of the waste system in the city of Pune. Door-to-door, primary, and secondary collection and four technologies for treating organics (landfilling, composting, anaerobic digestion, and pelletization) are analyzed with regard to cost and environmental performance. Because decentralized waste system architectures minimize transportation and allows wastepickers to maintain jobs, particular emphasis is made in this thesis to understand the cost and environmental implications treatment at a range of scales.

To determine the quantity and composition of waste, we conducted waste audits of MSW that was collected from 2,650 households during two different seasons. Per-capita MSW generation in Pune was found to be 134, 309, and 401 grams/day for the lower, middle, and upper income residents, respectively. Of these totals, 80%, 66%, and 69% of the MSW was biodegradable. Given that middle and upper income residents generate 2.3 to 3 times what lower income residents generate, India can expect to see a significant increase in waste volumes as its population becomes wealthier.

By comparing the spatial footprints of the technologies at a range of scales, it was found that pelletization of organic MSW (although it is not a fully developed technology) has great potential to reduce the spatial footprint of organic waste management.

Cost modeling is used to identify the drivers of cost for each process and to identify the least-cost options. The cost per ton of waste managed using anaerobic digestion, composting, and pelletization decreases significantly with larger scale of treatment. Alternative organics management technologies used at small scales (less than 0.5 TPD) are more expensive than landfilling; however, if a facility of at least 0.5 TPD is used, anaerobic digestion is less expensive than landfilling. Pelletization and composting become less expensive than landfilling at the scale of 5 TPD and 200 TPD, respectively. Although the average cost of centralized organic waste systems is lower, the difference in cost between the lowest-cost decentralized systems and lowest-cost centralized systems was relatively small.

A review of the relevant literature is used to identify the global warming impacts of organic waste processing. The global warming potential (GWP) of anaerobic digestion, pelletization, composting, and landfilling is estimated to be -51, -42, 38, and 510 kg CO_2-eq/ton, respectively. A city looking to minimize its contribution to global warming could achieve significant reductions in emissions by biodigesting food waste and pelletizing yard waste. Such systems would have a net greenhouse gas emissions savings of over 750 tons CO_2-eq each year.

Of the technologies assessed, anaerobic digestion (at scales of 5 TPD or larger) has the best combination of cost and GWP performance. However, because woody material cannot be digested, pelletization (at 10 TPD plants) has the best combination of cost and GWP performance specifically for handling yard waste. These findings suggest that for handling organic MSW, anaerobic digestion in combination with pelletization produces the best combination of cost and GWP performance.

Acknowledgements

My research has been made possible by funding from the National Science Foundation (Graduate Research Fellowship), MIT's Collamore Rogers Fellowship, and MIT's Tata Center for Technology and Design.

I would like to thank my supervisors at MIT Materials Systems Laboratory, Randy Kirchain and Jeremy Gregory, for providing guidance all along the process and for sharing their expertise on methods and subject matter. I would also like to thank Libby McDonald, Caroline Howe, Kate Mytty, and Abdullah Sheikh for their assistance in conducting field work in India and establishing key connections in Pune.

Of course, I thank my family and friends for supporting me throughout the entire process.

Within the Tata Center, I would like the thank Chintan Vaishnav for providing guidance on conducting research within the Indian context. I would also like to thank the Tata Foundation for its generosity in making my trips to India so informative and enjoyable.

Several contacts in Pune, India have graciously provided me with feedback, data, and insights on various waste systems. These individuals include Lakshmi Narayan, Malati Gadgil, Maitreyi Shankar, Aparna Susarla, Harshad Barde, Santosh Gondhalekar, Suresh Jagtap, and Suresh Rege. Lastly, I would like to extend a large thank you to the dozens of waste pickers who participated in our study, shared their experience with us – you were inspirational.

Contents

FIGURES

TABLES

Chapter 1: Introduction

1.1 Motivation for Study of Organics in India

Cities within the developing world face increasing volumes of municipal solid waste (MSW) and limited budgets and space for managing the waste. Urban waste management in India requires special attention given the magnitude of waste being generated, the demographic shift and population growth, the size of the informal sector, and the large organic fraction of waste. In India, population growth, especially in cities, is putting pressure on the capacity and function of waste infrastructure; more waste is being generated per square kilometer than ever before. Moreover, as India experiences upward mobility and a growing middle class, city residents are consuming more and disposing of more, driving up per-capita waste generation. The city of Pune, India spends over 11 million USD (71 Crore Rupees) on solid waste management – collection, processing, and disposal – each year (Times of India, 2012). Indian cities are seeking new strategies to manage MSW in an effort to improve efficiency, reduce costs, and attain environmental standards.

One of the most challenging MSW streams in urban India is biodegradable waste. In India, the majority household waste is biodegradable and is composed of food and yard waste. A large portion of commercial waste, generated by restaurants, hotels, and produce markets, is also organic. This biodegradable material (also termed organic waste) often ends up in open-air dump sites, as is common in low and middle-income countries. These unlined and uncovered landfills have negative environmental impacts on climate change and water quality. Additionally, more and more cities are struggling with the fact that residents living near landfills are protesting and pressuring the government to close the landfills. These residents are averse to continuing to landfill organic waste because it is leading to acute pollution and landfill fires from intense heat generated from the decomposing organics. Furthermore, it can be argued that piling up all of the city's waste in one neighborhood (often outside of the actual city in which it is generated) creates an unfair burden on residents living near the landfill and a violation of environmental justice.

Management of organics is particularly challenging not only because of its volume, but also because of its high water content, which makes it heavy and expensive to transport. From a health and safety and legal standpoint, cities in India are required to collect and process organic waste. If ill-managed or left in the streets to rot, decomposing organic waste generates methane and unwelcome odors, attracts animals, and leaches contaminants into waterways. In order to be economical, cities have an incentive to minimize transport and keep organics management more localized. Alternative models that involve decentralized organic waste management rather than centralized landfilling have the potential for lessening both the economic and environmental burden.

Organic waste is rich in nutrients and can be processed for the production of energy or valuable end-products; some of the treatment methods that can be used for organic waste are described in the callout box at the end of this section. The callout box describes the basic processes involved in landfilling, composting, anaerobic digestion, and pelletization; these are only four methods of treating organic waste, but other alternatives exist. However, organic waste is often an underutilized resource. Unless organic waste is segregated, it has little monetary value and cannot easily be used to its full capacity. For instance, if non-biodegradables such as multi-layer packing or diapers are mixed in with biodegradable waste, the material cannot be composted. In India, recycling rates of plastics, paper, glass and metal are relatively high because the informal sector has a direct economic incentive and channel for income generation through the collection, sorting, and selling of those materials. Unlike dry recyclable materials, organic waste does not have many value-driven channels for its use. Household waste collectors (such as waste pickers) rarely have the opportunity to sell the biodegradable material. The recovery of biodegradable waste rarely happens unless the system incentives or requires it.

Although one method for reducing the burden of organic waste management is to reduce the amount of waste generated in the first place, this is challenging for city governments to accomplish, given the disaggregated nature of MSW generation. Furthermore, even if food waste is reduced, organic waste will inevitably continue to be a large component of household waste. Therefore, cities need to find the most pro-active way to avoid negative impacts of organic waste is to use alternative methods of management that are more sustainable. Improved management of organic waste would divert significant amounts of waste from landfills, provide the potential for additional value creation, minimize the spatial footprint, and increase nutrient cycling.

General description of four methods for treating the organic fraction of MSW

Landfilling: When organic waste is landfilled, it is dumped in a large pile either in a hole or directly on the ground. If the landfill is engineered to reduce environmental pollution, it is lined with a bottom liner to prevent liquids from seeping into the soil and groundwater, designed with cells for old and new waste, covered and equipped with a system to capture methane. If it lacks most of these features, such a site is simply an open-air dump, where waste piles up and may be regularly compacted or physically stabilized. Organic waste that is landfilled may slowly decompose anaerobically, or may remain relatively unchanged for long periods of time. Unless the landfill is generating energy from captured methane, landfilling does not generate any valuable resource from organic waste.

Composting: Composting accelerates the natural (aerobic) biological decomposition process by aggregated the material, often in some sort of container. In order for composting to function properly, the mixture of organic wastes must contain both nitrogen- and carbon-rich material, some moisture, oxygen, and naturally present bacteria. A diversity of materials, such as leaves, twigs, manure, food scraps, grass, wood chips, and paper can be composted. Composting significantly reduces the volume of material, as water and CO_2 off-gas. Shredding material before composting reduces the decomposition time and improves the quality of finished compost. After a period of maturation, which may take weeks or months, the end product of the process is compost, which is a biologically-active, nutrient rich soil-like material that can be used as a soil amendment. There are many versions of composting, such as vermi-composting (using worms), windrow-composting, pit composting, and bin composting.

Anaerobic Digestion: Anaerobic digestion processes organic waste in a tank digester under oxygen-free conditions. Micro-organisms biologically decompose the (often wet) material, generating biogas, which is principally composed of methane and carbon dioxide, as well as a liquid fertilizer (sludge). Anaerobic digesters can process food waste, waste oils, animal waste, and sewage, but cannot process woody materials such as twigs or coconut husks. The more putrescible the material, the higher the biogas yields of the digester will be. The biogas is filtered and the methane can be fed into an engine to generate electricity. The sludge can be applied to garden or agriculture fields as a fertilizer.

Pelletization: Pelletization of organic waste is a physical process in which the material is screened, shredded, dried, and densified to create fuel pellets or briquettes. These pellets can be burned as a fuel in cement kilns, power plants, boilers, or stoves. As is the case when burning any solid fuel, pellet burning systems should have scrubbers or other systems to reduce the emission of air pollutants. Pelletization is most energetically efficient if the input material is drier and has a high-calorific value.

1.2 Objectives and Research Question

This thesis aims to explore the tradeoffs of various organic waste management strategies in the urban Indian context. Specifically, this thesis uses environmental and economic metrics to quantify and characterize the impacts of organic waste management; it also uses qualitative social and labor indicators to assess the impacts of waste management on stakeholders. Stages of collection and technologies for treating organics are analyzed using these metrics. Particular emphasis is made to understand the implications of the scale of treatment, given that this can impact cost-effectiveness, environmental burden, and social acceptability. Using decentralized system architectures for waste management is beneficial in that it enable effective manual segregation, maintain jobs for wastepickers, manage the health exposure risks, and minimize transportation. This thesis aims to test the hypothesis that there are decentralized waste system architectures that can improve on the economic and environmental performance of organic waste management systems. This thesis aims to answer the question, what are the characteristics of a decentralized system that:

(1) Is appropriate for the quantity and composition of waste generated in urban Indian?
(2) Is cost-effective collecting and treating organic waste?
(3) Reduces global warming impact (i.e.., greenhouse gas emissions)?
(4) Impacts stakeholders, including the informal sector, positively?

1.3 General Approach and Structure

In order to answer the above question, I use a multi-pronged analysis that looks at the economic, environmental, and social impacts of waste management in order to identify sustainable organic waste management. I have applied these analyses to the case study of one of India's largest cities, Pune. Through the use of one city as a case study, I am able to use primary data, conduct in-depth analysis of scenarios, and provide useful results to decision makers in India.

In this thesis, I use a variety of tools to analyze organic waste management strategies. I use interviews, personal observations, and literature review to understand the historical and political context of waste management in the city. I also use stakeholder analysis to understand incentives, needs, and constraints on the system and its actors. I use materials flow analysis to map municipal waste streams from generation to treatment. Additionally, I use the empirical results of two waste audits to analyze the quantity and composition of waste as a function of income and seasonality. Cost modeling is used to identify the drivers of cost for various technologies and processes and to identify the least-cost options. A review of the relevant literature is used to identify the global warming impacts of organic waste processing. And stakeholder perspectives on the waste management system and its future direction were obtained by hosting a workshop and conducting surveys.

This thesis is structured in the following way: Chapter 2 characterizes the policies, logistics, processing methods, and stakeholders related to the waste management system of Pune, the location serving as the central case study of the thesis. Chapter 3 analyzes the quantities, composition, and per-capita generation of MSW in Pune, as they relate to socioeconomic status. Chapter 4 uses primary and secondary data to analyze the social and labor impacts of waste management from the perspective of the informal sector and other actors. In Chapter 5, I use cost modeling to quantify the costs of various processes involved in managing biodegradable waste, including door-to-door collection, primary and secondary collection, landfilling, composting, anaerobic digestion, and palletization. Chapter 6 quantifies and compares the global warming impact of a number of waste processing activities. Chapter 7 uses scenario analysis to identify management strategies that space-saving, cost-effective and environmentally responsible. Chapter 8 concludes, highlighting the key findings and lessons about what comprises sustainable organic waste management in urban India.

Chapter 2: Pune as a Case Study

2.1 Motivation for Studying Pune

In order to explore the central topics of this thesis using in-depth systems analyses, we focus on the case study of one city within India. We chose Pune as the location of the case study after visiting several cities within India and learning the different waste systems in place and projects in planning. Pune has a population of over four million and is located in the state of Maharashtra. **Error! Reference source not found.** shows some general demographics about une. We were drawn to select Pune as our case study because of the innovative projects going on, the organizational strength of the informal sector, and the potential for partnerships and information exchange with the government and businesses.

Table 1: Demographics of Pune City.

Demographics of Pune Municipality (2011)	2011 Indian Census (Government of India, 2012)	Estimated 2014 figures based on 5% annual urban growth rate
Total Population Persons	3,304,888	4,643,130
Total Population Male	1,700,867	2,389,596
Total Population Female	1,604,021	2,253,534
Children Age 0-6	355,703	499,737
Number of Households	781,507	-
Average Household Size	4.2	-
Average yearly income of working class family (Pune Bureau of Labor)	119,943 Rs	-

Pune is nicknamed the "Oxford of the East," because of its strong reputation in higher education. Pune has a high concentration of universities, colleges, and other institutes dedicated to education in a variety of disciplines; we were told students account for 40% of the city's population (Jagtap, 2013). Pune is multicultural, young, well-educated, and relatively progressive. Waste management is one area where Pune is indeed more progressive than most other cities in India.

Like other large cities in India, Pune is experiencing a number of challenges regarding the economic, environmental and social pressures of waste organic waste management. Not only has Pune's population size increased by 30% between 2001 and 2011 (Government of India, 2012), but the city's growing middle class and prosperity has contributed to increasing per-capita waste generation. The city estimates that it produces about 1,600 metric tons per day, which is up from the 1,100 tons per day produced in 2006 (Kale et al., 2008; Isalkar, 2013).

As is the norm in India, Pune chose to handle such large volumes of waste by trucking it to an unoccupied piece of land and dump it, forming an unlined, untreated landfill. Open dumping of Pune's waste created methane emissions, water pollution, and unhappy residents. When local residents won a court case against the Pune Municipal Corporation in 2001, they forced the city to close it original landfill in area called Paud (Pallavi & Dutta, 2015). The city then created a new unlined landfill area in the South-eastern outskirts of the city, in the village of Uruli Devachi. What was promised to be a landfill of limited size kept growing, and this lead to heated protests by residents living close to Uruli Devachi. For the past few decades, social pressure to close the landfill has pushed Pune to explore alternative strategies for dealing with waste. For instance, the Pune Municipal Government (PMC) began by investing in large-scale waste-to-energy plants using technologies such as gasification and pyrolysis; however, the facilities have experienced operational problems and have only been running at a fraction of their intended capacity. The city has also established centralized composting facilities, anaerobic digesters, and is in the process of piloting a pelletization plant – all in an effort to accomplish its publically-announced goal of "zero waste." All in all, Pune has made a substantial effort to handle the city's waste in a more environmentally responsible way, and is using a combination of methods to do so, making it a complex and exciting case study.

Moreover, Pune has supported decentralized waste solutions and novel partnerships with the informal sector, which makes the city's waste system unique. With the help of a local university, wastepickers in Pune first unionized in 1993, forming the union KKPKP and eventually the waste picker cooperative, SWaCH (Solid Waste Collection and Handling, or, officially Seva Sahakari Sanstha Maryadit, Pune); now, Pune has one of the most organized wastepicker communities in the developing world. By 2008, after much activism and a long process of negotiation, the city made a formal agreement to partner with the waste picker cooperative and authorize wastepickers to do door-to-door waste collection. Pune's waste collection and processing system truly is a collaborative effort between the informal and formal sectors, involves both decentralized and centralized solutions.

2.2 Waste Laws and Policies

2.2.1 Organics Source Segregation Policies

In 2009, the city passed a regulation mandating that all restaurants and hotels (large generators of food waste) separate out food waste before it is picked up by the city. Interviews with hotels and restaurants, conducted by Howe (2014), found that these generators are indeed aware of the regulation and comply with it. To enforce the regulation, the city does not pick up the generator's waste if it is not properly segregated. This method of enforcement seems to be effective. The food waste generated by restaurants and hotels is transported to either a biogas or composting facility.

Despite that the city technically requires source segregation of organic waste, residents generators often do not consistently comply, and simply combine all of their waste for collection. As shown in **Error! Reference source not found.**, essentially all types of generators f organic waste within Pune are required to separate out organics, in addition to recyclables. While most residents will separate out high-value recyclables to sell to itinerant buyers, some residents do not feel compelled to segregate organics (potentially viewing this as the job of wastepickers). According to PMC, 44% of households segregate their organic waste (Suresh, 2012) When organics are not properly separated, they end up going to a commercial facility along with other mixed waste, and are made into low-grade compost or refuse-derived fuel pellets.

Table 2*:* Legally mandated rules for source segregation of materials for various generators, as outlined in Pune Municipal Corporation Public Health and Sanitation Bylaws (Pune Municipal Corporation, 2014)

Generators	**Waste Streams to be Separated (by law)**											
	Organics	Recyclable	Refuse	Construction waste	E-waste	Hazard & Sanitary	Reusable in the same site	Inert for landfill	Biomedical	Garden	Effluents	Batteries
Individual houses	X	X		X	X	X						
Govt and private societies	X	X		X	X	X						
Bungalows, apts	X	X		X	X	X						
Slums and chawls	X	X	X									
Hotels and restaurants	X	X		X	X	X						
Shops and offices	X	X		X	X	X						
Marriage halls, trade fairs, etc.	X	X	X									
Vegetable/fruit markets	X	X	X									
Fish/meat markets	X	X	X									
Street vendors	X	X	X									
Construction sites							X	X				
Educational institutions	X	X		X	X	X						
Hospitals	X	X		X	X				X			
Gardens	X	X								X		
Heritage buildings	X	X	X									
Religious places	X	X	X									
Industries	X	X		X	X	X						
Household industries	X	X		X	X	X						
Dairy and cattle sheds		X				X					X	
Garages/workshops	X	X		X		X						X

2.2.2 Waste Collection Policy

In 2000, India passed the Municipal Solid Waste Management and Handling Rules, which required that all cities be responsible for the door-to-door collection, segregation, transportation, processing, and disposal of MSW (India Ministry of Environment and Forests, 2000). Pune was forced to organize and implement cost-effective door-to-door waste collection, and this opened the door for SWaCH to acquire formal rights for wastepickers to perform waste collection. SWaCH successfully made the case that a model in which wastepickers are responsible for door-to-door collection would be efficient and socially inclusive. Consequently, in 2008, PMC and SWaCH agreed to a Memorandum of Understanding (MOU); although informal wastepicking had already gone on in Pune for decades, door-to-door collection of waste by wastepickers became formally authorized and institutionalized by the MOU. The MOU also allocated funds to infrastructure and management for SWaCH and required generators to pay user fees for collection by wastepickers (Maharashtra Government, 2008). As part of the agreement, SWaCH wastepickers must collect organic waste (traditionally something that has little commercial value to them) and dispose of it in the local dumpsters. In this way, the city has involved the informal sector in collection of organics. It remains to be seen how this arrangement will evolve in the coming years, given that the MOU expired in 2013, and has not be renewed.

As of 2012, SWaCH wastepickers collect waste from 48% of the city's households (Chikarmane, 2012). The rest of the city's households are served one of the following: (1) wastepickers that are not part SWaCH, (2) private waste haulers hired by residential communities, or (3) public collection trucks that empty out dumpsters outside of housing complexes. Commercial businesses generally receive collection service from PMC waste hauling trucks, and hotels are serviced separately to transport the segregated food waste to biogas or compost facilities (Tangri, 2012). The city estimates that 97% of MSW generated in the city is collected (Jagtap, 2013).

2.2.3 Waste Processing Policies

With the passage of the 2000 MSW Rules, Pune has an obligation to make sure all of its city's waste is responsibly processed, and not openly dumped. Furthermore, organic waste can create major problems with sanitation and pollution if it is not collected and processed, so the city does not want organics piling up around the city. Recycling of paper, plastics, and metals will usually occur in Indian cities even without government intervention because of the market incentives; but, organics recovery and processing may not be profitable and often need policy and economic incentives.

Tax rebates are one type of mechanism the city has used to encourage sustainable management of organics. Any residential society (neighborhood or apartment complex) that composts its waste onsite receives a 5% property tax rebate. Also, any apartment complex built after 2010 is required to compost its waste (Howe, 2014). The Institute of Natural Organic Agriculture (INORA) is one organization that helps communities set up compost systems and train residents on its maintenance. However, a large percentage of the compost pits in existence in societies are not consistently used or dysfunctional (Shetty, 2014). Furthermore, to encourage entrepreneurs and businesses to enter the biogas business, the city gives producers of green energy, such as biogas plants, tax benefits. Biogas companies only have to pay tax on 20% of their profits (as opposed to fossil-fuel energy companies that pay tax on 100% of their profit) (Rege, 2014).

The PMC has publically committed Pune to becoming a "Zero Garbage" city, meaning that it aims to recycle or process all waste using methods other than landfill. The zero garbage model also involves reducing transportation costs and increasing source separation. The city's plan involves recycling recyclables, using non-recyclable waste to create refuse-derived fuel pellets, and processing organic waste with composting, biogas, and palletization (Suresh, 2012). As of 2015, the city has not yet reached this goal, but is making efforts to eliminate landfilling completely, as well as to keep waste processed within the same ward it is generated. **Table 3** summarizes the processing and disposal method rules and guidelines outlined in the 2014 PMC bylaws.

Table 3: Legally mandated rules on processing and disposal methods by generator, as outlined in Pune Municipal Corporation Public Health and Sanitation Bylaws (Pune Municipal Corporation, 2014).

	Waste Processing and Disposal Methods			
Generators	Organics "may" be processed by composting, biogas etc.	Recyclables "may" be recycled	"Shall" establish and maintain own facilities	If cannot process waste onsite, must pay per ton for management
Individual houses	X	X		
Govt and private societies	X	X		
Bungalows, apts	X	X		
Slums and chawls	X	X		
Hotels and restaurants			X	X
Shops and offices	X	X		
Marriage halls, trade fairs, etc			X	X
Fish/meat markets			X	X
Educational institutions	X	X		
Hospitals			X	X
Gardens			X	X
Industries			X	
Household industries			X	
Dairy and cattle sheds			X	
Garages/workshops			X	

2.3 Pune's Waste System

2.3.1 Logistics

Since waste collection in Pune is executed by a number of actors in both the informal and formal sectors, the logistics of waste collection and transportation are relatively complex. As described above, door-to-door collection is mainly conducted by wastepickers. **Error! eference source not found.** diagrams the process of collection of waste from households, as it is intended to occur.

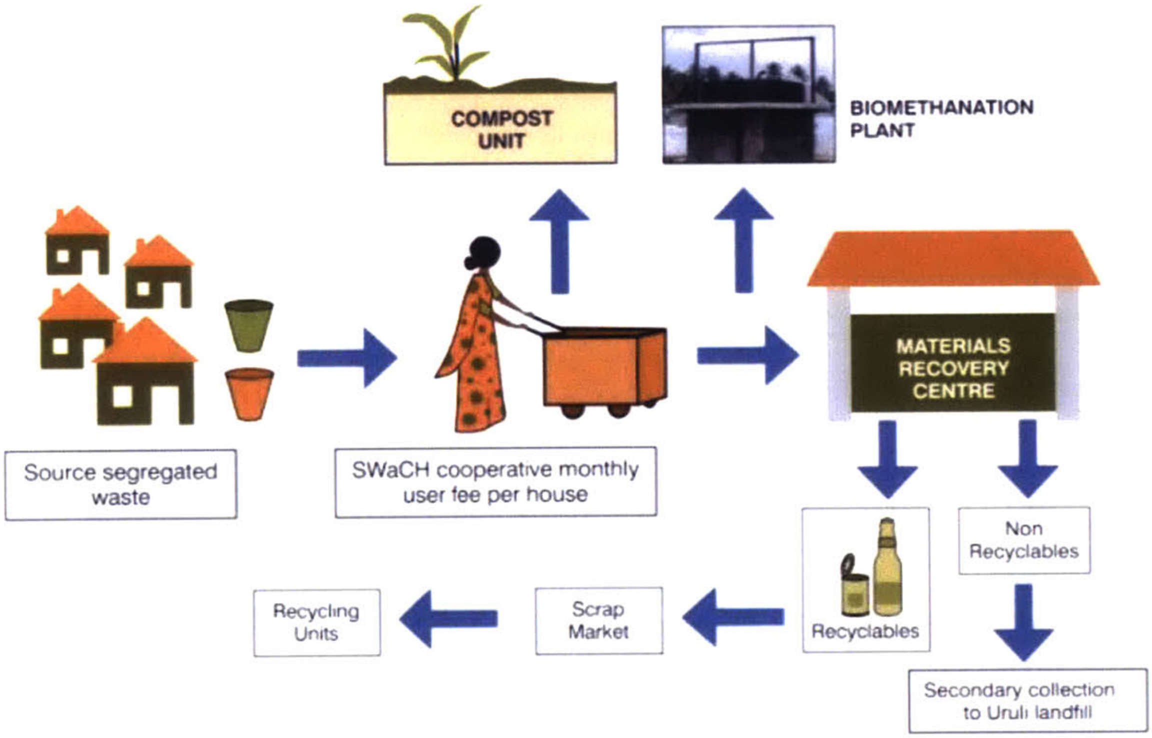


Figure 1: The movement of municipal solid waste form households through the waste system. Source: Figure taken directly from *Integrating Waste Pickers into Municipal Solid Waste Management in Pune, India* (Chikarmane, 2012).

Besides door-to-door collection, waste collection in Pune can be broken down into two steps – primary collection and secondary collection. A schematic of waste collection and transport can be found in **Error! Reference source not found.**. Primary collection consists of rucks picking up and transporting waste from dumpsters or large generators to a transfer station. Secondary collection is when waste is further consolidated and larger, bulk refuse carriers (BRCs) transport the waste to a centralized processing or disposal site (such as a large-scale compost plant or the landfill).

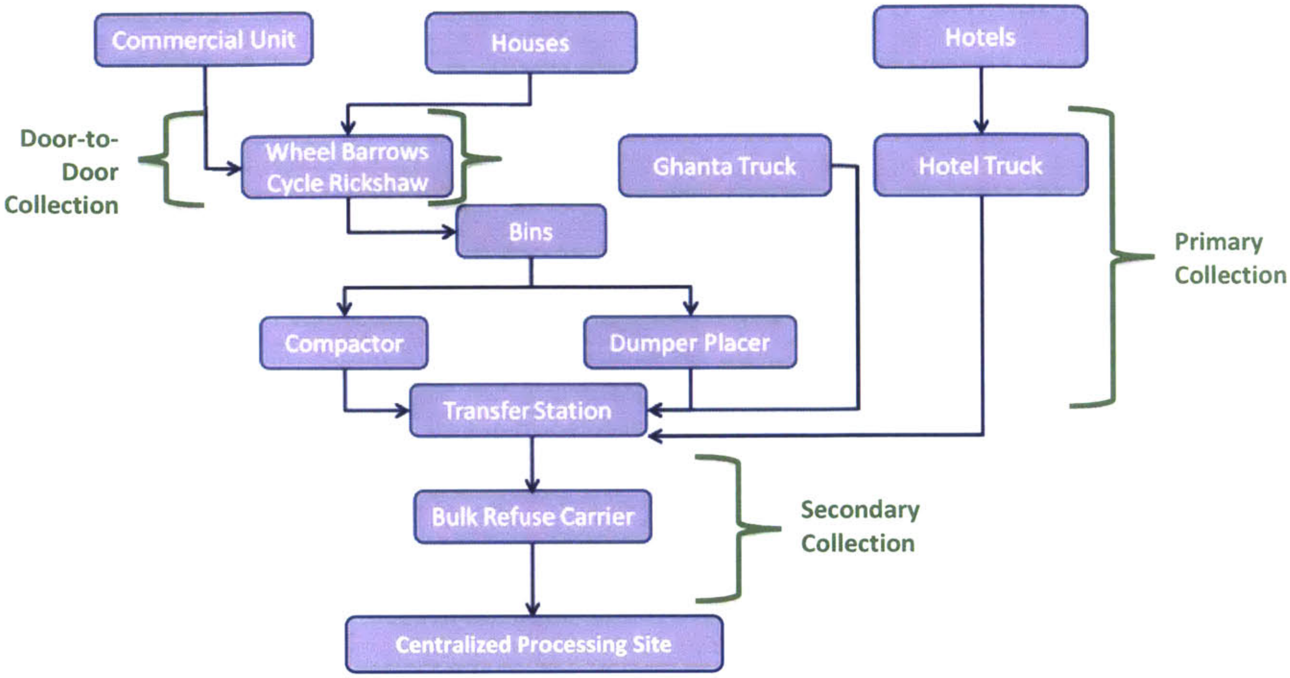


Figure 2: The solid waste collection and transportation system of Pune.
Source: Figure is adapted from a figure from the City Sanitation Plan of Pune, 2012.

Pune utilizes seven transfer stations, geographically distributed around the city, as shown in the map in **Error! Reference source not found.**. When this waste is landfilled, it is rucked to the Uruli Devachi landfill site, located to the South-east just outside the city boundaries. When segregated organic waste from the transfer station is sent to biogas or compost facilities, it is trucked to one of the locations mapped in **Error! Reference source not ound.** or **Error! Reference source not found.**, which show the centralized organic processing sites.

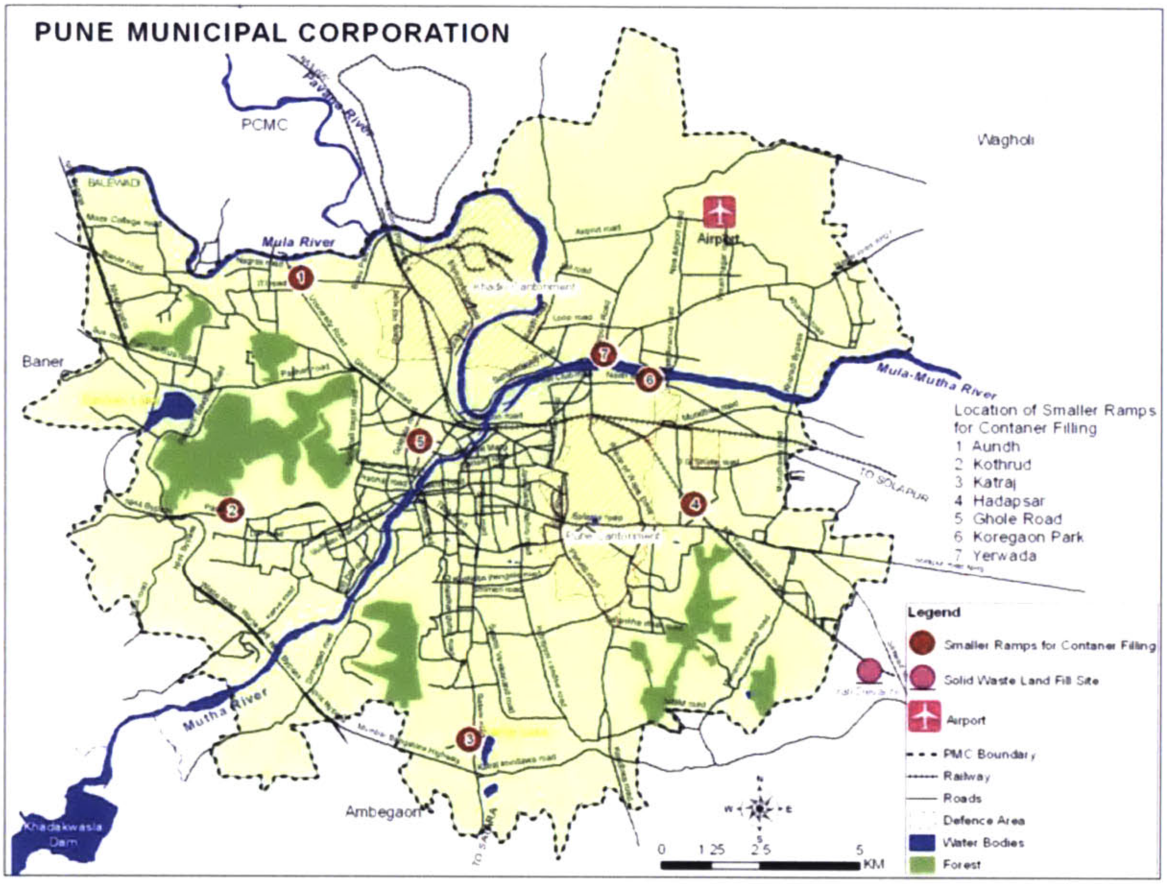


Figure 3: Map of Pune's seven transfer stations (red circles) and Uruli Devachi landfill (pink circle). Source: figure taken directly from (Mundhe, 2014).

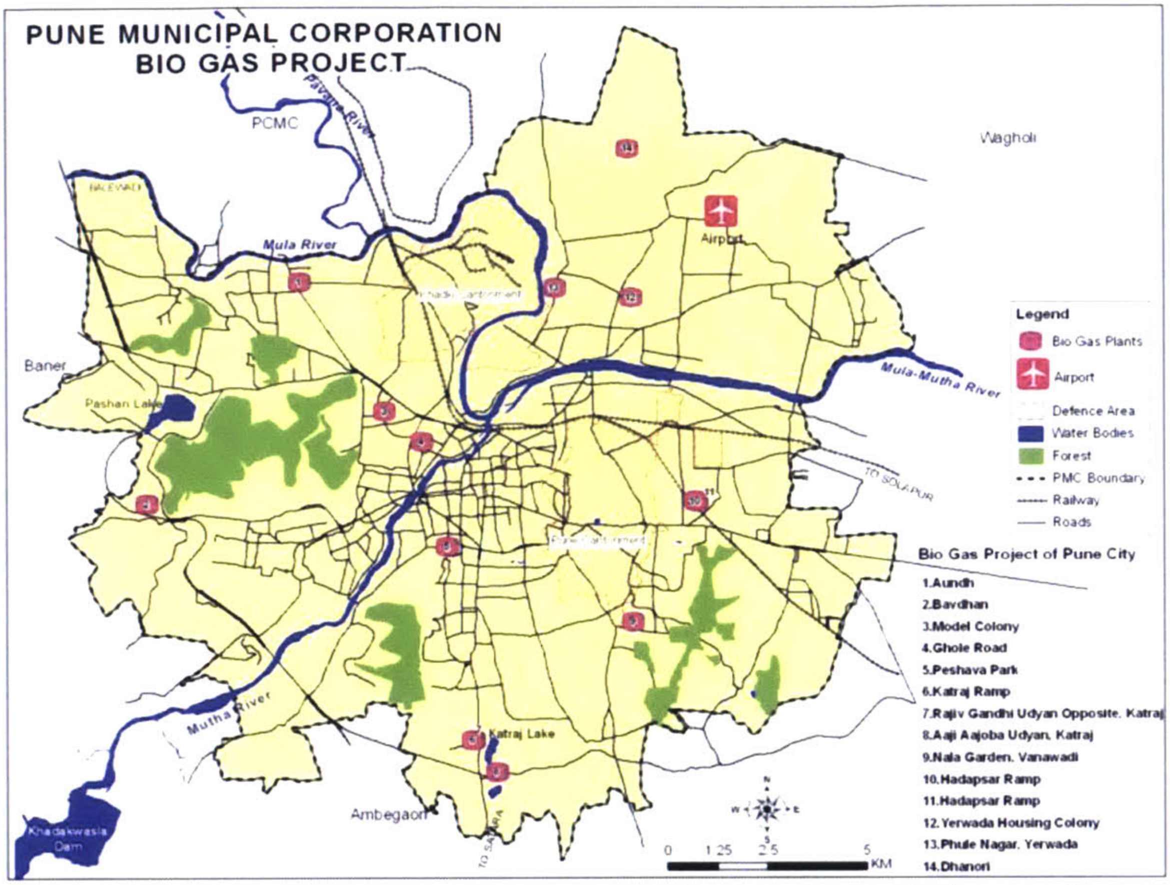


Figure 4: Map of fourteen Pune's biogas plants (shown by the pink rectangles). More plants have been built since this map was created. Source: figure taken directly from (Mundhe, 2014).

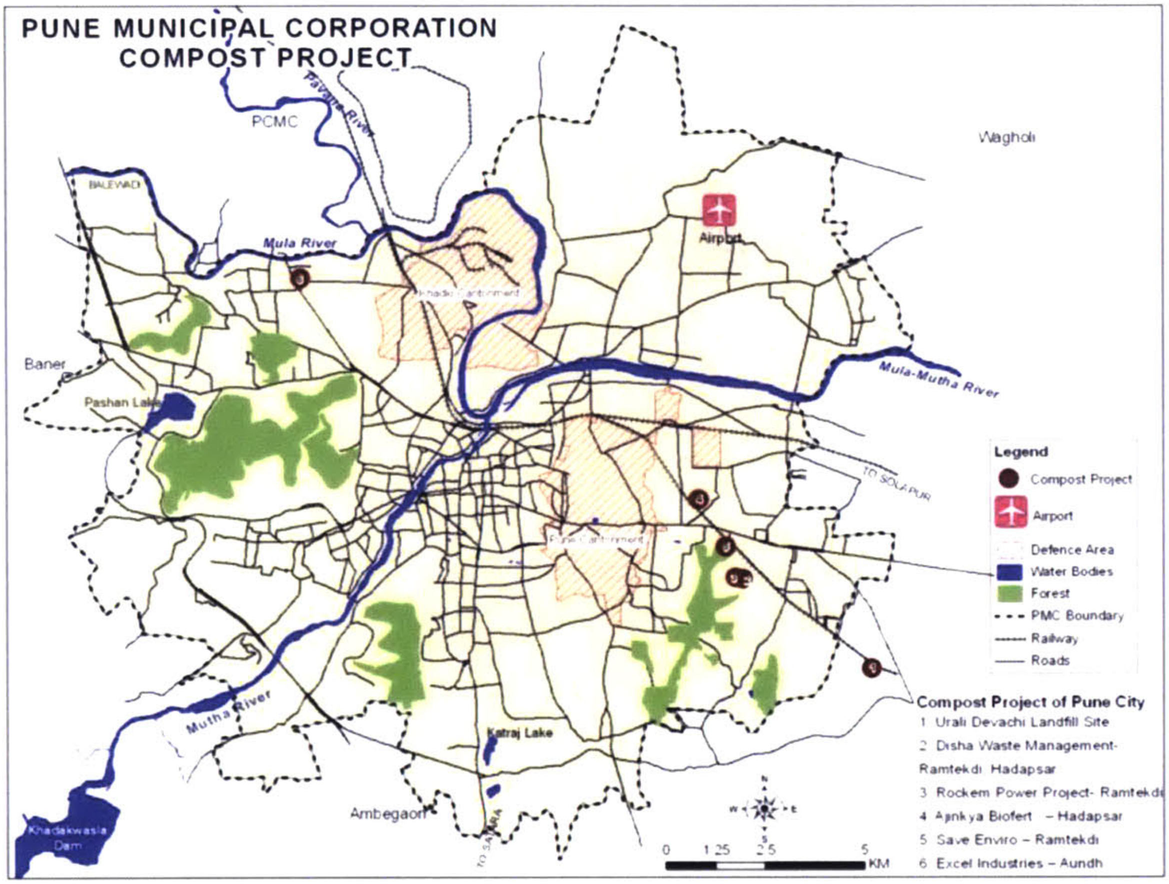


Figure 5: Map of Pune's centralized compost facilities (shown by the brown circles). Source: figure taken directly from (Mundhe, 2014).

2.3.2 Waste Generation and Processing Volumes

Due to the complexity of the waste management system within Pune and the lack of aggregated data on generation and processing, mapping the flows of waste throughout the entire city was challenging. Although a number of sources estimate that the daily generation (as of 2014) of MSW is 1600 tons/day, it is unclear how this number was calculated and what data is based on. I compiled information from a number of sources to determine the waste flows within the city. I interviewed PMC officials in both the sanitation and transportation departments twice, which provided information on the quantities of waste generated and hauled. I also used published presentations by the PMC to estimate the amount of waste going to composting and biogas sites (Dighe, 2015; Pathak, 2014). I also obtained processing quantities from journal publications that document Pune's waste flows (Mundhe, 2014; Scheinberg, 2011) as well as recent news articles discussing waste generation and disposal issues (Mascarenhas, 2014). In **Table 5**, I have summarized the amount and types of waste generated within the city. The majority of MSW (about 72%) comes from residential waste, with all forms of commercial waste (hotel and restaurant, produce, and other businesses) making up 12% of the city's waste.

Table 4: Sources and quantities of MSW generated in Pune.

Sources of Waste	Quantity Generated (tons/day)	Percentage of Total	Source of Information for Quantity Generated
Residential	1,198	72%	Waste audit and model described in Chapter 3
Hotel and Restaurant	150	9%	PMC, 2014
Other Commercial	50	3%	PMC, 2014
Produce and Fish Markets	7.5	0.4%	PMC, 2013
Biomedical Waste	3	0.2%	Mascarenhas, 2014
Construction and Demolition	70	4%	PMC, 2014
Street Sweeping	140	8.4%	PMC, 2014
Miscellaneous	47	3%	PMC, 2013
TOTAL	1,666	100%	

Of the MSW generated in the city, only a relatively small portion of waste goes uncollected (this uncollected miscellaneous waste is estimated to be 47 tons/day). The rest of the waste is collected and processed in numerous ways, ranging from large-scale centralized plants to community-run compost pits. **Table 5** lists the quantities of waste processed by each method throughout the city. The bulk of biodegradable waste is sent to the two centralized compost facilities, the biogas plants, or the landfill. In mapping these flows, the most challenging figure to verify was the amount of waste sent to the landfill, as the city does not openly share this figure. The estimate of 400 tons/day was calculated using the knowledge that 1,666 tons/day waste are generated in the city (**Table 4**), and all but 47 tons of this are collected and processed. Having relatively reliable estimates of the quantities of waste processed using all of the other technologies and methods, I was able to deduce the remainder quantity of waste that must be going to landfill. The city's waste flows, from source to treatment, are visualized in a Sankey diagram in Error! Reference source not found.. The colors sed in the flow chart roughly indicate the general category of waste; green flows are biodegradable, grey flows are refuse, blue flows are recyclable, orange flows are mixed with a high percentage of refuse, and purple flows are mixed with a high percentage of organics.

Table 5: Waste processing destinations of MSW generated in Pune.

Treatment	**Waste processing sites**	**Type of Waste Processed**	**Quantity Processed tons/day**	**Source of Information for the Quantity Processed at Each Site**
Landfill	Uruli Devachi Dumpsite	Mixed	400	Estimate, based on total city generation of 1600 ton/day
Refuse-derived-fuel	Hanjer 1 & 2	Mixed	250	Jagtap, 2014
Gasification	Rochem WTE	Mixed	200	(Isalkar, 2013)
Vermi-Composting	Disha Waste Management	Biodegradable	100	(Mundhe, 2014)
Vermi compost and Compost	Ajinkya Compost	Biodegradable	200	(Mundhe, 2014)
Anaerobic Digestion for Electricity	Biogas plants (16 plants)	Biodegradable	98	(Pathak, 2014)
Mechanical Composting	Ram Tekdi and Aundh Ward Office	Biodegradable	7	(Dighe, 2015)
Decentralized Vermicomposting pits	989 Sites	Biodegradable	16	(Dighe, 2015)
Decentralized anaerobic digestion	25 Sites	Biodegradable	10	(Dighe, 2015)
Decentralized Organic Waste Converter	42 Sites	Biodegradable	11	(Dighe, 2015)
Biomedical Landfill	Passco Biomedical Facility	Medical and hazardous waste	3	(Mascarenhas, 2014)
Informal and Formal Recycling	Large number of sites	Recycling	323	(Scheinberg, 2011)
Uncollected or Burned	Unknown	Miscellaneous	47	PMC, 2013
		Total	**1,665**	

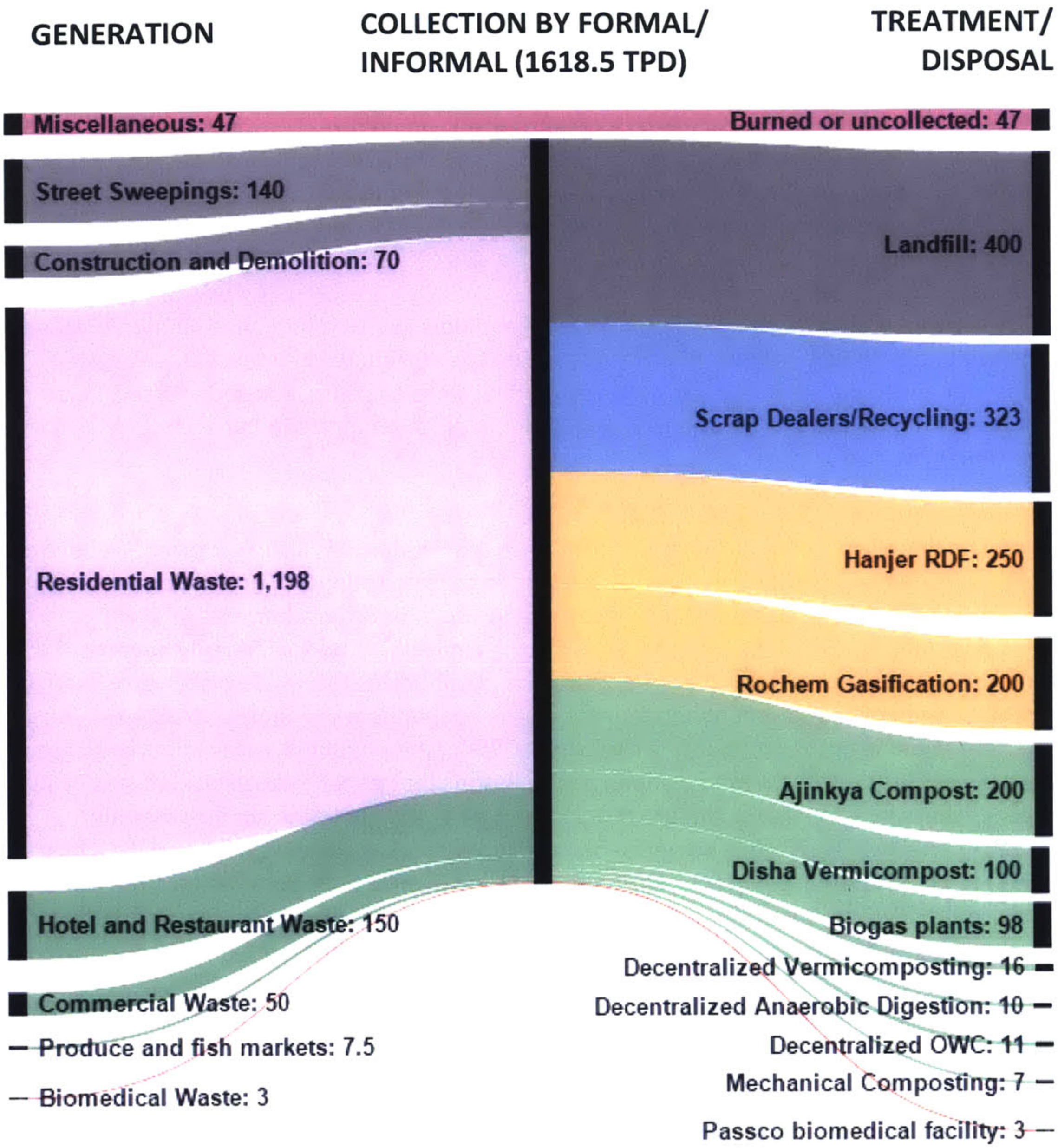


Figure 6: Mass flow diagram of municipal solid waste in Pune. The size of each flow (various colors) corresponds to the magnitude of that flow. The black bars are nodes – the nodes on the far left indicate the points of generation; the node in the middle indicates collection by the informal or formal sectors; the nodes on the far right indicate points of treatment.

2.4 Pune Stakeholders

The management of municipal solid waste is a highly interactive process that involves many stakeholders. Specifically, waste management in India has an even greater variety and complexity of stakeholders, because it is decentralized and involves the informal sector. Since India does not have a well-defined or systematic process of waste collection, there are many layers of individuals and bodies who participate in or are impacted by the handling of waste within the municipality. Because waste pickers are an integral part of the waste system in Indian cities, the urban poor must be considered in designing Indian waste management solutions.

I have outlined many of the principal stakeholders involved in managing municipal solid waste in the city of Pune, India. In order to analyze the current waste management system, the groups influenced by and influencing the system first need to be understood. Below, I discuss the agendas, influence, and relationships of a variety of stakeholders in Pune's waste management system.

2.4.1 Pune Municipal Corporation (PMC)

The Pune Municipal Corporation (PMC) has proven that it is a city government devoted to better waste management. It has been receptive to waste advocacy groups, created regulation that benefits waste pickers, and has made substantial investments in environmentally-friendly technologies (such as biogas plants). The PMC openly advertises its goal to have "zero waste" landfilled. Furthermore, it subsidizes the waste picker cooperative, SWaCH, by providing equipment and help when the cooperative encounters problems. The PMC is functioning in the context of a city where 37% of the population lives in slums (Jagtap, 2013). By prioritizing waste management and solutions that benefit waste pickers, the PMC increases the quality of life for the urban poor, as well as the quality of life for wealthier residents. The PMC is clearly a powerful body, given that it is a city government with a large budget; it has the power to create regulation that directly alters the system at a large scale. Furthermore, PMC staff members are probably more environmentally-conscious and educated than most Indian municipal staff, given the high caliber of education in Pune.

Yet, since it is a democratic body in the developing world, the PMC still suffers from slow, bureaucratic processes and a lack of resources for proper enforcement. It is also possible that the PMC battles with controlling internal corruption. Additionally, the PMC must balance its priority of waste management with other immediate concerns and responsibilities that pertain to safety, infrastructure, food security, transportation, employment, etc. The PMC will probably limit its investment in waste infrastructure, given that it is likely stretching its budget for other basic needs within the city.

2.4.2 KKPKP, SWaCH, and waste pickers

Pune has approximately 15,000 waste pickers that earn a living by selling the recyclable material that they hand-sort from municipal solid waste (Desai, 2013). Ninety-two percent of these waste pickers are women, and the majority of these women come from families considered to be in the lowest, or Dalit, caste (GAIA, 2012). Waste pickers are very poor, and usually earn less two dollars a day, despite that they work long hours in unsanitary conditions. Poor women often become waste pickers because of family legacy, the independence and flexibility the job offers, or because it is a reasonable alternative to less respectable avenues such as prostitution. Waste pickers have historically been oppressed, accused of theft, and neglected because of cultural stigma due to caste and gender discrimination. Waste pickers work in the informal sector, and for many years they were not organized or recognized as legitimate workers in Pune. Thus, they had little to no power within the city to advocate for their own rights or for change in the waste system.

However, in 1993, a group of waste pickers and iterant scrap buyers came together (with support from a local university) to form a trade union called Kagad Kach Patra Kashtakari Panchayat (KKPKP). KKPKP was the first waste pickers' trade union in India. Now, between 8000-9000 of Pune waste pickers are unionized in KKPKP, which provides members a platform to campaign for their rights (Desai, 2013). Since the formation of KKPKP, waste pickers have had more leverage with police and politicians, who had formerly abused or neglected the waste pickers. For example, KKPKP convinced the PMC to issue waste pickers identity cards, which are of social value and are required for opening a local bank account. By unionizing, waste pickers have been able to demonstrate to the PMC that their door-to-door collection and segregation of waste is an economically and environmentally valuable service.

In 2008, a subset of KKPKP formed a worker's cooperative called Solid Waste Collection and Handling (SWaCH) to better organize the logistics of waste picker services in a way that could more easily interface with the PMC. Currently, 2,300 of those in KKPKP are also members of SWaCH. SWaCH has a formal relationship with the PMC; the cooperative has designated collection routes for its members and has the authority (granted by the PMC) to collect monthly fees from each household to pay for their door-to-door service. SWaCH waste pickers are allowed to pocket the fees, in addition to their sales of collected waste material, and thus SWaCH members have a steadier and more predictable income than waste pickers outside of the cooperative. In order to cover cooperative overhead, members of SWaCH must pay 5% of their income to the cooperative.

SWaCH and KKPKP both advocate for decentralized waste management solutions that ensure that waste pickers are treated fairly and given sufficient access to solid waste, so that they can continue to derive income from sorting. Both organizations function harmoniously, given that they have developed together; however SWaCH is in a more powerful position and is able to offer its members more tangible benefits. Although SWaCH has a close relationship with the government, the organization feels it is not receiving sufficient government funding to expand the size of the cooperative, which has the effect of excluding other unionized waste pickers that want to join (Desai, 2013). Furthermore, despite that the government signed a contract stating that it would pay for SWaCH members to have sorting sheds and equipment (gloves, uniforms, push carts, etc.), it has not followed through with this promise. SWaCH has also expressed that it faces opposition from politicians who are bitter about not getting a cut from the cooperative's activities. The above issues demonstrate that SWaCH feels its influence is not large or stable enough, meaning that the organization will likely be defensive and will continue to pressure the government to consistently provide sufficient resources.

2.4.3 Generators of MSW

Households, hotels, restaurants, businesses, and markets all generate MSW. It is estimated that per-capita MSW generation in Pune is between 0.35 and 0.75 grams per day (Jagtap, 2013). Historically, waste handling has been the responsibility of the municipality, not the individual producer of the waste. Many people feel entitled to produce as much trash as their lifestyle requires, since such trash is a byproduct of their consumption of goods. The aspiring Indian sees consumption of goods (that ultimately are disposed of) as a sign of prosperity. In this sense, the household or businesses has an incentive to hold on to its "right to produce trash." Furthermore, most Indians are not aware or motivated to segregate their waste, and are most inclined to dispose of their waste in the simplest way possible. Indians are accustomed to having their mixed waste collected daily by waste pickers and appear to be content with such a collection system, since it requires low effort.

For many years, this waste collection exchange used to be at no-cost to the residents, who were happy to see their waste taken out of sight and out of mind. Meanwhile, the waste pickers received no direct payment for the act of collection, and only received revenue from the recyclables they could sell. However, since the PMC began collaborating with the SWaCH cooperative, the government now mandates that households pay Rs. 30 each month to the SWaCH waste picker in return for such collection. Many of Pune's middleclass households comply with this policy. According to SWaCH, the Pune residents who tend to refuse to pay the collection fee fit into the economic extremes – it is either the poorest residents living in slums or the wealthiest who live in gated communities who do not pay the collection fee to the waste pickers. This is likely occurring because the poorest cannot afford to pay, and because the wealthiest feel entitled to the collection service being free, as well as socially distanced from the waste pickers, who they judge for being in a "lowly caste." SWaCH waste pickers are suffering because a significant number of households are exerting their influence by refusing the pay the collection fee. Given that SWaCH and the government struggle with enforcement, residents have a relatively high level of power in this situation. On the other hand, if waste pickers in turn refuse to collect waste from residents who do not pay the required fee, residents may no longer be able to assert their dominance. Residents may not be willing to accept the alternative of waste piling up in their homes or yards.

A small fraction of Pune residents and businesses take initiative to process their own organic waste using small-scale biodigesters, which produce biogas. These individuals are typically more informed and motivated by environmental responsibility and have decided to take matters into their own hands. They have the potential to influence others by setting an example and informing their neighbors of innovative options for independent waste management. While they do not have many other resources to change the larger system, these residents do reap some benefit from small-scale biodigestion, because they can reduce their home's fuel cost by using the digester's biogas for cooking (replacing purchased LPG). They can also use the digester's sludge for compost if they have a garden. In addition to the residents managing their own waste, it is possible that some educated and willing Pune residents are taking measures to purchase more sustainably by buying products that are made from recycled material or have less packaging in the first place. This type of household-level buyer selection only occurs when consumers are properly informed and have environmental values.

2.4.4 Waste to energy companies

The government has contracted several companies to process the city's waste for the production of energy. These companies are using technology to a greater extent than other stakeholders, like waste pickers, who do not have access to much technology beyond automatic circular saws that remove PET bottle caps. Still, waste to energy technology is not exactly replacing waste pickers, since these companies are not yet using technology for the purpose of sorting waste.

Some of these companies compete with waste pickers, while others do not. One company, Concord Blue Technology Private Ltd, processes unsegregated waste using a patented method of thermal treatment in the absence of oxygen, and is able to cleanly produce syngas (a fuel cleaner than biogas) (Ahluwalia, 2012). Concord Blue is using state-of-the-art technology that meets emission standards of the EPA, which gives the company strong leverage in Pune, a city that is increasingly high-tech and aspiring to be a leader in waste management techniques. The company has high credibility and knowledge of the technical system, and thus its opportunity of influence is large. Concord Blue's preferred feedstock is plastics, which also happens to be one of the most valuable materials that waste pickers segregate and sell to recyclers. Concord Blue and waste pickers are in direct competition for waste plastics, and thus the company would likely oppose high inclusion of waste pickers in the city's management system. However, theoretically, there is a possibility that the company could team up with the waste picker community by employing waste pickers to collect waste from houses and transfer this unsorted waste to the waste-to-energy facility.

Another set of waste to energy companies in Pune is digesting biodegradable waste to produce biogas at moderate scale biogas plants that process five metric tons of waste per day. Currently, there are between 20 and 30 of such plants dispersed in the city. The PMC has directly promoted these plants by requiring the city's hotels, restaurants, and caterers to segregate their biodegradable waste for collection by the biogas facility. With the city's help, these biogas plants are successfully producing biogas, which is used to generate electricity that powers the city's streetlights. It is to the plants' advantage to receive biodegradable waste with as few contaminants of plastic or metal as possible. Since the biogas plants only utilize biodegradable waste (which has little value to waste pickers that derive value primarily from dry waste), biogas plants and waste pickers have little competition and can function in harmony. Paper is perhaps the one feedstock that both biogas plants and waste pickers might fight over. Furthermore, because the biogas plants are contracted by the government, which has made an effort to involve waste pickers in its activities, many of the employees at these plants are former waste pickers that have been trained in digester management. Pune's biogas plants appear to have sufficient community popularity and influence, because regulation is already in place to guarantee they have sufficient and reliable feedstock from hotel/restaurant waste.

2.4.5 Landfill operator and "Not In My Backyard" groups

Although Pune is able to divert much of its waste to recycling, composting, and energy, one estimate reported that 20% of the city's waste is still going to the landfill (Jagtap, 2013).

Since 1999, this trash has been going to the Uruli Devachi Landfill, which is a controlled open dump (not a sanitary landfill). In the US, private companies typically operate landfills, and charge municipal governments tipping fees to dump their trash to be landfilled. In the US scenario, the private landfill company has an incentive to collect more waste (as long as it has capacity), because its revenue increases with higher volumes of trash processed. The US municipalities have contracts with landfills and pay the landfill companies accordingly. However, in Pune's case, the landfill is operated directly by the Pune Municipal Corporation, which means the government has an incentive to reduce the cost of handling the waste, which potentially means hauling less to the landfill (Suresh et al., 2011). Uruli Devachi is a village outside of Pune, and the villagers living near the landfill have been unhappy with the garbage trucks passing through their town and with the unsightly and malodorous dump building higher and higher. For the past few years, Pune has been aware that the landfill was almost reaching capacity, and claimed that it would soon cap and close the landfill. Yet, the government postponed the closing because it had difficulty finding an alternative site to dump the waste. In April of 2013, a fire broke out at the dump, which precipitated the village to protest even further and to demand a compensation package of Rs. 10 crore (The Indian Express, 2013b; The Indian Express, 2013c). The Pune mayor and municipal commissioner tried to convince the villagers to relent, but were unsuccessful. As a result of pressure from the residents of Uruli Devachi and a lack of landfill capacity, the court ordered the Pune government to close the dump site. At present, it appears the Pune Municipal Corporation has not resolved this dilemma, and it is unclear where the city's landfill trash is going (The Indian Express, 2013a).

The conflict between the PMC and the villagers of Uruli Devachi illustrates a classic case of resident opposition, characterized by the sentiment, "Not In My Back Yard" (NIMBY). The locals experiencing the negative externalities of the landfill put up a fight, because (1) their quality of life was directly being affected and (2) most of the waste was coming from the dense, urban city, not from their own neighborhood. It is inevitable for a NIMBY conflict to arise over the siting of a landfill. However, the residents were surprisingly effective in their protesting, which reflects a high level of organization and commitment. Although the residents may have previously felt oppressed, they are now highly influential, with the power of the court on their side. It appears the residents were willing to make a tradeoff with the government by proposing a compensation package; the PMC likely rejected this because of financial limitation and because it realized such a compromise would not solve the underlying problem of needing more landfill space, and thus would not be sustainable. The PMC may have also felt the need to uphold its reputation by not wavering in the face of the complaints. When the conflict came to a climax, the PMC lost its decision power, because it had to obey the court's ruling. It may be a sign of weakness that the PMC is now floundering, unsure what to do with the 20% of its waste that needs to be landfilled. Yet, when the whole context is taken into account, the PMC is still a national and global leader, in that it is impressively diverting the other 80% of its waste to more sustainable uses. Going forward, the Pune government now has an incentive to restore their image and potentially do something productive with the landfill that is now closed. The PMC is considering sealing the dump to capture methane gas to generate power. This route has the potential to lead to an alliance between the two groups. Ideally, the PMC would work with the residents of Uruli Devachi to capture methane, so that the locals also benefit from the project, perhaps by receiving lower-cost power generated from the landfill.

2.4.6 Water quality regulators and water resource managers

The handling of waste is not only a logistical problem, but can also be a water pollution problem if not handled properly. Because Pune's dump site was not formally engineered or properly lined, it is polluting Pune's ground water, which is an environmental and health hazard. One study from the University of Pune found that "the leachate derived from the Pune municipal waste dumping site demonstrates exceedingly high values for almost all physio-chemical parameters analyzed, including potentially toxic heavy metals" (Kale et al., 2008). Fortunately, those concerned with the water supply and water quality of Pune would tend to advocate for the solutions similar to those promoted by SWaCH and KKPKP. From a water quality perspective, consolidating waste at one large dumpsite is most damaging, because it makes the pollution most acute, especially when not properly treated. Because dilution is viewed as the solution to pollution, it is best to have decentralized dumping sites; waste pickers also prefer a decentralized system, as it gives them better and safer access to material. To prevent water pollution, it is best to (1) segregate biodegradable and non-biodegradeable wastes, (2) compost the biodegradable waste locally, (3) recycle as much as possible, and (4) create a new site that is lined and contains leachate ponds for all waste that must be landfilled. Water resources management is technically carried out by the government, but (if I am not mistaken) is not directly the responsibility of the PMC; the state-level Maharashtra Water Resource Department oversees and advocates for environmental protection of water bodies in the region. Because water management is complex and relevant to a number of independent actors, including individual water users, it is likely that others, beyond water regulators, would prioritize and promote water quality. Water regulators in India suffer from poor enforcement of environmental regulation, and probably, in reality, do not devote the time they wish they could to dealing with the water problems that stem from solid waste management; they may have to devote most of their time to stopping major point sources of pollution from industries with toxic effluent (from smelting, mining, and tanneries). As Pune waste management solutions evolve, it is important that the PMC communicate with the Maharashtra Water Resource Department so that they accomplish multiple environmental goals at once (reducing carbon emissions as well as water pollution effects).

2.5 Key Findings and Need for Bottom-Up Exploration of Pune's System

In this chapter, I have explored Pune's waste system through the lenses of policy, materials, and stakeholders. This chapter is a top-down view of the waste activities in Pune. By interviewing city officials, SWaCH and KKPKP leaders, and head managers of waste processing facilities, I was able to learn about how Pune's waste system functions at a high-level. This city-wide analysis serves to establish waste challenges within the context of urban India, describe the roles of the informal and formal sector, highlight successes and areas for improvement, and identify driving forces behind changes within the waste system. The following are the key findings of this chapter:

FINDING 1: With some residents and businesses still mixing biodegradable waste with refuse and the city still sending a significant amount of biodegradable waste to the unlined landfill, Pune's current management of organic MSW needs improvement. Current practices do not meet regulations on source segregation and processing, nor do they meet the city's goal of sending zero-waste to the landfill. Given that the largest (by mass) component of MSW going to the landfill is biodegradable, the interests of many stakeholders could be met by using alternative treatment methods for managing organics.

FINDING 2: Based on data from interviews and literature, Pune generates about 1,666 tons of MSW per day. We estimate that 400 of these tons are landfilled, 323 tons of recyclable material is recycled, 450 tons of mixed waste used to for gasification and RDF, and that 442 tons of biodegradable waste is composted or digested.

FINDING 3: Pune's waste management logistics are complex in that the waste from 15 administrative wards is sent to large number of treatment sites, which are operated and owned by a number of different companies and organizations. The city uses a waste processing sites that have a wide range of facilities, including 2 TPD mechanical composting plants, 5 TPD biogas plants, and 200 TPD vermicomposting sites.

FINDING 4: Pune is using a number of waste processing methods, but the city does not have a strategic long-term plan for achieving its goal of "zero waste." The city would benefit from systematic analysis of waste management options, so that it could get closer to truly closing the landfill.

FINDING 5: Although the city keeps some records on total incoming waste volumes to some facilities, its data on the quantity and composition of waste generated in Pune is undetailed and limited. The quantities of waste reported are round numbers, and the composition descriptions given are only "biodegradable" or "mixed." A waste audit needs to be conducted to better determine the characteristics of the city's waste.

In the following chapter, I study Pune's waste flows and composition in more depth, using a bottom-up approach. I also do further in-depth analysis on the waste flows within one of Pune's wards, Aundh, so that in subsequent chapters I can then do a system-level economic and environmental analysis for that ward.

Chapter 3: Municipal Solid Waste Quantity and Composition

3.1 Purpose

This chapter discusses field work and analysis I have done to characterize Pune's waste, with regard to its material composition and the total quantity generated. I use empirically collected data from waste audits to conduct a materials flow analyses for Pune and Aundh ward. It is important to know the waste characteristics of a particular locality (in this case Pune, India) so that decision makers can design waste processing systems that meet the city's demand (of generated waste that must be processed), use technologies that are appropriate for the type of waste generated, and are designed for an appropriate scale. Quantifying the municipal solid waste flows of Pune will enable me to conduct an economic analysis and greenhouse gas emission analysis that is specific to the waste streams of urban India.

3.2 Background on Waste Characterization

A waste audit, or a "sample and sort" is direct examination of either (1) waste set out for collection at point-of-generation or (2) waste delivered to a waste processing facility or disposal site. This examination can focus on quantities, composition, or both. For a sample and sort, a statistically planned amount of MSW is collected, samples are taken, and the waste is hand-sorted into pre-determined material/product categories.

Having accurate data on the quantity and composition of waste streams is important for several reasons, including: (1) identification of potential for material recovery, (2) design of technologies for controlling air and water pollution, (3) prediction of greenhouse gas emissions from processing and storage, and (4) assessment of legislation on waste management (Brunner & Rechberger, 2011). The three main methods for conducting solid-waste analysis to characterize a waste stream are the following: (1) direct analysis in which a specified amounts of waste are sampled, sorted by hand into predetermined fractions that are then each weighed (2) indirect analysis of composition using market-product analysis in which economic data on produced/consumed goods and assumed average lifetimes of these goods are used to infer waste generation, and (3) indirect analysis of post-treatment waste products to infer pre-incineration waste composition.

Survey questionnaires completed by households or companies can also be used to estimate waste generation and composition. One study by Yu and Maclaren (1995) compared direct waste analysis (sample-and-sorts, which are labor and resource intensive) with questionnaire surveys (which are low cost) to assess the advantages and disadvantages of each of the two characterization methods. The study found that both direct analysis and surveys produced similar estimates of waste quantities, but that the direct analysis method produced more reliable compositional data (Yu & Maclaren, 1995).

Additionally, a study done by Burnley (2007) compiled survey data from five past MSW surveys of waste in the United Kingdom that were conducted between 1994-2006. The UK study found the total quantity of household-collected waste reported in the five studies ranged between 13-19 kg per household per week; however, there was relatively high agreement between studies with regard to the main components of household composition (paper and cardboard, kitchen and garden waste, plastics, glass, and metals) (Burnley, 2007).

A number of direct waste analyses have been conducted to characterize the streams generated in different geographical regions:

The Department of Sanitation conducted a Street Basket Waste Characterization study to quantify and characterize the contents of New York City's residential refuse, residential recycling, and street basket waste. The NYC study collected 200 samples from street baskets, as well as 1,609 samples of refuse, 325 samples of paper, 1,300 samples of comingled metals, glass, and plastic which were acquired from trucked waste at transfer facilities (Lange, 2005) Each sample weighed 200-300 pounds and was randomly selected, then sorted into several material categories and weighed by a hired crew. Some samples were also analyzed for moisture content and particulates. The study found that 39% of the mixed waste in street baskets was organic (13.5% was food waste, 4.2% is yard waste, 1.7% was animal by-products, 5.2% was non-recyclable paper and 16% was other organics).

Another sample-and-sort study was conducted in Chihuahua, Mexico in 2006 (Gomez et al., 2008). Gomez et al. characterized solid waste generation from urban households and compared the results across three different socioeconomic levels (Level I representing low income and Level III representing high income). The study collected 560 samples of solid waste from 80 Chihuahua households over the course of one week, and then sorted the material into 15 weighted fractions. The study found that average solid waste generation rate in April 2006 was 0.68 kg/capita/day, and that the average generation rate per neighborhood was 0.60, 0.70, and 0.73 kg per capita per for the socioeconomic levels I, II, and III respectively. The authors noted that although there was a slight positive trend from lowest to highest socioeconomic group, the differences were not statistically significantly.

The State of Vermont Department of Environmental Conservation (VT DEC) commissioned a state-wide waste composition study of MSW in 2012. The MSW was sampled from a four transfer stations during two different seasons (State of Vermont Department of Environmental Conservation, 2013). The study tested 100 samples of MSW, each weighing 200 to 250 pounds. The sorting crews hand-sorted the MSW into 55 primary categories, and with plastics sorted into 46 sub-sort categories. The crews used a sorting table and bins to contain the separated fractions. After sorting, each fraction was weighed, so that the data could be compiled to find the average percentage (by weight) of each type of waste. The VT DEC found that 28% of the waste was organic, which is the largest single component of residential waste in Vermont. The study also noted that due to the small sample size, the confidence interval for composition fractions was relatively large.

A waste characterization study was conducted in the Lower Rio Grande Valley in Texas sorted and classified MSW from 10 cities in the Valley (Chang & Davila, 2008). Twenty samples, each weighing 200-300 pounds, were taken from garbage trucks and were hand sorted into 21 categories. The researchers also used laboratory analyses to determine the physical and chemical composition of the waste; they tested for moisture content, carbon, chlorine, sulfur, nitrogen, hydrogen, and oxygen, as well as the heating value. Chang and Davila found that food waste made up 16% of residential waste and that the average moisture content of mixed MSW was 22%. The authors also remarked that the carbon/nitrogen ratio of the organic waste would make composting a feasible treatment option.

Rather than sample waste from waste baskets or transfer stations, a study conducted in Sioux Falls, South Dakota sampled the local landfill to characterize the types and quantities of waste (R.W. Beck, 2007). However, the waste being sampled was sourced directly from the trucks delivering waste to the site; the waste was freshly generated, rather than having sat in the landfill for an extended period of time. The study analyzed 50 MSW samples weighing roughly 200 pounds, all taken from one landfill. These samples were sorted in 48 categories and weighed. The study found that the city's MSW entering the landfill consisted of 16% food waste, 6% yard waste, and 2% other organics. Based on their finding that a large amount of food and compostable paper waste was being landfilled, the report recommended the city invest in composting this waste, possible thorough the use of curbside compost collection.

3.3 Gap and Objectives

The exiting literature leaves some factors and dynamics of waste characteristics unresolved; these aspects of waste are important for answering the questions posed by this thesis. Previous audits had high levels of uncertainty because they used a small number of samples or were not repeated during different seasons (Gomez et al., 2008; Chang & Davila, 2008). Previous audits also did not resolve income effects on waste generation for lower income countries. Lastly, the literature does not identify what fractions of waste are suitable for specific treatment technologies (composting, anaerobic digestion, and pelletization); past studies mostly identified the total fraction of organics, without specifying how much is food or garden waste.

Prior to our study, the publically-available data on the current quantity and characteristics of waste generated in Pune was limited in that the categorization was for very broad categories of MSW and the city government quoted unconfirmed quantities for the city's generation of organics (Pune Municipal Corporation, 2014b). The city has reported such numbers in its Pune City Sanitation Plan, 2011 and in PowerPoint presentations (Mundhe, 2014). SWaCH and KKPKP did already have some estimates of the quantity of recyclable and non-recyclable waste collected by its members, but the organizations had not done a detailed waste audit (Chikarmane, 2012). The last published study that involved a waste audit of garbage in Pune was conducted in 2005. Although it analyzed waste from over 1000 households, the study classified waste into only two categories, wet and dry (Kagad Kach Patra Kashtakari Panchayat, 2007b).

In doing our audit of residential waste generated in Pune, we wanted to collect more current, up-to-date data to better represent the true generation volumes within the city. Since per-capita waste generation in India has grown significantly, our audit provides a more accurate estimate of present-day generation (in the year 2014-2015). We aimed to generate waste characteristic data that was higher resolution than previous studies. We purposefully wanted to quantify the amount of specific materials, such as sanitary napkins, that had not been quantified, but were of interest to community stakeholders. We designed the waste audit to have a large number of classifications of materials in order to capture surprising trends, quantify rapidly-growing streams, and provide Pune's waste sector with useful, accurate data that could be used for economic analysis or making informed operational decisions.

Many other studies only capture one snapshot of waste composition at one part of the year, and assume that this composition holds true for the entire year. However, our study collected waste generation data at different times of the year (summer and winter). This allows us to test whether there is seasonal variation in the composition or volume of waste, and allows us to increase the accuracy of our results by repeating the audit process twice.

Lastly, by designing the audits to analyze waste from three different socioeconomic groups, we hoped to learn how income correlates with the quantity and composition of waste in India. It is generally accepted that as populations become wealthier, their consumption of disposable goods increases, and the generate larger amounts of waste (Hoornweg & Bhada-Tata, 2012). For instance, one researcher thoroughly studied the effect of income growth on the generation of MSW in California, and indeed affirmed that income positive correlates with per-capita generation; using statistical analysis, he also found that this increase waste is a direct result of wealthier individuals choosing to dispose of or replace items instead of repairing them (McCollough, 2002). By analyzing waste generation by different socioeconomic groups in Pune, we hoped to better understand the relationship between wealth and waste generation in the urban Indian context, where there is great concern about waste's growing strain on infrastructure and the environment.

Furthermore, our analysis will illustrate whether waste generation increases more drastically between the lower and middle income groups or between the middle and upper income groups. For instance, a study by SNDT Womens' University (2008) only reports one general-population figure for per-capita waste generation in Pune (the authors report that per-capita generation is 326 grams/day). Although Annepu (2012) reports a value for per-capita waste generation in Pune, he obtains this figure by dividing total waste generation (estimated by the city) by the city's total population; this method yields a total average per-capita generation value, and does represent the variation existing with a range of incomes. Using an average generation figure does not allow planners to accurately predict future waste generation volumes. Therefore, our analysis measures per-capita generation by income level, which allows us and others to model increases in total generation volumes as the socioeconomic demographics of urban India change.

3.4 Methods

In order to conduct the materials flow analysis, I needed to know the amounts and types of MSW generated. To empirically determine the volumes of each category of residential waste generated, we conducted a waste audit of residential MSW. Other methods were used to estimate the quantity of commercial waste generated. At a high level, the residential audit involved first selecting a number of neighborhoods (known as "societies") that represent various socioeconomic groups and doing a population count number of residents in that neighborhood. Most of the neighborhoods had between 50 and 300 homes. Several neighborhoods were selected in order to obtain a statistically significant sample. Then, for each neighborhood we collected all the residential waste, sorted and weighed this waste, and finally divided total generation by population to determine per-capita generation. Once I obtained per-capita generation values, I could combine this information with the city or the ward's population to estimate total generation in tons.

The waste audit conducted for this study analyzed waste generated at the neighborhood level for various socioeconomic groups. A schematic diagram of this sampling method is shown in **Figure 7**. Samples were taken directly from the doorsteps of "societies" (neighborhoods of households), where waste was left for wastepickers to collect. It should be noted that any materials that the household kept to sell to itinerant buyers (such as newspapers) were by nature not included in the collected waste. This waste audit was conducted once during the summer and once during the winter in Pune, India; the first was during June and July 2014 and the second was in February 2015. The waste audit was carried out by researchers from MIT and the Imperial College of London in conjunction with the waste picker organizations KKPKP and SWaCH.

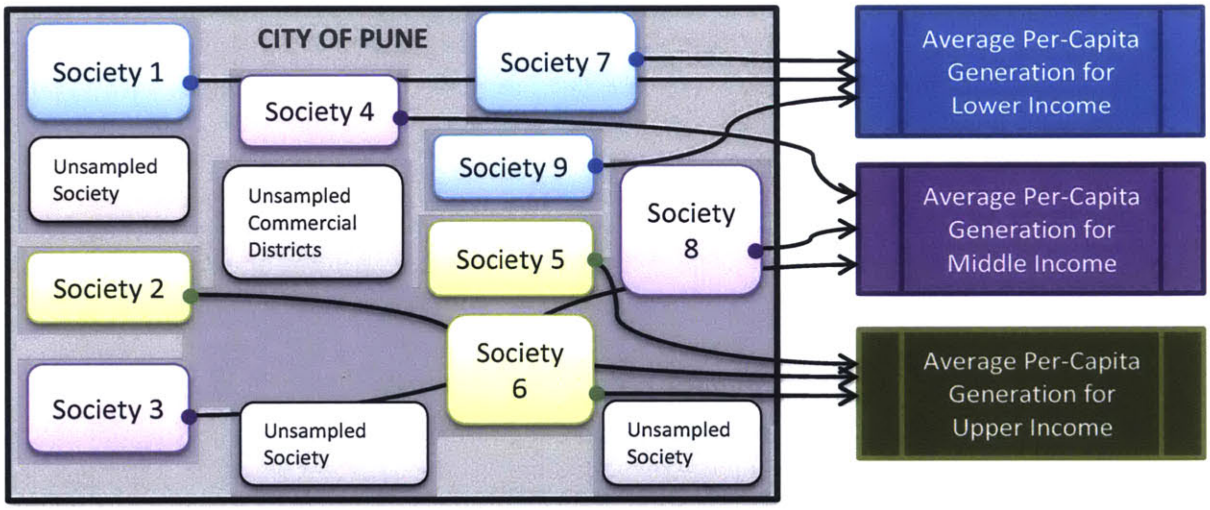


Figure 7: Schematic diagram of residential waste audit conducted in Pune. MSW was collected and sorted for a number of societies within Pune, in order to determine estimates for the MSW generation of lower, middle, and upper income residents.

3.4.1 Population Count

The waste sorts were done on the combined waste from all households along a given route (typically which included over 100 households). In order to later calculate per-capita generation, we needed to know the population of individuals in those households. We conducted a simple population survey along each route. During the first day of the audit in that neighborhood, we counted the number of houses served along the route and asked each household how many people lived in the house. The local supervisor assisted with the local language and the waste pickers identified the houses they did and did not serve, to assure accuracy. In cases where no residents were at home during the population count, neighbors and security guards assisted with providing an estimate of dwellers.

3.4.2 Socioeconomic Groups

Initially, we aimed to collect waste samples from residents in each of four income groups, as defined by India's National Council of Applied Economic Research:

Level I - annual income less than Rs. 1.5 lakh
Level II - annual income between Rs. 1.5-3.4 lakh
Level III - annual income between Rs. 3.4-17 lakh
Level IV - annual income more than Rs. 17 lakh (NCAER, 2010).

However, because India's census data does not include income statistics, we instead used less-precise categories to characterize waste generated across the range of socioeconomic strata. These categories were:

1) Lower income/slums
2) Middle income
3) Upper income

The waste picker cooperative helped us identify neighborhoods that represented each of these three socioeconomic groups. We relied on their expert opinion and visual observation of communities to categorize the neighborhoods, using knowledge about rent and property prices. For instance, neighborhoods with a majority of slum housing were classified as lower income, whereas neighborhoods with large bungalow properties and private yards were considered upper income. Middle income neighborhoods spanned a wider variety of housing types, but were still clearly identifiable as distinct from the extreme lower or extreme upper income neighborhoods.

3.4.3 Sampling

Each time an audit begun in a new location, the researchers were present to guide the process and help the supervisors and waste pickers develop a consistent workflow. We conducted waste audits of residential waste in two different seasons – in June/July of 2014 and February/March of 2015. Over the two seasons, we sampled waste from a total of 17 different neighborhoods (4 lower income, 8 middle income, and 5 upper income neighborhoods). Six of these neighborhoods were analyzed in both audits. In each audit, we collected waste from over 1000 individuals (over 400 households) in each of the socioeconomic groups. The sample size was 1,668 homes for the 2014 audit, and 2,052 homes for 2014 audit. Locations, population counts, and dates of collection can be found in **Table 6**.

Table 6: Neighborhoods analyzed in waste audit and their respective population counts.

Income Group	Neighborhood (society)	No of Homes	Population of society	2014 Start Date	2014 End Date	2015 Start Date	2015 End Date
Lower	Kastruba	450	2222	6/25/14	7/1/14	-	-
	Bopodi Vasti	128	675	-	-	3/17/15	3/24/15
	Kamble Vasti	188	1009	-	-	2/28/15	3/18/15
	Padal Vasti	122	710	-	-	3/24/15	3/31/15
Middle	Sawant Nagari	94	396	6/23/14	6/30/14	2/18/15	3/24/15
	Radha Nagri	57	244	-	-	3/17/15	3/24/15
	Parijaat Colony	54	212	6/23/14	6/30/14	2/26/15	3/24/15
	Katraj Gavthan	152	806	6/23/14	6/30/14	-	-
	Vascon Paradise	39	122	-	-	3/25/15	3/31/15
	Rajas Society	250	1146	6/23/14	6/29/14	3/25/15	3/31/15
	Maharshi Nagar	152	806	6/24/14	7/1/14	-	-
	Ramnagar	277	881	6/24/14	7/1/14	3/25/15	3/31/15
Upper	Prakriti	191	594	-	-	2/20/15	2/26/15
	National Society	98	315	-	-	3/17/15	3/23/15
	Sujay Garden	41	243	6/23/14	6/30/14	3/17/15	3/23/15
	Mystic Moods	198	657	6/27/14	7/3/14	2/28/15	3/18/15
	Abhimanshree	163	684	-	-	3/17/15	3/24/15

In each neighborhood, the waste audit was carried out daily, over the span of a full week. Within that neighborhood, the same houses were targeted each day (following a consistent route). A waste audit team consisting of 1-3 waste pickers and one supervisor jointly carried out the collection, sorting, and data collection. The supervisors spoke some English and were employees of SWaCH/KKPKP that had experience with supervising waste pickers and interacting with the community. A total of 7 supervisors and 17 waste pickers were involved in the waste audit. All of these supervisors and waste pickers were associated with the waste picker cooperative, SWaCH. We compensated them for their time. We held a training session prior to the audit to explain the purpose of the study, the methodology, and to answer questions.

Important note about scope: All of the data collected in the audit pertain to the waste collected during residential door-to-door collection. The results do not include any waste houses sell to itinerant buyers – commonly, houses sell of certain recyclables like newspaper. We believe the numbers presented below accurately capture the quantities of refuse and organic waste generated at the household level, but may underestimate the total recyclables generated.

3.4.4. Sequence of Waste Audit Steps

Collection of waste:

1. Waste pickers arrived at the destined location and start the waste collection (**Figure 8**).

2. They collecting waste from each residential unit, and when the buckets/cart was full, they aggregated it at a central point (***Figure 9***).

Segregation and Measurement:

1. The supervisor and the waste pickers set up the equipment (readying of the scale, putting out the tarp) to facilitate the sorting and weighing.
2. After the collection of waste form the allotted area, the waste was sorted into the 47 categories by the waste pickers (with the guidance of the supervisor and visual guide). Often times, waste of some less-common categories was not present (***Figure 13***).
3. The sorted category was placed into a bucket, and the supervisor weighed it and its contents (**Figure 12**).

Data Entry:

1. The weight of the bucket was subtracted from the total measurement and the resulting weight of the material was recorded in the worksheet.
2. This process was used for all other categories of segregated waste.

Clean Up:

1. At the end of the day, after the waste was separated, the waste pickers were free to keep all material of value to them (for sale to scrap dealers).
2. The waste pickers disposed of the rest of the material appropriately (***Figure 10***).

Figure 8: SWaCH wastepicker collecting waste as part of the audit, using buckets and push-carts.

Figure 9: Residential waste in a wastepicker's push-cart

Figure 10: A wastepicker emptying the unsaleable waste into the local dumpster at the end of the day.

Figure 11: SWaCH waste picker sorting waste into the audit categories.

Figure 12: SWaCH wastepicker sorting and weighing waste fractions.

3.4.5 Materials

We provided each team of supervisors and waste pickers with a waste audit kit with the necessary equipment to safely and efficiently sort and record the waste composition data. The kit included (1) comfortable, padded working gloves, (2) two types of face masks (**Figure 13**), (3) a large tarp, (4) a magnet, (5) waste audit worksheets, (6) a pencil, (7) a clip board, (8) batteries, and (9) a digital platform scale with a capacity to measure up to 200kgs with an accuracy of two decimal places. The magnet was provided to help sorters distinguish between ferrous and non-ferrous metals. The waste pickers used the tarp for shade, protection from rain, or to sort the waste on top of. The sorters used their own carts for transporting the waste, as well as sorting buckets, provided by SWaCH.

Figure 13: A wastepicker wearing one of the facemasks during the audit.

3.4.6 Segmentation Categories

Waste was separated into 47 categories sub grouped under 10 classes. The categories were determined according to the waste categories the waste pickers already sorted their waste into, and then were updated to add specific categories that were of interest to the researchers. The waste pickers were provided a visual guide which can be found in Appendix B, to assist them in determining which items belonged to each category. Because of the large number of categories and the limited number of buckets available, the waste was not sorted into all categories at once, but was rather done in a number of steps.

3.4.7 Data Worksheet

To ensure the entry of organized data, on every waste audit worksheet, the date and day were recorded. The auditor also answered questions related to the wetness of the waste and if it had rained recently. The wetness of the waste can significantly increase the weight of the waste, and thus it is important to know if such was the case. The start and end time of waste collection and sorting was also noted. Lastly, the auditor and the waste pickers' names were recorded to allow researchers to follow up with the individuals about particular data points or questions about methodology. A copy of the data worksheet can be found in Appendix A.

3.4.8 Limitations

Our study analyzed residential waste only, and therefore we had to use secondary data to estimate other (commercial) sources of MSW. Although we took measures to ensure consistency and accuracy in our methodology, our audit has some limitations. An audit of generated waste would ideally capture all of the waste that residents discard or sell, but we are aware that the material we collected from houses may not capture total generation. Some residents may have not set out certain waste materials at curbside for wastepickers to collect, either because they were saving the material to sell to a buyer or because they had already sold the material. Our estimated values of several types of high-value recyclables (such as newspapers) are likely an underestimate, given that our audit is based off of the waste residents were giving away, and therefore does not include the recyclables they sell directly to itinerant buyers (never reaching SWaCH waste pickers). However, our estimates of food scraps and refuse (such as diapers or chip bags) are likely more representative of true generation, given that households rarely have an incentive to save such items.

There also may be sources of error that might have affected our waste audit results. For instance, if a society's population count were inaccurate, this would alter the per-capita generation calculations. Also, despite the fact that we made an attempt to survey a number of neighborhoods representing each socioeconomic group, any error in classification could result in inaccuracies of the per-capita generation by income group. Neighborhoods are not entirely homogenous in income level, and families with incomes above or below the typical families in their neighborhood may have created unintended variation. Our audit only sampled a small number of the neighborhoods within Pune, so the results might differ if another set of neighborhoods were chosen. Additionally, as is always possible, human error could have occurred in the processes or sorting and weighing the waste fractions.

3.5 Waste Audit Results

FINDING 1: Residential Generation Increases with Income

The average daily per-capita generation (across both seasons) of the waste streams for each of the three socioeconomic groups is presented in **Table 7**. As is consistent with the studies by Gomez et al. (2008), Hoornweg & Bhada-Tata (2012) and McColloug (2002), this study found that per-capita waste generation increases with increasing income. It was found that the average per-capita MSW generation was 134, 309 and 401 grams/day for the lower, middle, and upper income residents, respectively. These figures were obtained through averaging all of the data from both seasons of waste audits in several neighborhoods. This means that low-income residents (specifically in slums) generate significantly less waste than the rest of the wealthier population – about one-third of what upper income residents generate. The widest gap in waste generation exists between the lower income and middle income groups; the middle and upper income groups' figures followed the trend, but were closer in value.

Table 7: Average daily per capita generation of waste for the lower, middle, and upper income neighborhoods analysed.

Waste Category	**Lower Income (grams/day per capita)**		**Middle Income (grams/day per capita)**		**Upper Income (grams/day per capita)**	
Organic	107	79.7%	203	65.7%	276	69%
Paper	7.5	5.6%	26	8.5%	34.4	8.6%
Plastic	6.3	4.7%	18	5.9%	24	6.0%
Multilayer Packing (mixed materials)	2.4	1.8%	25	8.0%	13	3.2%
Metal	0.2	0.2%	1.2	0.4%	1.8	0.5%
Glass	2.8	2.1%	9.8	3.2%	13	3.3%
Clothing	4.0	3.0%	9.8	3.2%	6.7	1.7%
Sanitary	1.0	0.8%	9.2	3.0%	17	4.3%
Electronic	0.02	0.0%	0.4	0.1%	0.26	0.1%
Other	2.9	2.1%	6.3	2.0%	15	3.8%
TOTAL	**134**	100%	**309**	100%	**401**	100%

For all of the waste categories except "multilayered packaging" listed in **Table 7** generation increased with increasing income.

In order to test the whether the average generation figures for each of the socioeconomic groups were statistically different from each other, t-tests were carried out. Two-sided t-tests were conducted in Excel, and the results are listed in **Error! Reference source ot found.**. The results indicate that for all waste categories, the lower income and middle income values are statistically distinguishable, with the middle income group having higher values. For all but one of the categories, the lower and upper income waste generation figures are also different, with the upper income group generating more waste. Statistically, the middle and upper income group averages were less easily distinguishable; however, the amount of organic waste generated by the upper income group was found to be statistically higher than the middle income group.

Table 8: P-values showing results of t-tests that compare per-capita waste generation by each of the socioeconomic groups. Cells highlighted in green indicate statistical significance ($p < 0.1$).

T-test Groups	Organic	Paper	Plastic	Multilayer Packaging	Metal	Glass	Clothing	Sanitary	Electronics	Other
Lower vs Middle	0.0018 Middle > Lower	0.0014 Middle > Lower	0.0005 Middle > Lower	0.0048 Middle > Lower	0.032 Middle > Lower	0.0099 Middle > Lower	0.0036 Middle > Lower	0.0009 Middle > Lower	0.0296 Middle > Lower	0.048 Middle > Lower
Lower vs Upper	0.0004 Upper > Lower	0.0002 Upper > Lower	0.0022 Upper > Lower	0.028 Upper > Lower	0.015 Upper > Lower	0.027 Upper > Lower	0.33	0.0063 Upper > Lower	0.011 Upper > Lower	0.011 Upper > Lower
Middle vs. Upper	0.042 Upper > Middle	0.20	0.22	0.13	0.34	0.47	0.32	0.11	0.39	0.044 Upper > Middle

FINDING 2: Future Wealth Growth will Place Increasing Pressure on the Waste System

Given that the waste audit data clearly shows that higher income populations generate significantly more waste, India can expect to see a significant increase in waste volumes as its population becomes wealthier (Ernst & Young, 2013). As the lower income bracket shrinks and the middle income bracket expands, the percentage of the population generating waste at the middle level will increase, thereby increasing total waste generation. The per-capita generation findings suggest that if 10% of the population moves from the lower-income group to the middle-income group, this would increase total waste generation by 8%.

FINDING 3: The Majority of Residential Waste is Biodegradable

For all socioeconomic groups, the majority of waste was biodegradable material, rather than recyclable or refuse. This is made apparent by the green portion of the bars in ***Figure 14***; in this figure, the biodegradable material category includes food and vegetative matter, recyclables include paper, plastic, metal, and glass, and refuse includes multilayer packaging, clothing, sanitary waste, electronics, and other miscellaneous items.

The lower income waste had the highest proportion of biodegradables; it was composed of 80% biodegradables. Waste from middle and upper income residents was composed of 66% and 69% biodegradables, respectively. The remaining fraction of the waste was about half recyclables and half other materials (refuse). Lower income waste likely has the largest relative amount of biodegradable waste, because families have less disposable income to spend on packaged goods that generate paper, plastic, etc. waste.

Figure 14: Daily per-capita generation of biodegradable, recyclable, and refuse material.

The high fraction of biodegradables found in Pune's residential waste is likely representative of other Indian cities. This large organic fraction makes the waste wet, heavy, and particularly important to manage for preventing methane emissions.

As shown in **Figure 15** the vast majority of this biodegradable waste is composed of food scraps, with only small amounts of yard trimmings. Because the source of this waste is homes in a dense city where only the wealthiest families have private yards, it is reasonable that families would mainly generate food scraps. As shown in the graph, the lower income families generate close to zero yard waste.

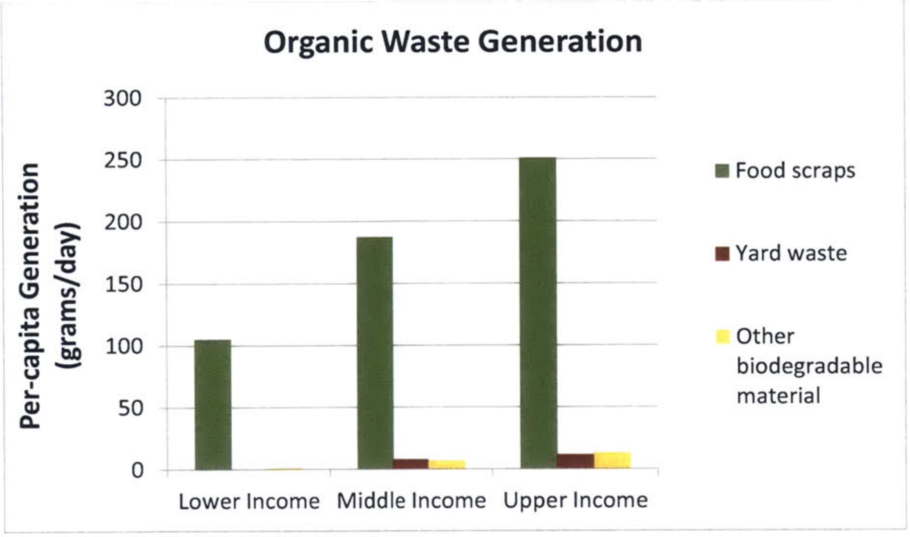
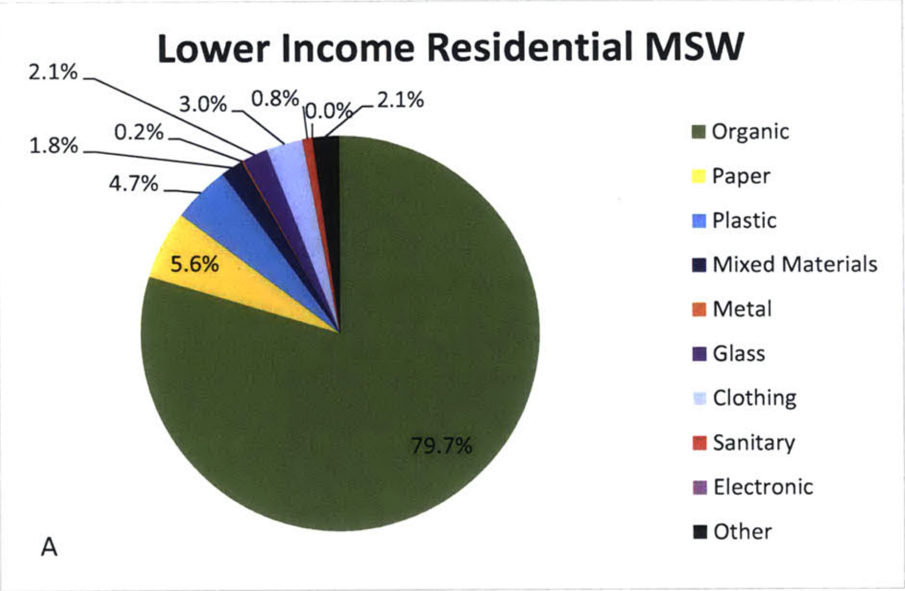


Figure 15: Per-capita residential organic waste generation.

The composition of waste for each of the three socioeconomic groups is visually presented in the pie charts in ***Figure 16*** **(parts A, B, C).**



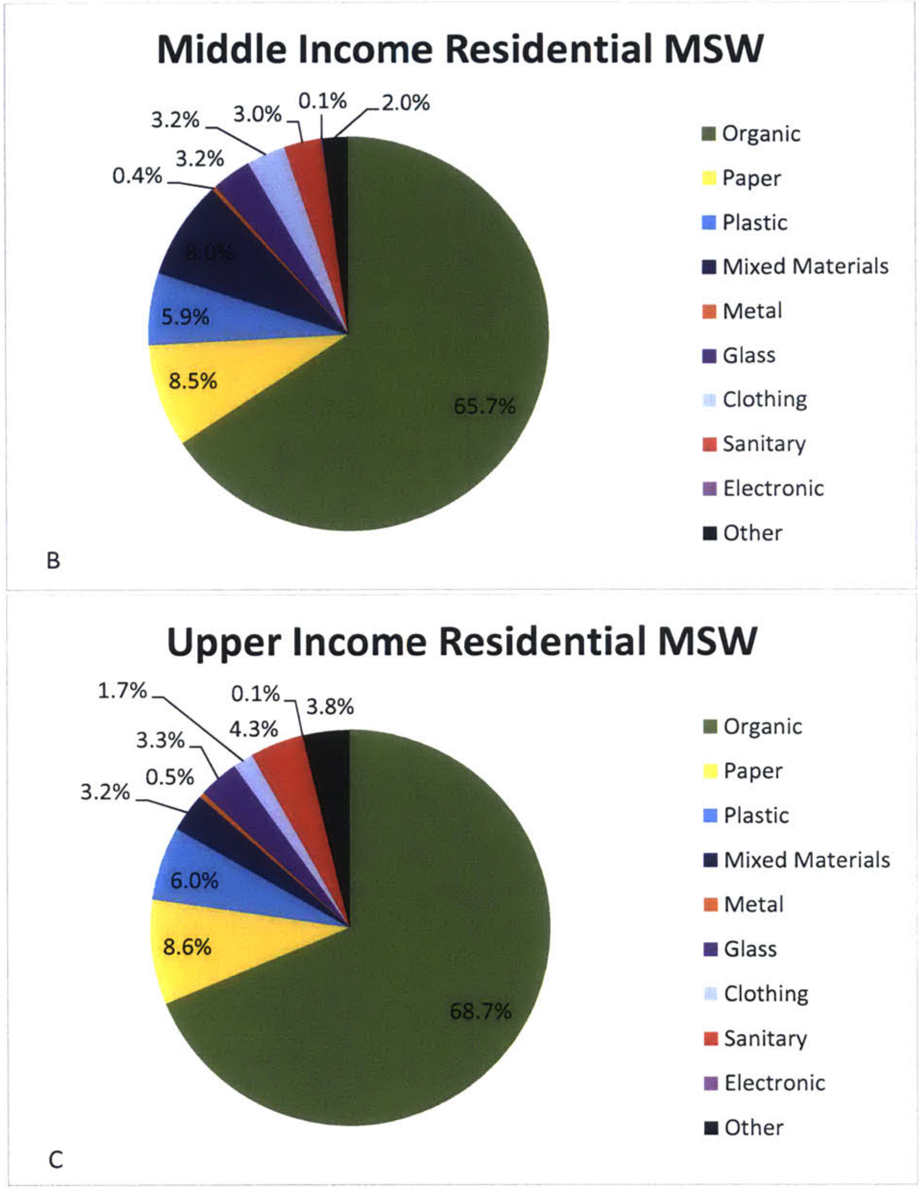


Figure 16: Pie charts showing the waste composition for lower income (A), middle income (B) and upper income (C) neighborhoods.

FINDING 4: There are Some Seasonality Differences

By conducting the waste audit in summer as well as winter in Pune, we were able to compare the volume and composition of waste generated by season. **Figure 17** shows the waste audit results for summer and for winter. Most trends regarding composition and a positive relationship between generation and income hold for both seasons. As seen in **Figure 18**, the composition of each waste stream in terms of percentage is comparably similar for each season. It does appear that there is a greater amount of multilayer packaging generated in summer.

With regard to per-capita waste volumes, the winter (February 2015) audit shows that the volumes of waste were larger than in July of 2014 for the lower and upper income residents; this may be a result of higher seasonal consumption or the fact that the set of neighborhoods sampled were slightly different for the two audits. In order to determine whether any seasonality trends exist, we analyzed the six neighborhoods that were audited in both seasons. Using two-sided t-tests in Excel, and a confidence interval of 90%, I checked whether the waste volumes for each stream were statistically different by season for each neighborhood. The results of these tests are shown in

Table 9 with the categories showing a statistically-defensible seasonal trend highlighted in green. Indeed, organic waste and multilayer packaging seem to vary by season. The results suggest that during the summer season, families generate more organic waste and more multilayer packaging waste. This may be an indication that more consumption and waste generation occurs in summer due to different produce availability or yard productivity and maintenance.

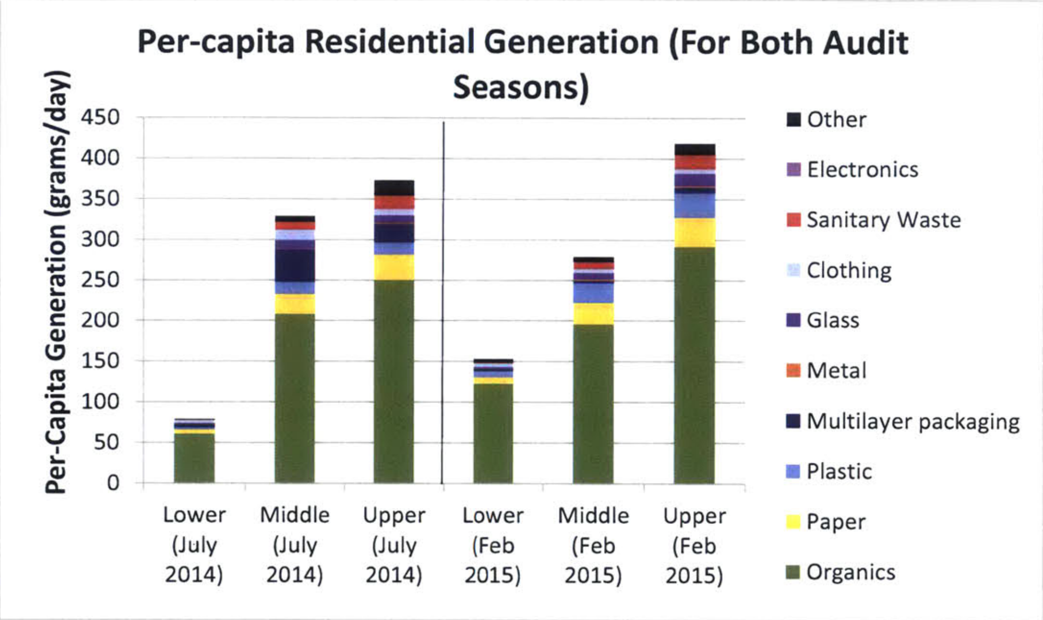


Figure 17: Per-capita residential MSW generation in summer (July 2014 audit) and winter (February 2015 audit)

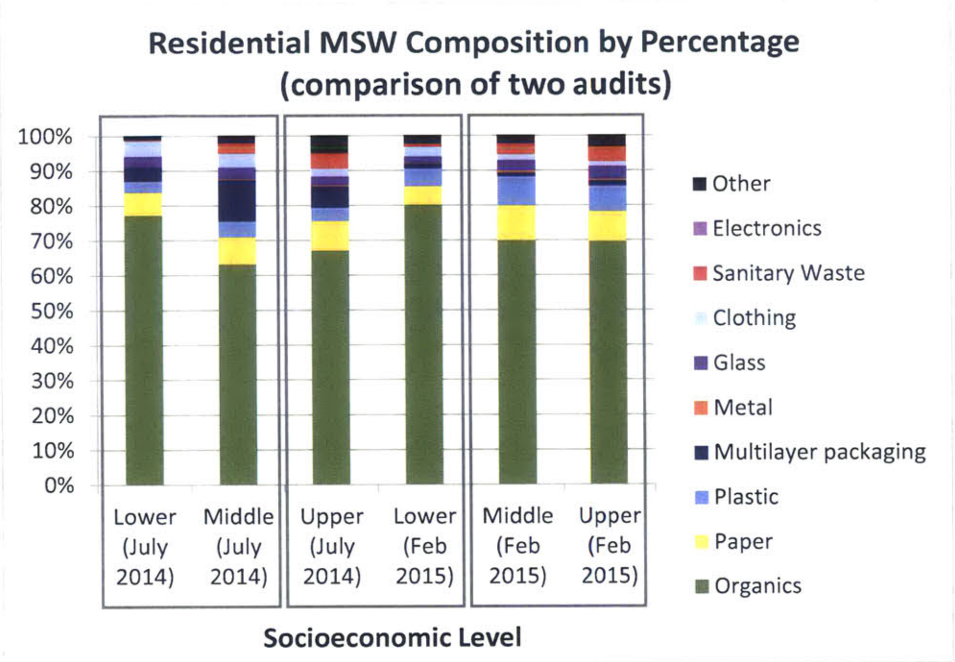


Figure 18: Residential MSW composition by percentage (comparison of two audits).

Table 9: P-values showing results of t-tests for per-capita waste measurements taken in summer (Smr.) 2014 vs. winter 2015 for the six neighborhoods that were analyzed both seasons. Cells highlighted in green indicate that the seasonal volumes are statically different at 90% confidence interval (p < 0.1).

	Waste Category									
Neighbor-hood	**Organics**	**Paper**	**Plastic**	**Multilayer packaging**	**Metal**	**Glass**	**Clothing**	**Sanitary Waste**	**Electronics**	**Other**
Mystic Moods	0.000 Smr. 2014 higher	0.10	0.036 Smr. 2014 higher	0.79	0.24	0.03 Smr. 2014 higher	0.15	0.11	0.34	0.076 Smr. 2014 higher
Sujay Gardens	0.033 Smr. 2014 higher	0.095	0.51	0.17	0.019 Winter 2015 higher	0.11	0.34	0.76	0.37	0.285
Rajas	0.087 Smr. 2014 higher	0.13	0.65	0.000 Smr. 2014 higher	0.34	0.40	0.25	0.94	0.24	0.015 Winter 2015 higher
Parijaat	0.35	0.12	0.14	0.008 Smr. 2014 higher	0.92	0.27	0.14	0.94	0.68	0.37
Sawat Nagri	0.035 Winter 2015 higher	0.31	0.028 Winter 2015 higher	0.000 Smr. 2014 higher	0.14	0.89	0.095 Smr. 2014 higher	0.88	N/A	0.57
Ramnagar	0.035 Smr. 2014 higher	0.003 Smr. 2014 higher	0.220	0.000 Smr. 2014 higher	0.015 Smr. 2014 higher	0.18	0.05 Smr. 2014 higher	0.21	0.11	0.80

FINDING 5: Most Paper Waste is Low Quality

Within the category of paper waste, this study further segregated paper into the categories of white office paper, newspaper, notebook paper, low quality scrap paper, cardboard, and sturdy boxboard. ***Figure 19*** shows the results of paper waste generation by socioeconomic group. The majority of paper waste was low quality scrap paper, which included receipts, brown paper, dirty scraps, and shreddings. Cardboard and white office paper were the next highest volume streams. The relatively low volume of newspaper and office paper may be a result of residents separating and selling high-value paper to itinerant buyers.

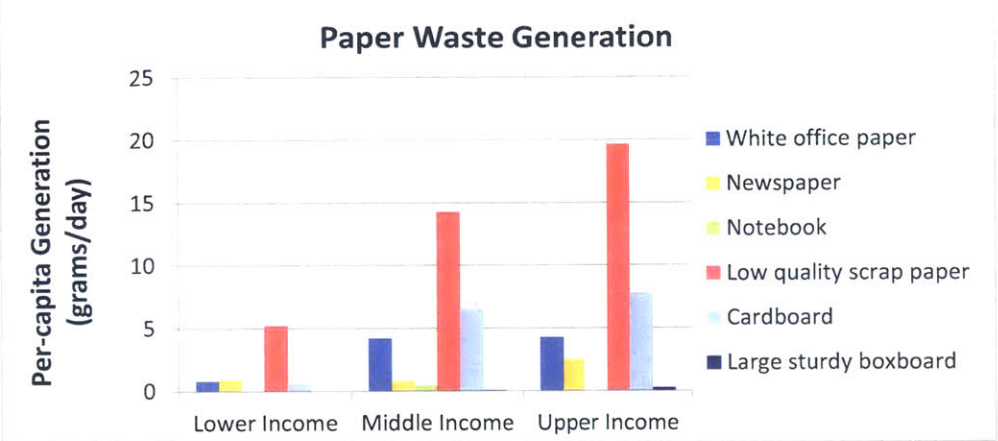


Figure 19: Per-capita residential paper waste generation.

FINDING 6: Plastic Streams are Diverse

Of the plastics, the largest streams were found to be colored plastic bags, thick polyethylene terephthalate (PET) bottles, and high-density polyethylene (HDPE) containers. **Figure 20** shows the results of plastic waste generation by socioeconomic group. For all three socioeconomic groups, colored plastic bags were the highest volume plastic (by weight). However, a number of other forms of plastic were found in measurable amounts in all neighborhoods, illustrating the ubiquity of disposable plastics.

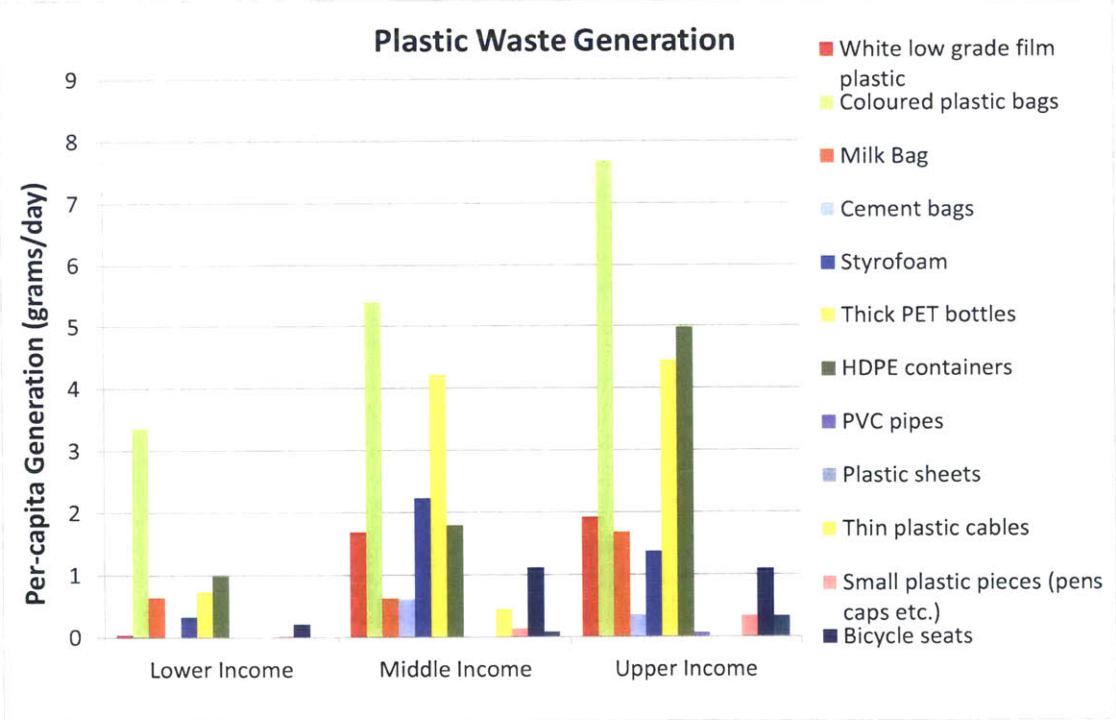


Figure 20: Per-capita residential plastic waste generation

FINDING 7: The Lower Income Residents Generates Little Metal

As shown in ***Figure 21***, the lower income households generated very little metal, as compared to the middle and upper income houses. The upper income residents' waste contained significantly more aluminum and steel cans, whereas such items were rare in slums.

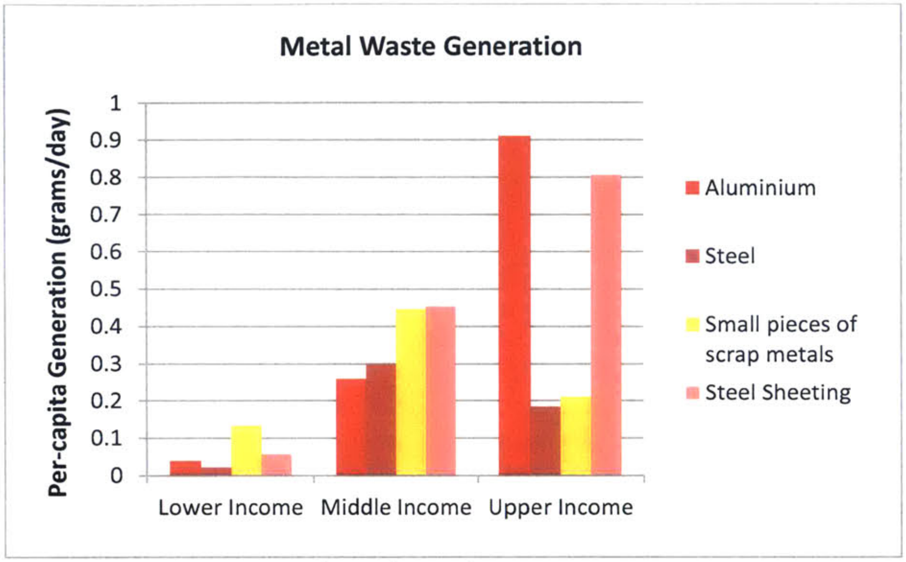


Figure 21: Per-capita residential metal waste generation.

FINDING 8: The Middle Income Residents Generate the Most Chip Bags and Packets

Multilayer packaging, which often consists of plastic, paper, and aluminum adhered together, was a large source of waste in the MSW from middle and upper income households (**Figure 22**). Despite Tetra Pak being a heavier material, chip bags and packets dominated in volume compared to Tetra Pak. Interestingly, the middle income generated more of these chip bags and packets than the upper income residents, which may be indicative of the middle income residents consuming more pre-packaged foods, while the upper income group has the privilege of having in-house helpers prepare home-cooked meals.

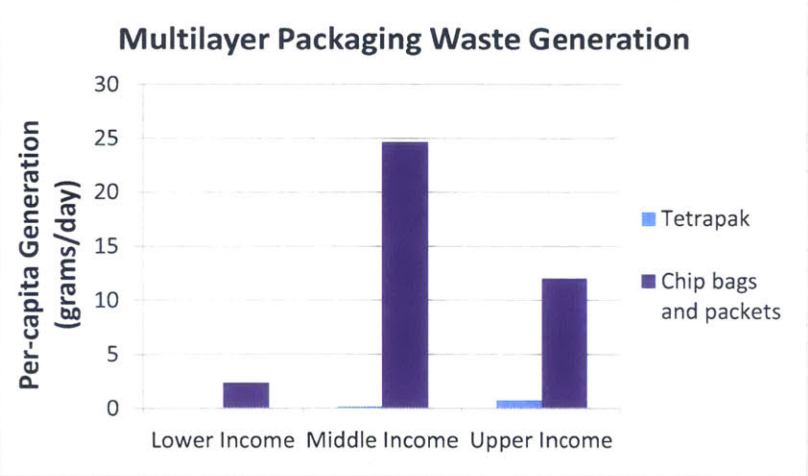


Figure 22: Per-capita residential multilayer packaging waste generation.

FINDING 9: Sanitary Waste Generation Increases with Income

Solid sanitary waste - waste that comes from human use of items like diapers, sanitary napkins and other feminine hygiene products - is another challenging waste stream for cities to handle sustainably. In contrast to organic waste, sanitary waste is only a small fraction of the total waste stream and has even less-obvious paths for sustainable management. Sanitary waste is a rapidly growing waste stream; women increasingly use disposable feminine hygiene products as they become aware of the options available and gain more control over their income, and as products become more accessible. However, it is still the case that lower-income women are less likely to use disposal menstrual products because they are less educated or cannot afford it. Furthermore, there is an increasing volume of soiled diapers being generated from India's growing middle class, in which more families are adopting disposable diapers for convenience.

Soiled sanitary napkins and diapers are complex waste streams; they contain a mix of plastic, human bodily fluids, and in many cases, proprietary materials and absorbents. The plastic is not easily recyclable, as it is contaminated. The bodily fluids make segregation and processing a potential health and occupational hazard. This makes their disposal much more complicated. Furthermore, taboos around menstruation inhibit the provision of designated waste containers and willingness of women to source.

Little literature on the quantity of sanitary waste generated in India could be found. Menstruation is still a taboo topic in India, and many women are as discrete as possible their sanitary napkin waste and do not discuss their usage of menstrual hygiene products. Furthermore, waste pickers normally do not separate out sanitary waste because, on top of not wanting to handle it, such material has no value to them.

As shown in ***Figure 23***, our audit results very much reflect the trend that sanitary waste consumption increases with income. Lower income residents produced almost no sanitary napkin waste, and only very little diaper waste (totalling 1 g/day). Upper income residents, on the other hand, generated 17 times that amount (17 g/day) of sanitary waste. Of all of the waste streams, sanitary waste generation was most sensitive to income such that higher income was associated with the largest factor of increase in volumes.

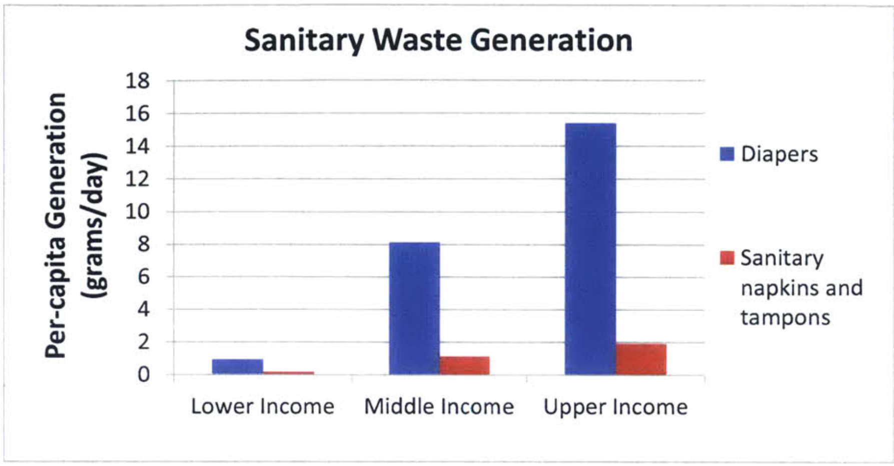


Figure 23: Per-capita residential sanitary waste generation.

FINDING 10: Lower Income Residents Throw Away Few Textiles

As was expected, we found that the amount of textiles found in the waste streams of the middle and upper income residents was higher than that of the lower income residents. This likely is a result of lower-income families reusing clothing and linens for longer, and having fewer items to begin with. As shown in ***Figure 24***, cotton and linen textile waste volumes consistently increased with income. Interestingly, synthetic textile generation values for the middle income group were higher than the upper income group; perhaps the upper income group does not tend to purchase clothing made of synthetic materials.

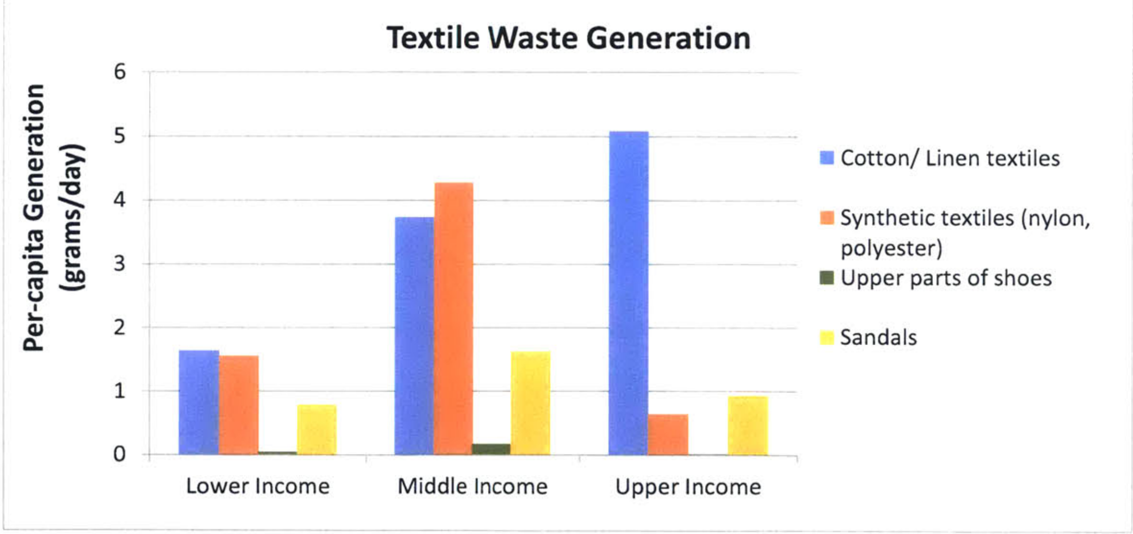


Figure 24: Per-capita residential textile waste generation.

FINDING 11: Middle and Upper Income Residents Throw Away More Electronics

In the waste we sampled, we found very little electronic waste. In particular, lower income residents threw away almost no electronics. Upper and middle income residents threw away less than 0.5 grams per capita each day (***Figure 25***). As is the case with newspapers and other recyclables, our measurement of electronic waste generation is likely an under-estimate of the true generation of electronic waste. It is common for Indian families often sell broken and unwanted electronics to itinerant buyers and scrap shops, and wealthy families may also donate these items. The city estimates that 4,000 tons of electronic waste generated each year (Jagtap, 2013); this works out to residents generating roughly 2.4 grams per-capita a day. Our finding is much lower, most likely because residents sell off their electronic waste.

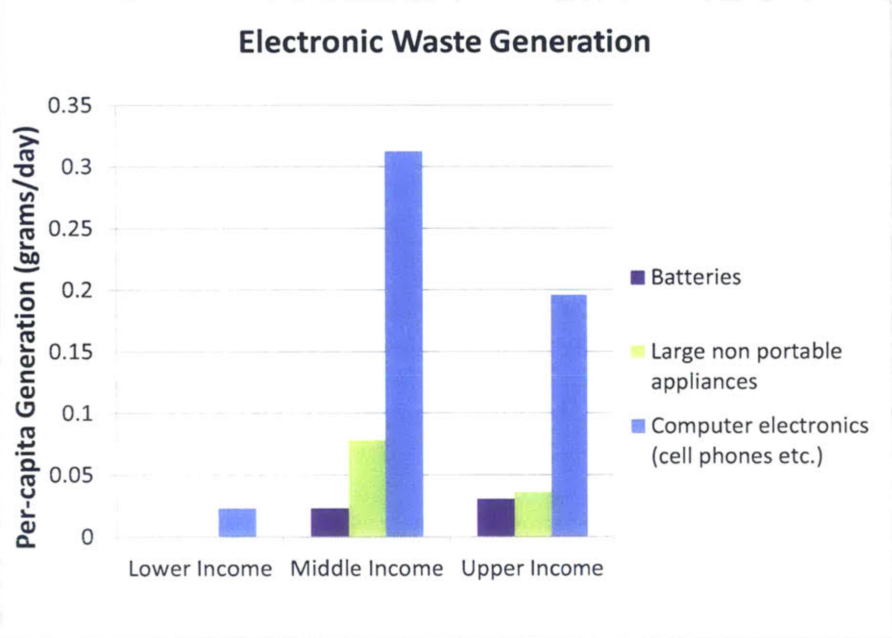


Figure 25: Per-capita residential electronic waste generation.

FINDING 12: Wood and Other Miscellaneous Items Vary with Income

As shown in **Figure 26**, higher income is also associated with increased generation of wood and other miscellaneous materials. This is another indication that wealthier families dispose of more materials that are difficult to recycle.

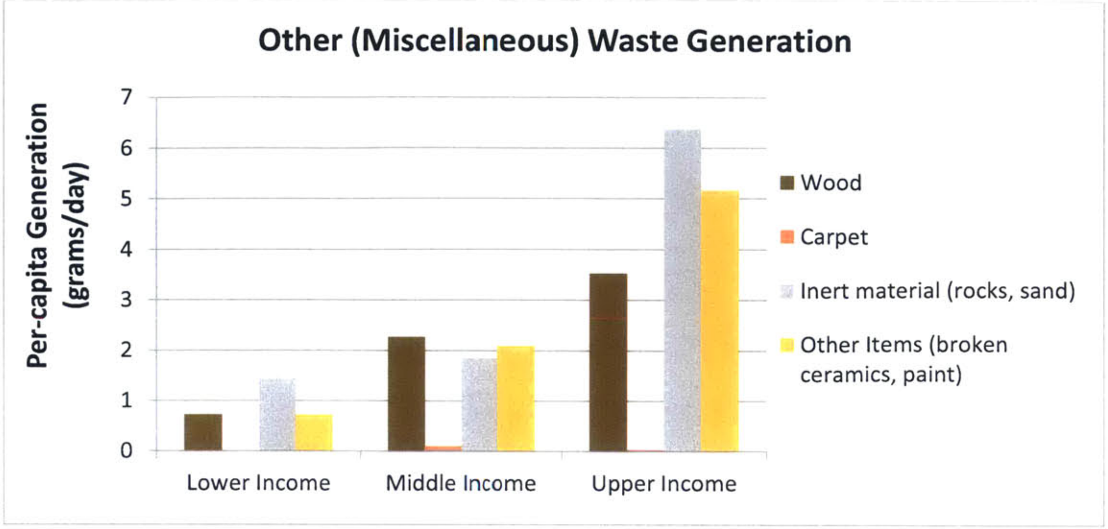


Figure 26: Per-capita residential miscellaneous waste generation.

Summary of Audit Results

In summary, the waste audit results indicate that per-capita MSW generation in Pune is 134, 309, and 401 grams/day for the lower, middle, and upper income residents, respectively. The middle income residents generate 2.3 times what lower income residents generate, and upper income residents generate 3 times what lower income residents generate. Most of this MSW (at least 65%, and often more) is wet, biodegradable organic waste. The next largest waste streams are paper and plastic. Per-capita generation of almost every type of MSW category increases with increasing income; this trend would imply that Indian cities will be facing an increasing load of MSW as demographics shift to a larger middle class.

3.6 Pune Residential Waste Flows and Recycling Value

Using the per-capita generation values from the waste audit results above (***Table 7***), the total volumes of residential MSW can be estimated. In order to do this, the population within each socioeconomic group must be estimated. Based on information from the PMC and SWaCH about Pune's demographics, we assume that the percentage of Pune's residents in each demographics is the following: 37% lower income, 48% middle income, and 15% upper income. This population distribution within socioeconomics is based on a combination of local expertise from SWaCH, 2011 census data, and the publications with demographic data. Unfortunately, India's census does not include household income, so the distribution could not be determined solely using the census. In **Table 10** the resulting population figures within each socioeconomic group has been calculated, as well as the total MSW generation in tons per day.

Table 10: The socio-economic distribution of Pune's population.

Socioeconomic Group	Percentage of Population	2014 Population (calculated using percentage times population from Table 1)	Municipal Solid Waste Generation (Tons/day)	Source of Socioeconomic Distribution
Lower Income	37%	1,717,958	230	Based on 2011 India Census, Pune population of residents living in slums and discussions with PMC
Middle Income	48%	2,228,702	689	100% minus lower and upper income populations
Upper Income	15%	696,469	279	SWaCH estimate of percentage of Pune in up; The Energy and Resources Institute, 2013
TOTAL	**100%**	**4,643,130**	**1,198**	

Using the population figures above in combination with the per-capita waste generation results, I estimated the total tons of waste generated each day for each category of waste. These results are found in the second column of **Table 11**Error! Reference source not found.. Based on our waste audit data, we estimate that Pune residents generate at least 1,198 tons of MSW a day, and that 773 tons of this are food scraps.

Table 11 also contains our estimate of the economic value of all of the recycling collected in Pune, based on their selling price within the recycling market. The selling price data for each item within the third column was obtained from SWaCH's data manager (Susarla, 2014). In total, recycling of residential waste yields a value of 1,916,214 Rs/day, which is the equivalent of 306,594 USD/day. For the purposes of this calculation, we assume that materials such as electronic waste, which involve specialized recycling, as well as biodegradable waste, have a value of zero. Therefore, this valuation should be viewed as a lower bound of the direct value of residential waste.

We found that plastic recyclables yield the largest share of the total value, with their combined worth being 941,317 Rs/day. Paper recyclables yield a value of 479,548 Rs/day. Metal recyclables yield a value of 36,358 Rs/day. And glass recyclables yield a value of 402,644 Rs/day. **Figure 27** shows the percentages of Pune's MSW by mass as well as the percentages of Pune's MSW broken down by economic value. It can be seen that even though plastic constitutes less than 6% of the mass, it contributes 60% of the economic value of MSW in the recycling market.

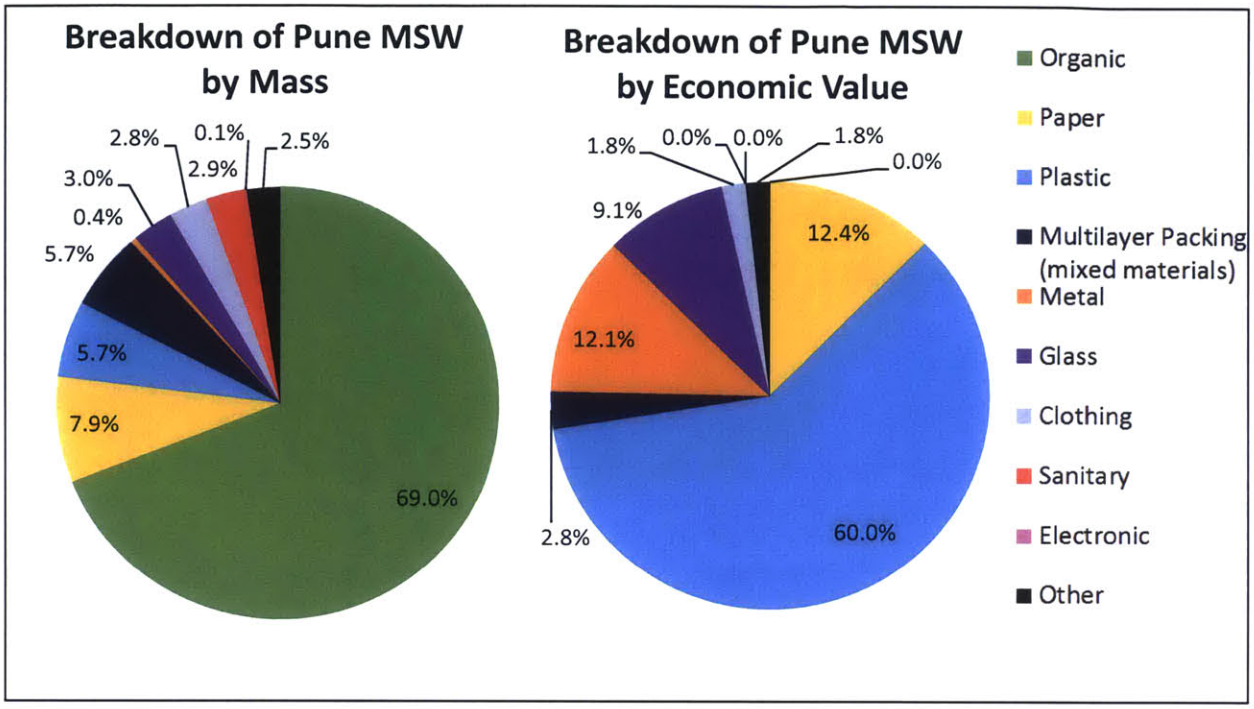


Figure 27: Pie charts showing Pune's MSW by percentage of total mass and by percentage of total economic value, based on the information in Table 11.

Table 11: Pune waste flow magnitudes and economic value (in the recycling market) listed by waste type.

MSW Category	Tons/day	Sale Rate (Rs/ton)	Value of Waste Sold (Rs/day)	Value of Waste Sold ($/day)
Food scraps	773	0	0	0
Yard waste	26.5	0	0	0
Other biodegradable material	27.8	0	0	0
White office paper	13.7	9,000	123,572	19,772
Newspaper	5.0	7,000	34,778	5,564
Notebook	0.99	9,000	8,900	1,424
Low quality scrap paper	54.3	3,000	163,063	26,090
Cardboard	21.0	7,000	146,667	23,467
Large sturdy boxboard	0.3	8,000	2,568	411
White low grade film plastic	5.2	7,000	36,123	5,780
Colored plastic bags	23.1	7,000	161,848	25,896
Milk Bag	3.7	2,000	7,321	1,171
Cement bags	1.6	10,000	16,106	2,577
Styrofoam	6.5	35,000	227,165	36,346
Thick PET bottles	13.7	20,000	274,822	43,971
HDPE containers	9.2	20,000	182,977	29,276
PVC pipes	0.045	30,000	1,336	214
Plastic sheets	0.004	7,000	27	4
Thin plastic cables	1.0	7,000	7,021	1,123
Small plastic pieces (pens caps etc.)	0.59	4,000	2,350	376
Bicycle seats	3.6	5,000	17,992	2,879
Rubber tubes	0.4	15,000	6,229	997
Tetra Pak	0.89	8,000	7,118	1,139
Chip bags and packets	67.4	0	0	0
Aluminum	1.3	8,000	10,225	1,636
Steel	0.83	18,000	14,881	2,381
Small pieces of scrap metals	1.37	7,000	9,584	1,533
Steel Sheeting	1.7	1,000	1,668	267
Glass bottles	21.5	18,000	387,463	61,994
Beer bottles	7.1	1,000	7,081	1,133
Kingfisher bottles	1.4	2,000	2,782	445
Liquor bottles (quarter litres)	2.7	1,000	2,656	425
Mini Liquor bottles	0.659	1,000	659	105
Ketchup Bottles	0.693	500	347	55
Glass soda bottles	0.013	1,000	13	2
Broken pieces of glass	1.643	1,000	1,643	263
Cotton/ Linen textiles	14.6	2,000	29,292	4,687
Synthetic textiles (nylon, polyester)	12.7	1,000	12,637	2,022

MSW Category	Tons/day	Sale Rate (Rs/ton)	Value of Waste Sold (Rs/day)	Value of Waste Sold ($/day)
Upper parts of shoes	0.44	1,000	440	70
Sandals	5.6	1,000	5,610	898
Diapers	30.3	0	0	0
Sanitary napkins and tampons	4.0	0	0	0
Batteries	0.072	0	0	0
Large non portable appliances	0.20	0	0	0
Computer electronics (cell phones etc.)	0.87	0	0	0
Wood	8.8	0	0	0
Carpet	0.25	5,000	1,251	200
Inert material (rocks, sand)	11.0	0	0	0
Other Items (broken ceramics, paint)	9.5	0	0	0
	1199 tons/day		1,916,214 Rs/day	306,594 USD/day

3.7 The Impact of Upward Mobility and Population Growth on Waste Generation

As India's economy and standard of living develops, the middle class is expected to expand and consumption of disposable goods will probably continue to increase. Furthermore, the population in India's cities is growing at a rate of 1.3% annually (The World Bank, 2014); as population increases, so will the total load of waste generated by residents. To understand the impact that upward mobility and population growth will have on the quantity of organic waste generated in Pune, I have estimated the quantity of (residential) organic waste under a number of scenarios. The results and descriptions of these scenarios are listed in **Table 12**, and are also graphed using bar charts in ***Figure 28***. All of these scenarios assume that the per-capita waste generation for the lower, middle, and upper income group is 107, 203, and 276 grams/day, respectively (same as that in ***Table 7***). These upward-mobility scenarios suggest that up growth of the middle and upper income groups could increase the city's total organic waste load by up to 10%. In other cities less affluent than Pune, this percentage increase would likely be higher, as their current population contains a larger percentage of individuals in the lower-income bracket. The population growth scenarios predict that by 2030, Pune could be generating 7-15% more organic waste than it is currently (2014), depending on whether this growth occurs mostly within the low-income demographic. Lastly, the final scenario estimates that with a growth rate of 1.3% in combination with upward mobility (in which 17% the population moves from lower to middle income), Pune's total organic waste generation will be 1,111 tons/day. This corresponds to a 34% increase in organic waste volume. These findings all signify that a combination of growth in wealth and in population will significantly increase organic waste volumes and will require the city to expand its waste system infrastructure.

Table 12: Pune residential waste generation projections for upward mobility and population growth scenarios.

Scenario Description of Pune's Demographics	Socio-economic Group	Percentage of population	Population	Total Volume of Organic Waste (tons/day)
Current 2014 population with current socioeconomic distribution	Lower	37%	1,717,958	184
	Middle	48%	2,228,702	452
	Upper	15%	696,469	192
	Total	**100%**	**4,643,130**	**828**
Upward Mobility Scenario 1: 17% of population moves from the lower to the middle income group	Lower	20%	928,626	98
	Middle	65%	3,018,035	566
	Upper	15%	696,470	175
	Total	**100%**	**4,643,130**	**838**
Upward Mobility Scenario 2: 32% of population moves from the lower to the middle; 5% of population moves from middle to upper income group	Lower	5%	232,157	24
	Middle	75%	3,482,348	653
	Upper	20%	928,626	233
	Total	**100%**	**4,643,130**	**910**
Population Growth Scenario 1: Year 2030, 1.3% annual population growth, evenly distributed across socioeconomic groups	Lower	37%	2,112,339	222
	Middle	48%	2,740,332	514
	Upper	15%	856,354	215
	Total	**100%**	**5,709,025**	**951**
Population Growth Scenario 2: Year 2030, 1.3% annual population growth, with 95% of this growth occurring within the lower income group	Lower	48%	2,730,559	287
	Middle	40%	2,255,349	423
	Upper	13%	723,116	182
	Total	**100%**	**5,709,024**	**891**
Population Growth plus Upward Mobility Scenario: Year 2030, 1.3% annual population growth; 17% of population moves from the lower to the middle income group	Lower	20%	1,141,805	122
	Middle	65%	3,710,866	753
	Upper	15%	856,354	236
	Total	**100%**	**5,709,025**	**1,111**

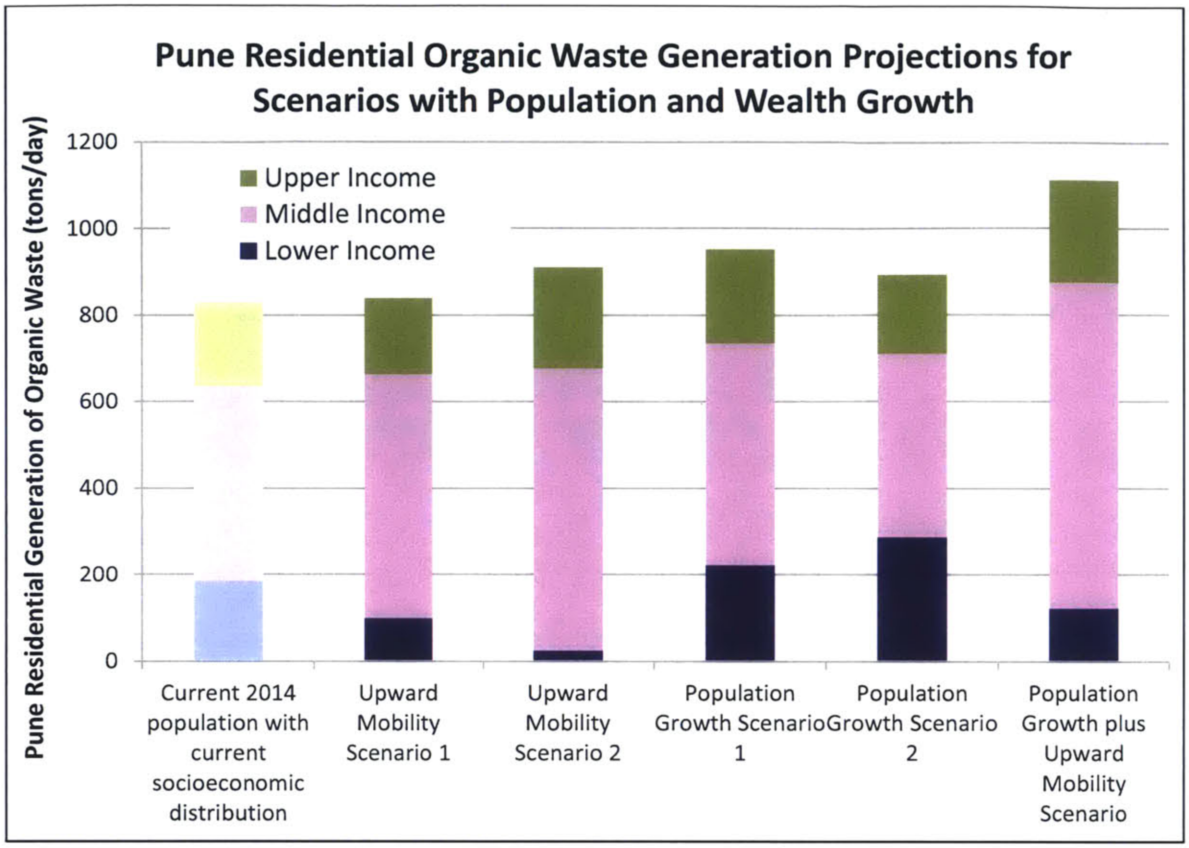


Figure 28: Pune residential organic waste generation projections for 6 scenarios involving population and/or wealth growth.

3.8 Organic Waste Flow Analysis of Aundh Ward

In addition to looking at MSW waste flows for the city in its entirety, we analyzed the waste flows within one of the city's fifteen administrative wards, called Aundh. This Aundh ward analysis focuses solely on organic waste. This ward-level waste flow analysis will be the focus for the economic and environmental scenario analyses in chapters 4 and 5. We focused on Aundh ward, specifically, because the PMC has committed to making Aundh and other wards "zero-waste" after proving it is possible with one of the city's other wards. With indispensable on-the-ground assistance from SWaCH and an organization called Waste Ventures, we were able to collect data on waste management within the ward.

Aundh ward is located in the northwestern corner of Pune, and is shown by the highlighted red area in the map in **Figure 29**. Aundh is about 40 square kilometers in area, and some general characteristics about the ward can be found in **Table 13**.

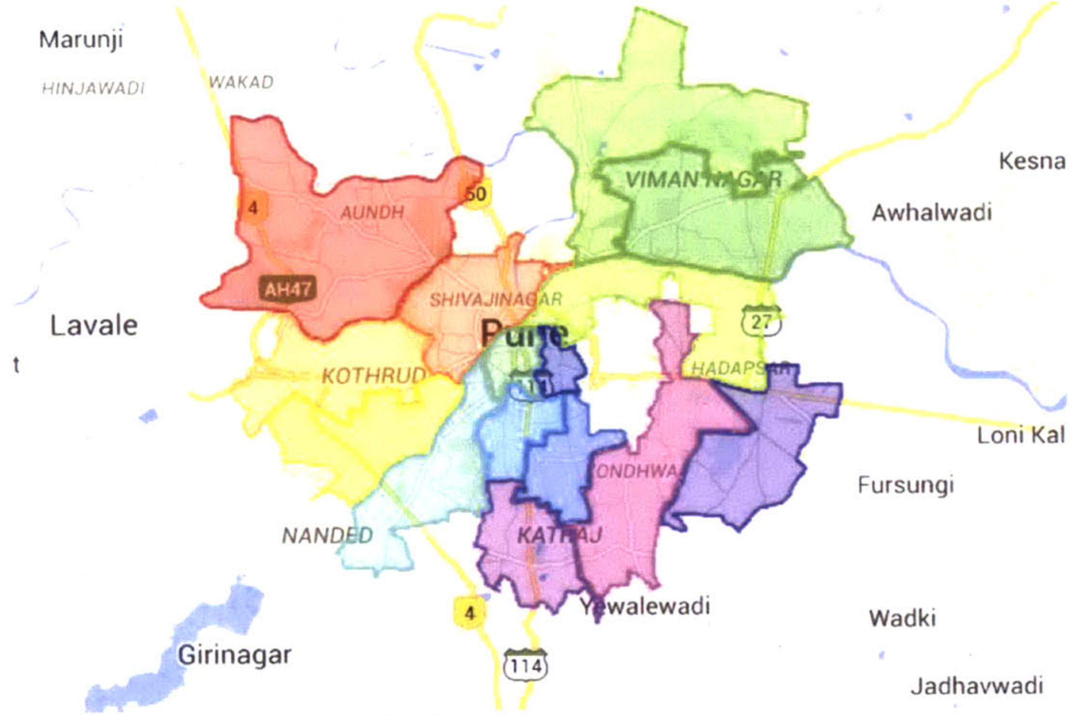


Figure 29: Map of Pune City, showing Aundh Ward in red.

Table 13: Aundh ward characteristics.

Aundh Ward Features		**Data Source**
Size	40.2 Sq. Km	Waste Ventures
Location	Northwestern periphery of Pune	Google Maps
Density per/hectare	45.05	Waste Ventures
Properties	51,654	Waste Ventures
Types of Properties	Residential, Commercial, Institutional, Slums	Waste Ventures
Urban India population growth between 2011 and 2014	1.3%	www.worldbank.org
Population	181,124	2011 India Census
Aundh Slum Population	39,380 (21.7%)	2011 India Census
Aundh Non-slum Population	141,744	2011 India Census
Pune entire city population (2011)	3,304,888	2011 India Census
Percent of Pune's population in Aundh	5.48%	Calculation
Estimated Aundh population in 2014	188,280	Calculation using annual urban growth rate of 1.3%

3.8.1 Residential Organic Waste

In order to estimate the amount of waste generated solely within Aundh ward, we used a method similar to that in Section 3.5, used for analyzing all of Pune city. We accounted for population growth and adjusted the 2011 population census data for the ward to determine the current population in Aundh. These population figures are listed in ***Table 13***.

Using the subset of our waste audit data that came specifically from neighborhoods in Aundh ward, we calculated the average per-capita volume of organic waste generated by each socioeconomic group. We based our assumptions about the demographic distribution of the population on the city's census data, which reported that 21.7% Aundh's residents live in slums. Because Aundh residents are generally wealthier than city's average residents, we assumed that 54.8% of residents are middle income and 23.5% are upper income. This allowed us to calculate the total volume of organic waste generated by Aundh's residents, which is reported in **Table 14**. We found that the ward's residents generate 39.8 tons/day of organic waste.

Table 14: Empirically-estimated volumes of residentially-generated organic waste in Aundh Ward.

	Per Capita Generation (g/day)			Population		Total Generation (tons/day)		
Socioeconomic Group	Food Waste	Garden & Other Organics	Total Organics	% of Population in each Group	2014 Aundh Population	Food Waste	Garden & Other Organics	Total Organics
Lower/Slums	120	2.2	122	22%	40,932	4.9	0.09	5.0
Middle	173	24.9	198	55%	103,177	17.9	2.6	20.4
Upper	293	32.2	325	23%	44,189	12.9	1.4	14.4
TOTAL					188,280	**35.7**	**4.1**	**39.8**

3.8.2 Commercial Organic Waste Generated in Aundh

To estimate the total amount of organic waste generated in the ward, both the residential and commercial volumes must be known. Because records were not kept about the amount of commercial organic waste in Aundh, we used a few different methods to determine the figure.

According to a report published by Kagad Kach Patra Kashtakari Panchayat (2007b), Aundh's total waste generation was 63.2 tons/day, which includes biodegradable and non-biodegradable waste. By subtracting 39.8 from 63.2 (the first number is based on 2015 data and the second number is based on 2007 data), we can say that 23.4 tons/day is a one estimate of the combined amount of Aundh's (1) non-biodegradable residential waste, (2) non-biodegradable commercial waste, and (3) biodegradable commercial waste. Consequently, the amount of biodegradable commercial waste must be less than 23.4 tons/day.

We also compiled more recent data on the volumes of organic waste generated in Aundh and its method of processing from PMC, INORA, SWaCH, and Waste Ventures, which is presented in **Table 15**. This data suggests that Aundh's combined volumes of residential and commercial organic waste is at least 44.25 tons/day. Subtracting the volume of residential waste from the 44.25 yields a lower bound of 4.4 tons/day for the volume of commercial organic waste. Consequently, the amount of commercial organic waste is somewhere between 4.4 and 23.4 tons/day.

Table 15: Processing destinations of organic waste generated in Aundh. Some of the waste generated in Aundh is processed within the ward, and some is processed in centralized facilities elsewhere in the city. Data sources: PMC, INORA, SWaCH, Waste Ventures.

Destinations of Organic Waste that is Generated in Aundh	Waste Quantity (from Aundh) that is Processed (tons/day)
OWC Composting Facility	2.1
Biogas	10.7
Farmers outside the city	7.8
Buried	1.1
Disha and Ajinkya Centralized Composting	16.1
Decentralized Composting Sites (Identified by INORA and SWaCH)	6.4
Uruli Devachi Dump (reported by PMC)	Unknown
TOTAL Organic Waste in Aundh	**≥44.3**

To narrow down the estimate from the bound of 4.4 - 23.4 tons/day to a smaller range, we looked at the number and types of commercial establishments in Aundh. **Table 16** lists the number of commercial properties in Aundh, as reported by the Aundh Ward Office. In total, there are 4,026 commercial establishments in the ward. The next step involved determining the amount of waste each type of commercial establishment generates. To do this, we used data from our colleague's study, which measured the quantity of waste generated by commercial hotels, restaurants, and banquet halls in the city of Muzaffarnagar, India (Mytty, 2015). Since the majority of the commercial waste in Indian cities is biodegradable, for the purpose of our calculations, we assumed that all of the commercial waste is organic. We also assumed that businesses in Pune generated the same volume of waste as businesses of the same type in Muzaffarnagar. Next, by multiplying the generation per business by the number of businesses in Aundh we calculated the volume of organic waste generated by all commercial establishments in Aundh, as shown in **Table 17**. This method of calculation yielded an estimate of 5.13 tons/day of organic waste, which indeed is between the expected range explained above.

Table 16: Aundh property types. Data source: Aundh Ward Office Report on Solid Waste Management 2015.

Property Category	Property Type	No. of properties
Residential	Housing Societies (1123)	51,654
	Slums	9,140
	Chawls/ Tenements	9,924
	Total number of residential units	**70,718**
Commercial	Shops/ Commercial Establishments	3,404
	Hotels and Restaurants	178
	Hair Salons	160
	Religious Sites	114
	Marriage Halls	18
	Meat Shops	145
	Market	7
	Total commercial establishments	**4,026**

Table 17: Estimation of commercially generated organic waste based on Mytty's (2015) empirically collected generation figures form the city of Muzaffarnagar.

Commercial Establishment Type	Average amount of waste generated per day in Muzaffarnagar (kg/day)	Assume Aundh establishments generate same amount and all of it is organic (kg/day)	Number of Establishments in Aundh	Quantity of commercial waste in Aundh
Hotel	49.7	49.7	20	994
Restaurant	9.38	9.38	158	1482
Banquet Hall	147.9	147.9	18	2262.2
	Estimated organic waste from Aundh hotels, restaurants, banquets			**5138 kg/day (5.14 tons/day)**

Lastly, we used PMC reported figures of commercial waste streams to develop another estimate. The third column of **Table 18** lists PMC reported volumes of commercial organic waste for all of Pune. As shown in **Table 18**, we assumed that commercial waste generation scales with population; because Aundh's population is 5.48% of the city, we assumed Aundh's commercial waste is 5.48% of Pune's commercial waste. We also assumed that the waste coming from hotels, restaurants, and markets is 90% organic, and that the waste coming from fruit, vegetable, and fish markets is all organic. This method of calculation led us to the estimate of 10.27 tons/day.

Table 18: Estimation of commercially generated organic waste in Aundh based on PMC figures.

Generation Source of commercial waste (all types)	Organic Fraction Assumed	Mundhe et al., 2014 Reported values	PMC Reported Commercial Generation for all of Pune (tons/day)	Estimate of Commercial Organic Waste (Assuming 5.48% of Pune waste generated in Aundh)
Street sweeping and drain cleaning	0%	-	140	0
Hotels and Restaurants	90%	250	150	7.40
Market/ Commercial Area	90%	300	50	2.47
Construction/ Demolition	0%	-	75	0
Fruit, veg, fish market	100%	50	7.5	0.411
Biomedical waste	0%	-	1.8	0
		Estimated amount of commercial generated organic waste in Aundh		**10.27 tons/day**

The above methods of calculation produced four different estimates of the volume of commercially generated organic waste. In order to narrow down the range of values, I conducted a data quality assessment (shown in ***Table 19***), in which I considered the assumptions and sources of information used to calculate the volume of commercial waste. Our best estimate of the volume of commercially generated organic waste in Aundh is 7.7 tons/day, which is the median value (average of the two middle estimates).

Table 19: Data quality assessment of four estimates of the amount of organic waste generated by commercial establishments in Aundh.

Estimates of Commercial Organic Waste Generated in Aundh (tons/day)	Source of Information that each Estimate Relies	Data Quality Assessment
4.4	Facilities processing organic waste; volumes mostly reported by PMC	Likely an underestimate because it is based on of the volume of waste going non-landfill processing sites
5.14	Commercial waste generation in another	Accurate only if commercial waste generation per establishment type

	Indian city, Muzaffarnagar	is similar across Indian cities; May be an underestimate, given that Muaffarnagar is a lower-income city
10.27	PMC reported figures of commercial waste in city of Pune; Aundh contribution based on population	Likely to be relatively accurate if PMC figures for the entire city's commercial waste generation is accurate
23.4	KKPKP estimate of waste generated in each of Pune's wards	Likely to be an overestimate, as it is based on an estimate of Aundh's waste generation that was calculating using a high per-capita generation

In summary, our findings indicate that Aundh generates 39.8 tons/day of residential organic waste, and 7.7 tons/day of commercial organic waste. In total, we estimate Aundh generates 47.5 tons of organic MSW daily.

Chapter 4: Social and Labor Impacts

Many thanks to Abdullah Sheikh, a collaborating researcher from the Imperial College of London, who conducted interviews in the field. The tables and charts below pertaining to the quality of life of wastepickers and itinerant buyers are adapted versions of figures in his thesis (Sheikh, 2014).

4.1 Introduction

This thesis now transitions from using mass flow analysis to using social, economic, and environmental assessment of existing and alternative waste system configurations. The social impacts are the first component analyzed (in this chapter); economic and environmental impacts are assessed in the following chapters.

This chapter seeks to understand how the current waste management systems and potential alternative systems impact various stakeholders. Particular emphasis is placed on characterizing the impacts waste management technologies have on the labor force (both formal and informal). Given that waste management in India combines work from both the informal and formal sectors, waste management issues have involved social and labor activism and political conflict. It is important to explore the source of these tensions and challenges. We identify specific strengths and weaknesses of the waste management system from the view of waste sector workers, as well as residents receiving waste services.

4.2 Background on Social and Labor Issues of Waste Management

Especially because waste management in India is carried out by both the informal and formal sectors, it is important to consider the impacts of waste practices, technologies, and system architectures on various stakeholders. In addition to being an environmental concern, waste has implications for human health, behavior, worker rights, and political tensions.

Since the responsibility of solid waste management in India lies with municipal governments, waste issues and services are localized and have local community impacts.

Historically, India's urban poor has had limited or no waste handling facilities or services. As a service, waste management is often unequitable and underprovided in developing countries. In the most basic sense, not receiving consistent waste collection and management will create litter on the streets, more uncontrolled burning, unpleasant stenches and rodents, unhappy residents and businesses dealing with an excess of trash. Because urban planning and public infrastructure in most of India's cities has been insufficient for handling increasing volumes of waste, much of the waste management occurs "informally." Waste management has become an especially noticeable political and social issue in India in recent years – it is the subject of protests at landfills and Prime Minister's "Clean India" campaign.

The informal waste sector, which includes wastepickers, itinerant buyers, and recyclers, is estimated to collectively employ 1-2% of the urban population in India (Chintan Environmental Research and Action Group, 2009). Traditionally, these informal waste workers are not organized by formal solid waste authorities, are not obliged to follow designated service routes or collection times, and are responsible for making their own business deals to buy and sell waste.

Due to cultural stigma and their lack of social power, wastepickers have historically been labeled as criminals and beaten or extorted for money by police (Chaturvedi, 2003). Waste workers have been linked with the Dalit caste, which is the most marginalized and shunned caste in India. Associated with the dirty nature of the waste itself, are marked with the stigma of being dirty scavengers. Members of the informal waste sector tend to have minimal education and are illiterate, which makes bargaining and pursuit of opportunities more difficult. Specifically in Pune, 90% of wastepickers are women, and therefore also face a unique set of safety and health issues (SNDT Womens' University, 2008); for instance, a female wastepicker may be forced to bring her children along with her to work if she does not have childcare.

Even though more than a million individuals in India rely on wastepicking as their primary source of income, their work yields unpredictable daily income (Chintan, 2012). The quality and quantity of recyclables fluctuates and some residents refuse to pay the monthly collection fee. Wastepickers and their families are often still trapped in the cycle of poverty; wastepickers who want their children to have a different profession when they grow up desperately want their children to receive a better education.

The work of waste picking is physically demanding due to heavy lifting, exposure to the elements, and typically non-motorized transport. According to Chintan Environmental Research and Action Group (2009), the average wastepicker walks or cycles 11-16 kilometers each day. Along their route, wastepickers pick up an average of 60 kg of waste per day (Chaturvedi, 2003). It is a long day in which they work 9 to 12 hours every day, six days a week (Chikarmane & Narayan, 2009). Informal wastepicking is a risky activity, especially if formal management of toxic and hazardous materials is not regulated or enforced. Such hazards are discussed in further detail in the subsequent section.

Although waste picking is labor intensive, it creates jobs and can help alleviate poverty. The informal waste sector in Pune is estimated to provide 630 jobs a year per 10,000 tons of waste generated; in contrast, mechanized systems similar to those in industrialized countries like the US generate 10-40 times fewer jobs (Linzner & Lange, 2013).

From a social standpoint, planned waste management systems in India vary in their level of inclusiveness of the informal sector. If systems do not acknowledge and actively include informal workers, they deny waste pickers representation and a voice, and potentially even eliminate their jobs.

From the government's point of view, the transactions that occur in the informal waste sector are not taxable and yield little government revenue. Yet, another perspective could be that waste pickers provide an environmental and sanitation service to the city at low cost.

Residents have varying notions of the informal sector, and may or may not segregate their waste, despite city rules. Engagement of residents is instrumental in making the waste system socially and logistically sound. Education of resident on the importance of source separation will be likely to segregate organic waste from recyclables and inform wastepickers of potential hazards, such as sharps, in the waste they hand over.

Meanwhile, wastepickers are often threatened by and opposed to the expansion of competing formal, privatized or public waste collection and sorting systems. For the informal sector, their "right" to the waste is instrumental to their livelihood. When waste is collected and sorted in large enough quantities, it is a valuable resource that creates competition. For instance, in a given city, both wastepickers and incinerating waste-to-energy facilities may compete over waste paper and plastics. Or, informal collectors and formal collectors may be competing to sell to the same recycling plants

Before the formation of SWaCH and KKPKP, waste pickers in Pune were socially invisible, dispersed and had little interaction with the city government. Only with the determination of KKPKP were wastepickers finally able to obtain government endorsed photo-identification cards in 1995 (SNDT Womens' University, 2008). Despite being labeled as a form of informal labor, waste picking is an economic contribution that has strong interactions with the formal sector. By coming together in cooperatives, wastepickers have been better able to establish respect within the community, leverage their rights, and lessen harassment and discrimination. In Pune, the wastepicker union and cooperative have given waste pickers the authorization to undertake door-to-door collection and municipal-provided medical insurance; the unification provides a network with social and tangible benefits.

4.3 Gap and Objective

Although secondary reports discuss the difficult working conditions of wastepickers, they do not always base their comments on information directly provided by wastepickers. Furthermore, little published material documents residents' view on the quality of waste management services. Pune's waste system is a unique case in which cooperation between the informal and formal sectors has been institutionalized, and the performance of the system relies daily on wastepicking labor. For these reasons, we felt it is important to assess the labor and social impacts of waste management practices on a variety of stakeholders. As foreigners assessing a complex system which we are not part of, we felt it was important to conduct a social implications of waste management that focused on personal accounts and interviews. By speaking with different parties involved in waste management (interviewing wastepickers, houses, etc.), we aimed to illustrate the diversity of perspectives and points of contention surrounding waste management. This chapter aims to understand (1) the health risks of collection and treatment of waste, (2) different community members' opinions on organic waste management, (3) the quality of life of informal waste sector workers, and (4) the quality of waste management services in lower, middle, and upper income neighborhoods.

4.4 Human Health Risks

When assessing the impact various waste management practices have on society, health risks must be accounted for. Waste collection and treatment may pose distinct health risks of various degrees for workers or residents living in the vicinity. In

Table 20, I have compiled a number of occupational and health risks that may result from various waste management practices that are relevant to management the organic fraction of municipal solid waste. The information in this table is non-exhaustive, but it does portray a representative picture of the most pertinent health risks.

Table 20: Human health risks of various waste management practices.

Waste Management Practice	Human health risks to workers	Human health risks to resident populations
Formal Sector Collection	• Occupational accidents[1] • Chronic musculoskeletal problems[2] • Road traffic accidents[4]	• Lack of sanitation if collection is irregular[6]
Waste picking	• Parasites[3] • Intestinal infections[3] • Coughing and eye irritation from waste burning[4] • Musculoskeletal problems[3] • Physical injuries from sharps, etc.[4] • Chronic injuries from lifting etc.[5] • Road traffic accidents[4]	• Lack of sanitation if collection is irregular[6]
Landfilling	• Accidents in loading/unloading[12] • Infectious disease (sometimes carried by rats)[12]	• Congenital malformations[11] • Low birth weight[11] • Emission of carcinogens[12]
Incineration	• Air emissions particulates, acidic gases, and metals[12] • Risk of lung cancer[12]	• Increased risk of non-Hodgkin's lymphomas and sarcoma[12]
Composting	• Higher risk of respiratory diseases[9, 10] • Exposure to bioaerosols[7, 12]	• Potential respiratory symptoms for close residents[9]
Pelletization	• Exposure to wood dust and resin acids, potential for respiratory health risk[13]	None found in literature
Anaerobic Digestion	• Respiratory symptoms from dust, bioaerosols, and microbial VOCs[8]	None found in literature

1. (Kagad Kach Patra Kashtakari Panchayat, 2007a)
2. (SNDT Womens' University, 2008)
3. (Chikarmane, 2012)
4. (National Solid Waste Management Commission, 2009)
5. (Panchayat, 2006)
6. Knowledge of author
7. (North Carolina Cooperative Extension, 2000)
8. (Monnet, 2003)
9. (CM Consulting, 2007)
10. (Shah & Sambaraju, 1997)
11. (Hogg et al., 2013)
12. (Rushton, 2003)
13. (Pool, 2013)

Whether waste collection is carried out by the formal or the informal sector, workers undeniably face a number of daily risks, as they work a physically-demanding job outdoors on city streets. Chronic pain from heavy lifting and injuries from falls or sharp punctures are unfortunately risks that waste haulers and pickers face daily; these injuries become more probable when workers are not equipped with adequate personal protective equipment and when hazardous waste is not responsibly disposed of. Waste pickers often have more direct exposure to the waste, given that they sort through the material with their hands, and therefore they have heightened risk of illness and disease as a result of their livelihood. In general, waste collection and waste sorting by waste pickers provides a sanitation service to society, rather than creating any health risk to residents. However, it should be noted that if communities are underserved with respect to waste collection waste may accumulate, litter streets, pollute waterways, attract vectors and pests, and lead to more open burning. A shortage of waste collection may arise due to poor central planning, poor road quality, passageways too narrow for vehicles, or the undesirability of a particular district's "low-value" waste.

In comparing organic waste treatment options with respect to human health, incineration and landfilling are the most likely to cause health problems to residents, primarily due to uncontrolled emissions that have been linked to cancer and developmental problems (Hogg et al., 2013; Rushton, 2003). The less pollution control technology, such as scrubbers in an incineration plant or gas capture in a landfill, the greater the health risk is. For workers, who have amplified exposure to these emissions, health risks can be more severe. Landfill employees also can face the occupational risks of injury. In comparison, composting, anaerobic digestion, and pelletization of organic waste create few health risks for local residents. Due to the nature of the processes, in which material is ground and mixed, particulates and aerosols can certainly be generated. These emissions are of most concern for workers, who may suffer respiratory damage if they are not provided and required to wear masks.

4.5 Stakeholder Analysis for Pune

On August 18-20, 2014, a workshop entitled "The Role of the Informal Sector in Sustainable Management of Sanitary and Organic Waste" was held in Pune, India. The workshop was co-organized by the MIT Tata Center for Technology and Design, SWaCH (a wastepicker cooperative) and KKPKP (a trade union for wastepickers and itinerant scrap buyers). It brought together municipal actors, informal workers, business leaders, activists, legal experts, policy makers, and academics to strategize economically and environmentally sustainable approaches to managing organic and sanitary waste. In total, roughly 60 people attended the workshop; a photo of one of the wastepickers who attended and spoke at the workshop is shown in ***Figure 30***. The workshop's goal was to explore how stakeholders may contribute to the design of socially inclusive, environmentally sustainable, financially viable, and logistically participatory strategies for managing solid waste. Discussion centered on waste collection, handling, and processing of two particularly challenging streams: organic and sanitary waste. With the ideas and opinions voiced at the workshop, I was able to record various stakeholders' implicit and explicit views and priorities about organic waste management.

Below, I have synthesized the major findings from workshop:

1. Wastepickers, activists, and academics were strongly anti-incineration. Their aversion to incineration was rooted in a number of reasons, such as fear of environmental pollution, association of incineration with centralized plants that exclude waste pickers, and the potential to disincentive source separation. Although incineration is not a technology well suited for handling wet, biodegradable waste, it was important to understand that many members of the community associate centralized, "high tech" facilities with the problems that come with incineration.
2. The group displayed a close-to unanimous desire for decentralization. Most participants believed that waste management of organics would only be sustainable and inclusive of the informal sector if the system were decentralized. Various stakeholders suggested creating systems the "ward-scale;" however, there was no clear identification of the ideal scale of treatment. This finding revealed that when weighing the pros and cons of small versus large scale waste treatment facilities, the social preference for decentralization should be taken into account, even if larger scale facilities have economies of scale.
3. There was general recognition and frustration that residents do not consistently source separate organics. Although they were aware of this reality, most participants at the workshop had high expectations for source separation in that they held residents to high standard, and placed the responsibility to separate on the generators. With the knowledge that achieving proper source segregation of organics is still challenging, we were made aware that this limitation must be incorporated into the design of processing and treatment systems; for instance, costing and logistics must account for the extraction of contaminants.
4. The Pune city government reports that it does not send any organic waste to the landfill, but other stakeholders doubt that this is the truth. Consequently, there is a lack of reliable data on the amount of organic waste currently going to landfill. Going forward, if the city wants to achieve its goal of "zero waste" it must measure its progress, and keep better records of the quantity of waste landfilled.
5. With regard to treatment options, most stakeholders were generally comfortable with composting as solution. There was also strong support and interest in using anaerobic digestion to process organic waste.
6. The majority of stakeholders believed that there was no need to pick one technology as the go-to solution for managing organic waste, but rather that a mix of technologies should be used in combination to handle the large volume of organic waste. Regardless of what technological solution is implemented, there was agreement that where possible, waste pickers should be involved in the process and potentially employed.

Figure 30: Photo of one of SWaCH's members telling the other participants at the waste workshop about her experience as a wastepicker.

4.6 Quality of Life of Informal Sector Workers

4.6.1 Purpose

To assess the system's inclusiveness of the informal sector and the quality of life experienced by waste pickers and others involved in the informal sector, we conducted interviews with local workers. In Pune, we interviewed unionized waste pickers, itinerant waste buyers, and staff members of the wastepicker organizations, SWaCH and KKPKP. The goal of the interviews was to quantify the social benefits of an integrated waste management system (in which the formal and informal sectors work together). To do this, we used a modified version of the Organization for Economic Cooperation and Development (OECD) Better Life Index (OECD, 2013). Semi-structured interviews were used to assess stakeholders' quality of life using the OECD Better Life Index indicators contextualized within the topic of waste management.

4.6.2 Interview Method

Within the city of Pune, roughly 9,000 wastepickers, itinerant buyers, and waste picker supervisors are unionized within KKPKP (according to the union itself). The total number of individuals within the city's informal waste sector is even larger. This survey only involved a small subset of these individuals, given the time constraints on field work. We interviewed 15 wastepickers in the field; 10 of them collected waste door-to-door, 2 worked at a sanitary waste incinerator, and 3 worked at a waste transfer facility. Because access to the landfill was not permitted, wastepickers working directly at the landfill were not interviewed. We interviewed waste pickers of both sexes (though, the majority of Pune wastepickers are women) and a variety of ages.

In addition to wastepickers, a small number of itinerant buyers and staff members of SWaCH and KKPKP were also interviewed about quality of life. The same interview procedures were used for all subjects.

The Better Life Index consists of 11 parameters that the OECD has recognized as being essential to the overall quality of life of an individual. **Table 21** lists the parameters and shows a template of the semi-structured interview questions asked during interviews with wastepickers. Interviews were conducted in Hindi and were done through verbal conversations, while the interviewer noted down responses.

Interviewed individuals were asked to rank each quality of life parameter on the following scale:

1 = very poor 2 = poor 3 = okay 4 = good 5 = excellent

Table 21: Template of interview questions related to wastepickers.

Quality of Life Parameter	**Related questions**
Housing	Type of housing? Availability of living space? Are you satisfied with your house? Is your house weatherproof?
Job	Do you like your job? Is it stable? Do you see yourself doing and growing with this job in the future?
Education	What level of study have you done? Do your children go to school? How much do you know about the work you do?
Civic engagement	Are you given a chance to voice your opinion where you live and work? Is it valued?
Income	Do you earn enough to eat well? Do save any of your income? Are you satisfied with the amount you earn? Has it increased in recent times?
Community	Does the community you work and live in respect and support you?
Environment	How clean is the environment that you work or live in? Method of cooking? How is waste disposed of? Water and sanitation facilities?
Health	Do you have any chronic injuries or recurring injuries due to work? How is your health?
Safety	Provision of safety equipment's at work? Any harassment experienced? Do you feel safe at home and work?
Work life balance	Enough time to spend with family or friends? Enough time for personal care? How many hours do you work in a day?
Life satisfaction	Are you satisfied with your life?

The general procedure used for interviewing consisted of:

1. **Personal introductions and asking the individual for permission to interview**:
   First, permission to interview the interviewee was requested, informing the individual that this process would take 5-10 minutes. The interview was only conducted if the

individually verbally consented to participate and was comfortable responding to the questions. The participant was also informed that his/her personal, identifying information would not be reported in results, but that all results would be anonymized. This was done to ensure the interviewee's personal information was respected and to maximize the likelihood of full cooperation. t

2. **Explanation of interview procedure:**
   Before the start of the questions, we explained the interview procedure (i.e. scoring system, type of questions to be asked etc.). The wastepicker was briefed on the purpose of the study and encouraged to be open and honest with their answers, so that the information collected was accurate.
3. **Survey of individual's background:**
   Some general information about the wastepicker, such as his/her first name, age, gender, and profession were collected.
4. **Questions and responses**
   The interviewee was then presented with questions similar to those in **Table 21**, and was requested to answer with reasons or explanations. For example, when asked, "Is your house weather proof" to inquire about the wastepicker's housing condition, and the answer received may have been "Well, it does leak a little in heavy rains, but otherwise it's fine," which was more informative than a simple yes or no. This method of interviewing was preferred to requests for one-word answers, as it allowed the author to distinguish if the question was understood. Explanation and reasoning from the wastepicker allowed the author to consistently code/score the responses. The open-ended format allowed the wastepickers to communicate their opinions and justifications, which kept the participants more engaged.

   In asking questions, the language and wording was kept simple. Most wastepickers spoke Hindi, however language barriers were occasionally problematic if wastepickers spoke Marathi and knew little Hindhi. In such cases, help from other SWaCH members was sought if possible, to facilitate with translation. In cases when this was not possible, another participant was interviewed. If we felt that there was a lack of interest in the conversation or the wastepicker was preoccupied while answering questions, the interview results were discarded and not considered, as to exclude poor-quality data. It was ensured that the language and wordings being used for the questions were kept as simple as possible to ease the understanding of the questions. The same procedure was followed when interviewing social workers and itinerant waste buyers.
5. **Recording of data**:
   During the verbal interview, the interviewer recorded the scores for each of the parameters on a worksheet.

4.6.3 Results of Quality of Life Interviews: Wastepickers

The results of the interviews, showing the reported quality of life of wastepickers, are summarized in **Table 22**, and some relevant anecdotal comments and explanations are listed in **Table 23**. Of the 11 parameters, wastepickers rated their environment lowest and community highest. These results are also visualized in **Figure 31**. Given that environment quality is highly related to housing quality, it is not surprising that housing was also scored low. Most wastepickers are low-income earners and live in slums. Even though houses are usually durable enough to protect residents from inclement weather, they are very small and crowded by large families. Slum communities often lack essential facilities and are overcrowded; ironically, in Pune's slums, there is no proper system to dispose of municipal solid waste. Wastepickers tend not to collect waste from slums, as they have a harder time getting residents to pay collection fees. This contributes to improper disposal of waste in slums. This, on top of the fact that wastepickers handle waste in a dirty environment, detracts from wastepickers' quality of housing and environment.

Health also received a low rating, and follow-up explanations often attributed health concerns and illness to slum life and work-related activities. Slums also have limited public toilets, which are unclean and overcrowded. Much of the wastepickers cook using wood-stoves inside the house, which emits unpleasant and unhealthy smoke that can lead to respiratory problems. Wastepickers' sorting sheds and areas are often vector-infested and attract other animals such as pigs and stray dogs. Health and safety equipment is only provided occasionally, but when provided, sometimes wastepickers prefer not to use it. Some wastepickers report that gloves slow down their sorting speed and that face masks feel suffocating. Wastepickers traditionally use a scarf to cover part of their face while sorting. These factors make an already-unhygienic environment more hazardous and helps explain why health is scored low.

In contrast, wastepickers were most satisfied with their quality of community, education, and safety. After SWaCH was established and the agreement with PMC was made, SWaCH members were trained and educated about their rights, responsibilities, and interactions with the community. Legal recognition of the wastepickers appears to have been influential in improving their quality of life. They are now respected in the community, paid better and have stable jobs Having a union (KKPKP) also allowed wastepickers a united-front for fighting for equality. These factors unique to Pune have improved the public's treatment of wastepickers, and have created a community that is generally supportive of wastepickers and their work. One comment from a resident in one of Pune's middle income neighborhoods is indicative of this supportive atmosphere and justifies the high community score; the resident explained, "We are very thankful to the wastepickers for being brave and doing the job they do - it definitely isn't easy."

Table 22: Summary of the scored responses from interviews with wastepickers. In the rating system 1=very poor and 5=excellent.

Quality of Life Parameter	Mean Numerical Rating out of 5	Interpretation	Standard Deviation
Housing	2.8	Poor-okay	0.86
Job	3.7	Okay-good	0.70
Education	4.0	Good	0.85
Civic engagement	3.6	Okay-good	0.91
Income	3.6	Okay-good	0.91
Community	4.1	Good	0.26
Environment	2.6	Poor-okay	1.30
Health	2.8	Poor-okay	1.15
Safety	4.0	Good	0.00
Work life balance	3.7	Okay-good	0.70
Life satisfaction	4.0	Good	0.76

Table 23: Selection of anecdotal comments from wastepickers during the interview.

Quality of Life Parameter	Comment
Housing	"There is no privacy, as the space is limited and there are many people"
Job	"It has perks such as donation of clothes, food etc."
Education	"Our children go to school now"
Civic engagement	"Monthly meeting with the union is very useful"
Income	"We are higher paid than before and are paid regularly"
Community	"We are not seen as thieves anymore"
Environment	"Suffocation from indoor wood cooking"
Health	"I get sick (cold, fever etc.) 3-4 times a month due to sorting in rain"
Safety	"There is no harassment by anyone"
Work life balance	"I have to come to work even if I'm sick"
Life satisfaction	"I'm happy because I know my kids will have a better future"

Figure 31: Radar chart showing wastepickers' average rating of quality of life parameters.

4.6.4 Results of Quality of Life Interviews: Itinerant Buyers

As compared to wastepickers, itinerant buyers have lower life satisfaction. As seen in **Figure 32**, civic engagement and education scored very low in comparison to other parameters. One explanation for this is that even though itinerant waste buyers are members of KKPKP, they cannot be part of the SWaCH model. This means itinerant buyers are not given specific training and are not kept formally informed of developments in the waste management system. Furthermore, even though they are included in the monthly KKPKP meetings and are given a chance to express their opinion, SWaCH first-most prioritizes wastepickers' needs. For instance, recently, a decision regarding electronic waste went against what they lobbied for, and ultimately decreased the quantity of and income from electronic waste. In any case, it was found that itinerant waste buyers were moderally content with their job and income, implying that their lack of power for decision making has not significantly affected their business.

Housing, environment and health of the itinerant waste buyers were ranked higher by itinerant buyers than by wastepickers. Itinerant buyers commented that their working environment was much cleaner. The items they purchase tend to be in good condition and pre-sorted, so their work is less messy than a wastepicker. It logically follows that they feel their health was better than that of the wastepickers. In terms of housing, itinerant waste buyers also live in slums just as wastepickers do, so their higher rating of housing may be due to a difference of opinion. Itinerant buyers generally felt safe, but some did mention they experienced police harassment.

Figure 32: Radar chart showing itinerant buyers' average rating of quality of life parameters.

4.6.5 Results of Quality of Life Interviews: SWaCH and KKPKP Staff

Figure 33 shows the quality of life of the social workers who have also been referred to as supervisors or activist in previously sections. On first glance, one can tell that their QOL is well balanced. Social workers earn higher than WPs and itinerant buyers and therefore live in better houses. They come from good backgrounds often with university qualifications and therefore understand the WMS very well. As their job involves more of activism and administrative work, the environment they work in is clean and safe and as a result their health is good. They are key to giving learned opinion to improve the SWaCH model and so are fairly engaged with the decision making process. Social workers do this job due to their preference of it and with the sense of helping the community rather than out of necessity. Therefore they value their jobs and in fact are also supported by the community for doing the kind of work they do.

Social workers do think however that the volume of work involved is overwhelming, at times. Additionally, there are no specific working hours. For example, in case of emergency, if a WP calls them late at night, they are obliged to go and resolve the issue. This does affect their family life and so the work-life balance parameter scores low. Owing to the extra hours of work, supervisors also feel underpaid. Nonetheless, overall they seem to be happy with their life due to the sense of achievement that the work they do ameliorates the community.

Figure 33: Radar chart showing KKPKP and SWaCH staff's average rating of quality of life parameters.

4.7 Quality of Waste Management Services

4.7.1 Purpose

In addition to assessing the inclusiveness of the informal sector and the impact waste management work has on workers, we assessed the experience residents have with waste management services. When considering the social impacts of the system, household waste practices and experience with services must be taken into account; residents disposing of waste are an important stakeholder in the system. A socially-functioning waste system would ideally keep residents informed and engaged about waste management practices, provide consistent collection, and lead to rule-following (i.e. source separation). In order to assess the social impact of the current waste management system on residents, we interviewed households on the quality of waste management services.

4.7.2 Method

In total, 38 households were interviewed about quality of waste management. The sample size for each socioeconomic group was as follows: 12 lower income houses, 20 middle income houses, and 6 upper income houses.

Although the specific questions asked differed, the procedure of the interview with the household members was identical to that used for workers (outlined above).

4.7.3 Results of Household Interviews

Table 24 shows the format followed to interview the different economic households. Only five parameters were used to assess quality of waste management services. Several of the parameters used for assessment of quality of life were not considered directly applicable to quality of waste management service, and were therefore excluded for this analysis. Also, some parameters were altered to make them more appropriate to waste management topics. For example, instead of asking about the quality of their physical house, we asked about their in-home their waste management practices (such as source separation, daily disposal/collection). An attempt was made to capture a diversity of ages and professions in the pool of interviewees. Also, given that men are often out of the house during the day, we varied the time of data collection to be able to interview both men and women.

Table 24: Template of the semi-structured interviews with a households.

Parameter	Related questions
Waste management in house	How is waste managed in your house? Is it picked up daily? Do you source separate waste? Is the daily gate collection system better than the previous one?
Awareness on WM	Do you know why is source separation done? What happens to waste after collection? Do you know of the changes in the WMS?
Civic engagement	Do wastepickers cooperate with you? Is your opinion on WM asked for and valued in your locality and city?
Environment	Is there waste lying around/dropped around your community/building? Does the W.P's sorting create a mess? Are there skips overflowing?
Satisfaction with the current WMS	Do you prefer the current WMS over the old one? Has it made your life better?

The results of the interviews are summarized in **Figure 34**, which shows the reported quality of each parameter on a scale of 1 to 5. The most striking result is that overall quality of waste management was higher for higher income households.

Upper income households ranked all five parameters as good or excellent, with household waste management ranking the highest with a score of 4.6. Upper income households were well educated about source separation and viewed the SWaCH wastepicker model positively. They also commented that daily collection minimalized odor and that they believed in-house waste management.

Middle income residents were generally aware of the waste management system and its benefit. Some middle income household reported that the wastepickers came at irregular times, and with further investigation, it was discovered that houses that paid wastepickers more consistently received better service. Middle income households were typically happy with the waste system, but did comment that waste in slums needs to be better managed and that better composting systems were required.

Lower income houses reported the lowest quality of waste management, with education only scoring 1.3. Lower income families were unaware of the changes that had been going on the in waste management system. However, they were still overall happy with the environment and in house waste management. Regarding in house waste management, residents explained that they were happy that the waste was being picked up from their doors now. Previously, they had to carry the waste to a skim located outside of the slum, since there was skip in the slum itself. When this was the case, many families simply stored waste just outside their households for days at a time to avoid walking to the skip; this contributed to bad odors. Consequently, the viewed the current system favorably, as it saved residents walking time and kept the sidewalks cleaner and more attractive.

As a whole, we observed that the level of awareness about the waste system does affect the degree to which people cooperate with the system. Wealth positively correlated with most qualities, which suggests that the waste management system is most functional in wealthier communities, and requires attention in poorer neighborhoods.

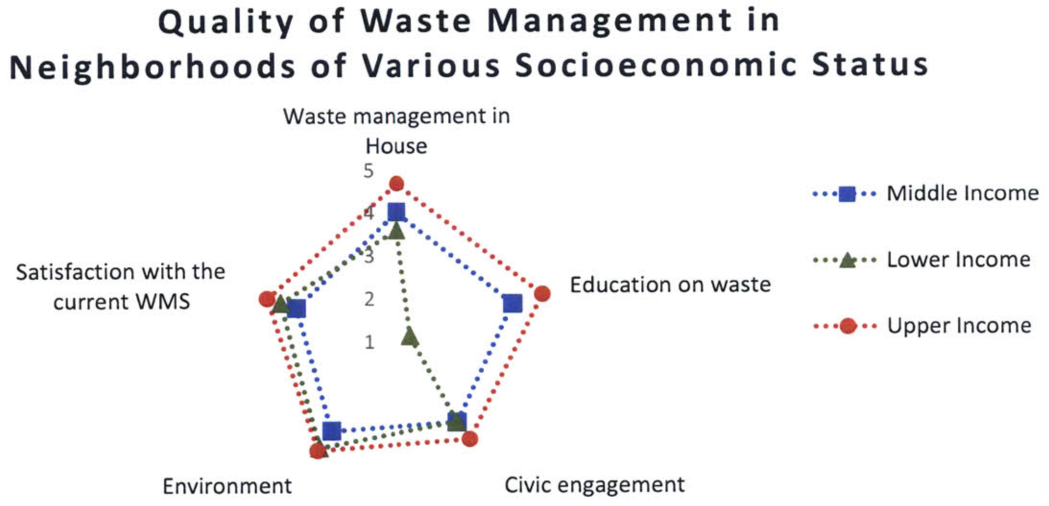


Figure 34: Radar chart showing the average rating of waste management services by lower, middle, and upper income residents.

4.8 Social Impacts Conclusions

The following are the key findings of this chapter:

FINDING 1: Per the findings of the literature review in section 4.4, waste sector workers are vulnerable to health and occupational risks if not provided adequate safety equipment.

FINDING 2: Per the findings of the literature review in section 4.4, compared to other organic waste treatment strategies, landfilling and incineration have the most harmful health impacts on residents.

FINDING 3: The findings of interviews with residents of various socioeconomic groups indicates that slums experience the lowest quality waste management services (***Figure 34***).

FINDING 4: Interviews with waste pickers on various aspects of quality of life indicate that wastepickers suffer from relatively poor quality of housing, health, and living environment. However, wastepicker report a relatively high quality of education, community support, safety, and overall life satisfaction (***Figure 31***).

FINDING 5: Interviews with itinerant buyers on various aspects of quality of life indicate that itinerant buyers are not receiving adequate education and community engagement (***Figure 32***).

FINDING 6: The stakeholder workshop discussions illustrated that wastepickers, activists, and academics strongly believe that an organic waste system inclusive of the informal sector must involve decentralized processing and incentives for source segregation of organics.

Chapter 5: Economic Analysis

This chapter analyzes the costs and revenues from various practices involved with organic waste management at a range of plant scales. The analysis in this chapter determines the net cost per ton of waste managed for door-to-door collection, primary collection, secondary collection, landfilling, composting, anaerobic digestion, and pelletization. These per-ton costs are later used in Chapter 7, along with the Aundh material flows (from Chapter 3), to estimate the total cost of organic waste management using various management technologies and scales of treatment.

5.1 Literature on Economics of Alternative Organics Processing Methods

5.1.1 Literature on the Economics of Composting

Composting effectively reduces the volume and weight of organic material, and produces a product which is valuable for soil protection and crop growth (López et al., 2010). As opposed to anaerobic digestion, compost systems can handle substantial amounts of yard waste (leaves, branches, grass), making them useful for integrated urban waste management systems. Past research has shown that composting can produce a high quality product both from source-segregated and mechanically-sorted organic material, as long as the process is catered to the particular bio-chemical profile of the material (López et al., 2010). As cities consider opting to compost with intention of achieving environmental benefits, they will likely be concerned with the cost of the transition and the cost of maintaining compost systems.

Although region- or city-specific analyses likely are needed to accurately estimate the absolute cost of a compost system, economic analyses done for systems in other regions can provide valuable guidance and a general sense of relative costs. Generally speaking, the costs incurred from composting urban municipal solid waste include costs from collection, capital investment (for bins, shredders, infrastructure, etc.) and operational costs (for fuel to run tractors or mixers and labor for monitoring the process and running the system). Revenues from composting can come from the sale of the finished compost as a soil amendment or carbon offsets. The selling price of compost is determined by factors such as (1) the quality of the compost, based on moisture, odor, and particle size (2) the uniformity, color, and appearance, (3) the availability of information about the compost, namely its nutrient content and pH, and (4) the reliability of supply.

One challenge cities may face when pursuing the option of composting is balancing supply and demand; the supply of compost inputs is high in a city, but the city's demand for the yielded finished compost may not be. The demand is likely higher outside the city, in more rural farming areas. This creates a need for transporting the finished compost, which results in additional environmental and economic cost (Sonesson, 1998). Additionally, commercialization of composting may be more costly relative to bio-energy processes if fertilizers are subsidized by the government (making the price of finished compost less competitive). Quality control is another issue that may be of concern when producing and selling compost; it is important that finished compost not have unsafe levels of heavy metals (which tend to exist in higher concentrations in urban environments), especially if the compost is sold to consumers or applied to food crops.

The scale of a compost system and the system architecture can greatly affect the cost-effectiveness of composting. A study by Adhikari et al. (2010) compared various scales of composting systems for managing urban organic waste as alternatives to landfilling that waste. The study pulled its data from existing organic management systems in European countries and in Canada. Three systems of composting (at different scales) were compared: (1) centralized composting facility, (2) community composting, and (3) home composting. In all three scenarios, composting of source-segregated organic waste (rather than mixed waste that required sorting on site) was found to produce better quality and more valuable finished compost. Both community-level and home-level composting were found to be less expensive than the baseline of landfilling the organic material (which was found to have a cost of \$165/ton). Adhikari et al. found that community and home compost can save a dense city with constrained landfill availability about \$25,000/km^2.

Adhikari et al. also found that the smaller the scale of composting, the more cost-effective the system is; this was primarily due to the fact that smaller scale composting has lower capital and transportation costs (Adhikari et al., 2010). Adhikari and his colleagues found that centralized composting was most costly, estimating it to have a cost of \$241/ton; this high cost was mainly attributed to the transportation associated with having double the amount of collection in a system where organics are segregated (assuming that separate trucks pick up organics vs. other residuals) (Adhikari et al., 2010). This figure should be considered an upper estimate, as it is possible to develop alternative, more cost-effective collection systems, for instance, that involve retrofitting traditional trash collection trucks to contain two compartments to hold segregated waste. Community composting, done at the neighborhood scale, was found to be significantly cheaper than having a city-level facility, primarily due to the assumption that in such a community system, residents would be responsible for dropping off their organic waste at the site. Therefore the authors assumed the community collection cost is zero. Home composting was found to be cheapest, because the capital and operational costs of backyard compost bins are minor, as compared to larger systems that require significant infrastructure development. The study concluded that on-site treatment of source-separated organics is inexpensive, and produces a dry, stabilized and volume-reduced soil amendment usable for urban gardens.

Other studies have confirmed that on-site composting is most economical. Mitchell (2001) quantified the costs of on-site composting of restaurant waste, as compared to off-site composting and landfilling. For a given restaurant, it was found that on-site composting was preferable to transporting the waste off-site. The economic analysis estimated that when the landfill transportation cost and tipping fees are eliminated with on-site composting, the payback time for purchasing and using a vessel compost machine is about 8-12 years (Mitchell, 2001).

In addition to scale and siting, costs can vary significantly depending on the type of composting technology used. Within the broad category of composting, there exist many subtypes, such as vermicomposting (with worms), outdoor windrow composting, and in-vessel composting. Van Haaren et al. (2009) compared the costs of various composting technologies/methods, as well as the use of yard waste as an alternative daily cover on a landfill. Van Haaren controlled for scale by comparing the systems all under the condition of processing 40,000 tons/year, which is a typical scale for industrial composting. The study assumed that the interest rate was 6% and that the composting systems each had a 15 year lifetime. The study found that in-vessel aerobic composting, aerated static pile composting, and windrow composting, had total costs of $147/ton, $42/ton, and $21/ton, respectively. In-vessel aerobic composting was most costly due to the high energy needs and the maintenance cost of the rotating drums used inside the vessel. In the aerated static pile, costs originated from the laying of the concrete foundation and the installation of aeration tubes on the ground surface, as well as the energy needed to shred the waste and pump the air. However, it should be noted that the aerated static pile accelerates the decomposition process and produces throughput faster than the windrow composting, and therefore may be preferable in some circumstances. Since the study did not take into account the revenue from the end products of composting, the reported results do not account for faster processing time. The windrow composting was the cheapest of the three composting options, as it required the least infrastructure and energy to operate. However, the even cheaper option was using shredded yard waste as a daily landfill cover, which was found to only cost $14/ton (van Haaren et al., 2009). In such a scenario, the yard waste (instead of soil) is placed over newly landfilled material, each day in order to reduce odors and pests. This alternative use of organic waste was deemed most cost-effective because it would provide extra revenue from increased refuse capacity in the landfill and lower use of purchased soil for landfill covering (which is often a regulatory requirement in developed nations). However, one negative environmental tradeoff to this economic benefit is that food waste is not recovered, but rather is sent to landfill.

The papers mentioned above strictly assess the realized costs of composting, rather than fully accounting for the "true cost" that occurs when the environmental benefits are monetized. A study conducted by CM Consulting (2007) attempted to calculate the true cost of particular composting systems by accounting for the health and environmental impacts of the organics management, as well as for the operations costs. In this analysis, the following equation was used: $ True Costs = $ Net cost of operations - $Environmental cost/benefit. The environmental cost/benefit is the sum of the monetized value of the impacts of various pollutants, such as particulates and greenhouse gases, or the avoided pollution that results from using finished compost to replace synthetic fertilizer. CM Consulting found that the environmental benefit of composting is greatest if the finished product is used as fertilizer replacement, thus displacing a significant amount of greenhouse gas emissions (GHGE). The company also found that composting has a significantly lower cost to society than landfilling or incineration (termed energy-from-waste), which is consistent with the findings of studies described above. The study found that composting leaf and yard waste had a net benefit (or a negative true cost). Composting of food waste was slightly more costly than yard waste, given that the operations costs are higher, but was still only half the cost of landfilling with flaring. In addition to assessing these costs, the study tested the cost sensitivity to carbon offset valuation, which is one of the contributing factors to quantifying the environmental benefit. The study found that irrespective of the value assigned to carbon dioxide, composting consistently remained the environmentally preferable option from a monetized environmental-benefit perspective (CM Consulting, 2007). This is a source of optimism for cities enthusiastic about composting, but wary of the carbon trading market.

The general consensus from the literature is that composting is a less costly management practice than landfilling organic waste. Although the scale, technology type, and scope of the analysis all affect the cost of composting, cities can expect to see savings from composting. Although composting may not be profitable, it is more cost-effective than landfilling.

5.1.2 Literature on the Economics of Biodigestion

While composting is an accessible technology with potential for cost savings, the economics of anaerobic digestion of organic waste also are promising. Biodigesters have small footprint requirements, produce "green" energy, and have the potential to bring in revenue from GHGE trading. In many circumstances, anaerobic digestion is economically preferable to most other disposal options and has few environmental drawbacks (Sylvan, 2006). Anaerobic digestion is suitable for treating sewage sludge, manure, the organic fraction of MSW, and grass and leaves. However, straw and wood should not be digested because they digest poorly and can cause scum or blockages in a digester (Monnet, 2003).

The capital costs in anaerobic digestion include the digester, the digester feeding system (with pumps and pipes), storage tanks or balloons for holding biogas, an engine to convert methane to electricity, and building infrastructure (Massaro et al., 2015). Operational costs come from the labor and energy required in sorting, pre-treating, mixing, and pumping, as well as maintenance. As with any treatment process, collection and transport of waste used in the digester also contributes to the cost of anaerobic digestion. Revenue from anaerobic digestion comes from the sale of methane directly as a fuel or the sale of electricity, as well as the sale of fertilizer, a byproduct of digestion. In some regions (but not typically in India), a gate or tipping fee per ton of waste can generate revenue for the processor, and a cost for the government. The type of digestion process used and the quality of the biomass determine the efficiency of methane production from anaerobic digestion. If the system converts methane to electricity, then the efficiency of the engine also impacts the quantity of electricity generated from anaerobic digestion. Also, biomass with a higher fraction of total solids and fat will generate more biogas per ton. Lastly, factors external to the waste system, such as the price of electricity and fertilizer in the region, impact the magnitude of possible revenue from those products.

The net cost of anaerobic digestion can also depend on the size of the plant. Two opposing forces have generally been observed with plant size: per unit investment and operating costs decrease with the increase of plant size; meanwhile, larger plants require larger volumes of waste that must be collected from a larger area, which increases transportation costs (Massaro et al., 2015)

Whyte and Perry (2001) used generic data from manufacturers to estimate the capital and operational costs of an anaerobic digestion facility that processes mixed vs. source segregated residential waste. By analyzing how the costs vary for digestion plants of different sizes, ranging between 10,000 to 100,000 tons/year, they found as plant sizes increase, costs decrease. They also found that, for a comparably sized facility, the capital cost of a mixed waste facility is approximately 5-10% higher than a facility that only accepts segregated organics. This is primarily due to the fact that a mixed plant has an extra cost of a sorting system to ensure an adequate quality of pure organic input material. Whyte and Perry found that a facility that processes 10,000 and 100,000 tons/year of segregated organics has a capital cost between $635 and $245/ton. They estimate that the annual cost ranges between $107 and $446/ton of design capacity for plants that that process 10,000 to 100,000 tons/year.

A study by Kandpal et al. (1991) specifically looked at the economic feasibility of small anaerobic digesters for use at the household scale in India and found that the system is more cost-effective if the biogas is used for cooking, as opposed to converted for electricity, but noted that this is dependent on the region's cost of fuel and energy and current government subsidies of fuels. The study also found that the payback period for small-scale digesters ranged between 3 and 11 years for digesters designed for volumetric capacities of 2 to 14 cubic meters.

A study conducted by Rajendran et al., (2014) also analyzed the costs of different-sized anaerobic digestion plants, as well as incorporated the cost of various biogas upgrading methods. Biogas upgrading is the process by which a facility concentrates the methane in biogas to meet natural gas standards. Like Whyte and Perry, Rajendran et al. found that the bigger the biogas plant, the more energy- and economically-efficient it is. Among the scenarios they tested, the designs with one large digester were less costly than designs with multiple, smaller digesters. The study highlights that upgrading biogas to meet fuel standards requires about 13% of the total financial investment in a biogas plant and 52% of the energy consumption, and thus should be considered in any economic analysis of anaerobic digesters. Upgrading through the use of water scrubbing was found to be less costly than carbon dioxide absorption by amine (Rajendran et al., 2014). The analysis also found that collection and transportation costs significantly affect the profitability of an anaerobic digester, which is consistent with other economic analyses of organics waste management.

Another study by Massaro et al. (2015) assessed the cost of anaerobically digesting the source-sorted organic fraction of MSW in Sweden under scenarios with various total solids concentrations and electricity generation rates. Massaro et al. found that depending on the amount of total solids and efficiency of electricity generation, the total cost of anaerobic digestion was between 127 and 149 euros per ton. The largest drivers of cost were found to be the equipment and energy involved in pre-treatment and the digestion itself.

Anaerobic digesters can take many forms and can be incorporated into other waste management systems within in a city. For instance, co-digestion of food waste with sewage sludge is another model for anaerobically digesting waste. Because such a variety of digestion systems are available for policy makers and planners to choose from, circumstance-specific cost analyses are often useful. The National Research Institute of Science and Technology for Environment and Agriculture in France developed a software cost estimation tool that can be used to compare different process management scenarios (IRSTEA, 2014). This tool, called Ecobio, allows the user to model the economic implications of different local conditions, equipment, treatment processes, and method of collection. Tools similar to Ecobio have great potential for helping cities identify anaerobic digestion opportunities for lowering their overall waste management costs.

5.1.3 Literature on the Economics of Pelletization

As compared to anaerobic digestion and composting, there is little literature on the economics of pelletizing the organic fraction, specifically, of MSW. Kevin Kung, an MIT researcher studying processes for creating solid fuels out of biomass in India and Kenya, stated that the only project he is aware of that is pelletizing biodegradable MSW is in Pune (Kung, 2015). Meanwhile, economic analyses of direct incineration of waste with energy recovery are relatively common. Most systems pre-treating urban waste for solid fuel utilize MSW as a whole to make refuse-derived-fuel, rather than using segregated biodegradable waste; this is because "dry" waste (such as plastics and paper) tends to have higher energy content to begin with. Pelletization of wood waste (sawdust and wood shavings) is also relatively common. Most studies looking at refuse-derived fuel pellets/briquettes analyze the energetics of the process and report their findings in terms of MJ per kg or ton, as opposed to cost per ton (e.g., Alsheyab et al., 2013 and Lombardi et al., 2015). However, some studies report various costs associated with general MSW RDF. Dedinec et al. (2014), report that the investment and operational cost of producing energy from MSW-based RDF in Macedonia is $21.67 USD/ton and $5.04 USD/ton, but they do not report the revenue or net cost. The only publications assessing the economics of bio-based pellets that I could find were for processes using agriculture feedstocks or wood. Thek & Obernberger (2009) reported that pellet production in Sweden costs about $78 USD/ton of pellets. Samson & Duxbury (2000) estimated that fuel pellets made of wood, switchgrass, and willow cost $94, $69, and $100 USD per ton of pellets, respectively. (Mani et al., 2006) et al. found that the cost of making pellets from sawdust and wood-shavings in North America costs $51/ton of pellets.

Although pelletization of biodegradable MSW is not a widespread practice, it is a focus of economic analysis in this thesis because it is one of the treatment methods being actively pursued in Pune.

5.2 Gap Analysis

The above literature suggests that some economic conclusions are common to many systems. For instance, Sonesson's finding that anaerobic digestion has high costs and high revenues, whereas composting has low costs and low revenues, does seem to be a common finding for developed countries. Also, one can also expect that the major costs associated with anaerobic digestion come from separation, maceration, and running the reactor. In composting, costs often come from sieving, turning, loading, and the diesel-run equipment (Sonesson, 1998). Typically, the major source of revenue from biodigestion comes from the use of biogas as fuel. In contrast, finished compost may bring in only minor revenue in developed countries. However, the comparative revenues from composting and biodigestion may be less predictable in developing countries.

Most analyses find that both composting and anaerobic digestion options allow a city to avoid paying a landfill tipping fee to dispose of organic waste (DSNY, 2004). However, in comparing anaerobic digestion and composting, the literature offers mixed results on which option is more economical. Although the majority of cases find that biodigestion is economically preferable to composting, one case that studied organic waste management in a city in Sweden found that composting has lower net-costs than biodigestion (Sonesson, 2000).

There is still a need for clarity and for a direct comparison of the costs of composting and anaerobic digestion, especially at different scales of treatment. Moreover, with the lack of literature on the cost of pelletization of organic MSW, it is important that this technology be analyzed from an economic perspective so that the feasibility of using pelletization can be compared to more well-known processes.

Furthermore, the absolute cost of processing organics cannot as easily be generalized. Although the literature offers cost estimates for composting and anaerobic digestion in a number of geographic locations, accurate costing of such systems cannot necessarily be generalized because of the variations that exist between countries and cities. Specific circumstances pertaining to a location's economy, policies, and resources must be accounted for in order to quantify the cost of processing organic waste within a city or country. For instance, in India, landfilling often does not involve tipping fees or high costs of maintenance given the simplicity of the dump; this means that alternative practices may not be as economically advantageous in India. Lastly, since most of the literature assessing the economics of these technologies is based off data from the developed world, there is a need to quantify the India-specific costs of organics management.

5.3 Purpose and Approach

This chapter aims to quantify the economic costs of a number of waste management practices (at a range of scales) involved with organic waste management in the urban Indian context. By comparing the net cost of various technologies, alternative scenarios for managing organic waste can be compared, and a least-cost solution can be identified. Identifying lower-cost alternatives for managing organic waste in a sustainable manner can help guide policy makers in planning and investment decisions.

In order to do this cost analysis, I developed bottom-up cost models in Excel. These models all represent the costs within the city of Pune, which controls for location-specific factors and policies. Although the specific data used in the model comes from Pune, the results of the models are likely applicable to other cities in India.

A cost model uses information about raw materials, labor, equipment, and energy and financial computations to create cost accounting allocations (Field et al., 2007). Cost modeling keeps track of the contributions to total cost, such that the user can identify what activities drive up cost and how much of the financial cost is borne by a given stakeholder. Cost modeling is particularly useful because it creates a repeatable process that allows the creator and future users to vary parameters or assess alternative scenarios, without varying the major structure of the model. Cost modeling also allows one to test the sensitivities of certain inputs that may have intrinsic variation or uncertainty; the outputs of such a sensitivity test give the user a sense of the range of possible cost outcomes. It should be noted, however, that cost modeling, like other forms of modeling, relies on assumptions, and the quality of the results produced are only as reliable as the input data used.

By using a tailored-cost model, I was able to analyze costs for various processing capacity sizes, which allowed me to quantify the economics of decentralized vs. centralized system architectures. Furthermore, by creating bottom-up models, I was able to itemize the costs of a technology by elements such as capital, labor, and transportation. In doing so, I identify the main drivers of cost, so that attempts to reduce costs can be appropriately targeted. The cost models also quantify revenue streams from technologies producing energy and marketable products, which help offset the processing costs. In constructing the cost models, I quantified the cost of each process element in terms of yearly cost (Rupees per year), as well as cost per ton (Rupees per ton of organic waste managed). Evaluating the per-ton cost of a process facilitates the direct comparisons of elements and processes.

Economic analyses were conducted on the following processes:
Collection:

- Door-to-door collection (by the informal sector)
- Primary collection (by the formal sector)
- Secondary collection (by the formal sector)

Processing:

- Landfilling
- Composting
- Anaerobic Digestion
- Pelletization

To create the models, I used data from waste processing facilities in Pune, which I obtained through interviews, site visits, and official documents. This information was collected in the form of paper documents, digital documents, and personal interviews during the period of August 2013 through August 2015 in Pune, India. These primary sources of information were:

- SWaCH
- KKPKP
- Mailhem Engineers
- Enprotech Solutions
- Pune Municipal Corporation Department of Solid Waste Management and Department of Transportation
- Institute of Natural Organic Agriculture (INORA)
- Gangotree Eco Technologies

When other information needed for modeling was not available from primary sources, I used and adjusted figures from relevant literature on markets, technologies, and industry.

The cost models, including the model inputs, assumptions, calculations, and data sources are included in Appendices C, D, E, F, G, and H.

5.4 Collection

5.4.1 Door-to-Door Waste Collection

Unlike in developing countries, where trucks are used to pick up bins at curbside, door-to-door collection of waste in Pune occurs by foot or by cycle, with wastepickers manually emptying bins into carts. Especially in slums, door-to-door collection requires navigating through narrow streets and alley ways to collect waste, as shown in **Figure 35**. The costs involved with door-to-door collection by SWaCH wastepickers come from the monthly collection fee residents pay (directly to wastepickers), the equipment and benefits provided by PMC to wastepickers, and the cost of administration of SWaCH as an organization with full-time staff.

It is important to note that the revenues from the recovered recyclables is a substantial cash flow associated with wastepicking (and is the primary source of revenue for wastepickers). More information about the sale price of different materials and the value of recyclables can be found in Section 3.6. However, our cost analysis of door-to-door collection does not include revenue from recyclables. We chose to exclude this revenue from the cost model for a few reasons. Because our analysis specifically looks at the processes involved in handling biodegradable waste, any processes and revenue streams specifically attributable to recyclables was deemed outside of the scope. Moreover, at present, Pune has no way to collect biodegradable materials door-to-door other than through collaboration with wastepickers, and as such this activity only avoids additional landfilling cost. So, the door-to-door collection of biodegradables and recyclables occurs all at once. If there were some other option for Pune to collect and recover biodegradable waste, door-to-door collection by wastepickers would primarily involve the collection of recyclables and would be more cost-effective (especially when revenues from recyclables are taken in to account).

In developing the cost model for door-to-door collection, we made the following assumptions:

- Waste is collected by a SWaCH wastepicker
- Each of the households being serviced pay the full amount of the collection fee to the wastepicker each month (30 Rs/month)
- PMC pays SWaCH and the wastepickers the amounts outlined in the 2008 Memorandum of Understanding (Maharashtra Government, 2008). This includes the allotted amount for cycle rickshaws, uniforms and gloves, and insurance for wastepickers, as well as salaries and budgets for the SWaCH organization.
- Each wastepicker collects 94.4 kg of organic waste a day, which is based on the assumption that a wastepicker collects waste from an average of 100 houses per day, which each generate 944 g/day. This household generation figure is based on waste audit per-capita generation results and finding that the average household size is 4.5 persons.

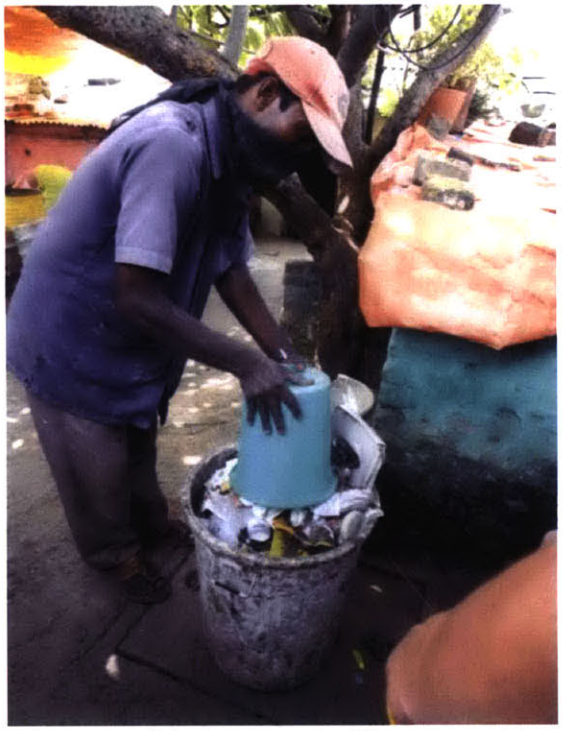


Figure 35: SWaCH wastepicker consolidating household waste on his route through Pune slums.

The processes and system boundary used to model the costs of door-to-door collection are diagramed in ***Figure 36***. The results of the model are shown below in **Table 25**, and are visualized in the bar chart in **Figure 37**. The total cost of door-to-door collection is estimated to be 1,628 Rs/ton. The majority of this cost comes from labor, which intuitively makes sense, given that the collection process mainly involves manual labor, rather than trucking or mechanization. The sub-elements included in the cost of labor were the resident-paid collection fee and the cost of PMC-provided insurance/education benefits. **Figure 38** shows the distribution of costs borne by residents versus the government, revealing that about two-thirds of the cost is borne by residents.

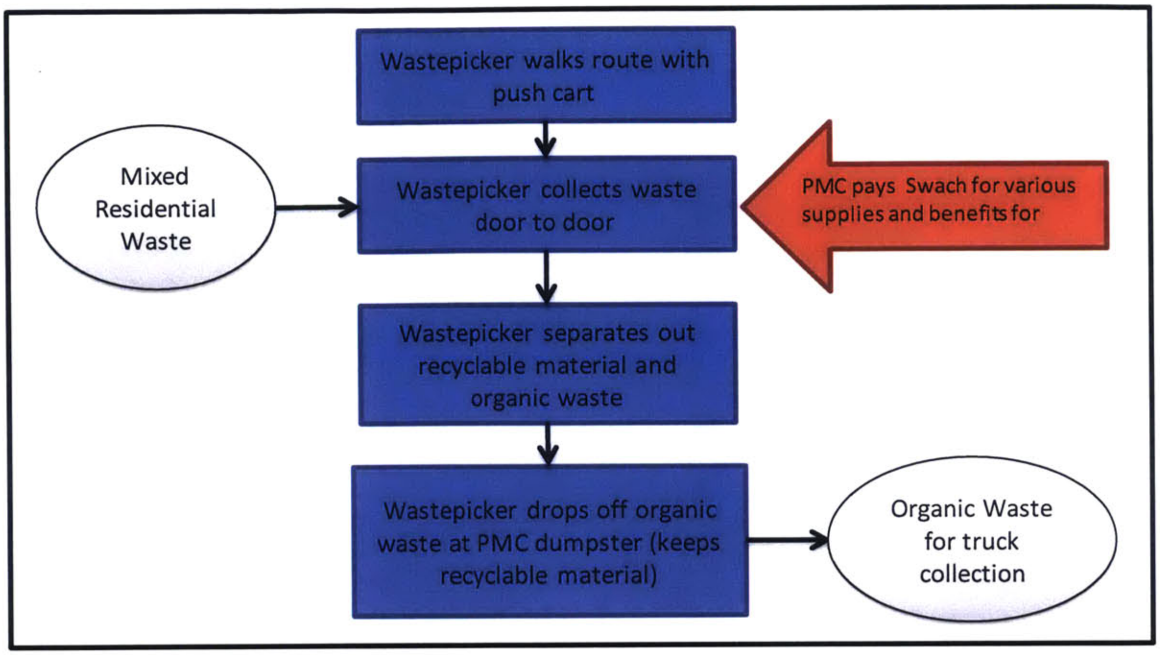


Figure 36: Processes and system boundary of the cost model for door-to-door collection. The costs of processes colored in blue are paid by residents; processes in red are paid by the PMC.

Table 25: Costs of door-to-door collection by element.

Breakdown by Element	Cost of Door-to-Door Collection (Rs/ton)	Cost of Door-to-Door Collection Rs/kg
Capital	264	0.264
Maintenance	14.5	0.015
Labor	1,074	1.07
Operations & Energy	0	0
Material	0	0
Building and Land	0	0
Overhead	276	0.276
Total Cost	**1,629**	**1.63**

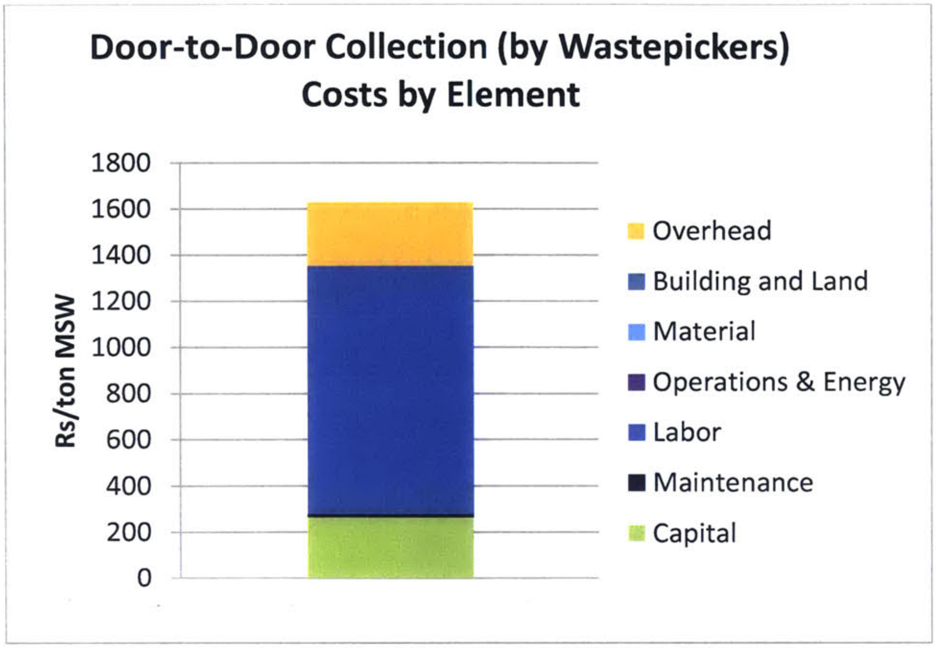


Figure 37: Door-to-door collection costs broken down by element.

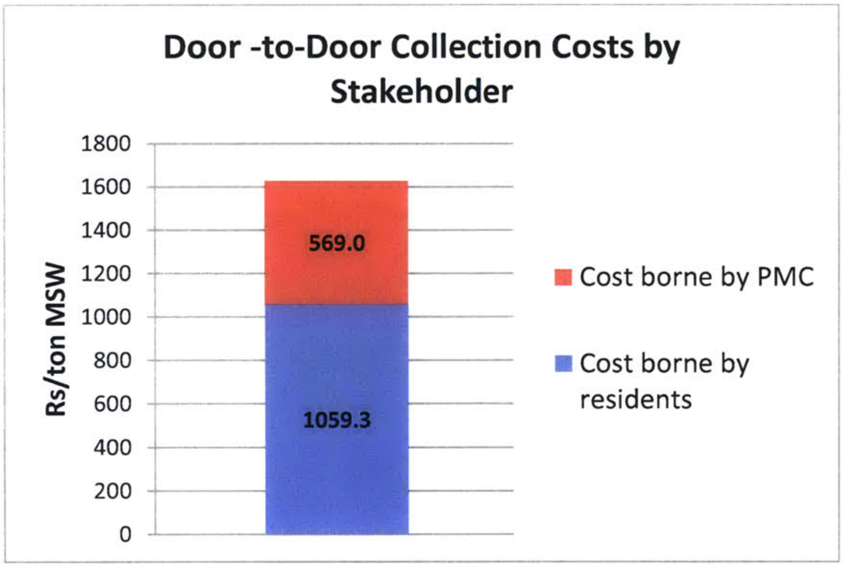


Figure 38: Door-to-door collection costs borne by each stakeholder.

5.4.2 Primary and Secondary Waste Collection/Transportation

In residential neighborhoods, after wastepickers drop off organic waste into local dumpsters, the waste is picked up by "dumpster placer" trucks such as that shown in **Figure 39**. Larger commercial generators of organic waste (such as restaurants and hotels) will often be serviced by tipper trucks with a capacity of 1 or 2 tons, such as that shown in **Figure 40**. After these primary collection trucks pick up the waste, they transport it to one of the seven transfer stations in the city, where the waste is unloaded and consolidated. This step of collection is called primary transportation. The process of picking up and trucking waste from the transfer station to a centralized waste facility (such as the landfill or the 100 TPD composting facility) is called secondary transportation. The processes and system boundary used in the cost model for primary and secondary collection are shown in the diagram in **Figure 41.**

Figure 39: Dumpster placer truck picking up waste in Pune.

Figure 40: Hotel and restaurant organic waste collection truck in Pune.

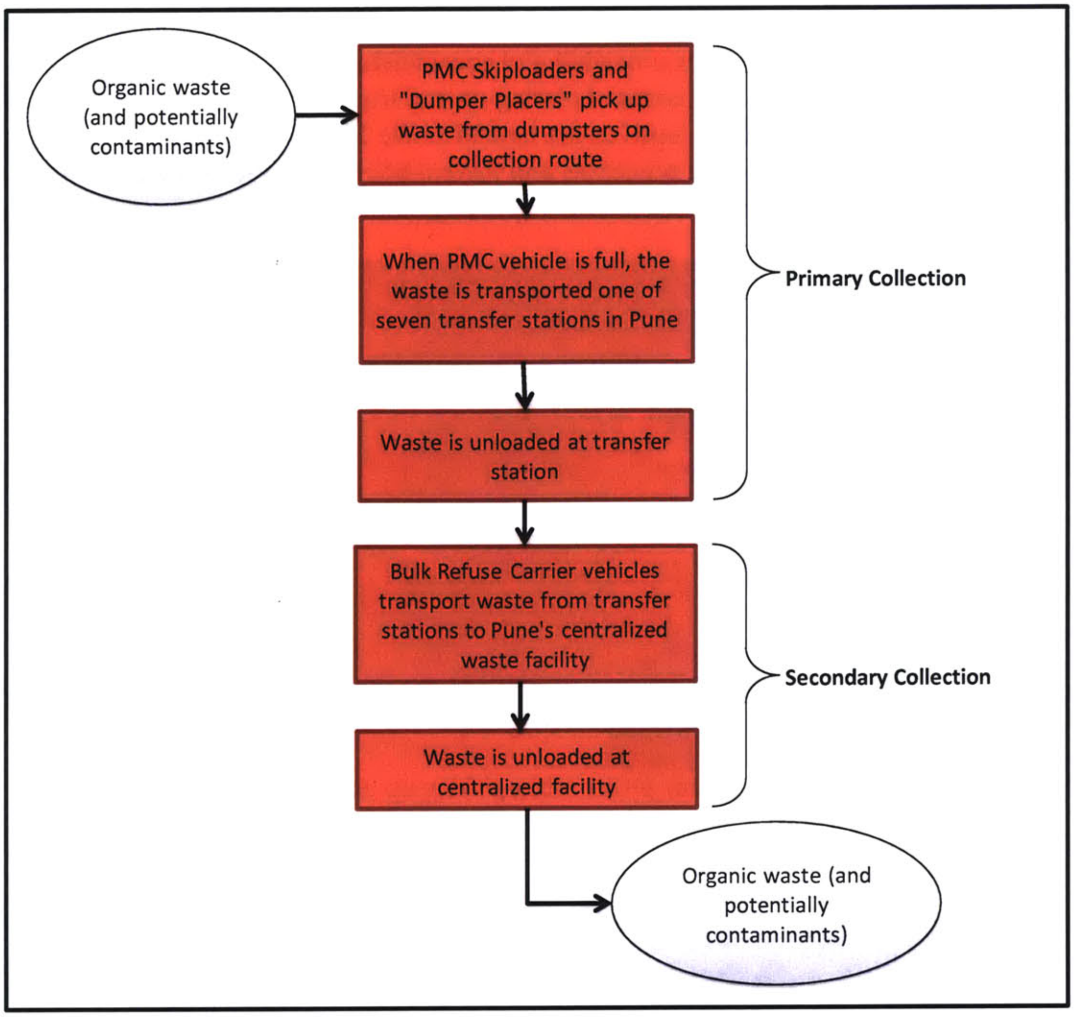


Figure 41: Processes and system boundary of the cost model for primary and secondary collection. The costs of processes colored in red are paid by the PMC.

The major costs involved with primary and secondary collection come from purchase and maintenance of waste hauling vehicles and compactors, fuel for those vehicles, and the labor for drivers, engineers, and mechanics. To develop the cost models of primary and secondary collection, we obtained data from PMC's vehicle depot, which handles the government-operated vehicle fleet. The general approach we used to estimate the cost per ton of waste transported involved estimating the total cost of primary collection and the total cost of secondary collection in Aundh ward, and dividing those costs by the tonnage of waste transported in Aundh. We obtained daily volume records from Aundh transfer station, which indicates the amount of waste entering (from primary collection) and exiting (for secondary collection) the transfer station. From the transportation office, we obtained a list of the labor positions and salaries for the entire vehicle depot. We also obtained a list of the trucks used for primary and secondary collection in Aundh and the purchase cost of those trucks. Lastly, we obtained data on the diesel consumption and distance traveled by each type of the Aundh trucks. We use the website "mypetrolprice.com" to find that the average price of diesel in Pune during the time period of cost analysis was 55.3 Rs/liter.

In developing the cost model for primary and secondary collection we used the following assumptions:

- Although roughly one-third of the city's vehicles are waste vehicles, about half of the labor cost of the transportation system is for transportation of waste. Therefore, to find labor allocation of waste transportation, we assumed that the cost of waste transportation labor was one-half the total cost of the transportation department's labor.
- Given that Aundh ward contains about 1/15th of the city's population, we assumed that the cost of waste transportation labor for primary and secondary transportation in Aundh ward was 1/15th of the total city's waste transportation labor cost.
- We assumed ½ of the waste transportation labor is allocated to primary collection, and that ½ of the waste transportation labor is allocated to secondary collection.
- We assumed 2/3 of vehicle maintenance is allocated to primary collection and that 1/3 of vehicle maintenance is allocated to secondary collection. Primary collection trucks likely go through more wear-and-tear in the process of street collection.

The results of the cost model are presented in **Table 26**, which reports the cost per ton and cost per kilometer for both primary and secondary transportation cost. The per-ton costs are also visualized in a bar chart in ***Figure 42***. We found that primary collection costs 296 Rs/ton and that secondary collection costs 284 Rs/ton of waste transported; this means that the cost per ton for primary and secondary collection are similar. For both primary and secondary collection, the largest contributor to cost is operations and energy, specifically from the diesel consumption. Diesel cost per ton is slightly higher for secondary collection because the road distance traveled is slightly larger. The capital cost of the vehicles is similar for both primary and secondary collection; while primary transportation requires a larger number of vehicles, these vehicles cost less than the larger secondary collection vehicles.

Table 26: Primary and secondary collection costs per ton and per kilometer.

Cost Element	Primary Transportation Costs		Secondary Transportation Costs	
	By weight (Rs/ton)	By distance (Rs/km)	By weight (Rs/ton)	By distance (Rs/km)
Capital	62.6	12.6	59.4	8.8
Maintenance	70.2	14.1	35.1	5.2
Labor	69.3	13.9	69.3	10.2
Operations and Energy (Diesel)	93.6	18.8	120	17.7
Materials	0	0	0	0
Building and Land	0	0	0	0
Overhead	0	0	0	0
Total Cost	**296**	**59.5**	**284**	**41.9**

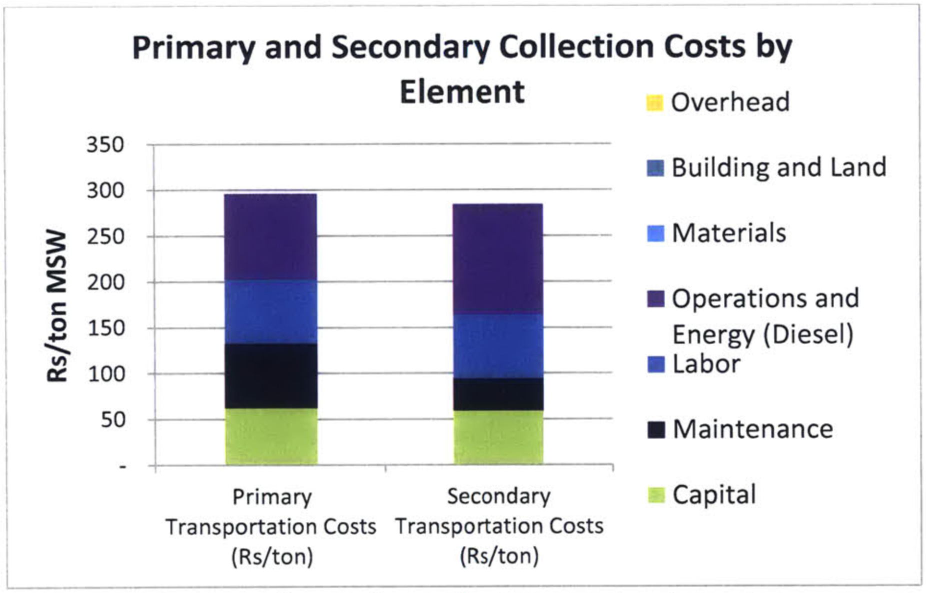


Figure 42: Primary and secondary collection costs by element.

5.4.3 Cost of Full Collection

The full cost of waste collection (when transporting waste to a centralized facility) is the sum of the costs from door-to-door collection, primary collection, and secondary collection. As shown in **Figure 43**, this combined cost of these three steps of collection is 2208 Rs/ton of waste, with the majority of this cost coming from door-to-door collection. This means that even if waste is handled within a local ward, the cost of collection will not change significantly, assuming that door-to-door collection is still required. Additionally, as shown by ***Figure 44***, this total collection cost is borne almost equally by residents and by the PMC.

The cost estimates found in this section are used in subsequent analyses of treatment technologies to determine the total cost of organics management, which always involves the cost of door-to-door collection and sometimes involves primary and secondary collection (depending on the scale of treatment).

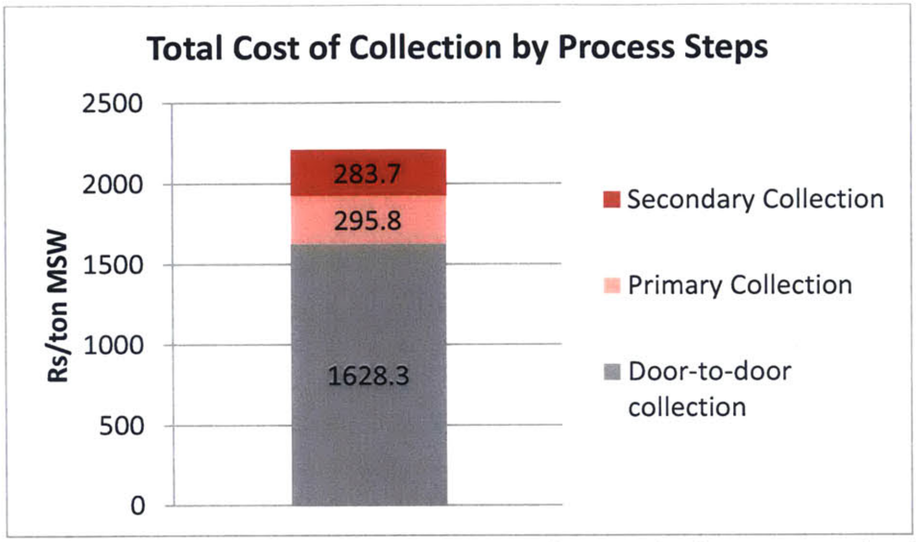


Figure 43: The total cost of waste collection from curbside to a centralized facility.

Figure 44: The cost of waste collection from curbside to a centralized facility borne by PMC vs. residents.

5.5 Landfilling Costs

Landfilling organic waste involves little processing and is still a common method of disposal. Aside from collection and transportation, the major costs of landfilling in Pune come from site construction, the purchase or lease of land, and the labor, fuel, and maintenance involved with using tractors and other machinery to move and compact material. The processes and system boundary used in the cost model for landfilling is presented in **Figure 45**. Attempts to obtain data about the costs of activities at Uruli Devachi landfill were unsuccessful, and the PMC would not provide us with specific information on how much money it spends on landfilling. We were also not permitted to enter the landfill. Therefore, in order to develop a cost model of landfilling, we made the following assumptions:

- We used nearby property values of undeveloped land in Uruli Devachi village to estimate the land values of the plot area of the landfill, which is reported to be 22 hectares in size per an EPA report published about the landfill (Goldstein, 2015). Nearby property values sold for roughly 5350 Rs/square meter.
- As far as we could determine, the PMC did not have to pay a permit cost for the landfill, so the cost of permitting was assumed to be zero.
- We assumed the PMC would have to budget 5 million Rs to close the landfill when it is finally closed (to cap and seal it).
- We assumed that in addition to routine operations and maintenance costs, the PMC would intermittently have to deal with unplanned costs from protests or landfill fires.
- There is no tipping fee for waste at the landfill, because the city government both owns and operates the landfill.

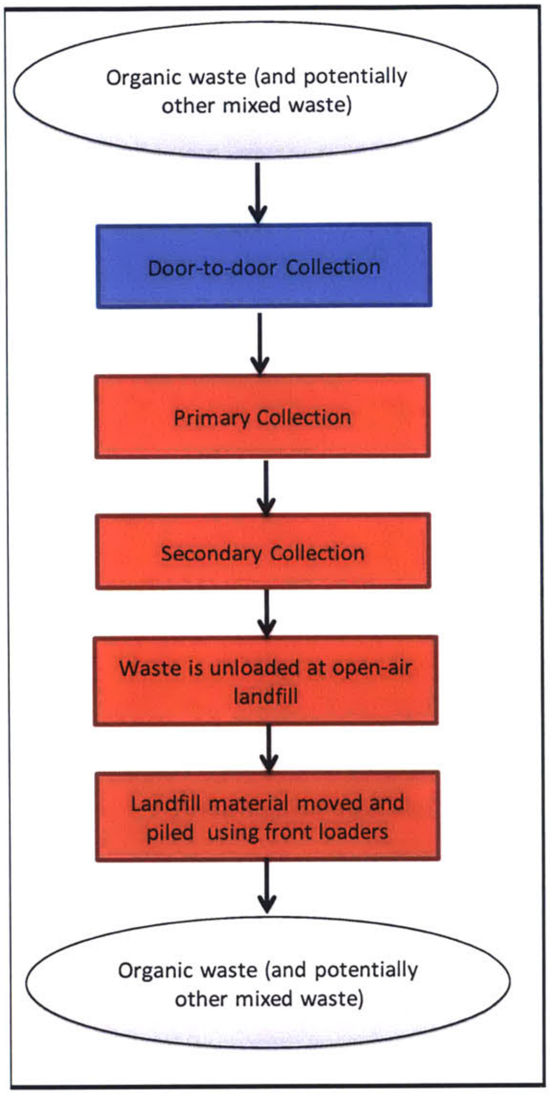


Figure 45: Processes and system boundary of the cost model for landfilling. The costs of processes colored in red are paid by the PMC and the process in blue is paid mainly by residents.

The results of the cost model for landfilling are shown in **Table 27.** The total cost of landfilling, including the cost of collection and transportation, was found to be 2,929 Rs/ton. As the bar graph in **Figure 46** shows, the main costs of landfilling come from the cost of door-to-door collection, followed by building and land, and transportation (from primary and secondary collection). Apart from collection costs, the main driver of cost for landfilling is the cost of land; this finding would likely apply largely to the urban Indian context as a whole, given that landfills tend not to be scientifically managed and do not require waste tipping fees.

Table 27: Costs per ton of landfilling listed by cost element. (Note: landfilling is assumed to always occur at a large, centralized scale).

Costs per ton of Landfilling	Rs/ton
Capital	2.8
Maintenance	0.30
Labor	15.2
Operations and Energy	30.3
Materials	0
Building and Land	673
Overhead	0
Transportation	579
Door-to-Door Collection	1,628
Total Cost (Rs/ton)	2,929

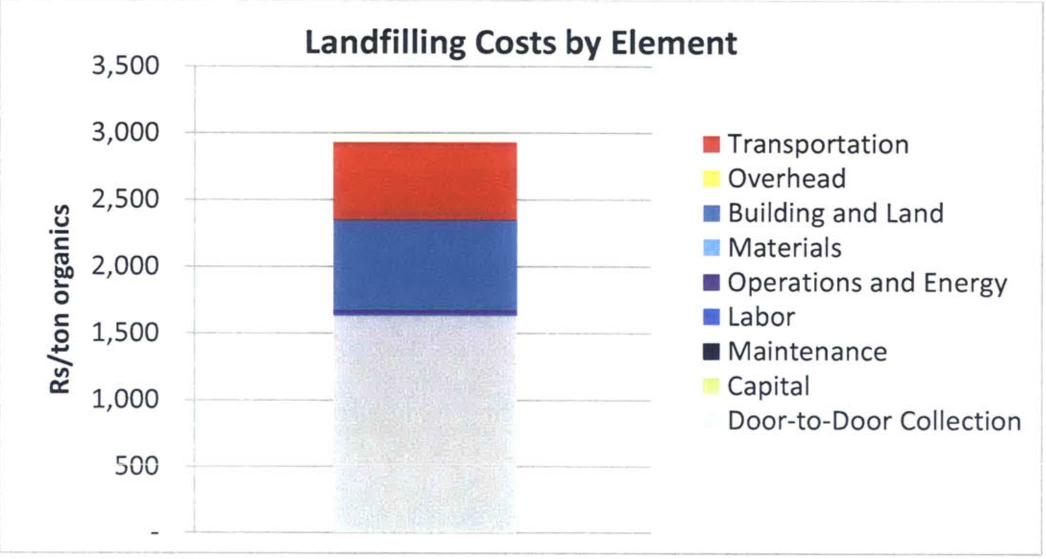


Figure 46: Landfilling costs by element.

5.6 Composting Costs

Pune utilizes a number of composting technologies and composting scales. INORA runs several composting facilities in Pune that utilize bin-composting, such as the facility pictured in **Figure 47**. Bin composting involves adding garden and food waste to containers that allow for air flow, and turning this material every few weeks. The city and many residential societies have opted to use organic waste converter systems that use a combination of mechanical and biological processes to generate compost; the organic waste converter machine grinds and pulverizes the waste and uses heat to sterilize it of pathogens. Once waste has gone through the machine, it must cure in piles, pits, or bins. **Figure 48** shows an example of an organic waste converter machine and the bin curing system at the Aundh facility. Societies using organic waste converters often cure the processed waste in pits. The other popular composting method in Pune is vermicomposting, which uses earthworms in bins to process organic material into worm castings, which is a high-quality soil amendment. Pune's large-scale vermicomposting at the Disha facility is pictured in **Figure 49**. Both of Pune's large-scale vermicomposting systems are located on the eastern periphery of the city.

Figure 47: Medium-scale bin composting site in Pune run by INORA.

Figure 48: Organic Waste Converter (OWC) machine and curing compost that has been processed with the OWC.

Figure 49: Large scale vermicomposting at Disha compost plant in Pune.

In developing a cost model for composting at different scales, we obtained information from INORA, PMC, and KKPKP. The cost model for composting assessed the cost per ton of composting at the scales of 0.2, 2, 100, and 200 tons per day. Although composting can certainly be done at mid-range scales between 2 and 100, Pune does not have facilities such scale (perhaps due to space limitations in the down-town area), and thus data on such facilities was not available and those scales were not analyzed directly. The system boundaries and processes modeled for the 0.2 and 2 TPD plants (which use OWC machines) are shown in **Figure 50**, and those for the 100 and 200 TPD plants (which use vermicomposting) are shown in **Figure 51**.

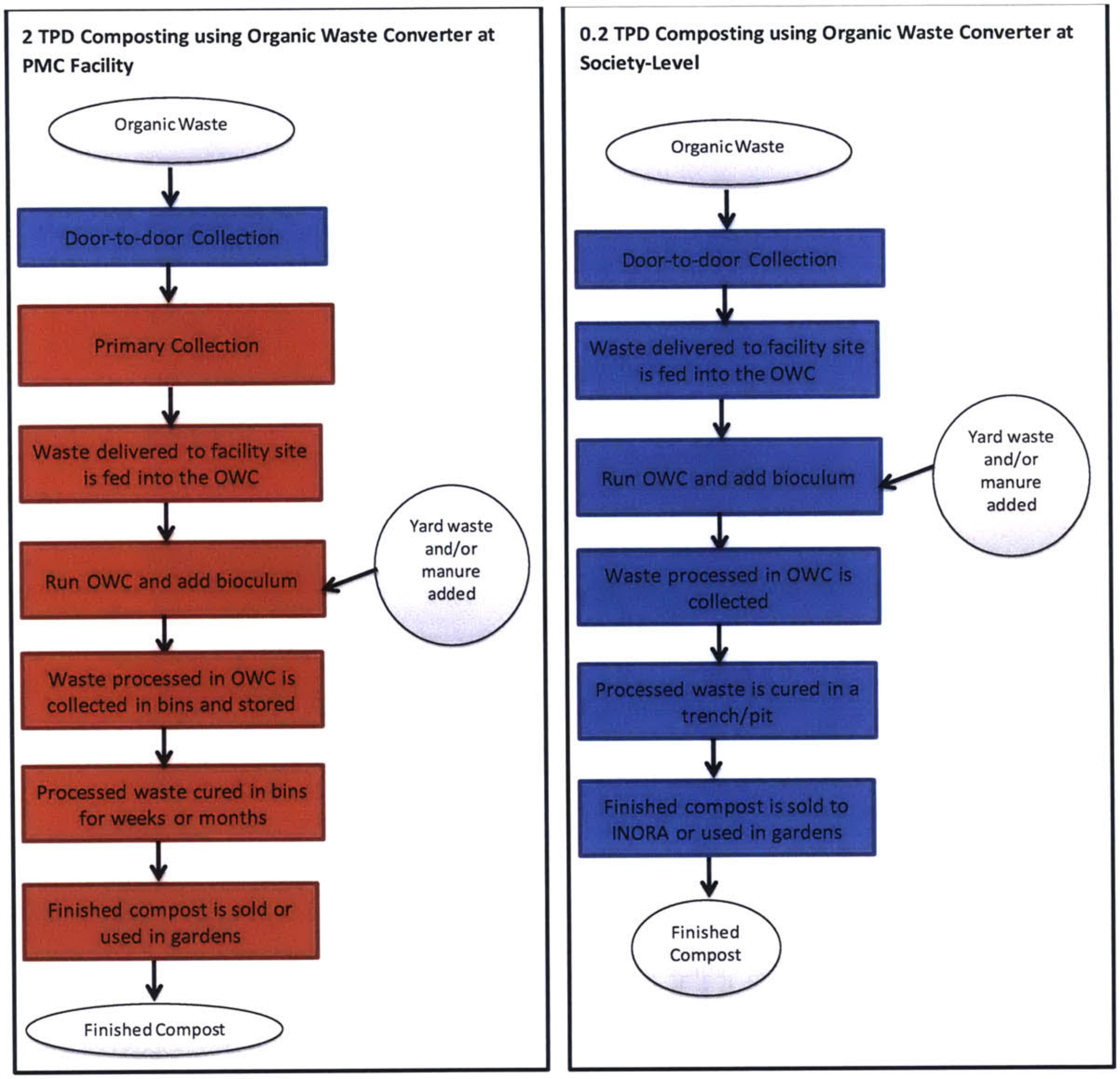


Figure 50: Processes and system boundary of the cost model for 2 and 0.2 TPD composting systems using an organic waste converter machine. The costs of processes colored in red are paid by the PMC and the process in blue is paid mainly by residents.

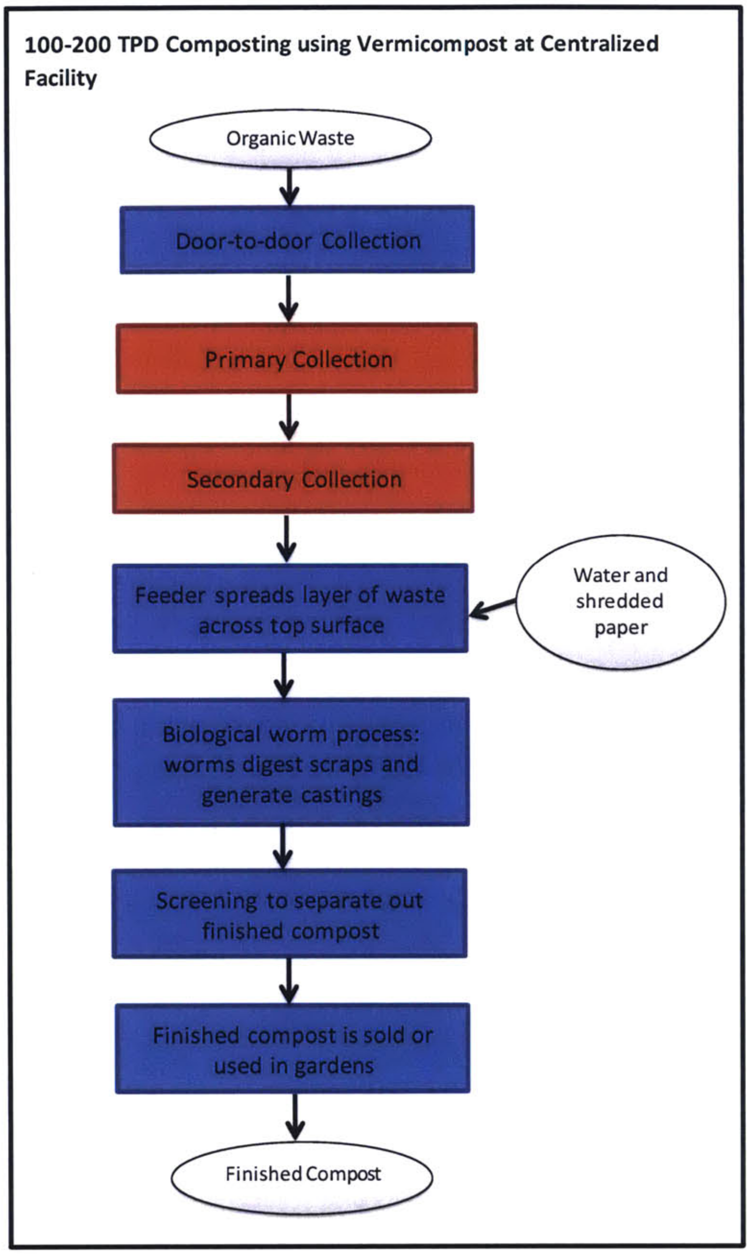


Figure 51: Processes and system boundary of the cost model for 100 and 200 TPD vermicomposting systems. The costs of processes colored in red are paid by the PMC and the process in blue is paid mainly by residents.

In addition to the collection and transportation of waste the major costs of composting organic waste come from the facility structure or shed, the purchase and installation of the bin system and necessary machines, and labor to run the plant. Depending on the size and type of facility, the cost of leasing land can also be a significant contributor to cost, given that technologies like vermicomposting use require large facilities. As shown in **Figure 49**, the worm bins must be shallow for the worms and are designed to be narrow enough for workers to reach across the bins; this makes the bins long and the plant large.

In addition to involving costs, composting can generate revenue. Successful composting produces finished compost that can be used to stabilize and add nutrients to soil, similar to a fertilizer. This finished compost has economic value, and can potentially be sold, generating revenue. If the generators of compost do not use the compost, they may be able to sell it to greenhouses, farmers, landscapers, the government for landscaping roadsides and parks, topsoil sellers, golf courses, and homeowners.

The cost model for composting made the assumptions listed below.

- Transportation:
    - The 0.2 TPD plant does not require any transportation beyond door-to-door collection, because processing is done onsite at the society.
    - The 2 TPD plant requires primary collection, but not secondary collection, because the plant is located right next to the transfer station.
    - The 100 and 200 TPD plants require both primary and secondary collection, because the plants are located about on the periphery of the city.
- Overhead:
    - For the 2, 100, and 200 TPD plants, the for-profit companies operating the facilities are paid for their contractual work. The true cost of contracting these companies was not available to us, so it was assumed that this contractual cost is 12% of the operations cost.
- Building and Land:
    - We obtained construction cost estimates from processors and PMC, and estimated the cost of land using the footprint size of facilities and property values for the area.
- Materials:
    - The cost of input materials was assumed to be zero.
- Labor:
    - Society-scale composting systems (0.2 TPD) require the full-time labor of one wastepicker, who is paid 72,000 Rs/yr. This is based on the assumption that the cost of employing a wastepicker full-time would be equivalent to the average annual earnings of a SWaCH wastepicker, which was determined to be 72,000 Rs/yr by Chikarmane (2012).
    - The 2 TPD plant requires 5 operators, 1 supervisor, and partial-employment of a manager that oversees several plants.
    - The 100 TPD plant requires 30 operators, 8 supervisors, and 4 managers.
    - The 200 TPD plant requires 45 operators, 12 supervisors, and 4 managers.
- Capital:
    - Equipment lifetime was assumed to be 20 years, and a discount rate of 7% was used.

- Compost Generation and Revenue:
    - The 0.2 TPD plant was assumed to generate 0.05 TPD of compost.
    - The 2 TPD plant was assumed to generate 0.3 TPD of compost.
    - The 100 TPD plant was assumed to generate 12.3 TPD of compost.
    - The 200 TPD plant was assumed to generate 24.6 TPD of compost.
    - The sale price of compost was assumed to be 8000 Rs/ton of finished compost.

The results of the cost model for composting are shown in **Table 28**. These results are also visually represented in **Figure 52**, which shows the breakdown of cost by element, and **Figure 53**, which compares cost and revenue. We find that the net cost of composting is between 2,144 and 5,725 Rs/ton. The model shows that cost of composting is significantly decreases with increasing plant scale. The economy of scale mainly results from more efficient energy consumption, labor needs, and a smaller relative amount of capital cost from equipment and construction per ton of waste managed. These economies of scale outweigh the increase in cost of transportation that is involved in using larger, centralized facilities. Our findings indicate that when the value of finished compost is considered, composting generates enough revenue to offset about one-third of the cost of processing.

Table 28: The costs and revenues of composting at various scales.

	Plant Scale			
Cost Per Ton (Rs/ton)	0.2 TPD Plant (OWC)	2 TPD Plant (OWC)	100 TPD Plant (Vermi)	200 TPD Plant (Vermi)
Capital	2,147	349	59.1	29.6
Maintenance	258	1,110	388	200
Labor	1,103	909	178	117
Operations and Energy	672	194	77.4	58.1
Materials	0	0	0	0
Building and Land	1,916	947	945	473
Overhead	0	276	77.2	43.2
Transportation	0	296	579	579
Door-to-door Collection	1,628	1,628	1,628	1,628
Total Cost Per Ton	7,725	5,709	3,932	3,128
Revenue Per Ton	2,000	1,246	984	984
Net Cost Per Ton	5,725	4,462	2,948	2,144

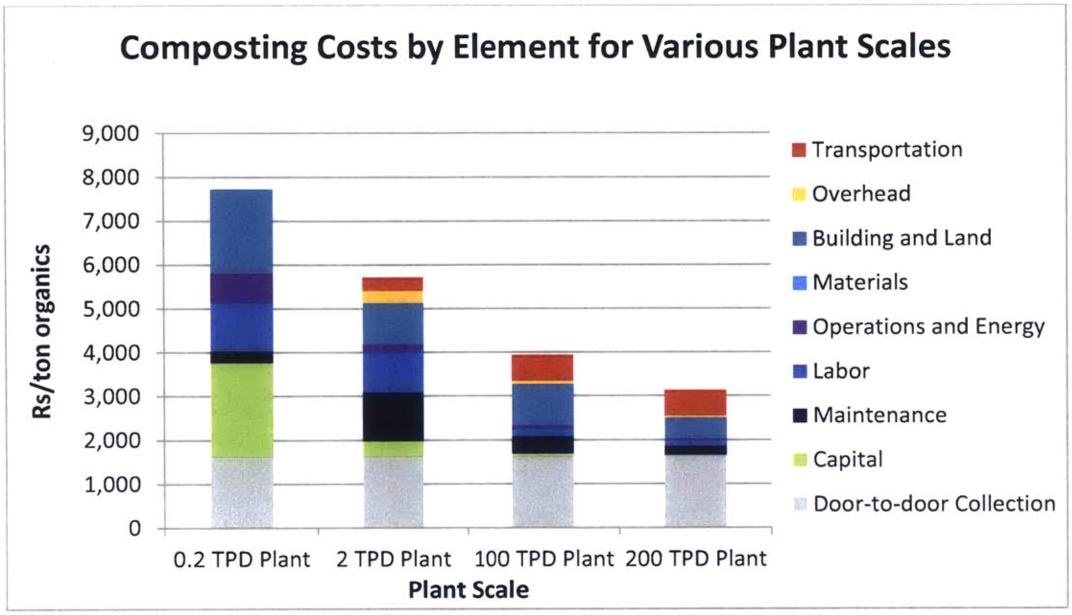


Figure 52: The costs of composting by element for a range of plant scales.

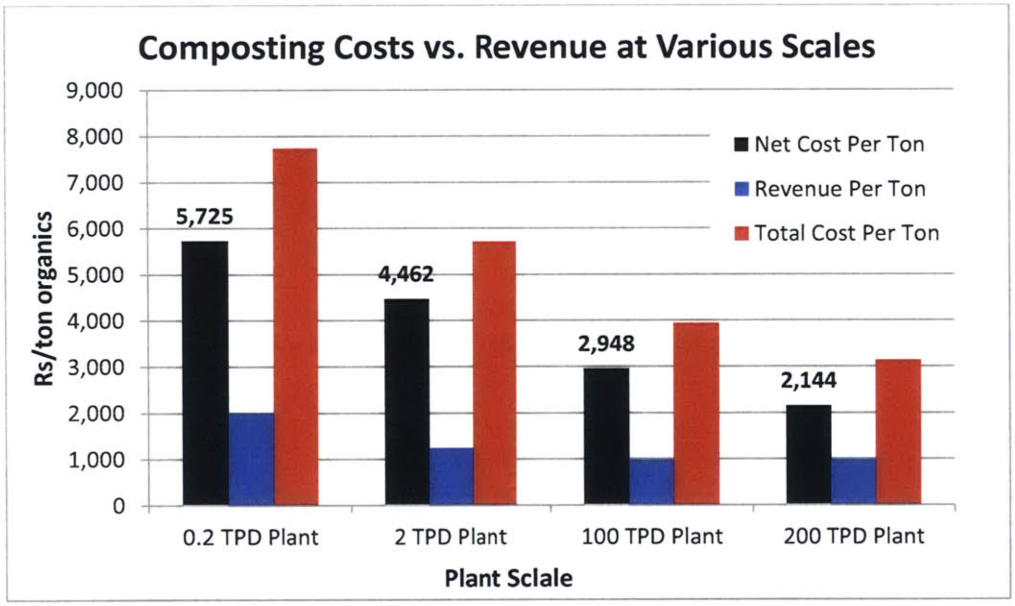


Figure 53: The total cost, revenue, and net costs of composting for a range of plant scales.

5.7 Anaerobic Digestion Costs

Anaerobic digestion is already a relatively common solution for managing food scraps from hotels and restaurants in Pune. Two of Pune's digesters are pictured in **Figure 54**. The processes and system boundary used for the cost model of anaerobic digestion are shown in the diagram in **Figure 55**. As shown by the diagram, the type of biodigestion system analyzed generates electricity from methane, and also utilizes the liquid fertilizer from the digester.

Figure 54: Five-ton per day anaerobic digesters in Pune.

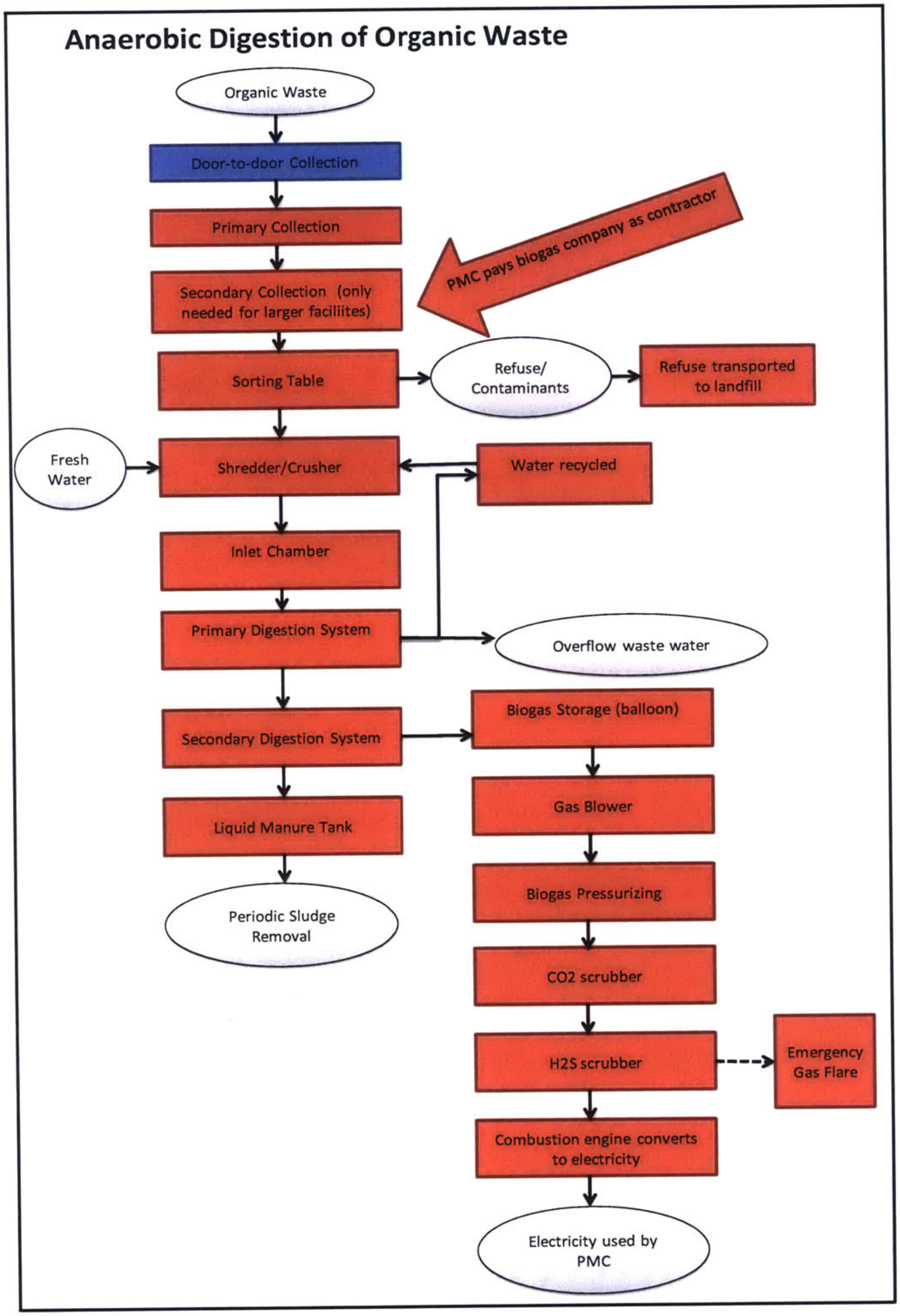


Figure 55: Processes and system boundary of the cost model for anaerobic digestion. The costs of processes colored in red are paid by the PMC; the ones in blue are paid mainly by residents.

Data on the processing characteristics and costs were obtained from interviews and site visits with managers and engineers at companies running biogas plants in Pune. These companies provided information on the capital, labor, electricity consumption, biogas generation rate, and other features of the digestion process. The cost of biodigestion was modeled for plant sizes of 0.1, 0.5, 0.6, 2, 5, and 100 TPD, based on the availability of data. The facility sizes modeled are based off of real biogas plants operated at that scale in Pune or other Indian cities.

The cost model for anaerobic digestion used the following assumptions:

- Transportation:
  - 8% of the incoming waste to the plant was assumed to be non-digestible contaminants that then need to be transported to the landfill.
  - The 0.1, 0.5, 0.6, and 2 TPD plants only require primary collection for delivery of organic waste.
  - The 5 and 100 TPD plants require primary collection and some amount of secondary collection for delivery of organic waste.
- Overhead:
  - The company running the biogas plant was assumed to make a profit of 12% of the total cost of operation. This is based off of the contractual terms between PMC and one of the operators in Pune to run 5 TPD biodigesters.
- Materials:
  - The annual cost of consumables and lubricants was obtained from the contract between PMC and one of Pune's biogas operators and was assumed to scale linearly with capacity.
  - The annual cost of personal protective equipment was obtained from the contract between PMC and one of Pune's biogas operators was assumed to scale linearly with the number of operators needed at a facility.
- Operations and Energy:
  - The annual amount of electricity consumed by the facility was assumed to scale linear with capacity.
  - The cost of laboratory testing was obtained from the contract between PMC and one of Pune's biogas operators and was assumed to remain constant across all modelled facility scales.
- Labor:
  - The 0.1 TPD, 0.5 TPD, and 0.5 TPD plants were assumed to have 1 operator.
  - The 2 TPD plant was assumed to have 2 operators and 1 supervisor.
  - The 5 TPD plant was assumed to have 4 operators and 1 supervisor.
  - The 100 TPD plant was assumed to have 40 operators and 3 supervisors.
- Outputs and Revenue:
  - The market price for electricity in India is 7 Rs/KWH and the market price for solid fertilizer (with 10-26-26 ratio of NPK) is 20 Rs/KWH.
  - Based off of chemical sampling done by one of the biogas plant operators, the output sludge from the digester has a nutrient composition of 4500, 3500, and 1100 ppm of nitrogen, phosphorus, and potassium, respectively. With

potassium to be considered the limiting nutrient for the sludge's quality as a fertilizer, the sludge comparably has 236 times less nutrients than solid fertilizer per kilogram. The economic value of 236 kg of liquid sludge from the digester was assumed to be equivalent value of 1 kg of solid fertilizer.

- The rate of biogas generation was assumed to be 70 cubic meters per ton of food waste.

The results of the cost model for anaerobic digestion are shown in **Table 29**. These results are also visually represented in **Figure 56**, which shows the breakdown of cost by element, and **Figure 57** which compares cost and revenue. We find that the net cost of anaerobic digestion is between 8,069 and 2,706 Rs/ton, depending on the scale of treatment. The model shows that cost of anaerobic digestion rapidly decreases with increasing scale of facility, with the largest cost reduction occurring between the treatment scale of 0.1 and 0.5 TPD. The economy of scale mainly results from more efficient energy consumption, labor needs, and a smaller relative amount of capital cost from equipment and construction per ton of waste managed. These economies of scale outweigh the increase in cost of transportation that is involved in using larger, centralized facilities. Our findings indicate that when the value of electricity and fertilizer (sludge) is considered, revenue from anaerobic digestion at most offsets one-fourth of the cost of processing.

Table 29: The costs and revenues of anaerobic digestion at various scales.

	Plant Scale					
Cost Per Ton (Rs/ton)	**0.1 TPD Plant**	**0.5 TPD Plant**	**0.6 TPD Plant**	**2 TPD Plant**	**5 TPD Plant**	**100 TPD Plant**
Capital	1,373	366	735	275	515	400
Maintenance	27	7	15	27	10	8
Labor	3725	745	621	652	410	91
Operations and Energy	217	71	65	44	39	35
Materials	238	56	49	34	29	15
Building and Land	26	29	27	23	29	29
Overhead	516	117	101	102	70	30
Transportation	319	319	319	319	469	469
Door-to-door Collection	1,628	1,628	1,628	1,628	1,628	1,628
Total Cost Per Ton	8,069	3,339	3,559	3,104	3,199	2,706
Revenue Per Ton	694	694	694	694	694	694
Net Cost Per Ton	**7,375**	**2,645**	**2,865**	**2,410**	**2,504**	**2,012**

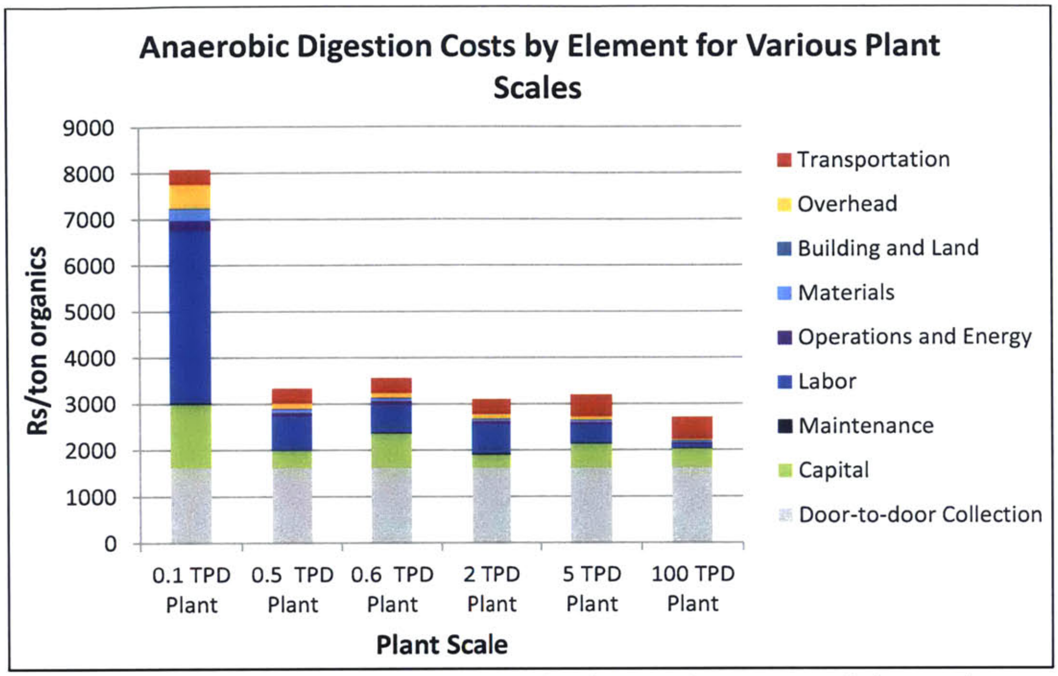


Figure 56: The costs of anaerobic digestion by element for a range of plant scales.

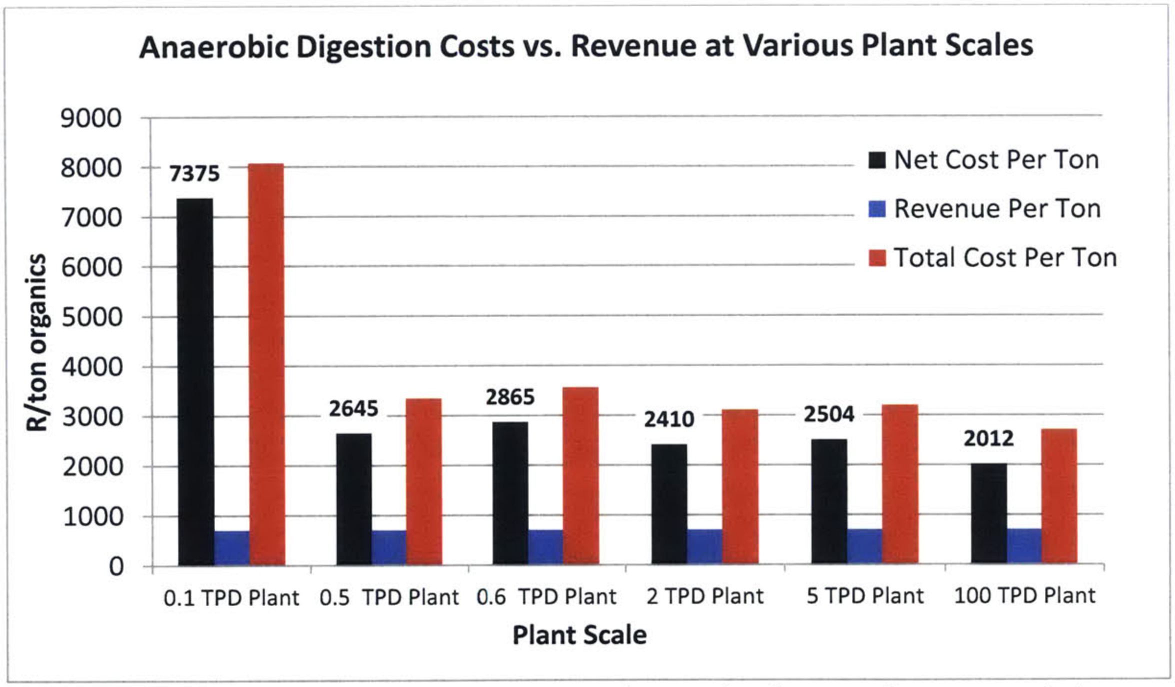


Figure 57: The total cost, revenue, and net costs of anaerobic digestion for a range of plant scales.

5.8 Pelletization Costs

Unlike the technologies analyzed above (landfilling, composting, and anaerobic digestion), pelletization of organic waste in Pune is still in its piloting phase. Gangotree Eco Technologies, a bio-energy start-up owned by Dr. Santosh Gondhalekar, is piloting this technology in a 0.5 TPD plant in Aundh ward. The pelletization process can be used to produce small pellets to be burned in small ovens or larger briquettes to be burned in larger industrial furnaces. A sample of the pellets and briquettes is pictured in **Figure 58**. Once the technology and business model are finalized, Gangotree plans to license the technology to other businesses in India.

Figure 58: A sample of the pellets (left) and briquettes (right) generated by the pelletization process at Gangotree. Source of images: Kornstein, 2012.

The data used to create the cost model for pelletization was obtained from site visits to the plant and from conversations with Dr. Gondhalekar, an energy and expert in bio-based energy. Although currently only a 0.5 TPD plant is in existence, costs were modeled for pelletization at plant scales of 0.5,1, 2, 5, and 10 TPD using expertise from Dr. Gondhalekar. It should be noted that that the cost model findings for the plants with capacities above 0.5 TPD are for hypothetical system scales, as opposed to currently operating plants. The pelletization technology is only feasible for plant sizes up to 10 TPD, so larger plant sizes were not modeled.

The processes and system boundary used for the cost model of pelletization are shown in the diagram in **Figure 59**. The key assumptions used in the cost model of pelletization are listed below.

- Transportation:
    - All scales of pelletization require primary collection. The 1, 2, and 5 TPD plants also require transportation from the transfer station to the facility, and the 10 TPD plant requires secondary collection.
- Overhead:
    - The cost of administration for the 0.5, 1, 2, 5, and 10 TPD plants are 50,000; 75,000; 200,000; 300,000; and 300,000 Rs/yr respectively.
- Building and Land:

  - The cost of building construction for the 0.5, 1, 2, 5, and 10 TPD plants are 100,000; 150,000; 250,000; 600,000; and 1,000,000 Rs respectively.
  - The building lifetime is assumed to be 20 years.
- Materials:
  - The water content of the input organic waste is assumed to be 70%.
- Labor:
  - The number of employees needed at the 0.5, 1, 2, 5 and 10 TPD plants is assume do to be 2, 3, 4, 6, and 10, respectively.
- Capital:
  - The main pieces of equipment needed for the processing are a shredder, and dryer machine, and a pellet press.
- Pellet Generation and Revenue:
  - The pelletization process generates 200 kgs of pellets per ton of organic waste processed.
  - The sale price of pellets is 5 Rs/kg.

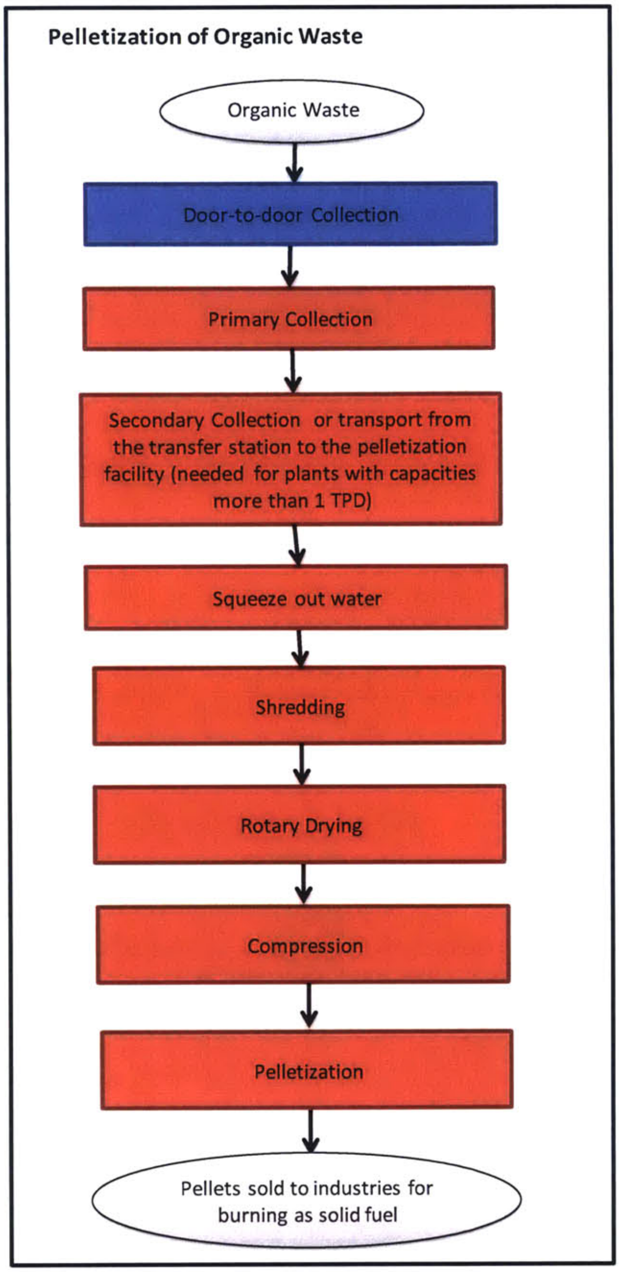


Figure 59: Processes and system boundary of the cost model for pelletization. The costs of processes colored in red are paid by the PMC.

The results of the cost model for pelletization are shown in **Table 30**. These results are also visually represented in **Figure 60**, which shows the breakdown of cost by element, and **Figure 61**, which compares cost and revenue. We find that the net cost of pelletization is between 2,332 and 4,395 Rs/ton, depending on the scale of treatment. The model results show that per ton cost of pelletization decreases with increasing scale of facility. The economy of scale results from a combined reduction in almost all cost elements (capital, maintenance, labor, energy, construction, and overhead) per ton of waste managed. When combined, these economies of scale outweigh the increase in cost of transportation that is involved in using larger, more centralized facilities. Our findings indicate that when the revenue from the sale of pellets is considered, the revenue from pelletization offsets between one-fifth and one-third of the cost of processing.

Table 30: The costs and revenues of anaerobic digestion at various scales.

	Plant Scale				
Cost Per Ton (Rs/ton)	**0.5 TPD plant**	**1 TPD plant**	**2 TPD plant**	**5 TPD plant**	**10 TPD plant**
Capital	1,036	472	336	275	200
Maintenance	303	227	189	182	152
Labor	1,212	909	606	364	303
Energy	560	490	455	420	350
Materials	0	0	0	0	0
Building and Land	57.2	42.9	35.8	34.3	28.6
Overhead	303	227	303	182	90.9
Transportation	296	446	446	446	580
Door-to-door Collection	1,628	1,628	1,628	1,628	1,628
Total Cost	5,395	4,442	3,999	3,530	3,332
Revenue	1,000	1,000	1,000	1,000	1,000
Net cost	**4,395**	**3,442**	**2,999**	**2,530**	**2,332**

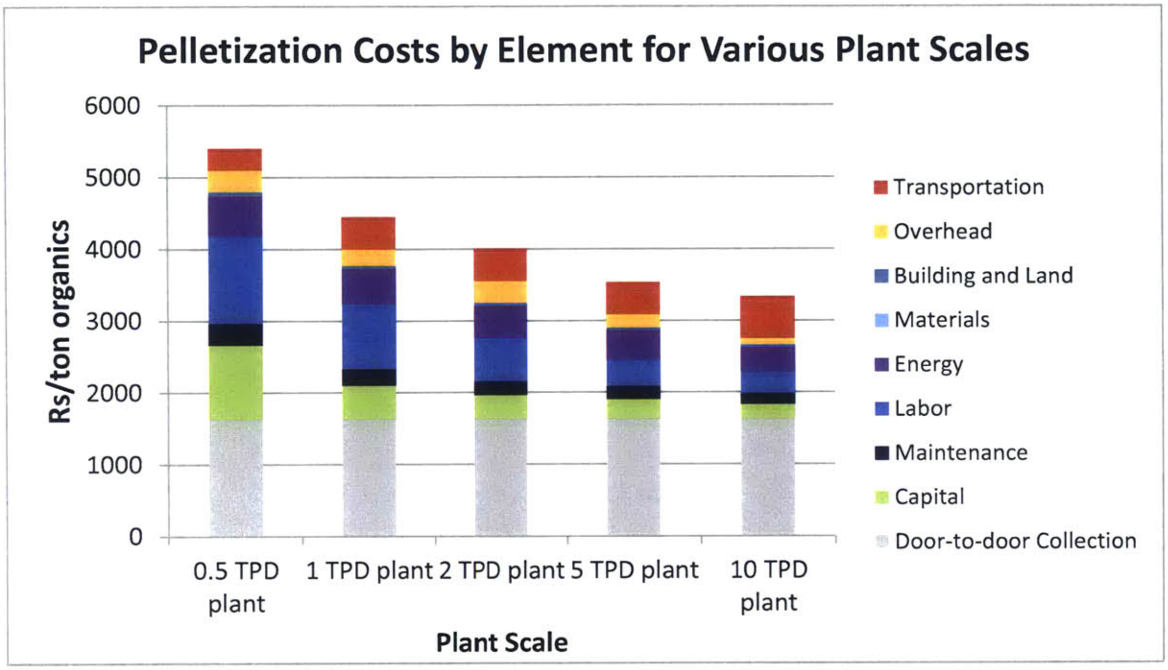


Figure 60: The costs of pelletization by element for a range of plant scales.

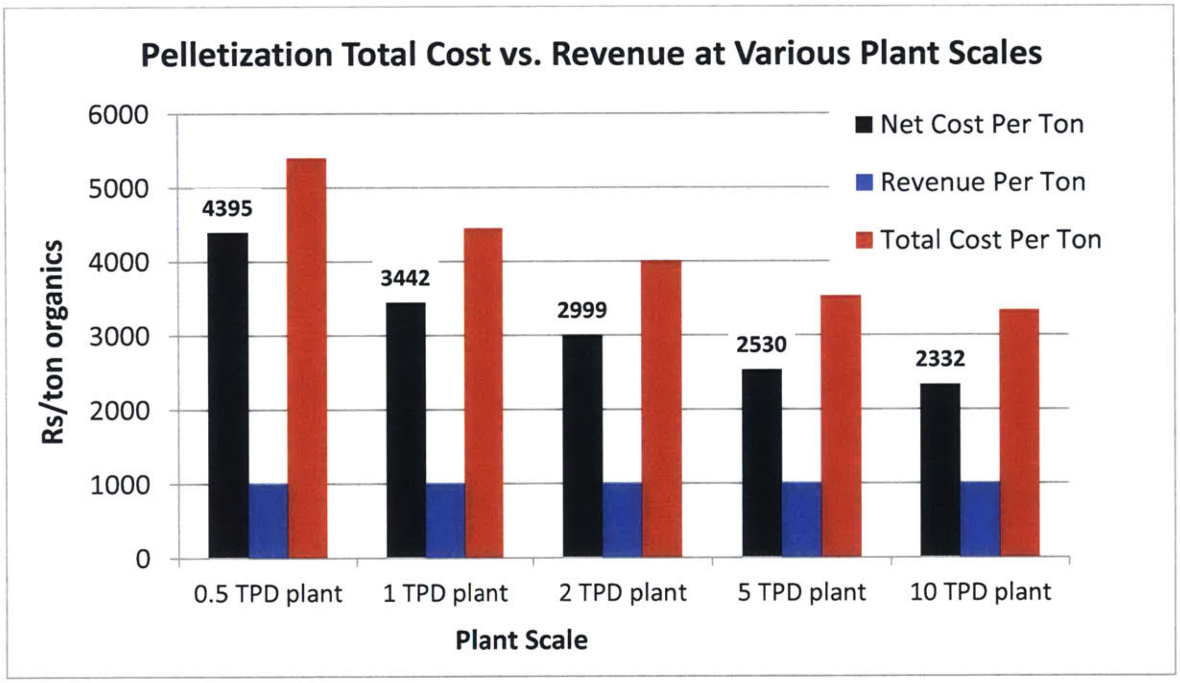


Figure 61: The total cost, revenue, and net costs of pelletization for a range of plant scales.

5.9 Summary of Costs and Sensitivity Analysis

5.9.1 Comparison of Technologies

In order to compare the net costs of various treatment options for composting, the results from the above sections must be compared. **Table 31** summarizes the net cost per ton of managing organic waste using anaerobic digestion, composting, pelletization, and landfilling at different scales ranging from 0.1 to 200 tons per day. Because not every scale of plant could be modeled, some cells are left grey to indicate that the technology was not estimated for that particular scale. The color-coding in the table helps illustrate the range of values, with higher costs shown in warmer colors such as red, and lower costs shown in cool colors such as green. In this table, the general trend of cost decreasing with increasing scale (from left to right) can be seen across the technologies. Furthermore, by comparing the costs in each column, the different technologies can be compared at the same treatment scale. Landfilling costs are assumed to not vary with scale of treatment, as it is assumed the landfill is already constructed and will continue to have a large capacity.

As **Table 31** shows, alternative organics management technologies used at small scales (less than 0.5 TPD) are more expensive than landfilling; however, if a facility of at least 0.5 TPD is used, anaerobic digestion is less expensive than landfilling. At the scale of 100 TPD, anaerobic digestion is 30% cheaper than landfilling. Pelletization also becomes less expensive than landfilling at the scale of 5 TPD. At the scale of 10 TPD, pelletization is 20% cheaper than landfilling. Furthermore, at the scale of 200 TPD, composting also becomes cheaper than landfilling.

Table 31: The net cost per ton of each treatment technology compared for a range of scales. Grey cell indicate that the cost was not estimated for that particular scale in this study. N/A indicates that the technology is not applicable at a particular scale. The color-coding helps illustrate the range of values, with higher costs shown in warmer colors such as red, and lower costs shown in cool colors such as green.

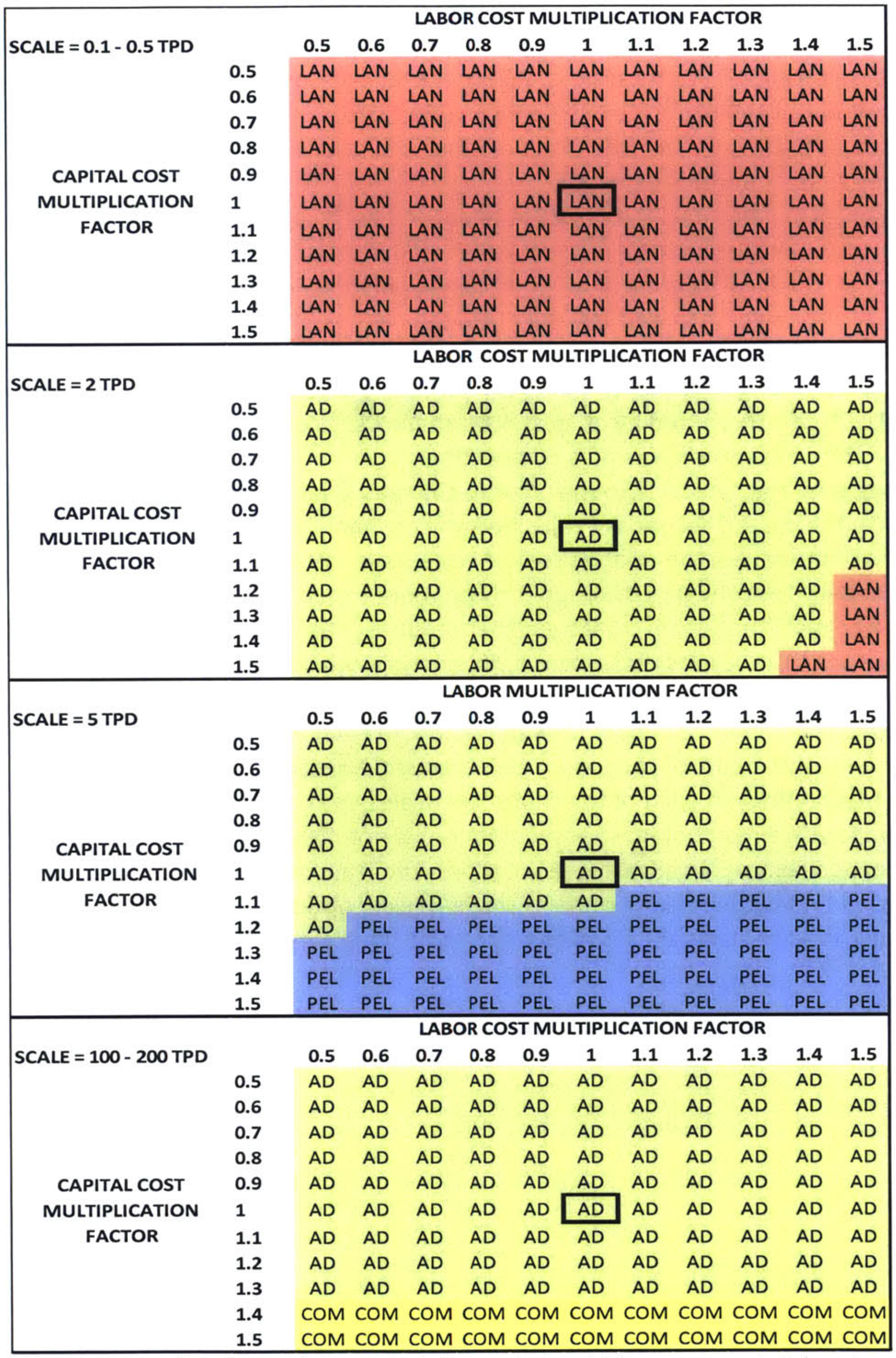
Technology	Scale of Treatment (tons/day)								
	0.1	**0.2**	**0.5**	**1**	**2**	**5**	**10**	**100**	**200**
Anaerobic Digestion	7375		2,645		2,410	2,504		2,012	
Composting		5,726			4,462			2,948	2,144
Pelletization			4,395	3,442	2,999	2,530	2,332		
Landfilling	2,929	2,929	2,929	2,929	2,929	2,929	2,929	2,929	2,929

5.9.1 Cost Sensitivities

As is the case with any form of cost modeling, error from assumptions or inaccurate cost estimates from experts may lead the resulting cost figures to over- or under-estimate. In order to test how uncertainty in the cost model inputs impacts the findings, a sensitivity analysis can be conducted. I used a sensitivity analysis to see how increasing or decreasing the cost of certain elements changes the net cost results and the resulting least-cost technology at a given scale. The two most significant drivers of cost for the majority of technologies assessed in this chapter were labor and capital cost. So I tested the sensitivity of how a change in capital cost and labor cost would affect the net cost of treatment at a given scale. I varied capital costs between 0.5 and 1.5 times the original value to test the impact of having a lower and higher capital cost, respectively; the same analysis was done for labor costs.

The results of this sensitivity analysis for capital and labor costs are found in **Figure 62**. Each section of the figure (from top to bottom) represents the sensitivity analysis for a different scale of treatment; a separate sensitivity analysis is done for four scales of treatment: 0.1-0.5 TPD, 2 TPD, 5 TPD, and 100-200 TPD. For some of these scales, plants of similar (but not exactly the same) sizes had to be compared across technologies. For instance, the sensitivity analysis on the smallest scale compared composting at 0.2 TPD, biodigestion at 0.1 TPD, and pelletization and 0.5 TPD (these are the minimum scales modeled for each technology). At the next largest scale, all technologies were indeed based off of 2 TPD scale plants. The sensitivity analysis for the 5 TPD scale compared biodigestion and pelletization at the 5 TPD scale and c composting at the 2 TPD scale. For the largest scale, the analysis compared composting at 200 TPD, anaerobic digestion at 100 TPD, and pelletization at 10 TPD (these are the maximum scales modeled for each technology). In **Figure 62**, the row and column labels ranging from 0.5 to 1.5 indicate the multiplication factor used for labor and capital cost values; when the multiplication factor is 1 for both variables, the original labor and cost values are used. The output in each cell (such as LAN or AD) indicates the least-cost technology across the four alternatives for the particular sensitivity scenario. "LAN" means landfill, "AD" means anaerobic digestion, "COM" means composting, and "PEL" means pelletization.

The center cell of each section (outlined in a black box) indicates the resulting least-cost technology using the original labor and capital costs as modeled above. If all or most of the output cells are the same as the original center cell, the analysis indicates that the modeled findings are relatively robust; if the resulting output changes significantly with even a minor increase in multiplication factor, the results are highly sensitive and the findings are more uncertain.



		LABOR COST MULTIPLICATION FACTOR										
SCALE = 0.1 - 0.5 TPD		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
	0.5	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	0.6	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	0.7	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	0.8	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
CAPITAL COST MULTIPLICATION FACTOR	0.9	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	1	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	1.1	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	1.2	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	1.3	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	1.4	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN
	1.5	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN

		LABOR COST MULTIPLICATION FACTOR										
SCALE = 2 TPD		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
	0.5	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.6	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.7	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.8	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
CAPITAL COST MULTIPLICATION FACTOR	0.9	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1.1	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1.2	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	LAN
	1.3	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	LAN
	1.4	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	LAN
	1.5	AD	AD	AD	AD	AD	AD	AD	AD	AD	LAN	LAN

		LABOR MULTIPLICATION FACTOR										
SCALE = 5 TPD		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
	0.5	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.6	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.7	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.8	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
CAPITAL COST MULTIPLICATION FACTOR	0.9	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1.1	AD	AD	AD	AD	AD	AD	PEL	PEL	PEL	PEL	PEL
	1.2	AD	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL
	1.3	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL
	1.4	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL
	1.5	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL	PEL

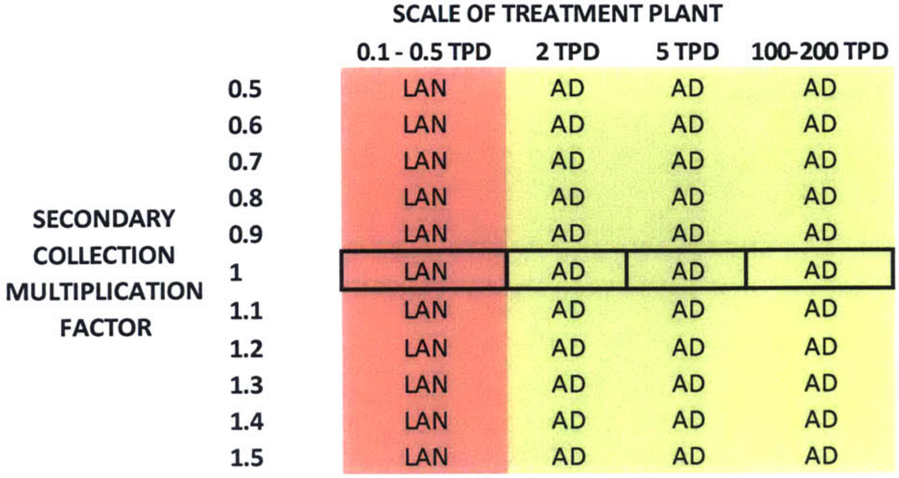
		LABOR COST MULTIPLICATION FACTOR										
SCALE = 100 - 200 TPD		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
	0.5	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.6	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.7	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	0.8	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
CAPITAL COST MULTIPLICATION FACTOR	0.9	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1.1	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1.2	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1.3	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
	1.4	COM	COM	COM	COM	COM	COM	COM	COM	COM	COM	COM
	1.5	COM	COM	COM	COM	COM	COM	COM	COM	COM	COM	COM

Figure 62: Results of sensitivity analysis for capital and labor costs on total cost.

For each scenario, in which capital and labor costs are multiplied by a factor (ranging from 0.5 to 1.5), the corresponding cell indicates the treatment technology that has the lowest net cost. For all of the above sensitivity scenarios, either landfilling or anaerobic digestion is the least-cost treatment choice. LAN = Landfill (colored red); AD = Anaerobic Digestion (colored green); COM=Composting (colored yellow); PEL=Pelletization (colored blue).

The sensitivity analysis reveals that at the smallest scale (0.1-0.5 TPD), the results remain the same (landfilling is cheapest), even if both capital and labor costs are both increased by 50% or both decreased by 50%. At the scale of 2 TPD, the lowest-cost technology remains anaerobic digestion, except at the highest extreme when labor costs are at least 40% higher and capital costs are at least 20% higher; when cost of labor and capital is higher, landfilling becomes cheaper relative to anaerobic digestion. At the scale of 5 TPD, the results are not highly sensitive to changes in labor, but are sensitive to an increased capital cost. If capital costs are increased by 30%, and labor costs remain anywhere between the range of 50% to 150% of the original cost, the least-cost technology becomes pelletization, as opposed to anaerobic digestion. At the largest scale of 100-200 TPD, the net cost of treatment is also more sensitive to changes in capital cost. Changing the labor cost to a value that is 50% or 150% of the original value does not change the result unless capital cost is at least 40% greater than the original value. If capital cost is increased by at least 40%, the lowest-cost technology is no longer anaerobic digestion, but rather becomes composting.

In addition to testing the sensitivity of net cost to changes in labor and capital cost, I tested the sensitivity to the cost of secondary collection. If secondary collection is much less expensive than originally modelled, the relative cost of large-scale, centralized treatment will become relatively cheaper; if secondary collection is much more expensive than originally modelled, the relative cost of small-scale treatment that requires little to no trucking will become relatively cheaper. The results of the sensitivity analysis, which assesses the impact of increasing and decreasing the cost of secondary collection by 50%, is shown in **Figure 63**. The lowest cost technology at each scale is reported as the output in each cell. The results of the analysis indicate that even if the cost of secondary collection is decreased by 50% or increased by 50%, the least cost technology at each of the treatment scales does not change. We can conclude that the comparative result of least-cost treatment is not highly sensitive to changes in the cost of secondary collection. In all of these scenarios, the least-cost option does not change from the original finding: landfilling remains the least-cost option for scales of 0.1-0.5 TPD, and anaerobic digestion remains the least-cost option at the scales of 2 TPD, 5 TPD, and 100-200 TPD.



SECONDARY COLLECTION MULTIPLICATION FACTOR	SCALE OF TREATMENT PLANT			
	0.1 - 0.5 TPD	2 TPD	5 TPD	100-200 TPD
0.5	LAN	AD	AD	AD
0.6	LAN	AD	AD	AD
0.7	LAN	AD	AD	AD
0.8	LAN	AD	AD	AD
0.9	LAN	AD	AD	AD
1	LAN	AD	AD	AD
1.1	LAN	AD	AD	AD
1.2	LAN	AD	AD	AD
1.3	LAN	AD	AD	AD
1.4	LAN	AD	AD	AD
1.5	LAN	AD	AD	AD

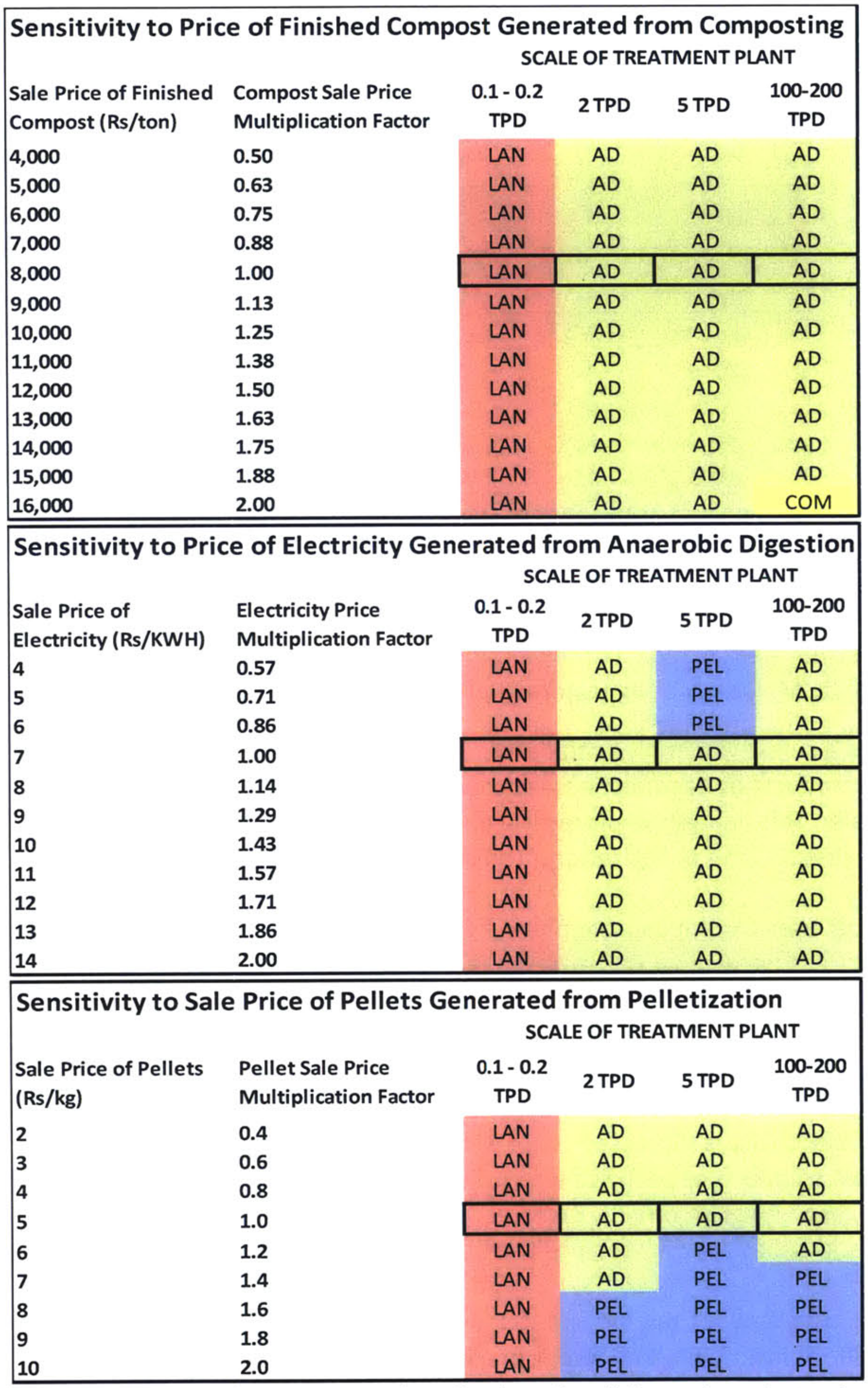
Figure 63: Results of sensitivity analysis for the cost of secondary transportation on total cost. For each scenario in which the secondary transportation cost is multiplied by a factor ranging from 0.5 to 1.5, the corresponding cell indicates the treatment technology that is has the lowest net cost. For all of the above sensitivity scenarios, either landfilling or anaerobic digestion is the least-cost treatment choice. LAN = Landfill (colored red); AD = Anaerobic Digestion (colored green); COM=Composting (colored yellow); PEL=Pelletization (colored blue).

Lastly, I conducted a sensitivity analysis to determine whether increasing or decreasing the sale price of the end-products of each technology changes the results of which technology is least-cost at a given scale. This analysis explores the uncertainty in revenue streams from composting, anaerobic digestion, and pelletization. The results of this analysis are shown in **Figure 64**.

The originally model uses a compost sale price of 8,000 Rs/ton. The results show that when the compost sale price is between 4,000 and 15,000 Rs/ton, the least-cost solution remains landfilling at the scale of 0.1-0.2 TPD and anaerobic digestion at all larger scales. However, if compost sells for an extremely high price of 16,000 Rs/ton (twice the price used in the original model), then composting finally becomes less expensive than anaerobic digestion at the scale of 100-200 TPD.

When the price of electricity is increased to up to twice the original assumed sale price of 7 Rs/KWH, the least-cost solutions at each scale remain unchanged. However, if the sale price of electricity is decreased by even one Rs/KWH, anaerobic digestion becomes less profitable (more costly), and pelletization becomes the least-cost technology at the 5 TPD scale only.

The original model uses a pellet sale price of 5 Rs/kg. When the sale price of pellets is decreased, the resulting set of least-cost technology at each scale remains unchanged. However, if the price of pellets is increased by 33% or more, pelletization, rather than anaerobic digestion, becomes the least-cost technology at 5 TPD. Furthermore, if the price of pellets is increased by 67% or more, pelletization becomes the least-cost technology at 100 TPD.



Sensitivity to Price of Finished Compost Generated from Composting

Sale Price of Finished Compost (Rs/ton)	Compost Sale Price Multiplication Factor	SCALE OF TREATMENT PLANT 0.1 - 0.2 TPD	2 TPD	5 TPD	100-200 TPD
4,000	0.50	LAN	AD	AD	AD
5,000	0.63	LAN	AD	AD	AD
6,000	0.75	LAN	AD	AD	AD
7,000	0.88	LAN	AD	AD	AD
8,000	1.00	LAN	AD	AD	AD
9,000	1.13	LAN	AD	AD	AD
10,000	1.25	LAN	AD	AD	AD
11,000	1.38	LAN	AD	AD	AD
12,000	1.50	LAN	AD	AD	AD
13,000	1.63	LAN	AD	AD	AD
14,000	1.75	LAN	AD	AD	AD
15,000	1.88	LAN	AD	AD	AD
16,000	2.00	LAN	AD	AD	COM

Sensitivity to Price of Electricity Generated from Anaerobic Digestion

Sale Price of Electricity (Rs/KWH)	Electricity Price Multiplication Factor	SCALE OF TREATMENT PLANT 0.1 - 0.2 TPD	2 TPD	5 TPD	100-200 TPD
4	0.57	LAN	AD	PEL	AD
5	0.71	LAN	AD	PEL	AD
6	0.86	LAN	AD	PEL	AD
7	1.00	LAN	AD	AD	AD
8	1.14	LAN	AD	AD	AD
9	1.29	LAN	AD	AD	AD
10	1.43	LAN	AD	AD	AD
11	1.57	LAN	AD	AD	AD
12	1.71	LAN	AD	AD	AD
13	1.86	LAN	AD	AD	AD
14	2.00	LAN	AD	AD	AD

Sensitivity to Sale Price of Pellets Generated from Pelletization

Sale Price of Pellets (Rs/kg)	Pellet Sale Price Multiplication Factor	SCALE OF TREATMENT PLANT 0.1 - 0.2 TPD	2 TPD	5 TPD	100-200 TPD
2	0.4	LAN	AD	AD	AD
3	0.6	LAN	AD	AD	AD
4	0.8	LAN	AD	AD	AD
5	1.0	LAN	AD	AD	AD
6	1.2	LAN	AD	PEL	AD
7	1.4	LAN	AD	PEL	PEL
8	1.6	LAN	PEL	PEL	PEL
9	1.8	LAN	PEL	PEL	PEL
10	2.0	LAN	PEL	PEL	PEL

Figure 64: Results of sensitivity analysis for the price of the end-products of composting, anaerobic digestion, and pelletization. For each scenario, the corresponding cell indicates the treatment technology that is has the lowest net cost. LAN = Landfill (colored red); AD = Anaerobic Digestion (colored green); COM=Composting (colored yellow); PEL=Pelletization (colored blue).

5.9.2 Regression Analysis of Cost by Scale

In order to predict the cost of managing organic waste based on the technology used and the scale of treatment, I used regression analysis of the cost model outputs at various scales. Regression was done in Excel using decaying power functions. The cost of treatment per ton was regressed on scale for each treatment technology, and the results are shown in **Table 32**. The resulting regression equations are listed in the second column, with the independent variable being scale in TPD and the dependent variable being cost in Rs/ton. The goodness-of-fit for regression was very high for composting and pelletization, which had R^2 values of 0.95 and 0.97; the R^2 of the regression for anaerobic digestion was moderately high at 0.63. The regression equations were used to fill in the missing values from **Table 31**; the numbers colored in red are the treatment cost estimates obtained from the regression equation. The cost values in black are those ones obtained from cost modelling, and were the values used to derive the regression equation; they are the same values as those listed in **Table 31**. For pelletization specifically, the regression analysis is assumed to only apply to up to the scale of 10 TPD, given that that is the maximum treatment capacity; consequently the cost per ton of treating 100 TPD with pelletization is assumed to be the same as that for a 10 TPD plant (then 10 TPD would simply be used).

The net cost values in **Table 32** as well as the regression functions are plotted in **Figure 65**. It should be noted that the x-axis showing plant size in tons/day is shown using a logarithmic scale. The points at which the different-colored regression functions intersect roughly show the cross over points for where the costs of one technology changes from being more expensive to less expensive than another technology. From this plot, it can be seen that landfilling is lower cost than the other technologies implemented at the smallest scales (less than 0.5 TPD). At scale larger than 0.5 TPD, anaerobic digestion generally is the least cost option. At 5 to 10 TPD, pelletization becomes cost-competitive with anaerobic digestion (the costs are very close). Composting is generally more expensive than both anaerobic digestion and pelletization, but, at large scale, composting becomes cost-competitive with pelletization. Using the regression function for composting, composting becomes less expensive than landfilling at a scale of roughly 60 TPD.

In the final row of **Table 32**, the least cost technology at the given scale is identified. If treating waste using a scale smaller than 0.5 TPD, landfilling is the cheapest option. Anaerobic digestion is the cheapest option for capacities of greater than 1 TPD.

Table 32: The regressed cost per ton of each treatment technology at various scales. The equations used are listed in the second column and the results obtained for power regression of cost with scale for each technology are the red values. Cost values in black are those obtained from cost modelling and are the same as those in Table 31. Pelletization cost values in blue are indicate that the cost per ton would not decrease beyond the cost at 10 TPD, given that 10 TPD is the maximum capacity per plant for that technology.

Technology	Regression Equation Used for Interpolation (x = scale in TPD)	R^2	Scale of Treatment (tons/day)								
			0.1	0.2	0.5	1.0	2.0	5.0	10	100	200
Anaerobic Digestion	$C_{AD}= 3375*x^{-0.157}$	0.63	7375	4346	2645	3375	2410	2504	2351	2012	1469
Composting	$C_{COM}= 4772*x^{-0.13}$	0.95	6438	5726	5222	4772	4462	3871	3538	2948	2144
Pelletization	$C_{PEL}= 3594*x^{-0.206}$	0.97	5776	5007	4395	3442	2999	2530	2332	2332	2332
Landfilling	$C_{LAN}= 2929$	N/A	2929	2929	2929	2929	2929	2929	2929	2929	2929
Least Cost Technology at Each Scale			**LAN**	**LAN**	**AD**	**LAN**	**AD**	**AD**	**AD**	**AD**	**AD**

C = cost in Rs/ton; LAN = Landfill; AD = Anaerobic Digestion; COM=Composting; PEL=Pelletization.

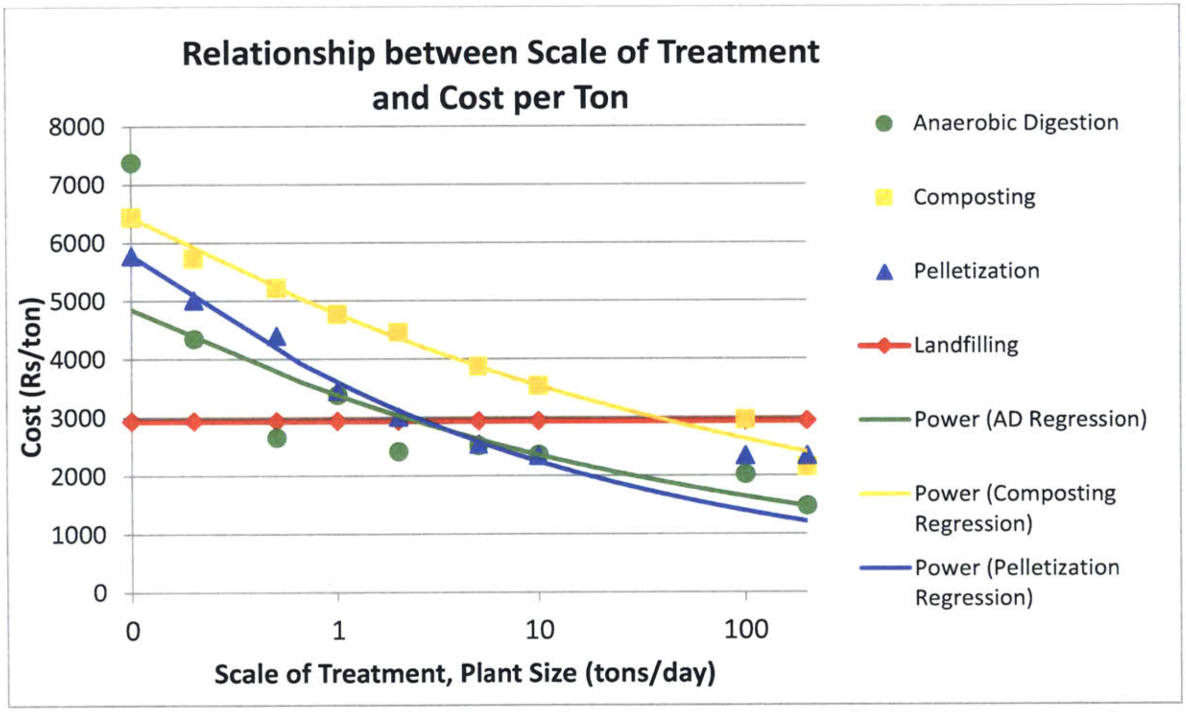


Figure 65: Plot of cost as a function of scale of treatment for anaerobic digestion, composting, pelletization, and landfilling. This plotted points includes cost estimates from the models, as well as from the regression analysis (the same data as Table 32). The curves show the regression functions.

5.10 Limitations of Cost Models

We took several measures to increase the accuracy of our cost models, including collecting and using real cost records or communicated quotes from Pune facilities, organizations, and government, as well as having experts and managers review and provide feedback on the models. Our sensitivity analyses imply that our results are robust, even if some of the assumptions regarding capital, labor, secondary transportation, or sale price of end-products contain uncertainty. Still, our net cost results for collection and treatment processes are limited in that they are based on models that contain some cost factors that we were forced to estimate as best as possible due to a lack of data. In particular, we were unable to obtain data on the non-transportation related operation and maintenance costs of landfilling, and instead used best estimates that are uncertain. For composting, we were unable to obtain electricity usage records for the vermicomposting plants, and therefore used best estimates to determine the electricity consumption at the 100 and 200 TPD plants. Although we had detailed facility and cost projections for pelletization, all of this data for plants larger than 0.5 TPD was based on an expert's estimate of the costs for hypothetical plant scales, given that the technology is still being piloted. Lastly, for door-to-door collection, our cost estimates are based on the assumption that SWaCH wastepickers are paid the full amount they are legally supposed to receive from the government and residents, which may not reflect a reality where residents and the government do not fully comply or pay on time.

5.11 Key Findings from Economic Analysis

FINDING 1: Alternative organics management technologies used at small scales (less than 0.5 TPD) are more expensive than landfilling; however, if a facility of at least 0.5 TPD is used, anaerobic digestion is less expensive than landfilling. Furthermore, if a facility of at least 5 TPD is used and the technology progresses as expected, pelletization becomes cost-competitive with anaerobic digestion (the costs are very close). Composting at the scale of 200 TPD is also less expensive than landfilling. We are confident that these assertions are robust, given that the findings regarding comparison of net cost across technologies were generally not sensitive to variations in assumptions about the cost of capital, labor, secondary transportation, and the sale price of end-products.

FINDING 2: The cost per ton of waste managed using anaerobic digestion, composting, and pelletization decreases significantly with larger plant scales, as shown by **Figure 65**.

FINDING 3: Using treatment scales up to 10 TPD, the cost per ton is similar for pelletization and composting. However, if large scale plants of 100-200 TPD are used, then composting becomes significantly cheaper than pelletization. This is shown by **Figure 65**.

FINDING 4 The cost per ton of door-to-door collection is much higher than the cost of primary or secondary collection, as shown by ***Figure 43***. Door-to-door collection is a significant contributor to the cost of organics waste management from collection through disposal, as shown by the cost model results, broken down by element. Furthermore, sensitivity analysis shows that even if secondary collection costs are decreased on increased significantly, the least-cost technology for a given scale does not change.

FINDING 5: Apart from the cost of door-to-door collection, which was constant across all technologies, our analysis found that the major drivers of the total cost of anaerobic digestion, composting, and pelletization were labor and capital costs; for landfilling, the major drivers of the total cost were transportation and land.

FINDING 6: Our cost modeling results indicate that a significant portion of the cost of processing waste using anaerobic digestion, composting, and pelletization is offset by revenues from the end-products of the processes. The ratio of revenue to cost was highest for composting. Sensitivity analysis shows that least-cost technology for a given scale does not readily change when the magnitude of revenue is increased or decreased. The ranking of technologies by cost is robust with regard to variation in sale price of finished compost or electricity, and is somewhat sensitive to increased sale price of pellets (which makes pelletization relatively cheaper).

Chapter 6: Environmental Assessment

6.1 Background on the Environmental Impact of Organic Waste Management

Although there is general agreement the environmental community that landfilling organic waste is an inferior strategy for managing organic waste, there is less agreement on which alternative method(s) should be used. A number of alternative options exist for processing/treating organic wastes, including:

- Direct feeding to livestock
- Composting
- Anaerobic Digestion
- Pyrolysis/Gasification
- Incineration of Pellets/Briquettes

With so many options, cities and waste managers must consider the advantages and disadvantages of each, and determine which method is the most sensible from an environmental or logistical standpoint. A number of variables, such as contamination rate, public participation, and the composition of the waste, can also influence the success of particular organic processing strategies. **Figure 66** shows the US Environmental Protection Agency's hierarchal prioritization of best management practices for discarded food scraps (Barrows, 2011). In this figure, "Industrial Uses" refers to the rendering fats for use in products, biodiesel production, or anaerobic digestion for the production of biogas.

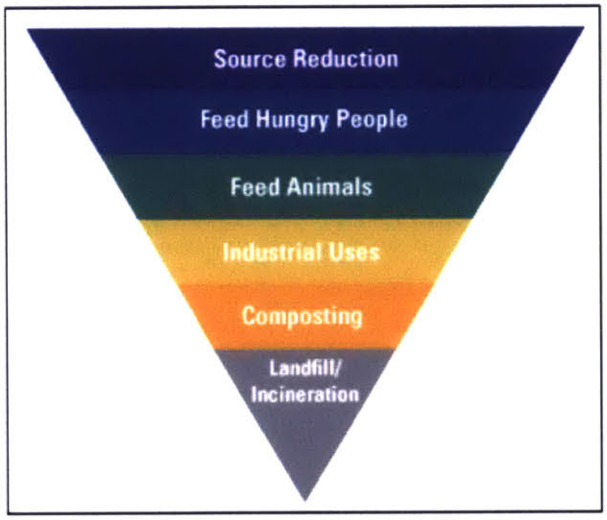


Figure 66: EPA's prioritization of practices for managing food waste (Barrows, 2011).

Although source reduction and feeding hungry people are two ways of avoiding organic waste generation, those methods are not considered within the scope of organic waste management described in this thesis.

Additionally, even though using food scraps to feed livestock (pigs and cows) is a traditional practice that makes efficient use of nutrients and energy, that option is also not analyzed in this thesis. It is excluded from analysis because using biodegradable MSW from cities to feed animals has many limitations. A modern city concerned with federal health and environmental regulation may be reluctant to directly feed food waste to livestock. First of all, they might encounter difficulty complying with relevant regulations; many aspects of the processes involving animal feed are heavily regulated and inspected by a nation's national agency for agriculture and/or food. Many governments also require that the food waste be "cooked" before it is given to animals, so that bacteria and viruses are eliminated. Additionally, sending food waste to animals imposes constraints on the type of scraps that can be included in the stream; some items, such as coffee grounds, cannot be given to animals, meaning that they will contaminate the stream if accidentally mixed in. Furthermore, feeding animals food scraps containing meat should be avoided, as this can lead to higher disease risk. Consequently, ensuring that the quality of the food scraps is suitable for livestock consumption requires careful monitoring. Lastly, the city would need to invest resources in hauling the waste outside of the city to farms large enough to consume the generated scraps.

Instead, this chapter considers the environmental analysis of two industrial uses (anaerobic digestion and pelletization), composting, and also landfilling organic waste. When considering the environmental impact of each of these technologies, a number of factors come in to play: the vehicles and fuel consumption involved in collection and transportation, the energy inputs needed for intermediate treatment, the direct emission of greenhouse gases, and the nature of final disposal. Selection of the appropriate processing technology is context-specific to a city's needs and constraints.

I have summarized the environmental impacts to air, soil, and water from a number of organic waste management processes in **Table 33**. In addition to emitting methane and carbon dioxide, landfilling organics can contaminate soil and water with heavy metals and organic compounds, especially if the landfill is unlined. Composting generates some carbon dioxide emissions, and can pollute water if runoff is not properly collected and treated. Both anaerobic digestion and pelletization can generate aerosols, but the burning of pellets (a solid fuel) creates more particulate matter than the burning of methane from biodigestion. However, the anaerobic digestion process generates wastewater, which will pollute the environment if it is not treated before being discharged.

Table 33: Summary of air, soil, and water emissions from processes for managing organic waste. Information in table from Vergara & Tchobanoglous (2012), Beauchemin & Tampier (2010) and Giusti (2009).

	Process for Managing Organic Waste				
Environmental Sink	**Transportation**	**Landfilling/ Dumping**	**Composting**	**Anaerobic Digestion**	**Pelletization**
Air	CO_2, SO_2, NO_x, Odor	CO_2, CH_4, Odor, Noise, VOCs	Odor, CO_2, (minor)	Dust, bioaerosols, and microbial VOCs, odor from loading docks	Odor, particulate matter from processing and burning the pellets, CO, NO_x
Soil	Minor Impact	Heavy metals, organic compounds	Minor impact	Minor impact	Minor Impact
Water	Fallout of atmospheric pollutants such as nitrate	Leachate, heavy metals, organic compounds	Leachate	Wastewater must be treated before released into environment	Minor impact

6.2 Need for Comparative Understanding of Global Warming Impact of Organic Waste Management Practices

It is well known that landfilling organic waste in an open site generates a substantial amount of greenhouse gas emissions (GHGE), as methane and some carbon dioxide is generated as waste decomposes. According to US EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks, landfills account for 18 percent of the total anthropogenic methane emissions in the US (US EPA, 2015). The GHGE of landfilling is increased when (1) more organic waste is landfilled, (2) the operational lifetime of landfill is longer, and (3) methane is not recovered for flaring or energy (US EPA, 2015). If a city currently landfilling organic waste is seeking to reduce GHGE from organics management, it must seek the use of alternative management strategies that have lower GWP.

However, clear comparative analyses of the global warming impacts of non-landfill treatments of organic waste are rare. In Laurent et al.'s (2014) review of the literature on life cycle assessments of waste management strategies, they found that there is no consensus as to which alternative method for treating organic waste has the lowest environmental impact; a review of 29 studies had mixed results as to whether anaerobic digestion, composting or thermal treatment of organic waste had better environmental performance. In a review of 25 life cycle assessments of different food waste treatment alternatives, Bernstad & La Cour Jansen (2012) found that the absolute values and relative ranking of compared treatment alternatives differs greatly in relation to impact on GWP; the studies reviewed assessed landfilling, thermal treatment, small and large scale composting, and anaerobic digestion.

Furthermore, in my review life cycle assessments of organic waste treatment alternatives, I found no analyses of the global warming impact of pelletization of the organic fraction MSW.

My review of the literature does, however, suggest that energy-producing processes and composting tend to generate fewer GHGE per ton of organic waste than landfilling. Specifically, if there is an energy recovery component to organics management, cities may be able to yield negative emissions from management of organics (Yoshida et al., 2011). For instance, Yoshida et al. (2011) conducted a study that modeled the life cycle greenhouse gas reductions achieved by (1) windrow composting, (2) high-solids anaerobic digestion (producing biogas), and (3) co-digestion of organic waste at waste water treatment plants. The study compared these processes to the baseline of composting yard waste and directly landfilling all other organic material; this baseline scenario was estimated to emit 224 kg CO_2-eq./ton of material. In comparison, windrow composting was found to have a (positive) net emission of 81.5 kg CO_2-eq./ton. Therefore, the researchers estimate that composting food waste emits 42 kg CO_2-eq./ton less than landfilling it. The study also found that anaerobic digestion and co-digestion both had negative net emissions (i.e., a reduction) of -46 kg CO_2-eq./ton and -189 kg CO_2-eq./ton, respectively. These results indicate that anaerobic digestion of food waste has great potential for emissions reductions.

Composting also offers a measurable climate benefit as compared to the current practice of landfilling. The EPA's WARM model estimates the emission reduction potential of composting (as compared to landfilling) to be 200 kg CO_2-eq./ton of food scraps (US EPA, 2011). The WARM model does not take into account that there would also be additional carbon savings from using nutrient-dense compost in place of fertilizer, allowing less mineral fertilizer to be manufactured. In addition to improving soil structure and water storage, finished compost also sequesters carbon in the soil; about 0.05 metric tons of carbon per wet ton of finished compost is sequestered after 10 years (US Composting Council, 2008).

Although compost cannot act as a permanent carbon storage material, it does allow for temporary storage. When compost is added to soil, it continues to be converted to humus, thereby converting a fraction of soil carbon to CO_2. It has been found that 82% of all the carbon added with compost remains in the soil after one year (Biala, 2008). Biala's carbon sequestration model for compost shows that mature compost retains 45%, 35% and 10% of carbon over 20-, 50-, and 100-year time steps. Diesel use by vehicles and equipment used to move the material at a compost facility can also be a source of GHGE (US Composting Council, 2008). The US Composting Council (2008) estimates that the diesel use of a compost facility releases 16 kg of CO_2 per wet ton of processed feedstocks. However, if large-scale composting were to become widespread, fuel consumption for waste transportation to the site would likely be less than for hauling the same waste to a landfill. Compost facilities are usually much closer to the point of collection than the closest landfill (US Composting Council, 2008). This is probably due to the fact that compost facility permits/licenses are easier to obtain than those needed for landfill construction, because the zoning requirements are less strict and less land area is required.

Furthermore, as shown by case studies for the states of California, Oregon, and Washington, diverting food scraps from landfills to composting offers the greatest GHGE reduction of any category of material, as a result of the tremendous quantity of food that is discarded and sent to landfills (US EPA, 2011). When food scraps, paper, and other organics are composted in a well-managed, aerobic heap, CO_2 and water, and very little methane or nitrous oxide are produced (US Composting Council, 2008). Since CO_2 has a much lower global warming potential (GWP) than methane (the EPA cites methane as having 21 times the GWP of CO_2), composting organic waste is beneficial from a GHGE perspective. Although some methane from landfills could be captured over time for burning (converting it to CO_2), this option does not solve landfill space problems nor offer any of the nutrient recovery benefits that composting offers.

6.3 Purpose and Approach of Environmental Analysis

The waste management processes analyzed in this chapter with regard to environmental impact are: primary collection, secondary collection, landfilling, composting, anaerobic digestion, and pelletization. The focus of the remainder of the environmental assessment of organic waste processes is on greenhouse gas emissions, or global warming potential (GWP). Global warming impact was selected as the focus because it is one of the most pressing environmental concerns, and because lifecycle assessment data on GWP of waste processes is relatively available. However, in doing a holistic environmental analysis of organic waste management practices, toxicity, eutrophication, and other impacts on the environment should also be analyzed. In each of the subsequent sections of this chapter, I discuss the methods used (such as literature review or use of life cycle inventory data) to estimate the GWP of each process.

6.4 Global Warming Potential of Collection

To estimate the global warming potential of each stage of collection of organic waste, life cycle inventory data from EcoInvent was used in combination with data on the diesel consumption of waste collection obtained from the Pune Municipal Corporation. The GWP of door-to-door collection was assumed to be negligible, given that the process is typically done without motorized transport or energy consumption. Using the IPCC GWP factors from Forster et al. (2007) and the EcoInvent process "Transport, municipal waste collection, lorry 21 t/tk/CH," it was determined that a waste collection truck that consumes 0.4 liters of diesel per ton of waste transported has a GWP of 1.31 kg CO_2-eq/ton. Division of 1.31 by 0.4 yields the estimate that the GWP per liter of diesel used for trucking waste is 3.87 kg CO_2-eq. Next, using diesel consumption records, it was determined that on average, the diesel consumed during the process of primary collection is 1.7 liters/ton of waste managed and the diesel consumed during secondary collection is 2.2 liters/ton. Using this information, the GWP of primary collection was determined to be 6.6 kg CO_2-eq/ton (the product of 1.7 liters/ton and 3.87 kg CO_2-eq/liter), and the GWP of secondary collection was determined to be 8.4 kg CO_2-eq/ton (the product of 2.2 liters/ton and 3.87 kg CO_2-eq/liter). The figures used in and derived from this calculation are summarized in **Table 34**.

Table 34: Information used to calculate the global warming potentials per ton of primary and secondary collection.

	Primary Collection	Secondary Collection	Source of Information
Diesel used in trucking 1 ton of waste using an MSW lorry truck (L/ton of waste)	0.4	0.4	EcoInvent process "Transport, municipal waste collection, lorry 21 t/tk/CH"
GWP for trucking 1 ton of waste using an MSW lorry truck (kg CO_2-eq/ton)	1.31	1.31	EcoInvent process "Transport, municipal waste collection, lorry 21 t/tk/CH"
Diesel consumed by Pune waste trucks (L/ton of waste)	1.7	2.2	Calculated based off of diesel and volume records for Pune vehicle depot office
GWP of 1 liter of diesel used for trucking (kg CO_2-eq/L)	3.87	3.87	Calculation
GWP for transporting 1 ton of waste in Pune (kg CO_2-eq/ton)	6.6	8.4	Calculation

6.5 Global Warming Potential of Landfilling

An extensive review of publications containing life cycle assessments of landfilling organic MSW was conducted in order to aggregate a set of estimates for GWP per ton of waste landfilled. The findings from this review of literature are listed in

Table 35. In addition to listing the global warming potential per ton from twelve studies, the table denotes the functional unit, which typically was either 1 ton of organic waste or 1 ton of MSW (that contains some percentage of organic waste). The life cycle assessments mostly used a system boundary that included transportation, treatment, and disposal, however some studies excluded transportation from the scope. The GWP results are based on data and systems from all over the world – Europe, Asia, South America, and North America. The range of global warming impact estimates was very large, with the lowest estimate being 45 kg CO_2-eq/ton waste and the highest being 1,135 kg CO_2-eq/ton. Most, but not all, of the studies that excluded transportation from the scope had lower GWP values than those that included transportation. The study location was not found to correlate with GWP, based on the twelve studies. The median value of the 12 GWP values obtained from the literature is 510 kg CO_2-eq/ton waste. This median value is used as the best estimate of GWP for landfilling in subsequent analyses and discussion in this thesis.

Table 35: Various estimates of the global warming potential of landfilling 1 ton of organic or municipal solid waste based on literature review.

GWP (kg CO_2-eq/ton waste)	Functional Unit	System Boundaries	Location	Reference
44.9	1 ton MSW with 22% organics	Does not include transportation	Europe	EcoInvent with IPCC GWP factors
102	1 ton MSW	From collection to disposal. Emissions from construction facility not included	Thailand	(Wanichpongpan & Gheewala, 2007)
180	1 ton volatile solids	Does not include transportation	China	(Xu et al., 2015)
188	1 ton MSW	Includes transportation, treatment, and disposal	Indonesia	(Gunamantha & Sarto, 2012)
224	1 ton organic waste (food, contaminated paper, yard waste etc.)	Includes transportation, treatment and final disposal	Madison, WI, USA	(Yoshida et al., 2011)
460.7	1 ton MSW with 67% organics	Does not include collection and transportation. Only includes processing and disposal.	China	(Hong et al., 2006)
559	1 ton MSW	From collection to disposal. Emissions from construction facility not included. Landfill with gas recovery that is only 20% efficient	Thailand	(Wanichpongpan & Gheewala, 2007)
595	1 ton MSW with 40% biodegradable waste	Does not include collection and transportation. Only includes processing and disposal. Based off of open dumps in Mumbai.	India	(B. K. Sharma, 2014)
910	1 ton MSW with 49.5% food waste	Does not include transportation; Assumes 50% of landfill gas is collected and flared	Brazil	(Mendes et al., 2004)
1,175.9	1 ton MSW	Includes transportation, treatment and final disposal	USA	(Smith et al., 2015)
1,900	1 ton food waste	Includes transportation, treatment and final disposal	Sweden	(Finnveden et al., 2005)
1,135	1 ton MSW	Includes transportation, treatment and final disposal	Lithuania	(Staniškis & Miliūtė, 2010)

6.6 Global Warming Potential of Composting

An extensive review of publications containing life cycle assessments of composting organic waste was conducted in order to aggregate a set of estimates for GWP per ton of waste composted. The findings from this review of literature are listed in **Table 36**. In addition to listing the global warming potential per ton from seventeen studies, the table denotes the functional unit, which typically was either 1 ton of mixed organic waste, food waste, yard waste MSW containing some percentage of organic waste. The table also explains the type of composting system analyzed in the life cycle assessment when the information was available. The GWP results are based on data and systems from all over the world – Europe, Asia, South America, North America, and Australia. The range of global warming impact estimates was relatively large, and included both positive GWP values (net emission of greenhouse gases) and negative GWP values (net saving of greenhouse gases). The lowest GWP estimate for composting was -65 kg CO_2-eq/ton waste and the highest was 323 kg CO_2-eq/ton. The system boundaries of the life cycle assessments varied in terms of whether they included transportation and the use of finished compost as a replacement for chemical fertilizers. No consistent trend was found between the GWP values of studies that did versus did not include transportation in the system boundary. However, as expected, all of the studies that presented negative GWPs for composting accounted for greenhouse gas savings from the application of compost as a replacement for fertilizer. The study location was not found to correlate with GWP, based on the seventeen studies. The median value of the seventeen GWP values obtained from the literature is 38 kg CO_2-eq/ton waste. This median value is used as the best estimate of GWP for composting in subsequent analyses and discussion in this thesis.

Table 36: Various estimates of global warming potential of composting 1 ton of organic or municipal solid waste based on literature review.

GWP (kg CO_2-eq/ton waste)	Functional Unit	System Boundaries	Remarks	Location	Reference
-65	1 ton organic waste	Curbside collection through treatment; compost includes use of final product in agriculture	Aerated Static Pile Composting	California, USA	(Kong et al., 2012)
-57	1 ton organic waste	Includes transportation and treatment	Paper shows range of values. GWP ranges from -106 to -5, depending on process yields and energy consumption	Italy/Europe	(Rigamonti et al., 2010)
-48	1 ton wet organic matter	Curbside collection through treatment; compost includes use of final product in	Windrow Composting	California, USA	(Kong et al., 2012)

GWP (kg CO_2-eq/ton waste)	Functional Unit	System Boundaries	Remarks	Location	Reference
		agriculture			
-40	1 ton garden waste	Transportation (from collection) not included; Includes processing, and application of products	Windrow Composting	Australia	(G. Sharma & Campbell, 2007)
-26.8	1 ton organic waste (food and yard waste)	Does not include transport; just processing and recovery of materials; Compost used as substitute for peat and mineral fertilizers.		Italy	(Rigamonti et al., 2009)
-6.2	1 ton organic waste	Does not include transportation; just treatment/disposal and use of compost		Ottawa, Canada	(Mohareb et al., 2008)
13.9	1 ton MSW with 67% organics	Does not include transportation; just treatment, disposal	Biological-mechanical treatment compost	China	(Hong et al., 2006)
20	1 ton MSW with 70% organic fraction	Transportation not included; Emissions from construction of facilities not included; compost assumed to replace chemical fertilizer	Composting with a gas cleaning system that prevents 90% of ammonia and nitrous oxide emissions	Brazil	(Mendes et al., 2003)
38	1 ton MSW	Does not include transportation; just treatment		United Kingdom	(McDougall et al., 2008)
40	1 ton MSW with 70% organic fraction	Transportation not included; Emissions from construction of facilities not included; compost assumed to replace chemical fertilizer	Open-air composting	Brazil	(Mendes et al., 2003)
55	1 ton organic waste	Only includes process emissions from decomposition	In-vessel composting with mixer	Laboratory	(Jakobsen, 1994)
65	1 ton food waste	Includes transportation; for		Italy	(Giugliano et al., 2011)

GWP (kg CO_2-eq/ton waste)	Functional Unit	System Boundaries	Remarks	Location	Reference
		compost, 34% replaces peat and 62% replaces mineral fertilizers			
75.1	1 ton MSW	Transportation not included; Includes processing, and operational activities	Compost mixed in tumbler; finished compost applied to gardens	Australia	(Nair & Lou, 2009)
81.5	1 ton organic waste (food, contaminated paper, yard waste etc.)	Includes transportation, treatment and final disposal		Madison, WI, USA	(Yoshida et al., 2011).
109	1 ton MSW	Processing and disposal; does not include transportation		Europe	SimaPro/ Ecoinvent Traci
285	1 ton food waste	Includes transportation, treatment and final disposal		Sydney, Australia	(Lundie & Peters, 2005)
323	1 ton wet organic waste	Gases emitted directly from decomposition		Unspecified	(McDougall et al., 2008)

6.7 Global Warming Potential of Anaerobic Digestion

An extensive review of publications containing life cycle assessments of biodigestion of organic waste was conducted in order to aggregate a set of estimates for GWP per ton of waste composted. The findings from this review of literature are listed in **Table 37**. In addition to listing the global warming potential per ton from sixteen studies, the table denotes the functional unit, which typically was either 1 ton of mixed organic waste, food waste, or MSW containing some percentage of organic waste. The GWP results are based on data and systems from all over the world – Europe, Asia, South America, and North America. The range of global warming impact estimates was relatively large, and consisted of mostly negative GWP values (net saving of greenhouse gases) and some positive GWP values (net emission of greenhouse gases). The lowest GWP estimate for anaerobic digestion was -276 kg CO_2-eq/ton waste and the highest was 225 kg CO_2-eq/ton. The system boundaries of the life cycle assessments varied in terms of whether they included transportation. No consistent trend was found between the GWP values of studies that did versus did not include transportation in the system boundary. As expected, all of the studies that presented negative GWPs for anaerobic digestion accounted for greenhouse gas savings from the use of end-products such as electricity, fuel, and/or liquid fertilizer. The studies with the highest GWP estimates did not account for the use of end-products in their life cycle analysis. Study location was not found to correlate with GWP, based on the sixteen studies. The median value of the sixteen GWP values obtained from the literature is -51 kg CO_2-eq/ton waste. This median value is used as the best estimate of GWP for anaerobic digestion of organic waste in subsequent analyses and discussion in this thesis.

Table 37: Various estimates of global warming potential of processing 1 ton of organic or municipal solid waste using anaerobic digestion based on literature review.

GWP (kg CO_2-eq/ton waste)	**Functional Unit**	**System Boundaries**	**Location**	**Reference**
-276	1 ton MSW	Does not include transportation; only treatment and disposal, and use of end-products	Thailand	(Chaya & Gheewala, 2007)
-185	1 ton organic waste	Includes collection, transport, treatment, and use of end-products	California, USA	(Vergara et al., 2011)
-151	1 ton organic waste	Includes transportation and treatment. Paper shows range of values. GWP ranges from -240 to -62, depending on production quantity of biogas and way of utilization of biogas	Italy/Europe	(Rigamonti et al., 2010)
-116	1 ton MSW	Includes collection, transport, treatment, and use of end-products	USA	(Smith et al., 2015)
-95.3	1 ton MSW with 27% organics	Includes transportation; accounts for fertilizer and electricity offsets	Denmark	(Munster et al., 2015)
-73	1 ton organic waste	Includes collection, transport, treatment, and use of end-products	California, USA	(Kong et al., 2012)
-69	1 ton MSW	Includes transport, treatment, disposal and use of end-products	Spain	(Fernández-Nava et al., 2014)
-51.67	1 ton food waste	Includes transportation, treatment, and electricity contribution	Germany	(Poeschl et al., 2012)
-50	1 ton organic waste	Includes transport, treatment, disposal and use of end-products	Italy	(Giugliano et al., 2011)
-46	1 ton organic waste	Includes transport, treatment, disposal and use of end-products	Madison, Wisconsin, USA	(Yoshida et al., 2011)
-12	1 ton organic waste	Includes transportation; anaerobic digestion offsets from electricity counted	Sweden	(Carlsson et al., 2015)
-6.0	1 ton organic waste	Does not include transportation; just treatment/disposal and use of end-products	Ottawa, Canada	(Mohareb et al., 2008)

GWP (kg CO_2-eq/ton waste)	Functional Unit	System Boundaries	Location	Reference
96.97	1 ton organic waste	Does not include collection and transportation or utilization of resource products. Accounts for electricity and product as energy output	China	(Jin et al. , 2015)
169	1 ton volatile solids	Does not include transport	China	(Xu et al., 2015)
180.9	1 ton organic waste	Includes collection, treatment and disposal	Italy	(Di Maria & Micale, 2015)
225	1 ton MSW	Includes transportation, land-use, construction, treatment, and disposal	United Kingdom	(Patterson et al., 2011)

6.8 Global Warming Potential of Pelletization

After conducting a review of the literature, no life cycle assessments of pelletization of the organic fraction of MSW could be found. Therefore, I could not use estimates from the literature to estimate the GWP of pelletization. Instead, I used a combination of data available from GaBi and EcoInvent databases to estimate the global warming impact of pelletization.

Neither of these databases contained greenhouse gas emission data about pellets made from organic MSW. However, by using GaBi's country-specific greenhouse gas inventories for electricity mixes, I was able to estimate that the pelletization process in India has a GWP of 105 kg CO_2-eq per ton of waste (PE International, 2013). This figure is determined by multiplying 1.5 kg CO_2-eq./KWH – the GaBi (2013) estimate of GWP for electricity in India – by 70 KWH/ton of waste, which is the estimate Gangotree (2014) provided for the electricity consumed in the pelletization process.

In order to account for the greenhouse gas impact of pelletization that is consistent with the methods used by other studies that assessed waste-to-energy technologies like anaerobic digestion, I also included the GWP of burning pellets for energy (heat). To do this, I used the IPCC GWP factors with the EcoInvent process of burning of wood waste as a proxy for the burning of organic MSW pellets. I calculated that the EcoInvent process "wood waste, unspecified, combusted in industrial boiler/US" had a GWP of 2.66 kg CO_2-eq./ton of wood waste.

Lastly, if pellets are burned, we can assume that this material replaces gas for cooking or heating, which creates a greenhouse gas credit (for avoided use of fossil-fuels). The average of all the Ecoinvent processes for heat from natural gas has a GWP of 0.075 kg CO_2-eq. per MJ. The calorific density of fuel pellets made from mixed MSW is estimated to be 4000 kcal/kg, which is 16.7 MJ/kg (Zafar, 2015). The pelletization process generates 200 kg of pellets per ton of organic waste processed; consequently, when organic waste is pelletized and burned to replace heat from natural gas (replacing each MJ from gas with a MJ from pellets), pellet-based energy would have an energy credit of 3,347 MJ/ton of waste if thermal efficiency were 100%.

However, we assume that the thermal efficiency of the furnace/stove used to burn the pellets in India is 60% efficient; this figure comes from on laboratory-measured thermal efficiencies of higher-performing biomass cooking stoves (MacCarty et al., 2008). Consequently, we estimate the energy credit of pelletization to be 2,008 MJ/ton of waste (60% of 3,347). The avoided emissions (credit) of this energy is the product of 2,008 MJ/ton and 0.075 kg CO_2-eq./MJ, which is 150 kg CO_2-eq./ton of waste.

By adding 105 with 2.66, and subtracting the credit of 150 kg CO_2-eq./ton, I obtained the estimate that the GWP of pelletization of organic waste is roughly -42 kg CO_2-eq./ton. I use this value of -42 kg CO_2-eq./ton GWP for the analyses that follow in this chapter.

6.9 GWP Comparison and Summary of Findings

Using the results from the reviews of literature as well as analysis with life cycle assessment tools, I have plotted the range of GWP values for landfilling, composting, anaerobic digestion, and pelletization in **Figure 67**. The plot uses a box-and-whisker plot to show the interquartile range of the data set in the box; the ends of the whiskers illustrate the 2.5th and 97.5th percentiles. Because only one estimate of the environmental impact of pelletization was available, the GWP of pelletization is shown as a point, rather than a box-and-whisker plot. The spread (variation) in GWP estimates is largest for landfilling. However, based on both the median values and interquartile ranges, the comparison across technologies indicates that composting, anaerobic digestion, and pelletization all have GWPs lower than that of landfilling. The median GWP of landfilling was found to be 510 kg CO_2-eq/ton. The median GWP of composting was found to be 38 kg CO_2-eq/ton. The median GWP of anaerobic digestion was found to be -51 kg CO_2-eq/ton. Lastly, I estimate that pelletization has a GWP of -42 kg CO_2-eq/ton. This analysis shows that organic waste technologies in order of lowest to highest GWPs are anaerobic digestion, pelletization, composting, and then landfilling; anaerobic digestion and pelletization are the only two technologies with a negative GWP, meaning that such treatment methods result in a net savings of greenhouse gas emissions.

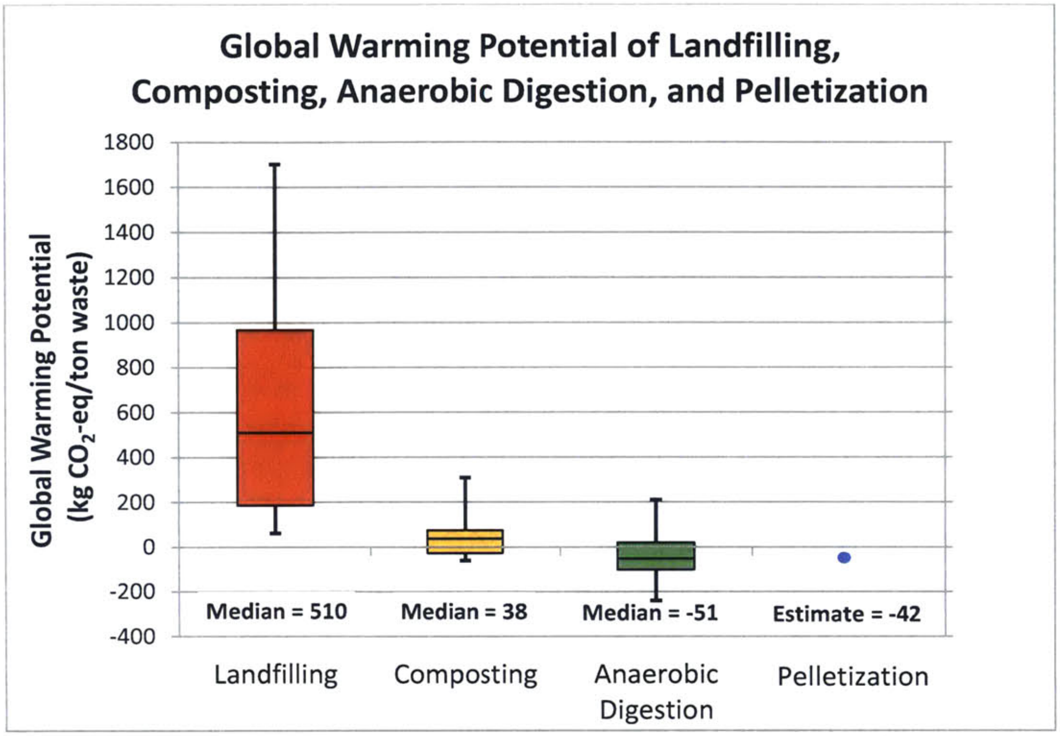


Figure 67: The range of values for the global warming potential for landfilling, composting and anaerobic digestion found from a review of the literature. The box and whisker plots show the 2.5 to the 97.5 percentiles. Our single-value estimate of the global warming potential for pelletization is also shown.

The median GWP values for landfilling composting and anaerobic digestion are based on a number of different life cycle assessments, some of which include emissions from collection of waste, and some of which do not. Given that most of the publications reviewed did not indicate the greenhouse gas contribution specifically from transportation, it was not possible to isolate the GWP of each of those technologies excluding transportation. Instead, the median value from the literature was assumed to be the base GWP, before transportation is included. In order to include the greenhouse gas emissions from waste collection in Pune in the total GWP or organics waste management, I have added the GWP of primary and secondary collection (listed in section 6.3) to the median GWP of each processing technology. The resulting GWPs for each of the treatment options with the added emissions of primary and secondary collection are reported in **Table 38**.

Table 38: The global warming potential of processing anaerobic digestion, composting, pelletization, and landfilling that includes the emissions from primary and secondary collection.

	Median GWP per Ton without Transportation	**Median GWP per Ton Plus Primary Collection**	**Median GWP per Ton Plus Primary and Secondary Collection**
Method Used for Estimation	*Median of literature values and life cycle inventories*	*Column 1 + GWP of primary collection modeled in Simapro*	*Column 2 + GWP of secondary collection modeled in Simapro*
TREATMENT TECHNOLOGY			
Anaerobic Digestion	-51	-44.5	-36
Pelletization	-42	-35.5	-27
Composting	38	44.5	53
Landfilling	510	517	525

Based on the values in **Table 38**, the global warming potential per ton of waste managed at plants of different sizes was then determined, based on whether the system required (a) only door-to-door collection, (b) door-to-door and primary collection, or (c) door-to-door, primary, and secondary collection. The GWP per ton of waste, accounting for emissions from transportation for each technology and scale of treatment are listed in ***Table 39***. These GWP values are used in the estimations of greenhouse gas emissions in the scenario analyses in Chapter 7. As the table shows, for each treatment technology, the smaller scales of treatment have lower GWPs than the larger scales, as a result of lower transportation needs. Given that Pune's landfill was already constructed at the periphery of the city, landfilling any amount of waste requires primary and secondary collection, and therefore the GWP per ton of waste landfilled does not vary with scale of treatment.

Table 39: The global warming potential (kg CO_2-eq) per ton of waste processed using each technology at various scales of treatment. These values include emissions from transportation.

Treatment Technology	Scale of Treatment (tons/day)								
	0.1 TPD	0.2 TPD	0.5 TPD	1 TPD	2 TPD	5 TPD	10 TPD	100 TPD	200 TPD
Anaerobic Digestion	-51	-51	-51	-44	-44	-44	-44	-36	-36
Pelletization	-42	-42	-42	-35	-35	-35	-35	-27	-27
Composting	38	38	38	45	45	45	45	53	53
Landfilling	--------------------------------525----------------------------------								

6.10 Summary of GWP Analysis

The following are the key findings from this chapter:

FINDING 1: The life cycle assessment literature on organic waste management treatment alternatives contains a very large range of impact estimates for technologies for landfilling, composting, and anaerobic digestion. This high variation does not appear to be a consequence of different system geographies, but rather depends on the individual studies' assumptions, scope, and system boundaries.

FINDING 2: Using published GWP figures from reviewed literature, we have aggregated an ordered range of estimates to identify median GWP values for landfilling, composting, anaerobic digestion. The median GWP of landfilling was found to be 510 kg CO_2-eq/ton. The median GWP of composting was found to be 38 kg CO_2-eq/ton. The median GWP of anaerobic digestion was found to be -51 kg CO_2-eq/ton.

FINDING 3: After conducting a review of the literature, no life cycle assessments of pelletization of the organic fraction of MSW could be found. Using combination of data available from GaBi and EcoInvent databases, we estimate the GWP of pelletization to be roughly -42 kg CO_2-eq/ton.

FINDING 4: Using life cycle inventory data from EcoInvent in combination with data on the diesel consumption of waste collection in Pune, the GWP of primary collection was determined to be 6.6 kg CO_2-eq/ton and the GWP of secondary collection was determined to be 8.4 kg CO_2-eq/ton. The GWP of door-to-door collection is negligible, given that the process is typically done without motorized transport or energy consumption.

Chapter 7: Scenario Analysis and Conclusions

7.1 Purpose and Approach:

Before a city invests in updating or developing new organic waste management systems, it will likely want to know a number of system characteristics and impacts, including the scale and technology used for treatment, cost, greenhouse gas impacts, and space requirements. Scenario analysis can be used to evaluate these system features for a number of potential alternatives; based on a city's constraints and priorities, it can then identify system designs that are preferable. This chapter uses the estimates derived for net cost and global warming potential for different organic waste technologies at different scales of treatment to analyse the impacts of various waste management scenarios for Aundh ward in Pune, India. The social and labor impacts of a waste system (such as those addressed in Chapter 4) are also important to consider when making design and implementation decisions; but they more difficult to quantify and therefore are not directly incorporated into our scenario analysis. The level of centralization is used as one (albeit imperfect) proxy for social acceptability and potential inclusiveness of the informal sector; we anticipate that less centralized systems (i.e., more decentralized) are socially preferable for the informal sector.

In total, 24 waste management scenarios are analyzed for the system's total cost, greenhouse gas emissions, space requirements, and level of centralization. Per the estimate determined in Chapter 3, Section 8 of this thesis, Aundh generates 47.5 tons/day of organic waste. Each scenario corresponds to a hypothetical system in which the 47.5 tons of organic MSW generated daily in Aundh ward are managed using one or a combination of the following technologies: landfilling, composting, anaerobic digestion, or pelletization. The scenarios also include a variety of scales of treatment, ranging between 0.1 and 100 TPD plants, for composting, anaerobic digestion and pelletization. The scenarios each involve the use of one or two treatment technologies, and one or two different plant sizes. The analysis contains scenarios representing the maximized use of a single technology, such that all of the organic waste is landfilled vs. all of the waste is composted vs. all of the waste is pelletized vs. all of the food waste is biodigested (the yard waste is assumed to be too woody for digestion). The scenarios analysed represent a number of different possibilities for system architectures, but do not exhaust all of the possible combinations of treatment scales and technologies. It should be noted that any reader can assess additional scenarios with different combinations of scales and technologies using the per-ton cost, GWP, and spatial footprint estimates presented in this document.

In order to determine the space requirements for each scenario, the spatial footprint of each plant size for each technology first needed to be estimated. The spatial footprint per each plant scale was estimated based on the spatial footprint of existing plants in Pune and expert opinion. The spatial footprints for a number of different-sized plants using anaerobic digestion, composting, and pelletization can be found in **Table 40**. At any given treatment scale, pelletization tends to have the smallest spatial footprint, followed by anaerobic digestion. The spatial footprints of composting and landfilling are both significantly higher. The spatial footprint of Uruli Devachi is 22 hectares (220,000 square meters), and based on the estimate that 400 TPD of waste are landfilled daily there, it was estimated that the per-unit spatial footprint of landfilling is 550 m^2 per ton.

Table 40: The spatial footprint (land area in m^2) per facility for various treatment technologies and plant scales. The footprint of landfilling is given in terms of total footprint and the estimate of space per ton, based on the estimate that 400 tons per day are sent to the landfill.

Treatment Technology	Scale of Plant (tons/day)								Data Source
	0.1	0.2	0.5	1	2	5	10	100	
Anaerobic Digestion	9	20	50	100	160	500	1,000	10,117	Mailhem, 2014
Pelletization	17	17	47	84	140	279	372	N/A	Gangotree, 2014
Composting	100	200	500	1,000	2,000	5,000	10,000	100,000	INORA, 2014
Landfill	--------------------220,000 m^2, or 550 m^2 per ton ------------------------								Calculation based on Uruli Devachi size and tonnage processed daily

In order to determine the level of centralization in system architecture for each scenario, a ranking system was employed in which each scenario was assigned a centralization rank of 1-4, using the rubric outlined in **Table 41.** Systems with a rank of 1 are considered to be highly decentralized, and systems with a rank of 4 are considered to be centralized. In thinking about the meaning of centralization and decentralization, it can help to imagine the following scenarios: If all of Aundh's organic waste were processed using 0.2 TPD plants, it would need 238 facilities. If the ward only used 0.5 TPD plants, it would need 95 different organic waste processing facilities. In contrast, if Aundh designed a 100 TPD organic waste processing facility, it would be operating under capacity unless the facility also received organic waste from another ward (which is a possible system design choice).

Table 41: Ranking system used for comparing the level of centralization in system architecture for a waste system. This ranking system based on the scales of facilities employed, and is independent of the technology used for waste treatment.

Centralization Rank	Categorical Description	Definitional Criteria for Waste System
1	Highly Decentralized	The majority of waste is sent to plants processing less than 1 TPD each
2	Somewhat Decentralized	The majority of waste is sent to plants processing at least 1 TPD, but less than 5 TPD
3	Somewhat Centralized	The majority of waste is sent to plants processing at least 5 TPD, but less than 50 TPD
4	Centralized	Centralized; the majority of waste is sent to plants processing 50 or more TPD

7.2 Results of Scenario Analysis

The 24 scenarios for managing the organic waste generated in Aundh are presented in **Table 42.** Each row represents a different scenario, which involves the use of the treatment technologies listed in the "Technologies Used" column. Each scenario is assigned a scenario number, which is later referenced in subsequent tables and figures. The last column of the table describes the type of waste being sent teach type of treatment and the scale of plants utilized. The second column presents the estimated total daily cost of managing waste under that scenario. The third column presents the estimated greenhouse gas emissions (or savings) associated with managing waste under that scenario. Lastly, the total amount of land area that would be needed for organic waste management is listed in the fourth column. The scenarios analyzed have spatial requirements ranging from 1,776 m^2 to 52,246 m^2, which demonstrates the large variation of spatial footprints involved with different organic waste management systems. The scenarios have net costs ranging from 99,662 to 343,804 Rs/day; there is a three-fold difference between the lowest and highest cost systems designs. The carbon footprints of the scenarios range a net savings of 2,074 kg CO_2-eq/day to a net emission of 24,951 kg CO_2-eq/day.

Table 42: The total daily cost, daily greenhouse gas emissions, and space requirements, and level of centralization associated with 24 organic waste management scenarios. The last column describes each scenario, which is coded with a scenario number (e.g., S1) in the first column. For the level of centralization, a scale of 1-4 is used, in which 1 indicates most decentralized and 4 indicates centralized.

S#	Net Cost (Rs./Day)	Green-house Gas Emissions (Kg CO_2-eq/day)	Spatial Footprint (m^2)	Level of Central-ization	Technologies Used	Scenario Description
S1	139,215	24,951	26,142	4	Landfill	All organics landfilled
S2	272,157	1,806	47,530	1	Compost	All organics composted, 0.2 TPD plants
S3	212,079	1,806	47,530	2	Compost	All organics composted, 2 TPD plants
S4	105,636	-1,385	14,200	4	Anaerobic Digestion, Compost	Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste composted at 2 TPD plants
S5	127,012	-1,749	8,428	3	Anaerobic Digestion, Compost	Food waste A.D. in 5 TPD plants; yard waste composted at 2 TPD plants
S6	122,928	-1,749	8,428	2	Anaerobic Digestion, Compost	Food waste A.D. in 2 TPD plants; yard waste rest is composted at 2 TPD plants
S7	133,138	-2,034	8,428	1	Anaerobic Digestion, Compost	Food waste A.D. in 0.5 TPD plants; yard waste composted at 2 TPD plants
S8	138,299	-2,061	8,428	1	Anaerobic Digestion, Compost	Food waste A.D. in 0.5 TPD plants; yard waste composted at 0.2 TPD plants
S9	338,642	-2,061	7,989	1	Anaerobic Digestion, Compost	Food waste A.D. at 0.1 TPD plants; yard waste composted at 2 TPD plants
S10	343,804	-2,061	7,994	1	Anaerobic Digestion, Compost	Food waste A.D. at 0.1 TPD plants; yard waste composted at 0.2 TPD plants
S11	99,662	-1,710	10,401	4	Anaerobic Digestion, Pelletization	Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste is pelletized at 2 TPD plants

S#	Net Cost (Rs./Day)	Green-house Gas Emissions (Kg CO_2-eq/day)	Spatial Footprint (m^2)	Level of Central-ization	Technologies Used	Scenario Description
S12	117,296	-2,018	3,712	3	Anaerobic Digestion, Pelletization	All yard waste and some food waste pelletized at 10 TPD plant; remainder of food waste A.D. at 5 TPD plants
S13	190,781	1,322	33,772	2	Pelletization, Compost	All yard waste and some food waste pelletized at 10 TPD plant; remainder of food waste composted at 2 TPD plants
S14	110,840	-1,664	1,766	3	Pelletization	All organics pelletized, 10 TPD plants
S15	120,251	-1,664	2,649	3	Pelletization	All organics pelletized, 5 TPD plants
S16	142,542	-1,664	3,310	2	Pelletization	All organics pelletized, 2 TPD plants
S17	163,598	-1,664	3,974	2	Pelletization	All organics pelletized, 1 TPD plants
S18	208,894	-1,996	4,411	1	Pelletization	All organics pelletized, 0.5 TPD plants
S19	145,477	22,989	27,979	4	Landfill, Compost	Food waste landfilled; yard waste composted at 2 TPD plants
S20	150,638	22,962	27,979	4	Landfill, Compost	Food waste landfilled; yard waste composted yard waste at 2 TPD plants
S21	119,122	-2,074	4,572	3	Pelletization, Anaerobic Digestion	Food waste A.D. at 5 TPD plants; yard waste pelletized at one 5 TPD plant
S22	120,752	212	6,591	3	Anaerobic Digestion, Landfill	Food waste A.D. at 5 TPD plants; yard waste landfilled
S23	137,587	22,664	24,123	4	Pelletization, Landfill	Food waste landfilled; yard waste pelletized at 5T PD plant
S24	140,118	2,516	22,000	4	Composting	All of Aundh's waste is composted at 100 TPD plant shared by two adjacent wards

7.2.1 Least-space Alternatives

As shown in **Table 43**, the scenarios requiring the least amount of land area use pelletization to process all organic waste. The least space-consuming system pelletizes all organic waste using 10 TPD plants. A scenario in which a combination of one 10 TPD pelletization plant and a number of 5 TPD anaerobic digesters are used also requires a relatively small amount of space. A dense, overpopulated city or a city with very expensive property values might consider using pelletization as a space-saving method of organic waste management that avoids the need to transport waste to a far-away landfill.

Table 43: Waste management scenarios requiring the least area of space.

Five Scenarios Requiring Least Space	Total Space Needed (m^2)	Level of Centralization	Scenario Description
S14	1,766	3	All organics pelletized, 10 TPD plants
S15	2,649	3	All organics pelletized, 5 TPD plants
S16	3,310	2	All organics pelletized, 2 TPD plants
S12	3,712	3	All yard waste and some food waste pelletized at 10 TPD plant; remainder of food waste A.D. at 5 TPD plants
S17	3,974	2	All organics pelletized, 1 TPD plants

7.2.2 Least-cost Alternatives

As shown in **Table 44**, the lowest cost scenarios utilize large and medium scale anaerobic digesters to process most of the organic waste. In the top five least-cost scenarios, the majority of organic waste is anaerobically digested. In these scenarios, yard waste is pelletized, composted, or landfilled. The least-expensive of these involve digesting food waste in a 100 TPD plant that would be shared by two adjacent wards, and pelletizing the yard waste at 2 TPD plants. Indian cities looking to minimize expenditures on organic waste management should consider using anaerobic digesters at the treatment scales 2 TPD or greater.

Table 44: Waste management scenarios that would cost the least.

Five Scenarios with Lowest Cost	Cost (Rs./Day)	Level of Centralization	Scenario Description
S11	99,662	4	Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste is pelletized at 2 TPD plants
S4	105,636	4	Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste composted at 2 TPD plants
S22	110,840	3	All organics pelletized, 10 TPD plants
S6	117,296	3	All yard waste and some food waste pelletized at 10 TPD plant; remainder of food waste A.D. at 5 TPD plants
S21	119,122	3	Yard waste pelletized at one 5 TPD plant; food waste A.D. at 5 TPD plants

7.2.3 Largest GHGE Savings Alternatives

As shown by **Table 45**, the scenarios with the largest GHGE savings (i.e., the smallest carbon footprint) all use anaerobic digestion to process all food waste. Four of the five scenarios with the largest GHGE savings anaerobically digest food waste in small scale plants (0.1-0.5 TPD plants), and use small- and medium-sized composting systems. The scenario with the largest GHGE savings scenario is somewhat centralized, using 5 TPD anaerobic digesters to process food waste and pelletization to process yard waste. The combined use of anaerobic digestion and pelletization appears to offer the lowest GWP, given that both technologies have negative GWPs and that pelletization can be used to process woody material that cannot be biodigested. Generally speaking, the scenario analysis shows that systems that are relatively decentralized, utilizing plants with capacities no larger than 5 TPD, have the largest GHGE savings. A city looking to minimize its contribution to global warming could achieve significant reductions in emissions through the use of anaerobic digesters to process food waste at 0.5 and 5 TPD plants, combined with the use of pelletization to process yard waste. Such systems could save 750 tons CO_2-eq each year.

Table 45: Waste management scenarios that provide the most greenhouse gas savings.

Five Scenarios with Lowest GHGE	Greenhouse Gas Savings (Kg CO2-eq/day)	Level of Centralization	Scenario Description
S21	-2,074	3	Food waste A.D. at 5 TPD plants; Yard waste pelletized at one 5 TPD plant
S8	-2,061	1	Food waste A.D. in 0.5 TPD plants; yard waste composted at 0.2 TPD plants
S9	-2,061	1	Food waste A.D. at 0.1 TPD plants; yard waste composted at 2 TPD plants
S10	-2,061	1	Food waste A.D. at 0.1 TPD plants; yard waste composted at 0.2 TPD plants
S7	-2,034	1	Food waste A.D. in 0.5 TPD plants; yard waste composted at 2 TPD plants

7.2.4 Decentralized vs. Centralized Alternatives

In **Figure 68**, the cost of each of the 24 scenarios, as well as the greenhouse gas emissions of each of the 24 scenarios, are plotted based on the level of centralization in the system architecture. As systems become more centralized, the net cost of organic waste management scenarios decreases, but the variation in cost between different treatment technologies also decreases (as shown by the smaller vertical scatter of the red points). This means that although somewhat centralized systems (using plants processing 100 TPD) do cost less, the lowest-cost highly decentralized systems are relatively close in value to the cost of the centralized systems. The upward trend the blue points plotted in the figure also demonstrates the finding that greater centralization of waste systems increase greenhouse gas emissions, because such systems involve increased transportation. These findings reveal that more decentralized organic waste systems tend to have a lower carbon footprint.

Although the average cost of centralized systems are less expensive, decentralized systems are not strictly more expensive than centralized systems, due to the variation of technology choice; consequently, some highly decentralized systems are just as low cost as centralized systems. As **Table 46** shows, the difference in cost between the lowest-cost decentralized systems and lowest-cost centralized systems is relatively small. The lowest-cost decentralized system has a cost that is 18% higher than the lowest-cost centralized system. It should also be noted that the all of the (low-cost) scenarios listed in **Table 46** create a net savings in greenhouse gas emissions.

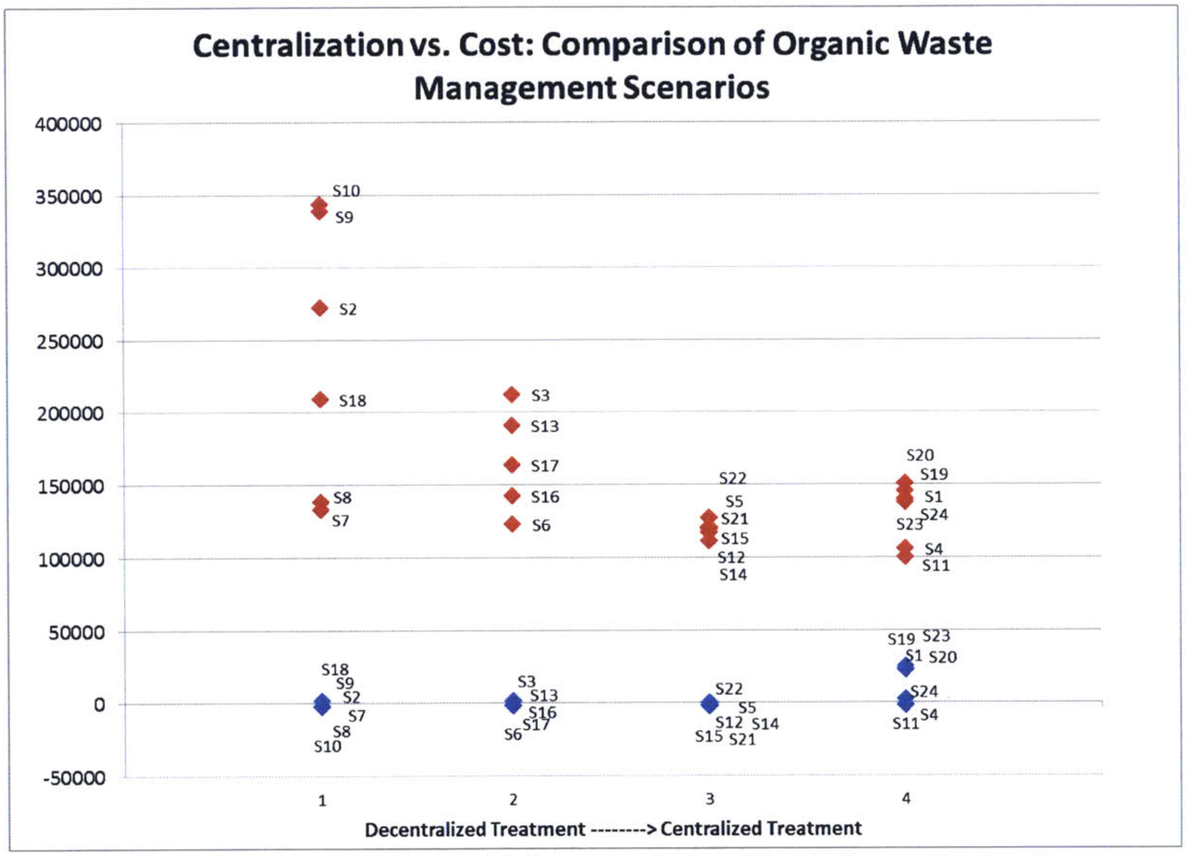


Figure 68: Graph showing the relationship between systems' level of centralization (further to the right on the x-axis indicates use of facilities with higher capacities) with net cost and with greenhouse gas emissions. Each point represents one of the scenarios in **Table 42**, and specifi scenarios in this figure are referenced in **Table 46**.

Table 46: The least-cost options of the decentralized organic waste management scenarios compared with the least-cost options of the centralized organic waste management scenarios.

	S#	Cost (Rs./Day)	GHGE (Kg CO_2-eq/day)	Space Needed (m^2)	Level of Central-ization	Scenario Description
Least Cost of Decentralized Scenarios	S6	122,928	-1,749	8,428	2	Food waste A.D. in 2 TPD plants; yard waste rest is composted at 2 TPD plants
	S7	133,138	-2,034	8,428	1	Food waste A.D. in 0.5 TPD plants; yard waste composted at 2 TPD plants
	S8	138,299	-2,061	8,428	1	Food waste A.D. in 0.5 TPD plants; yard waste composted at 0.2 TPD plants
	S16	142,542	-1,664	3,310	2	All organics pelletized, 2 TPD plants
	S17	163,598	-1,664	3,974	2	All organics pelletized, 1 TPD plants
Least Cost of Centralized Scenarios	S11	99,662	-1,710	10,401	4	Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste is pelletized at 2 TPD plants
	S4	105,636	-1,385	14,200	4	Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste composted at 2 TPD plants
	S14	110,840	-1,664	1,766	3	All organics pelletized, 10 TPD plants
	S12	117,296	-2,018	3,712	3	All yard waste and some food waste pelletized at 10 TPD plant; remainder of food waste A.D. at 5 TPD plants
	S21	119,122	-2,074	4,572	3	Food waste A.D. at 5 TPD plants; yard waste pelletized at one 5 TPD plant

7.2.5 Comparison of Costs and GHGE

Identifying waste management systems that would be both low in cost and have a small carbon footprint allows decision makers to invest in organics treatment systems that are more sustainable from both an environmental and financial standpoint. In ***Figure 69***, each of the 24 scenarios is plotted on a graph with the x-axis being net cost and the y-axis being greenhouse gas emissions. Each scenario is color coded indicate the technologies utilized in the particular system. Scenarios in the bottom left corner represent waste management scenarios with both small carbon footprints (sometimes negative) and relatively low cost. Scenarios in the upper left corner represent relatively low cost systems with high greenhouse gas emissions. Scenarios in the lower right corner represent high cost systems with low greenhouse gas emissions. As the graph shows, systems that use pelletization or a combination of anaerobic digestion and composting, anaerobic digestion and pelletization, and anaerobic digestion and landfilling are the ones with both low cost and carbon footprints. **Table 47** lists the five scenarios with lowest combined cost and global warming impact. These five scenarios include somewhat centralized as well as centralized systems. Four out of five of these scenarios involve anaerobically digesting food waste in 5 TPD or 100 TPD plants, and using composting or pelletization to process yard waste. One of the five scenarios involves pelletizing all organic waste at 10 TPD plants. These findings suggest that anaerobic digestion in combination with pelletization produces the best combination of cost and GWP performance.

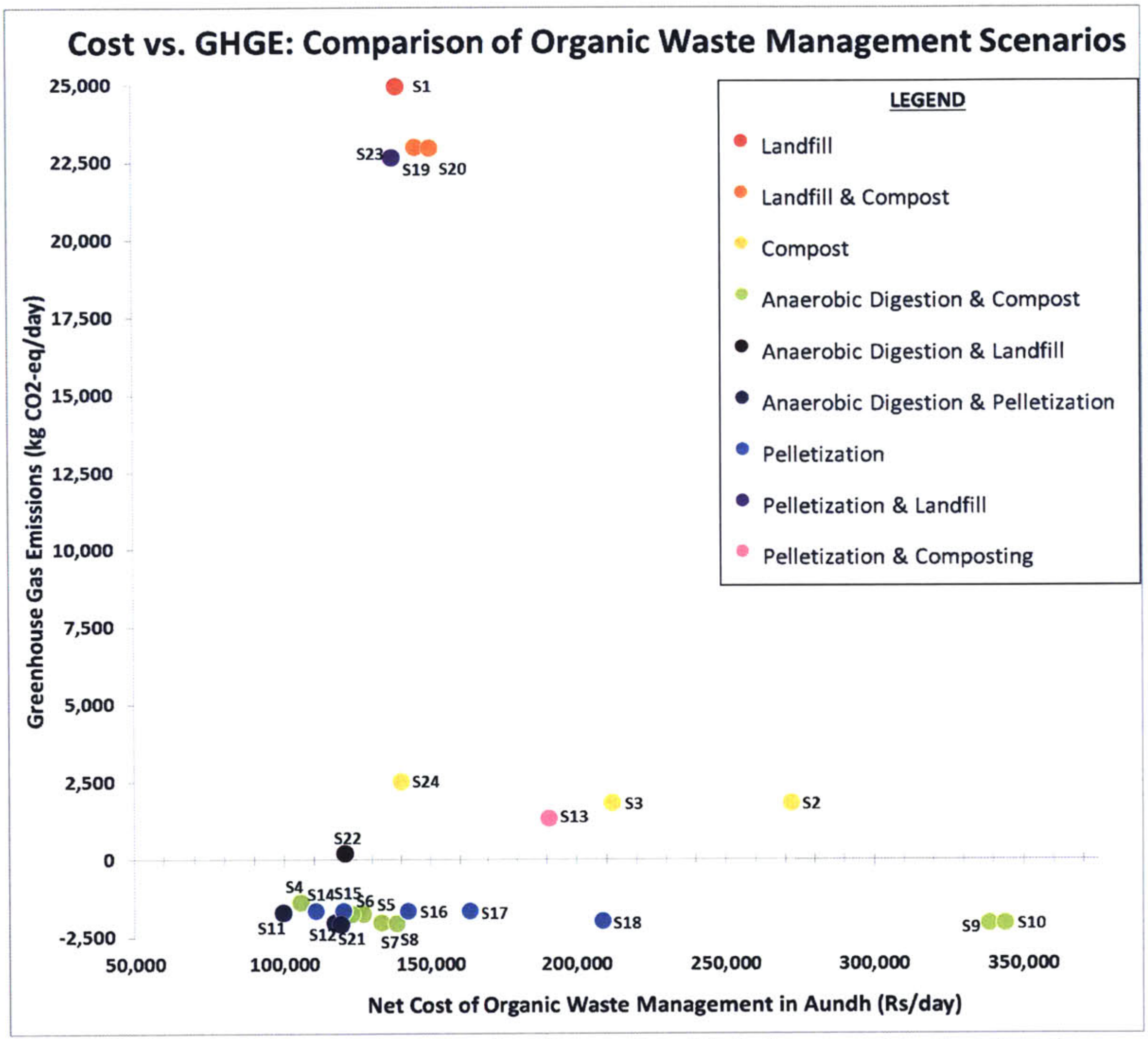


Figure 69: Scatter plot comparison showing the relationship between systems' cost and greenhouse gas emissions. Each point represents one of 24 scenarios, detailed above in **Table 42**. The color coding of the points indicates the treatment technologies employed in each scenario.

Table 47: The five organic waste management scenarios with the best combined environmental and cost performance.

	S#	Cost (Rs./Day)	GHGE (Kg CO_2-eq/day)	Space Needed (m^2)	Level of Centralization	Scenario Description
Lowest Cost and GHGE	S11	99,662	-1,710	10,401	4	Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste is pelletized at 2 TPD plants
	S4	105,636	-1,385	14,200	4	Food waste from Aundh A.D. in 100 TPD plant shared by two adjacent wards; yard waste composted at 2 TPD plants
	S14	110,840	-1,664	1,766	3	All organics pelletized, 10 TPD plants
	S12	117,296	-2,018	3,712	3	All yard waste and some food waste pelletized at 10 TPD plant; remainder of food waste A.D. at 5 TPD plants
	S21	119,122	-2,074	4,572	3	Food waste A.D. at 5 TPD plants; yard waste pelletized at one 5 TPD plant

In **Table 48**, I have estimated the greenhouse gas savings per unit of expenditure on anaerobic digestion and on pelletization (the two technologies found to have negative GWP) for each scale of treatment. The results show that for scales of 0.2 TPD or greater, anaerobic digestion has greater carbon savings per unit of expenditure than pelletization; but, at the 0.1 TPD scale, pelletization has a slightly higher carbon savings. The results indicate that anaerobic digesters designed to process at least 0.5 TPD would best allow a city to economically reduce greenhouse gas emissions, because such systems offer a larger reduction in GHGE per unit of expenditure.

Table 48: The greenhouse gas savings per unit of expenditure on anaerobic digestion of organic waste and pelletization of organic waste in India.

Technologies with GHGE Savings	**0.1**	**0.2**	**0.5**	**1**	**2**	**5**	**10**	**100**
Kg CO_2-eq saved per 1000 Rupees spent on Anaerobic Digestion	6.9	11.7	19.3	13.2	18.4	17.8	18.9	17.9
Kg CO_2-eq saved per 1000 Rupees spent on Pelletization	7.3	8.4	9.6	10.2	11.7	13.8	15.0	11.6

The above results indicate that Indian cities currently landfilling organic waste should consider processing such waste with anaerobic digestion and pelletization, because both have the potential to simultaneously reduce greenhouse gas emissions and the cost of treatment.

7.2.6 Comparison of Space and Costs

In order to understand what scenarios represent the best choice for cities forced to strictly consider space and cost, we have compared net cost and spatial footprint for the scenarios considered. In **Figure 70,** each of the 24 scenarios is plotted on a graph where the x-axis shows net cost and the y-axis shows total space needed for the system. The scenarios plotted in the bottom left corner represent systems which have relatively small spatial footprints and are relatively low in cost. **Table 49** lists the five organic waste management scenarios with the best combination for minimizing cost and spatial footprints. Most of these scenarios highly utilize pelletization and/or anaerobic digestion; pelletization is a compact process that helps drive down the total spatial footprint, and anaerobic digestion offers economic efficiency to bring down the cost of the system. Space-constrained cities with tight budgets looking to find alternatives to landfilling should consider using pelletization at the 5-10 TPD scale or a combination of anaerobic digestion and pelletization to process organic waste.

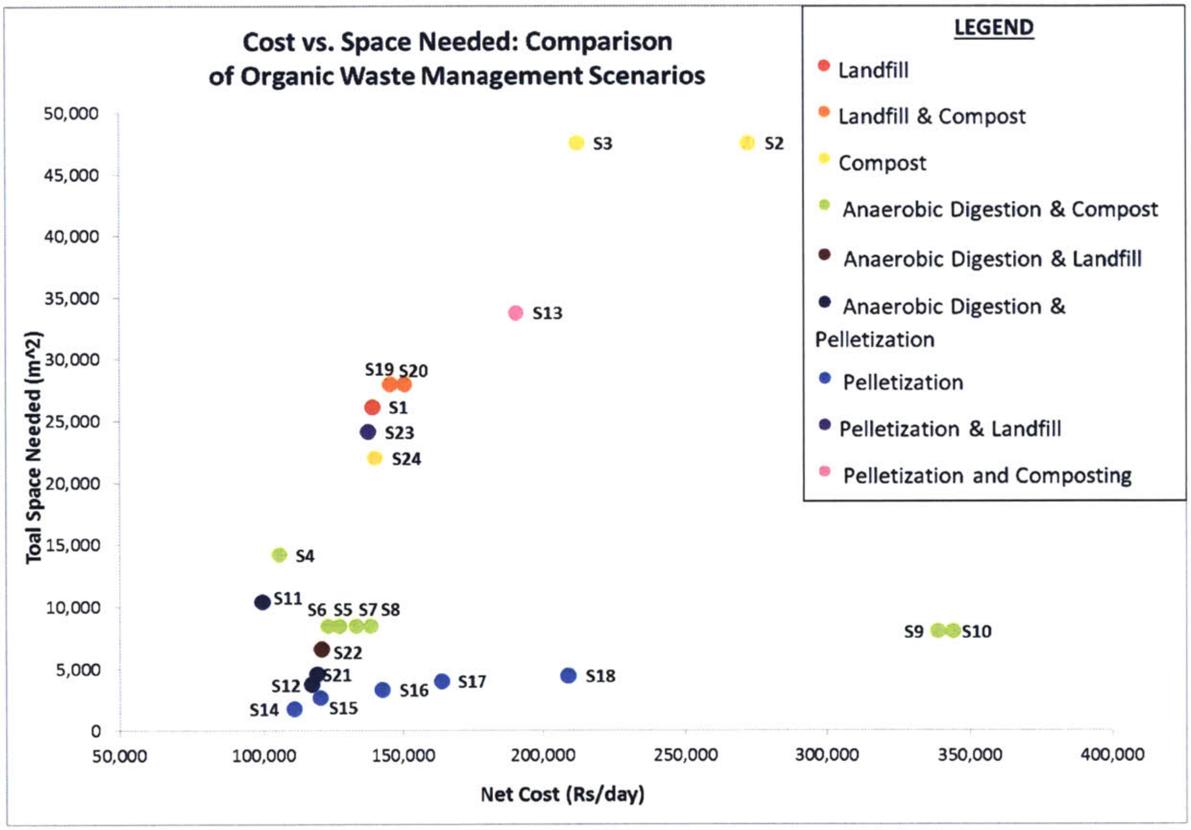


Figure 70: Scatter plot showing the relationship between systems' cost and space requirements. Each point represents one of 24 scenarios, detailed above in **Table 42**.

Table 49: The five organic waste management scenarios with the best combination for minimizing cost and spatial footprints.

	S#	Cost (Rs./Day)	GHGE (Kg CO_2-eq/day)	Space Needed (m^2)	Level of Centralization	Scenario Description
Least Cost & Least Space	S14	110,840	-1,664	1,766	3	All organics pelletized, 10 TPD plants
	S12	117,296	-2,018	3,712	3	All yard waste and some food waste pelletized at 10 TPD plant; remainder of food waste A.D. at 5 TPD plants
	S15	120,251	-1,664	2,649	3	All organics pelletized, 5 TPD plants
	S21	119,122	-2,074	4,572	3	Yard waste pelletized at one 5 TPD plant; food waste A.D. at 5 TPD plants
	S22	120,752	212	6,591	3	Food waste A.D. at 5 TPD plants; yard waste landfilled

Chapter 8: Conclusion

8.1 Conclusions and Policy Implications

The scenario analysis in Chapter 7, which builds off of the analyses and findings from previous chapters, helps answer the original question posed in the introduction. This thesis aimed to explore the tradeoffs of various organic waste management strategies in the urban Indian context. Specifically, this thesis used environmental, economic, and social analyses to quantify and characterize the impacts of organic waste management. The analyses focused on decentralized system architectures for waste management due to their reported benefits, such as compatibility with manual segregation, the ability to include or employ wastepickers in the system, and minimized transportation. The intention of this thesis was to test the hypothesis that there are decentralized waste system architectures that can improve on the economic and environmental performance of organic waste management systems. This thesis aimed to answer the question, what are the characteristics of a decentralized system that:

1. Is appropriate for the quantity and composition of waste generated in urban Indian?
2. Is cost-effective collecting and treating organic waste?
3. Reduces global warming impact (i.e., greenhouse gas emissions)?
4. Impacts stakeholders, including the informal sector, positively?

Although some economies of scale do create tradeoffs between cost and decentralization, the results of this thesis suggest that systems can be designed to process organic waste in a relatively decentralized way that is also relatively low in cost. Systems that utilize pelletization and anaerobic digestion plants processing 1-5 TPD appear to be appropriate for the urban Indian context given that they (1) have smaller spatial footprints, (2) are relatively cost-effective, (3) create a net savings in greenhouse gas emissions, and (4) create a decentralized system that can more easily involve and be compatible with the informal sector. Anaerobic digestion at the 2-5 TPD scale is especially effective for achieving greenhouse gas emission as well as cost savings, in comparison landfilling. Furthermore, given the interest so many stakeholders in Pune have in pursuing alternative organic waste management solutions over landfilling, it appears that anaerobic digestion – a well-established and proven technology – would also be socially accepted and politically supported.

It appears that composting, anaerobic digestion, and pelletization systems are all compatible with wastepickers access to organic waste and continued access to recyclables. Regardless of the scale used for such technologies, wastepickers could continue to conduct door-to-door collection; furthermore, if training programs were put into place, some workers that are currently part of the informal sector could become employees at processing facilities. Landfilling organic waste also does allow wastepickers to continue door-to-door collection, however, due to the highly centralized nature of landfilling and the relatively low need for human labor in the landfilling process, it is unlikely that landfills could safely employ informal sector workers. Furthermore, because the landfilling process is easily tolerates non-biodegradables, landfilling waste creates the additional risk that recyclable material (valued by wastepickers) is collected and mixed with organic waste; this is much less of a risk if the city uses technologies specifically designed for (and limited to) processing source-segregated organic waste. Given that landfills are hazardous places often fenced off from access by wastepickers, continued or expanded use of landfilling as a method for handling organic waste could negatively impact the informal sector's ability to generate revenue and could make landfilling any type of waste less desirable to the informal sector.

The key findings with implications for policy that are presented in this thesis are listed below.

- Given that organic waste was found to constitute between 66 and 80% of residential municipal solid waste, urban India has significant opportunity for making impactful changes by using alternative organic waste management strategies.
- Per-capita MSW generation in Pune is 134, 309 and 401 grams/day for the lower, middle, and upper income residents, respectively. The middle income residents generate 2.3 times what lower income residents generate, and upper income residents generate 3 times what lower income residents generate. Because higher-income populations generate significantly more waste, India can expect to see a significant increase in waste volumes as its population becomes wealthier.
- The findings of interviews with residents of various socioeconomic groups indicate that slums experience the lowest quality waste management services.
- Interviews with waste pickers on various aspects of quality of life indicate that wastepickers suffer from relatively poor quality of housing, health, and living environment. However, wastepicker report a relatively high quality of education, community support, safety, and overall life satisfaction.
- The cost per ton of waste managed using anaerobic digestion, composting, and pelletization decreases significantly with larger scale of treatment.
- Alternative organics management technologies used at small scales (less than 0.5 TPD) are more expensive than landfilling; however, if a facility of at least 0.5 TPD is used, anaerobic digestion is less expensive than landfilling. Furthermore, if a facility of at least 5 TPD is used and the technology progresses as expected, pelletization becomes cheaper than landfilling and cost-competitive with anaerobic digestion. Composting at the scale of 200 TPD is also less expensive than landfilling.
- A significant portion (up to one-third) of the cost of processing waste using anaerobic digestion, composting, and pelletization is offset by revenues from the end-products of the processes. The ratio of revenue to cost was highest for composting. Landfilling without gas capture generates no useful end product or revenue.
- Although the average cost of centralized organic waste systems are less expensive, decentralized systems are not strictly more expensive than centralized systems due to the variation of technology choice; consequently, some highly decentralized systems are just as low cost as centralized systems. The difference in cost between the lowest-cost decentralized systems and lowest-cost centralized systems was found to be relatively small (18% of the total cost).
- Indian cities looking to minimize expenditures on organic waste management should consider using anaerobic digesters at the treatment scales 2 TPD or greater.

- Both anaerobic digestion and pelletization create a net savings in greenhouse gas emissions. The global warming potential (GWP) of anaerobic digestion is estimated to be -51 kg CO_2-eq/ton. The GWP of pelletization is estimated to be -42 kg CO_2-eq/ton. The GWP of composting is estimated to be 38 kg CO_2-eq/ton. The GWP of landfilling is estimated to be 510 kg CO_2-eq/ton.
- Although pelletization of organic MSW is not a fully-developed technology, it has potential as an alternative management strategy that is especially efficient with regard to spatial footprint. A dense, overpopulated city or a city with very expensive property values might consider using pelletization as a space-saving method of organic waste management that avoids the need to transport waste to a far-away landfill. Space-constrained cities with tight budgets looking to find alternatives to landfilling should consider using a combination of anaerobic digestion and pelletization to process organic waste.
- Although composting is not the least-cost technology, it would be reasonable for a city to install some amount of composting because the technology is well-established, has a substantially lower global warming impact than landfilling, and can be less expensive than landfilling at large scales. Furthermore, if pelletization indeed develops into a well-performing and cost-effective technology, composting facilities could be converted to pelletization (which would also create space and greenhouse gas savings).
- A city looking to minimize its contribution to global warming could achieve significant reductions in emissions by biodigesting food waste and pelletizing yard waste. Such systems would have a net greenhouse gas emissions savings of over 750 tons CO_2-eq each year.
- Of the technologies assessed, anaerobic digestion (at scales of 5 TPD or larger) has the best combination of cost and global warming potential performance. Compared to other technologies, anaerobic digestion offers the largest reduction in GHGE per unit of expenditure. However, because woody material cannot be digested, pelletization (at 10 TPD plants) has the best combination of cost and GWP performance specifically for handling yard waste. These findings suggest that for handling organic MSW, anaerobic digestion in combination with pelletization produces the best combination of cost and GWP performance.
- Indian cities currently landfilling organic waste should consider processing such waste with anaerobic digestion and pelletization, because both have the potential to simultaneously reduce greenhouse gas emissions and the cost of treatment.

This thesis uses social, economic, and environmental analyses to assess a variety of organic waste treatment technologies and scales of treatment. Therefore, the findings in this thesis can help policy makers and planners in cities in India and other developing countries make informed choices about how to manage organic waste. As the burden of waste management increases with population growth and consumption, we expect that these cities will seriously need to consider the tradeoffs of different organic waste management systems. The impacts on the informal sector, the net cost, the global warming impact, and the spatial footprint of waste systems all need to be taken into account to truly make an informed decision on how to manage organic waste in a responsible and efficient manner.

8.2 Recommendation for Future Work

Although the results presented here explore a number of factors pertaining to management of organic waste in urban India, the analysis could be further developed in the following ways.

Given the lack of information on the global warming impact of pelletization, a full life cycle assessment that assesses the process of pelletizing the organic fraction of MSW and the burning of those pellets for energy would allow for a better comparison of the pelletization with other organic waste processing technologies.

Additionally, additional research could be done to quantify the environmental and economic costs and benefits of different types of composting systems. Most economic and environmental comparisons of composting focus on the scale of treatment, rather than the type of process used. Ideally, an analysis would compare windrow, in-vessel, aerated static pile, vermi, and pit composting using life cycle assessment and life cycle cost analysis.

Furthermore, more in-depth analysis of the cost and global warming implications of using different end-uses of biogas would provide useful information to cities considering different commercialization methods for anaerobic digestion; such an analysis might compare the life cycle emissions and costs of using the methane from biodigestion (a) for compressed natural gas that fuels vehicles, (b) as a fuel for cooking stoves, (c) for the production of combined heat and power, or (d) for the production of electricity.

Lastly, because this thesis found that anaerobic digestion of organic waste has great potential for achieving greenhouse gas and costs savings (as compared to composting and landfilling) further investigation should be done into the reason that only a small fraction of the organic waste generated in Indian cities is being biodigested. Unlike pelletization of the organic fraction of MSW, anaerobic digestion is a well-understood and developed technology. There is a need to understand the reasons why Indian cities are not more readily implementing anaerobic digestion systems. Perhaps an in depth analysis of this topic would reveal certain obstacles and limitations of using anaerobic digestion in the Indian context; for instance, it is possible that anaerobic digestion is perceived as a risky or intimidating due to the chemistry and engineering expertise needed for proper function of the system. If possible, a systematic assessment of the technical problems impeding the adoption of composting, anaerobic digestion, and pelletization in Indian cities should be conducted; such an analysis would make it easier for engineers, planners, and governments to troubleshoot these issues, thereby facilitating the adoption of more sustainable organic waste management systems.

References

Adhikari, B. K., Trémier, A., Martinez, J., & Barrington, S. (2010). Home and community composting for on-site treatment of urban organic waste: perspective for Europe and Canada. *Waste Management & Research, 28*(11), 1039–53. doi:10.1177/0734242X10373801

Ahluwalia, I.J. (2012). Clean it like Pune. The Financial Express. http://www.financialexpress.com/news/clean-it-like-pune/1024299/0

Alsheyab, M. a T., Schingnitz, D., AAl-Shawabkeh, a F., & Kusch, S. (2013). Analysis of the potential use of major refuse-derived fuels in Jordan as supplementary fuel. *Journal of Air and Waste Management Association, 63*, 902–908. doi:10.1080/10962247.2013.776998

Annepu, R. K. (2012). Sustainable Solid Waste Management in India. *Department of Earth and Environmental Engineering at Columbia University*, 1–189.

Barrows, B. (2011). *Briefing Paper: Best Management Practices for Discarded Food Scraps.* Retrieved from http://www.deq.state.or.us/lq/pubs/docs/sw/2050vision/BriefingPaperDiscardedFoodScraps.pdf

Beauchemin, P., & Tampier, M. (2010). *Emissions and Air Pollution Controls for the Biomass Pellet Manufacturing Industry.*

Bernstad, A. & La Cour Jansen, J. (2012). Review of comparative LCAs of food waste management systems - Current status and potential improvements. *Waste Management, 32*(12), 2439–2455. doi:10.1016/j.wasman.2012.07.023

Brunner, P., & Rechberger, H. (2011). *Practical Handbook of Material Fow Analysis*. Coca Raton, Florida: Lewis Publishers. doi:10.1016/B978-1-85617-809-9.10003-9

Burnley, S. J. (2007). A review of municipal solid waste composition in the United Kingdom. *Waste Management (New York, N.Y.), 27*(10), 1274–85. doi:10.1016/j.wasman.2006.06.018

Carlsson, M., Naroznova, I., Møller, J., Scheutz, C., & Lagerkvist, A. (2015). Importance of food waste pre-treatment efficiency for global warming potential in life cycle assessment of anaerobic digestion systems. *Resources, Conservation and Recycling, 102*, 58–66. doi:10.1016/j.resconrec.2015.06.012

Chang, N.-B., & Davila, E. (2008). Municipal solid waste characterizations and management strategies for the Lower Rio Grande Valley, Texas. *Waste Management (New York, N.Y.)*, *28*(5), 776–94. doi:10.1016/j.wasman.2007.04.002

Chaturvedi, B. (2003). *Space for Waste: Planning for the Informal Recycling Sector*.

Chaya, W., & Gheewala, S. H. (2007). Life cycle assessment of MSW-to-energy schemes in Thailand. *Journal of Cleaner Production*, *15*(15), 1463–1468. doi:10.1016/j.jclepro.2006.03.008

Chikarmane, P. (2012). *Integrating Waste Pickers into Municipal Solid Waste Management in Pune, India*.

Chikarmane, P., & Narayan, L. (2009). Rising from the Waste: Organising Wastepickers in India, Thailand and the Philippines. Retrieved from http://wiego.org/sites/wiego.org/files/publications/files/Chikarmane_Narayan_Asian_Wastepickers.pdf

Chintan. (2012). *What the Okhla Waste-to Energy Plant has Done to Local Wastepickers*. New Delhi.

Chintan Environmental Research and Action Group. (2009). *Waste Recyclers and Recycling Who Recycles Your Waste?*

CM Consulting. (2007). *Measuring the benefits of composting source separated organics in the Region of Niagara*.

Commission, N. S. W. M. (2009). *National Framework Plan for the Informal Waste Sector in Solid Waste Management*.

Dedinec, A., Markovska, N., Ristovski, I., Velevski, G., Gjorgjievska, V. T., Grncarovska, T. O., & Zdraveva, P. (2014). Economic and environmental evaluation of climate change mitigation measures in the waste sector of developing countries. *Journal of Cleaner Production*, *88*, 234–241. doi:10.1016/j.jclepro.2014.05.048

Desai, Manisha. (2013, August 21). *Personal interview.* Outreach Manager of SWaCH. Contact information: desai.manisha@gmail.com

Di Maria, F., & Micale, C. (2015). Life cycle analysis of incineration compared to anaerobic digestion followed by composting for managing organic waste: the influence of system components for an Italian district. *International Journal of Environment and Waste Management*, *20*, 377–388.

Dighe, M. (2015). *Best Practices - Pune City.*

Ernst & Young. (2013). *Hitting the sweet spot: The growth of the Middle Class in Emerging Markets*. doi:10.1111/tct.12028

Fernández-Nava, Y., del Río, J., Rodríguez-Iglesias, J., Castrillón, L., & Marañón, E. (2014). Life cycle assessment (LCA) of different municipal solid waste management options: a case study of Asturias (Spain). *Journal of Cleaner Production*, *81*, 178–189. doi:10.1016/j.jclepro.2014.06.008

Field, F., Kirchain, R., & Roth, R. (2007). Process cost modeling: Strategic engineering and economic evaluation of materials technologies. *Minerals, Metals & Materials Society*, *59*(10), 21–32.

Finnveden, G., Johansson, J., Lind, P., & Moberg, Å. (2005). Life cycle assessment of energy from solid waste—part 1: general methodology and results. *Journal of Cleaner Production*, *13*(3), 213–229. doi:10.1016/j.jclepro.2004.02.023

Forster, P., Ramaswamy, Artaxo, T., Berntsen, R., Betts, D. W., Fahey, J., ... Dorland, R. Van. (2007). *Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

Giugliano, M., Cernuschi, S., Grosso, M., & Rigamonti, L. (2011). Material and energy recovery in integrated waste management systems. An evaluation based on life cycle assessment. *Waste Management*, *31*(9-10), 2092–101. doi:10.1016/j.wasman.2011.02.029

Giusti, L. (2009). A review of waste management practices and their impact on human health. *Waste Management*, *29*, 2227–2239.

Goldstein, R. (2015). *Landfill Biogas Project Opportunity: Uruli Devachi Landfill.*

Gomez, G., Meneses, M., Ballinas, L., & Castells, F. (2008). Characterization of urban solid waste in Chihuahua, Mexico. *Waste Management (New York, N.Y.)*, *28*(12), 2465–71. doi:10.1016/j.wasman.2007.10.023

Gunamantha, M., & Sarto. (2012). Life cycle assessment of municipal solid waste treatment to energy options: Case study of KARTAMANTUL region, Yogyakarta. *Renewable Energy*, *41*, 277–284. doi:10.1016/j.renene.2011.11.008

Hogg, D., Favoino, E., Nielsen, N., Thompson, J., Wood, K., Penschke, A., ... Papageorgiou, S. (2013). *Economic Analysis of Options for Managing Biodegradable Municipal Waste*.

Hong, R. J., Wang, G. F., Guo, R. Z., Cheng, X., Liu, Q., Zhang, P. J., & Qian, G. R. (2006). Life cycle assessment of BMT-based integrated municipal solid waste management: Case study in Pudong, China. *Resources, Conservation and Recycling, 49*(2), 129–146. doi:10.1016/j.resconrec.2006.03.007

Hoornweg, D., & Bhada-Tata, P. (2012). A Global Review of Solid Waste Management. *World Bank Urban Development Series Knowledge Papers*, (15), 1–116.

Howe, C. L. (2014). *Building Stability Through Decentralization : The Environmental , Economic , and Ethical Argument for Informal Sector Collection and Decentralized Waste Processing in Urban India By*. Massachusetts Institute of Technology.

India Ministry of Environment and Forests. Municipal Solid Waste Management and Handling Rules, 2000, Pub. L. No. S.O. 908(E) (2000). India.

India, T. T. of. (2012, February 25). Rs 71 Cr. Likely for Waste Management. *The Times of India*. Pune, India. Retrieved from http://timesofindia.indiatimes.com/city/pune/Rs-71-cr-likely-for-waste-management/articleshow/12026759.cms

The Indian Express. (2013a). *Denied landfill sites, civic body in a bind.* Retrieved from http://www.indianexpress.com/news/denied-landfill-sites-civic-body-in-a-bind/1161062/0

The Indian Express. (2013b). *Garbage dumping site fire: Uruli Devachi residents suspend stir.* Retrieved from http://www.indianexpress.com/news/garbage-dumping-site-fire-uruli-devachi-residents-suspend-stir/1102986/

The Indian Express. (2013c.) *Uruli Devachi, Phursungi villagers don't budge, garbage stalemate on.* Retrieved from http://www.indianexpress.com/news/uruli-devachi-phursungi-villagers-don-t-budge-garbage-stalemate-on/460255/

Isalkar, U. (2013, August 29). Pune Municipal Corporation's waste-to-green energy project in Hadapsar is limping. *The Times of India*. Pune, India. Retrieved from http://timesofindia.indiatimes.com/city/pune/Pune-Municipal-Corporations-waste-to-green-energy-project-in-Hadapsar-is-limping/articleshow/22131853.cms

Global Alliance for Incinerator Alternatives (GAIA). (2012). On the Road to Zero Waste. Successes and Lessons from Around the World. http://no-burn.org/downloads/On%20the%20Road%20to%20Zero%20Waste.pdf

Government of India. (2012). Office of the Registrar General and Census Commissioner, India. Indian 2011 Census Data.

Jagtap, Suresh. (2013, August 21). Zonal Commissioner No. 4 of Pune Municipal Corporation Personal interview. Contact Information: suresh.jagtap@punecorporation.org

Jakobsen, S. T. (1994). Aerobic decomposition of organic wastes: I Stoichiometric calculation of air change. *Resources, Conservation and Recycling, 12*(3-4), 165–175. doi:10.1016/0921-3449(94)90004-3

Jin, Y., Chen, T., Chen, X., & Yu, Z. (2015). Life-cycle assessment of energy consumption and environmental impact of an integrated food waste-based biogas plant. *Applied Energy, 151*(July 2010), 227–236. doi:10.1016/j.apenergy.2015.04.058

Kagad Kach Patra Kashtakari Panchayat. (2007a). *A Study of Child Labour in the Waste Picking Sector.*

Kagad Kach Patra Kashtakari Panchayat. (2007b). *Solid Waste Generation and Collection in Pune: A Situational Analysis.* Pune, India.

Kale, S., Kadam, A.K., Kumar, S., Pawar, N.J. (2008). Evaluating pollution potential of leachate rom landfill site, from the Pune metropolitan city and its impact on shallow basaltic aquifers. *Environmental Monitoring and Assessment* 162: 327-346.

Kandpal, T. C., Joshi, B., & Sinha, C. S. (1991). Economics of family sized biogas plants in India. *Energy Conversion and Management, 32*(2), 101–113. doi:10.1016/0196-8904(91)90150-H

Kong, D., Shan, J., Iacoboni, M., & Maguin, S. R. (2012). Evaluating greenhouse gas impacts of organic waste management options using life cycle assessment. *Waste Management & Research, 30*(8), 800–812. doi:10.1177/0734242X12440479

Kornstein, S. (2012, January 26). Pune: A nearly waste-free city. Something's Brewing. Retrieved from http://www.somethingsbrewing.com/2012/01/pune-nearly-waste-free-city/

Lange, R. (2005). 2004-05 NYC Residential and Street Basket Waste Characterization Study. *Bureau of Waste Prevention, Reuse and Recycling: New York CIty Department of Sanitation*, 1–138.

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., … Christensen, T. H. (2014). Review of LCA studies of solid waste management systems - Part I: Lessons learned and perspectives. *Waste Management, 34*(3), 573–588. doi:10.1016/j.wasman.2013.10.045

Linzner, R., & Lange, U. (2013). Role and size of informal sector in waste management – a review, *166*, 69–84.

Lombardi, L., Carnevale, E., & Corti, A. (2015). A review of technologies and performances of thermal treatment systems for energy recovery from waste. *Waste Management*, *37*, 26–44.

López, M., Soliva, M., Martínez-Farré, F. X., Fernández, M., & Huerta-Pujol, O. (2010). Evaluation of MSW organic fraction for composting: Separate collection or mechanical sorting. *Resources, Conservation and Recycling*, *54*(4), 222–228. doi:10.1016/j.resconrec.2009.08.003

Lundie, S., & Peters, G. M. (2005). Life cycle assessment of food waste management options. *Journal of Cleaner Production*, *13*, 275–286. doi:10.1016/j.jclepro.2004.02.020

MacCarty, N., Ogle, D., Still, D., Bond, T., & Roden, C. (2008). A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. *Energy for Sustainable Development*, *12*(2), 56–65. doi:10.1016/S0973-0826(08)60429-9

Maharashtra Government. (2008). Memorandum of Understanding between Pune Municipal Corporation and SWACH. Pune, India: Pune Municipal Corporation.

Mascarenhas, A. (2014). Pune tops biomedical waste disposal compliance. *The Indian Express*. Retrieved from http://archive.indianexpress.com/story-print/1128968/

Massaro, V., Digiesi, S., Mossa, G., & Ranieri, L. (2015). The sustainability of anaerobic digestion plants: a win–win strategy for public and private bodies. *Journal of Cleaner Production*, *104*, 445–459. doi:10.1016/j.jclepro.2015.05.021

McCollough, J. (2002). *The Effect of Income Growth on the Generation of Municipal Solid Waste*.

McDougall, F., White, P., Franke, M., & Hindle, P. (2008). *Integrated solid waste management: a life cycle inventory. Second Edition.*

Mendes, M. R., Aramaki, T., & Hanaki, K. (2003). Assessment of the environmental impact of management measures for the biodegradable fraction of municipal solid waste in Sao Paulo City. *Waste Management*, *23*(5), 403–409. doi:10.1016/S0956-053X(03)00058-8

Mendes, M. R., Aramaki, T., & Hanaki, K. (2004). Comparison of the environmental impact of incineration and landfilling in Sao Paulo City as determined by LCA. *Resources, Conservation and Recycling*, *41*(1), 47–63. doi:10.1016/j.resconrec.2003.08.003

Mitchell, M. (2001). *On-site Composting of Restaurant Organic Waste: Economic, Ecological, and Social Costs and Benefits*.

Mohareb, A. K., Warith, M. a., & Diaz, R. (2008). Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. *Resources, Conservation and Recycling*, *52*(11), 1241–1251. doi:10.1016/j.resconrec.2008.06.006

Monnet, F. (2003). *An Introduction to Anaerobic Digestion of Organic Wastes*. *Remade Scotland* (Vol. 23). Retrieved from http://www.biogasmax.co.uk/media/introanaerobicdigestion__073323000_1011_24042007.pdf

Mundhe, N. (2014). Assessment of Municipal Solid Waste Management of Pune City using Geospatial Tools, *100*(10), 24–32.

Munster, M., Ravin, H., Hedegaard, K., Juul, N., & Ljunggren Soderman, M. (2015). Economic and Environmental Optimization of Waste Treatment. *Waste Management*, *28*(486-495).

Nair, J., & Lou, X. F. (2009). *Waste Management and greenhouse gas emissions from Bridgewater Lifestyle village, Mandurah, Western Australia.*

North Carolina Cooperative Extension. (2000). *Large-scale Organic Materials Composting.*

OECD. (2013). *How's Life? 2013: Measuring Well0being*. Paris: OECD Publishing.

Pallavi, A., & Dutta, A. P. (2015). *Lessons from Two Cities. Down To Earth.*

Panchayat, K. K. P. K. (2006). *Economic Aspects of Informal Sector Activities in Solid Waste Management*. Pune, India.

Pathak, M. (2014). *Biomethanation from Municipal Solid Waste.*

Patterson, T., Esteves, S., Dinsdale, R., & Guwy, A. (2011). Life cycle assessment of biogas infrastructure options on a regional scale. *Bioresource Technology*, *102*(15), 7313–7323. doi:10.1016/j.biortech.2011.04.063

PE International. (2013). GaBi Database Upgrade 2013 Upgrades and Improvements.

Poeschl, M., Ward, S., & Owende, P. (2012). Environmental impacts of biogas deployment - Part II: Life Cycle Assessment of multiple production and utilization pathways. *Journal of Cleaner Production*, *24*, 184–201. doi:10.1016/j.jclepro.2011.10.030

Pool, R. (2013). *The Nexus of Biofuels, Climate Change, and Human Health: Workshop Summary.*

Pune Municipal Corporation. Pune Municipal Corporation Public Health and Sanitation Bylaws 2014 (2014).

Pune Municipal Corporation. (2014b). *Pune's Arsenal Against Waste*.

R.W. Beck, I. (2007). *Sioux Falls Regional Sanitary Landfill Waste Characterization Study*.

Rajendran, K., Kankanala, H. R., Martinsson, R., & Taherzadeh, M. J. (2014). Uncertainty over techno-economic potentials of biogas from municipal solid waste (MSW): A case study on an industrial process. *Applied Energy*, *125*, 84–92. doi:10.1016/j.apenergy.2014.03.041

Rege, Suresh. (2014, June 20). *Personal interview*. Founder of Mailhem Engineers Pvt. Ltd.

Rigamonti, L., Grosso, M., & Giugliano, M. (2009). Life cycle assessment for optimising the level of separated collection in integrated MSW management systems. *Waste Management*, *29*(2), 934–44. doi:10.1016/j.wasman.2008.06.005

Rigamonti, L., Grosso, M., & Giugliano, M. (2010). Life cycle assessment of sub-units composing a MSW management system. *Journal of Cleaner Production*, *18*(16-17), 1652–1662. doi:10.1016/j.jclepro.2010.06.029

Rushton, L. (2003). Health hazards and waste management. *British Medical Bulletin*, *68*, 183–197. doi:10.1093/bmb/ldg034

S. Mani, S. Sokhansanj, X. Bi, & A. Turhollow. (2006). Economics of Producing Fuel Pellets From Biomass. *Applied Engineering in Agriculture*, *22*(3), 421–426. doi:10.13031/2013.20447

Samson, R., & Duxbury, P. (2000). Assessment of pelletized biofuels, 1–41.

Scheinberg, A. (2011). *Value Added : Modes of Sustainable Recycling in the Modernisation of Waste Management Systems*. Wageningen University.

Shah, E., & Sambaraju, K. (1997). *Technical and Economic Analysis of Composting Enterprises in Bangalore - India*.

Sharma, B. K. (2014). *Life Cycle Assessment of Various Municipal Solid Waste Management Options*. Indian Institute of Technology Bombay.

Sharma, G., & Campbell, a. (2007). Life cycle inventory and life cycle assessment for windrow composting systems. *Recycled Organics Unit, University of New South Wales*.

Sheikh, A. (2014). *Impact of the Informal Sector on the Waste Management System of Pune, India*. Imperial College of London.

Shetty, D. (2014, December 9). Green initiatives installed, but not maintained by residents. Pune. Retrieved from http://www.iamin.in/en/pune/news/green-initiatives-installed-not-maintained-residents-48094

Smith, R. L., Sengupta, D., Takkellapati, S., & Lee, C. C. (2015). An industrial ecology approach to municipal solid waste management: II. Case studies for recovering energy from the organic fraction of MSW. *Resources, Conservation and Recycling*. doi:10.1016/j.resconrec.2015.05.016

SNDT Womens' University. (2008). *Recycling Livelihoods: Integration of the Informal Recycling Sector in Solid Waste Management in India.*

Sonesson, U. (1998). Calculating transport labour for organic waste from urban to rural areas.pdf. *Resources, Conservation and Recycling, 24,* 335–348.

Staniškis, J. K., & Miliūtė, J. (2010). *Municipal Waste Management System Based On Life - Cycle Assessment.*

State of Vermont Department of Environmental Conservation. (2013). *State of Vermont Waste Composition Study Final Report.*

Suresh, J. (2012). *Solid Waste Management in Pune City.*

Susarla, Aparna. (2014, June 16). Personal interview. Data Manager of SWaCH. Contact information: aparna.SWaCH@gmail.com

Sylvan, D. (2006). *Municipal Solid Waste in New York City : An Economic and Environmental Analysis of Disposal Options.*

Tangri, N. (2012). *Waste Pickers Lead the Way to Zero Waste.*

The Energy and Resources Institute. (2013). *TERI Environmental Survey.* New Delhi.

The World Bank. (2014). *Population growth. Population Growth (Annual %).* Retrieved from http://data.worldbank.org/indicator/SP.POP.GROW

Thek, G., & Obernberger, I. (2009). Wood Pellet Production Costs Under Austrian Framework Conditions. *European Biomass Conference & Exhibition, 43*(July), 2131–2139.

Van Haaren, R., Themelis, N. J., Barlaz, M., Engineering, E., & Foundation, F. (2009). *Large scale aerobic composting of source separated organic wastes: A comparative study of environmental impacts, costs, and contextual effects*. Columbia University.

Vergara, S. E., Damgaard, A., & Horvath, A. (2011). Boundaries matter: Greenhouse gas emission reductions from alternative waste treatment strategies for California's municipal solid waste. *Resources, Conservation and Recycling*, *57*, 87–97. doi:10.1016/j.resconrec.2011.09.011

Vergara, S. E., & Tchobanoglous, G. (2012). *Municipal Solid Waste and the Environment: A Global Perspective. Annual Review of Environment and Resources* (Vol. 37). doi:10.1146/annurev-environ-050511-122532

Wanichpongpan, W., & Gheewala, S. H. (2007). Life cycle assessment as a decision support tool for landfill gas-to energy projects. *Journal of Cleaner Production*, *15*(18), 1819–1826. doi:10.1016/j.jclepro.2006.06.008

Whyte, R., & Perry, G. (2001). A Rough Guide to Anaerobic Digestion Costs and MSW Diversion. *Biocycle*.

Xu, C., Shi, W., Hong, J., Zhang, F., & Chen, W. (2015). Life cycle assessment of food waste-based biogas generation. *Renewable and Sustainable Energy Reviews*, *49*, 169–177. doi:10.1016/j.rser.2015.04.164

Yoshida, H., Gable, J. J., & Park, J. K. (2011). Evaluation of organic waste diversion alternatives for greenhouse gas reduction. *Resources, Conservation and Recycling*, *60*, 1–9. doi:10.1016/j.resconrec.2011.11.011

Yu, C.-C., & Maclaren, V. (1995). A Comparison of Two Waste Stream Quantification and Characterization Methodologies. *Waste Management & Research*, *13*(4), 343–361. doi:10.1177/0734242X9501300406

Zafar, S. (2015). *Pelletization of Municipal Solid Wastes. BioEnergy Consult.* Retrieved from http://www.bioenergyconsult.com/refuse-derived-fuel/

Appendices

Appendix A: Waste Audit Worksheet

Waste Audit Worksheet

कचरा ऑडिट

1. Date दिनांक: ____________________

2. Day of the week वार: ____________________

3. Area/district being covered प्रभाग: ____________________

4. Estimated population of the area लोकसंख्या: ____________________

5. Economic class of the area (circle all that apply): आर्थिक स्तर

   Slums वस्ति | Lower-middle class मध्यम | Upper-middle class उच्च मध्यम | Upper class उच्च

6. Did it rain (circle all that apply)? पाउस झाला का ?

   Yesterday काल | Earlier today आज | Now अत्ता

7. How wet is the waste? कचरा ओला होता का

   Wet हो | Not wet नाही | A little wet थोडा

8. Start and End time of कचरा घेणे ची वेळ

   Start Time सुरुवात ________

   End Time शेवट ________

9. Name of the auditor: माहिती घेणारी व्यक्तीचे नाव ____________________

10. Names of the waste picker(s): कचरावेचाकंचे नाव

    ________________________ ________________________ ________________________

Item No.	Categories	Marathi	Weight (Kg)
		ORGANICS	
1	Food scraps	खरकटे/ उरलेले अन्न	
2	Yard waste	पाला पचोळा	
3	Other biodegradable material	इतर जिरवण्या योग्य पधार्थ	
		PAPER	
4	White office paper	व्हाईट	
5	Newspaper	रद्दी	
6	Notebook	वही	
7	Road scrap/paper	आर एस	
8	Cardboard	पुठ्ठा	
9	Large sturdy Box	बॉक्स	
		PLASTIC	
10	White low grade film plastic	एल डी ?	
11	Coloured plastic bags	मेण	
12	Cement bags	रफिया	
13	Styrofoam	फोम/ थेर्माकोल	
14	Thick PET bottles	कडकडी	
15	HDPE containers	फुगा	
16	PVC pipes	पी वी सी	
17	Plastic sheets	शीट	
18	Thin plastic cables	केबल	
19	Small plastic pieces (pens caps etc.)	कडक	
20	Bicycle seats	सायकल सीट	
21	Rubber tubes	रबर टूब	
		MIXED MATERIALS	
22	Tetrapak	फ्रुटी/टेटरापेक	
23	Chip bags and packets	मिक्स मेण	
		METAL	
24	Aluminium	जर्मन	
25	Steel	स्टील	
26	Small pieces of scrap metals	भंगार	

Item No.	Categories	Marathi	Weight (Kg)
	GLASS		
27	Glass bottles	काच	
28	Beer bottles	बीअर	
29	Kingfisher bottles	के पी	
30	Liquor bottles (quarter litres)	क्वार्टर	
31	Mini Liquor bottles	पिल्लू	
32	Ketchup Bottles	टमाता	
33	Glass soda bottles	सोडा	
34	Broken pieces of glass	काच	
	CLOTHING		
35	Cotton/ Linen textiles	कॉटन	
36	Synthetic textiles (nylon, polyester)	कापड	
37	Upper parts of shoes		
38	Slippers	चप्पल	
	SANITARY WASTE		
39	Diapers	हगीज	
40	Sanitary napkins and tampons	प्याड	
	ELECTRONICS		
41	Batteries	ब्याटरी	
42	Large non portable appliances	मोठा ई वेस्ट	
43	Computer electronics (cell phones etc.)	छोटा ई वेस्ट	
	OTHER		
44	Wood	लाकूड	
45	Carpet	कारपेट	
46	Inert material (rocks, sand)	राबिट	
47	Other Items (broken ceramics, paint)	इतर वस्तू	

Appendix B: Source Separation Visual Guide

1

Food scraps

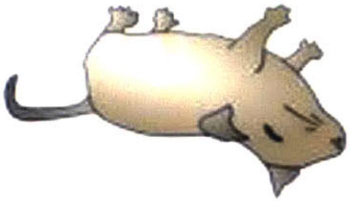
खरकटे/ उरलेले अन्न

2

Yard waste

पाला पचोळा

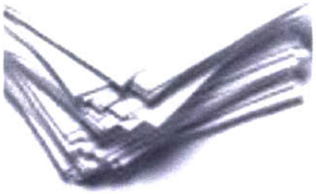
3



Other biodegradable material

इतर जिरवण्या योग्य पधार्थ

4



White office paper

व्हाईट

5

Newspaper

रद्दी

6

Notebook paper

वही

7

Road-scrap paper

आर एस

8

Cardboard

पुट्ठा

9

Large, sturdy boxes

बॉक्स

10

LD Plastic #1
White low-grade film plast

एल डी

11

LD Plastic #2
Colored plastic bags

मेण

12

Cement sacks

रफिया

13

Stryofoam

फोम/ थेर्माकोल

14

PET bottles

कडकडी

15

HDPE containers

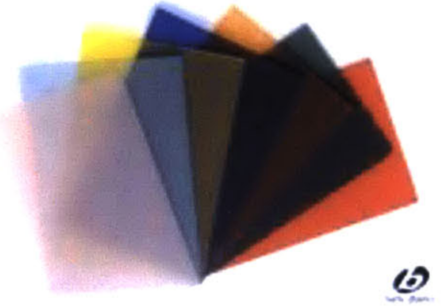
फुगा

16

PVC Pipes

पी वी सी

17



Plastic sheets

शीट

18

Plastic cables

केबल

19

Small plastic
(pens, caps, etc.)
कडक

20

Cycle seats
सायकल सीट

21

Rubber Bike Tubes
रबर टूब

22

Tetrapak
फ्रुटी/टेटरापेक

23

Chip bags
मिक्स मेण

24

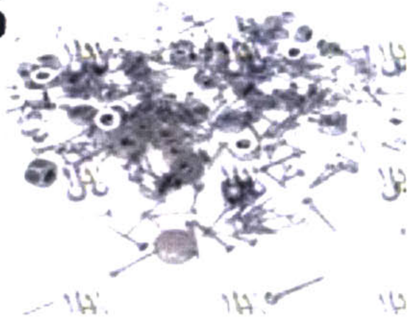
Aluminum
(nonferrous metals)
जर्मन

25

Steel (ferrous metals)

स्टील

26



Small pieces of scrap metal

भंगार

27

Glass bottles

काच

28

Broken glass

काच

29

Beer bottles

बीअर

30

King Fisher Bottles

के पी

31

Liquor bottles, ¼ liter

क्वार्टर

32

Mini liquor bottles

पिल्लू

33

Glass ketchup bottles

टमाता

34

Glass soda bottles

सोडा

35

Cotton or linen textiles

कॉटन

36

Synthetic textiles

कापड

37

Uppers of shoes
ज़ोडा वरील

38

Slippers
चप्पल

39

Diapers
हगीज

40

Sanitary Napkins/Tampons
प्याड

41

Batteries
ब्याटरी

42

E-waste - larger, non-portable, appliances
मोठा ई वेस्ट

43

E-waste – computer-electronics, cell phones
छोटा ई वेस्ट

44

Wood
लाकूड

47

Other Items
इतर वस्तू

45

Carpet
कारपेट

46

Inerts
राबिट

Appendix C: Door-to-Door Waste Collection by WP Cost Model and Data

Model Assumptions

Waste picker is a member of SWaCH

Each household pays SWaCH 30 Rs

PMC pays SWaCH/WPs the amounts outlined in the 2008 MOU

Waste picker collection fee		DATA SOURCE
Fee paid by household per month	30	SWaCH
Fee per household per day (Rs/day)	1	
Average waste generation per household of 4.5 people(g/day)	944	Waste Audit
Household waste generation (kg/day)	0.944	
No. houses served by 1 wastepicker per day	100	RP assumption
Waste collected by 1 waste picker (kg/day)	94.40	
Fee of wastepicker service (Rs/kg)	1.059	
Cost of wastepicker fee (Rs/kg)	**1.059**	
WP Needs		
Rickshaw Maintenance cost per wastepicker (Rs/yr)	500	MOU page 7
Wastepicker Insurance per wastepicker (Rs/yr)	200	MOU page 7
Educational incentives for children of WP per wastepicker (Rs/yr)	300	MOU page 7
Brooms etc. per wastepicker (Rs/yr)	600	MOU page 7
Uniforms and safety gear per wastepicker (Rs/yr)	1000	MOU page 7
Cycle rickshaw per wastepicker (Rs/yr)	7500	MOU page 7
Sum of WP needs cost (Rs/yr)	10100	
WP needs (Rs/day)	27.671	
Wp needs (Rs/kg)	0.293	
Equipment maintenance (Rs/kg)	0.0145	
WP Insurance (Rs/kg)	0.0058	
Educational incentives (Rs/kg)	0.0087	
Brooms (Rs/kg)	0.0174	
Unifroms and safety gear (Rs/kg)	0.0290	
Cycle rickshaw purcahse (Rs/kg)	0.2177	
SWaCH Administration and Salaries		
SWaCH Staff (Rs/yr)	9840000	MOU page 8
SWaCH training (Rs/yr)	1160000	MOU page 8
Citizen outreach (Rs/yr)	5000000	MOU page 8
Office exp (Rs/yr)	5860000	MOU page 8

PMC Cost of Running SWaCH Staff from MOU (Rs/yr)	21860000	
No. of WP in SWaCH	2300	SWaCH
Overhead cost of Wastepicker per year (Rs/yr)	9504.348	
Overhead cost of Wastepicker per day (Rs/day)	26.039	
Overhead cost of WP (Rs/kg)	**0.276**	
Total cost of wastepicker collection (Rs/kg of organic waste)	**1.628**	

Summary of D2D Wastepicker Collection Costs

Breakdown by Element	**Rs/ton**	**Rs/kg**
Capital	264.1	0.264
Maintenance	14.511	0.015
Labor	1073.8	1.074
Operations & Energy	0	0.000
Material	0	0.000
Building and Land	0	0.000
Overhead	275.8	0.276
Total Cost	**1628.3**	**1.628**
Revenue	**0**	**0**

Breakdown by Stakeholder	**Rs/ton**	**Rs/kg**
Cost borne by residents	1059.3	1.059
Cost borne by PMC	569.0	0.569
Cost borne by other (Donation/SWaCH)	0	0
Total Cost	0	0

Appendix D: Primary and Secondary Collection Cost Model and Data

Model Assumptions Regarding Primary and Secondary Collection

1/3 of city's vehicles are waste vehicles
1/2 of transportation labor is waste transportation labor
Aundh is one of 15 administrative wards in Pune, and contains about 1/15 of the city's population
1/2 of labor is allocated to primary collection
1/2 of labor is allocated to secondary collection
1/3 of vehicle maintenance is allocated to primary collection
2/3 of vehicle maintenace is allocated to secondary collection

Labor Positions	**Number of Workers in Each Position**	**Monthly Gross Cost of Labor**	**Yearly Cost of Labor**	**Data Source**
Executive Engineer	1	99280	1191360	PMC
Deputy Exec engineer	1	65266	783192	PMC
Junior engineer	5	268309.3	3219711.6	PMC
Transport inspector	1	591242	7094904	PMC
Forman	2	96710	1160520	PMC
Sub inspector of vehicles	2	89515	1074180	PMC
vehicle inspector	2	81860	982320	PMC
Senior clerk	3	122594	1471128	PMC
Painter	1	31421	377052	PMC
Head electrician	1	46653	559836	PMC
Gas welder	2	85202	1022424	PMC
Motor mechanic	15	562915	6754980	PMC
Head tire fitter	1	43838	526056	PMC
Senior carpenter	1	46653	559836	PMC
Welder	1	36983	443796	PMC
Metal worker	2	58984	707808	PMC
Cushion maker	1	40138	481656	PMC
Auto body fitter	1	33510	402120	PMC
Auto body laborer	30	875540	10506480	PMC
Battery remolding	1	38799	465588	PMC
Tool room assistant	1	29038	348456	PMC
Body assembly fitter	2	64681	776172	PMC
Auto electrician	3	89042	1068504	PMC
Store room assistant	1	38821	465852	PMC
Carpenter	2	68200	818400	PMC
Junior grade accountant	14	326463	3917556	PMC
Schedule coordinator	1	40229	482748	PMC
Welder	1	27744	332928	PMC
Garage assistant	5	182802	2193624	PMC

Tin smith	1	41500	498000	PMC
Fuel pump attendant	5	146782	1761384	PMC
Assistant fitter	19	479408	5752896	PMC
Assistant welder	1	30218	362616	PMC
Battery men	1	24906	298872	PMC
Head loaders	4	95586	1147032	PMC
Assistant body maintenance	1	31149	373788	PMC
Spray painter	1	35939	431268	PMC
Unskilled labor	71	1467809	17613708	PMC
Office Cleaner	1	22341	268092	PMC
Watchman	1	19776	237312	PMC
		TOTAL FOR ALL OF PUNE (Rs)	**78,934,156**	

Pune city transportation labor cost (Rs/yr)	78,934,155.60
Pune city waste transportation labor cost (Rs/yr)	39,467,077.80
Aundh ward waste transportation labor cost (Rs/yr)	2,631,138.52
Aundh primary collection labor cost (Rs/yr)	**1,315,569.26**
Aundh secondary collection labor cost (Rs/yr)	**1,315,569.26**

PRIMARY COLLECTION COSTS

		DATA SOURCE
Assumed Discount Rate	7%	Assumption
Tons waste transported to Aundh T.S. (tons/month)	1582.45	Aundh Transfer Station Records
Tons waste transported to Aundh T.S. (tons/day)	52.75	
Tons waste transported to Aundh T.S. (tons/year)	18989.40	

Capital Costs

Primary Collection Vehicles	**Purchase Cost (Rs)**	**Lifetime**	**Annualized Capital Cost (Rs/yr)**	
(transport from Aundh dumpsters to Aundh transfer station)				**DATA SOURCE**
Double Bucket Gadi	1,000,000	20	94,392.93	PMC Vehicle Depot records
Dumpster Placer 1	700,000	20	66,075.05	PMC Vehicle Depot records
Dumpster Placer 2	700,000	20	66,075.05	PMC Vehicle Depot records
Dumpster Placer 3	661,221	20	62,414.58	PMC Vehicle Depot records
Dumpster Placer 4	1,390,050	20	131,210.89	PMC Vehicle Depot records
Dumpster Placer 5	1,390,050	20	131,210.89	PMC Vehicle Depot records

Dumpster Placer 6	1,390,050	20	131,210.89	PMC Vehicle Depot records
Ghantagadi (Closed Gadi) 1	1,435,461	20	135,497.33	PMC Vehicle Depot records
Ghantagadi (Closed Gadi) 2	1,435,461	20	135,497.33	PMC Vehicle Depot records
Hotel Gadi	893,597	20	84,349.20	PMC Vehicle Depot records
Tipper 1	800,000	20	75,514.34	PMC Vehicle Depot records
Tipper 2	800,000	20	75,514.34	PMC Vehicle Depot records
Total	**12,595,889**		**1,188,963**	

Monthly Diesel Use (L/month)

Primary Collection Vehicles	**Jan-15**	**Feb-15**	**Mar-15**	**Average Monthly Diesel (L/month)**	**DATA SOURCE**
Double Bucket Gadi	0	0	0	0.0	PMC Vehicle Depot Diesel records
Dumpster Placer 1	16	20	30	22.0	PMC Vehicle Depot Diesel records
Dumpster Placer 2	0	0	0	0.0	PMC Vehicle Depot Diesel records
Dumpster Placer 3	224	302	507	344.3	PMC Vehicle Depot Diesel records
Dumpster Placer 4	480	728	489	565.7	PMC Vehicle Depot Diesel records
Dumpster Placer 5	362	297	358	339.0	PMC Vehicle Depot Diesel records
Dumpster Placer 6	541	445	690	558.7	PMC Vehicle Depot Diesel records
Ghantagadi (Closed Gadi) 1	82	165	252	166.3	PMC Vehicle Depot Diesel records
Ghantagadi (Closed Gadi) 2	381	176	218	258.3	PMC Vehicle Depot Diesel records
Hotel Gadi	180	140	135	151.7	PMC Vehicle Depot Diesel records
Tipper 1	67	134	210	137.0	PMC Vehicle Depot Diesel records
Tipper 2	240	20	150	136.7	PMC Vehicle Depot Diesel records

Monthly Diesel (L/month)	**2679.7**
Yearly Diesel (L/year)	**32156**

Diesel Prices

Date of data source	**Diesel price (Rs/litre)**	**DATA SOURCE**
12/16/2014	57.93	mypetrolprice.com
1/17/2015	55.46	mypetrolprice.com
2/4/2015	52.96	mypetrolprice.com
2/16/2015	53.17	mypetrolprice.com
3/1/2015	56.26	mypetrolprice.com
4/2/2015	55.71	mypetrolprice.com
4/15/2015	54.28	mypetrolprice.com

5/1/2015	56.65		mypetrolprice.com
Average Diesel Cost (Rs/L)	**55.30**		

Primary Collection Diesel Cost (Rs/yr)	**1,778,307.19**
Aundh primary collection labor cost (Rs/yr)	**1,315,569.26**

Vehicle Maintenance Cost		**DATA SOURCE**
Maintenance of waste trucks for all of Pune (Rs/yr)	30,000,000	PMC Vehicle Depot Staff
Aundh/Pune maintenance allocation	1/15	Assumption
Maintenance of waste trucks for all of Aundh (Rs/yr)	2,000,000	
Primary collection maintenance allocation	2/3	Assumption
Maintenance of primary collection waste trucks (Rs/yr)	**1,333,333**	

Distance Traveled

Primary Collection Vehicles	**Avg. No. Daily Trips**	**Estimated Distance per Trip (km)**	**Distance per day (km/day)**	**DATA SOURCE**
Double Bucket Gadi	4	4	16	PMC truck route/Google maps
Dumpster Placer 1	5	4	20	PMC truck route/Google maps
Dumpster Placer 2	5	4	20	PMC truck route/Google maps
Dumpster Placer 3	4	4	16	PMC truck route/Google maps
Dumpster Placer 4	2	4	8	PMC truck route/Google maps
Dumpster Placer 5	9	4	36	PMC truck route/Google maps
Dumpster Placer 6	5	4	20	PMC truck route/Google maps
Ghantagadi (Closed Gadi) 1	2	15	30	PMC truck route/Google maps
Ghantagadi (Closed Gadi) 2	2	15	30	PMC truck route/Google maps
Hotel Gadi	2	15	30	PMC truck route/Google maps
Tipper 1	2	15	30	PMC truck route/Google maps
Tipper 2	2	15	30	PMC truck route/Google maps
	Primary Transportation Distance (km/day)			286
	Primary Transportation Distance (km/yr)			94380

Primary Collection Summary

Element	**Per Year (Rs/yr)**	**Per Ton (Rs/ton)**	**Per kilometer (Rs/km)**
Annualized Capital	1,188,962.80	62.61	12.60
Labor	1,315,569.26	69.28	13.94
Diesel	1,778,307.19	93.65	18.84
Maintenance	1,333,333.33	70.21	14.13
Total Cost of Primary Collection	**5,616,173**	**295.75**	**59.51**

SECONDARY COLLECTION COSTS

		DATA SOURCE
Tons transported from T.S. to centralized (tons/month)	1582.45	Aundh Transfer Station Records
Tons transported from T.S. to centralized (tons/day)	52.75	
Tons transported from T.S. to centralized (tons/year)	18989.40	

(transport from Aundh transfer station to centralized compost facility or landfill)

Capital Costs

Secondary Collection Vehicles	**Purchase Cost (Rs)**	**Lifetime**	**Annualized Capital Cost (Rs/yr)**	
Bulk Refuse Carrier 1	1,700,000	20	160,467.97	PMC Vehicle Depot records
Bulk Refuse Carrier 2	2,300,000	20	217,103.73	PMC Vehicle Depot records
Bulk Refuse Carrier 3	1,400,000	20	132,150.10	PMC Vehicle Depot records
Bulk Refuse Carrier 4	1,700,000	20	160,467.97	PMC Vehicle Depot records
Bulk Refuse Carrier 5	2,300,000	20	217,103.73	PMC Vehicle Depot records
BRC (Closed Gadi)	839,597	20	79,251.99	PMC Vehicle Depot records
Compactor	1,700,000	20	160,467.97	PMC Vehicle Depot records
Total	**11,939,597**		**1,127,013**	

Diesel Costs

	Monthly Diesel Use (L/month)				
Secondary Collection Vehicles	**Jan-15**	**Feb-15**	**Mar-15**	**Average Monthly Diesel (L/month)**	
BRC 1	333	684	790	602.33	PMC Vehicle Depot Diesel records
BRC 2	388	170	450	336.00	PMC Vehicle Depot Diesel records

BRC 3	20	50	0	23.33	PMC Vehicle Depot Diesel records
BRC 4	597	868	1248	904.33	PMC Vehicle Depot Diesel records
BRC 5	760	948	1680	1129.33	PMC Vehicle Depot Diesel records
BRC Closed Gadi	140	85	135	120.00	PMC Vehicle Depot Diesel records
Compactor	295	295	360	316.67	PMC Vehicle Depot Diesel records
		Monthly Diesel (L/month)		**3432**	
		Yearly Diesel (L/year)		**41184**	

Average Diesel Cost (Rs/L)	**55.3025**
Secondary Collection Diesel Cost (Rs/yr)	**189,798.18**

Vehicle Maintenance Cost

Maintenance of waste trucks for all of Pune (Rs/yr)	30,000,000	PMC Vehicle Depot Staff
Aundh/Pune maintenance allocation	1/15	Assumption
Maintenance of waste trucks for all of Aundh (Rs/yr)	2,000,000	
Secondary collection maintenance allocation	1/3	Assumption
Maintenance of secondary collection waste trucks (Rs/yr)	**666,667**	

Distance Traveled

	Avg. No. Daily Trips	**Estimated Distance per Trip (km)**	**Distance per day (km/day)**	
BRC 1	1	40	40	PMC truck routes/Google maps
BRC 2	2	40	80	PMC truck routes/Google maps
BRC 3	2	40	80	PMC truck routes/Google maps
BRC 4	1	40	40	PMC truck routes/Google maps
BRC 5	1	40	40	PMC truck routes/Google maps
BRC Closed Gadi	2	40	80	PMC truck routes/Google maps
Compactor	2	15	30	PMC truck routes/Google maps
Secondary Transportation Distance (km/day)			**390**	

Summary Secondary Collection

Element	**Per Year (Rs/yr)**	**Per Ton (Rs/day)**	**Per ton per km (Rs/ton-km)**
Annualized Capital	1,127,013.46	59.35	8.76
Labor	1,315,569.26	69.28	10.22
Diesel	2,277,578.16	119.94	17.70
Maintenance	666,666.67	35.11	15.18
Total Cost of Secondary Collection	5,386,828	283.68	**41.86**

Appendix E: Landfill Cost Model and Data

Assumptions		**DATA SOURCE**
Landfill lifetime (yrs)	40	Estimate
Operation days per year (days/yr)	330	Industry Standard
Landfill is uncovered and without gas capture		
Tonnage of Waste Landfilled		
Tons of waste going to landfill (tons/day)	650	Waste audit and PMC
Tons of waste going to landfill (tons/year)	214500	Waste audit and PMC
Transportation		
Primary Collection (Rs/ton)	295.75	RP Model
Secondary Collection (Rs/ton)	283.68	RP Model
Capital Costs		
Size of Landfill (Square meters)	220000	Goldstein, 2015
Property Value (Rs/sq m)	5380	Nearby property values listed online
Land Value (Rs)	1183600000	Nearby property values and land area
Construction (Rs)	500,000.00	Estimate
Permit Cost (Rs)	0	PMC
Closure Cost (Rs)	5,000,000.00	Estimate
Operations		
Operations (tractor diesel etc.) (Rs/yr)	3,000,000.00	Estimate
Maintenance of equipment (Rs/yr)	40,000.00	Estimate
Unplanned Costs (protests, fires, etc) (Rs/yr)	1,000,000.00	Estimate
Labor		
Labor (Rs/yr)	2,000,000	Estimate
Summary of Costs		
Breakdown by Cost Element		
Annual Costs	**Rs/yr**	
Annualized Capital	375046	
Maintenance	40000	
Labor	2000000	
Operations	4000000	
Materials	0	

Building and Land	88818321
Overhead	0
Transportation	76484760
Total Cost (Rs/yr)	**171,718,127**
Total Revenue (Rs/yr)	**0**

Costs per Ton	**Rs/ton**
Capital	2.84
Maintenance	0.30
Labor	15.15
Operations and Energy	30.30
Materials	0
Building and Land	672.87
Overhead	0
Transportation	579.43
Door-to-Door Collection	1628.29
Total Cost (Rs/ton)	**2,929.18**
Total Revenue (Rs/ton)	**0**

Appendix F: Composting Cost Model and Data

Scale of Facility (tons/day)	**0.2**	**2**	**100**	**200**
DATA SOURCE (FOR EACH COLUMN)	**INORA**	**PMC & Excel Industries Limited**	**PMC & Disha**	**Ajinkya Biofert**
Type of Composting System	Society Mechanical+ Pit Composting	Mechanical Composting Plant	Vermi-composting; 220 pits each 6m x 1.4m x .75m	Vermicomposting
Location	Residential Society (unspecified)	Aundh Transfer Station	Plot No. 87, Ramtekdi Industrial State	Plot No. 100 Hadapsar Industrial Estate
Actor running the facility	PMC	Society Association & INORA	Disha Waste Management	Ajinkya Biofert
Owner of Finished Compost	Society (unless it sells it back to INORA)	Excel (but currently giving it to PMC)	Disha (but currently giving it to PMC)	Ajinkya (but currently giving it to PMC)
Equipment Used	OWC	1 OWC 500 Excel	High Speed Grader with 5 HP, 1440 RPM motor	2 Pre Segregation Trommels - 5 HP Motor, 20 mm Sieve
	10 kg machine batch	8 Composting Curing Systems	2 Pre Segregation Trommels - 5 HP Motor, 20 mm Sieve	2 Loaders
	capacity 2 tons/day	1 Composting Shredder	2 Loaders	Final Product Segregation Trommel - 5 HP motor, 2.5 mm sieve
		2 Iron Trolleys	Final Product Segregation Trommel - 5 HP motor, 2.5 mm sieve	9 conveyors
		1 Converyer	9 conveyors	Hand trolleys for material handling Electronic weighing scale Packing and sealing machine
			Hand trolleys for material handling Electronic weighing scale Packing and sealing machine	
Days operating per	330	330	330	330

year				
Transportation				
TRANSPORT FROM WASTE COLLECTION				
Cost of Primary Transportation (Rs/ton)	0	295.75	295.75	295.75
Cost of Primary Transportation (Rs/yr)	0	195196.96	9759847.92	19519695.85
Cost of Secondary Transportation (Rs/ton)	0	0	283.68	283.68
Cost of Secondary Transportation (Rs/yr)	0	0	9361289.54	18722579.08
TRANSPORT FROM TRUCKING FINISHED COMPOST				
Truck size (tons)	1.5	1.5	1.5	1.5
Distance traveled (km)	10	10	20	20
Cost of this transport (Rs.)	400	400	400	400
Annual Compost Generated (tons/yr)	16.5	102.828	4059	8118
Number of trucks needed to transport in a yr	0.011	0.068552	2.706	5.412
Overhead				
Profit to Excel Industries (12% of Operations Cost)	N/A	181,753.20	N/A	N/A
Profit to Disha (12% of Operations Cost)	N/A	N/A	2545933.997	N/A
Profit to Ajinkya (12% of Operations Cost)	N/A	N/A	N/A	2851446.077
Building and Land				
Space/Land Used (sq meters)	70	300.00	22,000.00	22,000.00
Cost of Land (Rs/sq meter/month)	150	150.00	102.00	102.00
Cost of Land (Rs/yr)	126,000.00	540,000.00	26,928,000.00	26,928,000.00

Construction (Rs)	5000	900,000.00	N/A	N/A
Building Lifetime (yrs)	20	20	20	20
Discont Rate	7%	7%	7%	7%
Construction at Disha & Ajinkya				
Construction of Bin Shed	N/A	N/A	21,428,612	21,428,612
Windrow Shed	N/A	N/A	9,183,691	9,183,691
Construction of 360 Bins	N/A	N/A	13,010,229	13,010,229
Office and Watchman Cabin	N/A	N/A	765,308	765,308
Electrical Work	N/A	N/A	765,308	765,308
Total Construction (Rs)	N/A	N/A	45,153,147.22	45,153,147
Annualized Cost of Construction	471.96	84953.63	4262137.67	4262137.67
Materials				
Cost of source-segregated organic waste (Rs/ton)	0	0	0	0
Percentage of input waste that is compostable	100%	82%	82%	82%
Quantity of Compostable organics (tons/day)	0.2	1.64	82	164
Percentage of input waste that is refuse	0%	8%	8%	8%
Quantity of Refuse (tons/day)	0	0.16	8	16
Quantity of Finished Compost (fraction of original organic mass)	0.25	0.19	0.15	0.15
Quantity of Finished Compost (tons/day)	0.05	0.31	12.30	24.60
Operations and Energy				
PACKAGING of INORA COMPOST				
Packaging process (Rs./ton compost)	170	N/A	N/A	N/A

Packaging process (Rs/yr)	2805	N/A	N/A	N/A
OPERATIONS				
Electricity Usage (KWH/day)	3	35.30	706.00	1,059.00
Base Cost electricity (Rs/kwh)	7	7	7.00	7.00
Electricity tax/other charges (Rs/KWH)	0	3.97	3.97	3.97
Cost electricity (Rs/day)	126	387.24	7,744.82	11,617.23
Cost electricity (Rs/yr)	41580	127789.53	2555790.6	3833685.9
Labor for collection and pile management				
PACKAGING of INORA COMPOST				
Labor cost Rs./1 ton compost	50	N/A	N/A	N/A
Average wastepicker earning (Rs/yr) (Chikarme, 2012)	72,000.00	N/A	N/A	N/A
Operators (Number of People)	N/A	5.00	30.00	45
Operator Salary (Rs/yr)	N/A	84,000.00	84,000.00	84,000.00
Supervisor (Number of people)	N/A	1.00	8.00	12
Supervisor Salary (Rs/yr)	N/A	126,000.00	150,000.00	150,000.00
Manager (Number of People)	N/A	0.10	4.00	4
Manager Salary (Rs/yr)	N/A	540,000.00	540,000.00	540,000.00
Total Cost of Labor (Rs/yr)	72825.00	600,000.00	5,880,000.00	7,740,000.00
Maintenance				
Machinery maintenance and repair (Rs/yr)	17000	732,856.57	12,790,182.64	13,170,604.56
Capital				
Discount Rate	7%	7%	7%	7%

Equipment Life (yrs)	20	20	20	20
Equipment at Society and OWC				
Set-up of compost site, after construction. Rs./kg waste processed daily	1500	N/A	N/A	N/A
Machinery (primarily OWC machine) Rs	1500000.00	2,441,600.00	N/A	N/A
Equipment at Disha & Ajinkya				
Pipeline Sprinklers	N/A	N/A	1,913,269	1,913,269
Machinery	N/A	N/A	9,948,999	9,948,999
2 Loaders and Internal Transport (6 conveyers)	N/A	N/A	4,591,845	4,591,845
Earthworms	N/A	N/A	2,295,923	2,295,923
Water Tank, Leachate Tank	N/A	N/A	1,913,269	1,913,269
Total Equipment	N/A	N/A	20,663,304.66	20,663,305
Revenue				
SALE OF FINISHED COMPOST				
Buyback rate (INORA buys from societies) Rs./kg compost	3.5	N/A	N/A	N/A
Selling rate (Nurseries/farms etc. buy from INORA) Rs./kg compost	8	N/A	N/A	N/A
Selling rate bulk Rs./ton compost	8000	8,000.00	8,000.00	8,000.00
Selling rate small orders Rs./ton compost	15000			
Sale of 100 kg (Rs)	1500			
Sale of truck load (Rs)	10,000			
Revenue from sale of finished compost (Rs/yr)	132,000	822,624	32,472,000	64,944,000

Cost Per Year (Rs/yr)				
Capital	141,730.98	230,469.77	1,950,469.78	1,950,469.78
Maintenance	17,000.00	732,856.57	12,790,182.64	13,170,604.56
Labor	72,825.00	600,000.00	5,880,000.00	7,740,000.00
Operations and Energy	44,385.00	127,789.53	2,555,790.60	3,833,685.90
Materials	0.00	0.00	0.00	0.00
Building and Land	126,471.96	624,953.63	31,190,137.67	31,190,137.67
Overhead	0.00	181,753.20	2,545,934.00	2,851,446.08
Transportation	0.00	195,196.96	19,121,137.47	38,242,274.93
Door-to-Door Collection	107,467.14	1,074,671.40	53,733,570.00	107,467,140.00
TOTAL COST (Rs/yr)	509,880.08	3,767,691.06	129,767,222.16	206,445,758.93
REVENUE (Rs/yr)	132,000.00	822,624.00	32,472,000.00	64,944,000.00
Net COST (Rs/yr)	377,880.08	2,945,067.06	97,295,222.16	141,501,758.93

Cost Per Ton (Rs/ton)	**0.2 TPD Plant**	**2 TPD Plant**	**100 TPD Plant**	**200 TPD Plant**
Capital	2,147.44	349.20	59.11	29.55
Maintenance	257.58	1,110.39	387.58	199.55
Labor	1,103.41	909.09	178.18	117.27
Operations and Energy	672.50	193.62	77.45	58.09
Materials	0.00	0.00	0.00	0.00
Building and Land	1,916.24	946.90	945.16	472.58
Overhead	0.00	275.38	77.15	43.20
Transportation	0.00	295.75	579.43	579.43
Door-to-door Collection	1628.29	1628.29	1628.29	1628.29
TOTAL COST (Rs/ton)	**7,725.46**	**5,708.62**	**3,932.34**	**3,127.97**
REVENUE (Rs/ton)	**2,000.00**	**1,246.40**	**984.00**	**984.00**
Net COST (Rs/ton)	**5,725.46**	**4,462.22**	**2,948.34**	**2,143.97**

Appendix G: Anaerobic Digester Cost Model and Data

Transportation		Data Source	**Comment**
Cost primary collection (Rs/ton)	296	RP Model	
Cost transfer station to biogas plant (Rs/ton)	150	RP Model	
Cost biogas plant to landfill (Rs/ton)	283.68	RP Model	
Relevant Prices and Cost Factors			
Market price for solid fertilizer (Rs/kg)	20	Market research	1000 Rs/50 kg bag
Market price for electricity (Rs/KWH)	7	Biogas company	
Tipping fee for refuse (Rs/ton)	0	Biogas company	PMC takes away rejects for free
Transportation cost of refuse to landfill, paid by PMC (Rs/ton)	700	Biogas company	
Discount Rate assumed	0.07	Assumption	Avg public and private risk
Water use cost	0	Biogas company	
Water treatment cost	0	Biogas company	
CNG market price (Rs/kg)	47	Market research	
Facility/ Process Features for a 5 ton plant			
Amount waste processed (Tons/day)	5	Biogas company	
Retention Time (days)	28	Biogas company	
Slurry storage capacity (kL)	10	Biogas company	
Days running per year (d/yr)	330	Biogas company	
Lifetime of equipment (yrs)	20	Biogas company	

Input waste % organic	92%	Biogas company
Input waste % refuse	8%	Biogas company
Water (M^3/ton waste)	5	Biogas company
Water (M^3/day)	1	Biogas company
Water recycing rate	5	Biogas company
Food waste solid content	0.7	Biogas company
Electricity for bower, crusher, etc (KWH/day)	25	Biogas company
Electricity for bower, crusher, etc (KWH/day/ton of waste)	5	Calculation
Refuse sent to dump (tons/d)	0.4	Biogas company
Liquid overflow (M^3/d)	5	Biogas company
Waste water (% of used)	0.3	Biogas company
Waste water (M^3/day)	1.5	Biogas company
Fertilizer generated (kg/d/1 ton organic waste)	100	Biogas company
Fertilizer generated for 5 ton plant, 7% TS(kg/d)	500	Biogas company
Equivalent amount of solid fertilizer generated (kg/d)	2.12	Calculation
Fertilizer density (kg/m^3)	1044	Fertilizer Company
Biogas generated from mixed waste (m^3/ton of waste)	60	Biogas company
Biogas generated from food waste (m^3/ton of waste)	70	Biogas company
Biogas per day (m^3/d)	300	Calculation
Electricity generated (KWH/1 M^3 biogas)	1.4	Biogas company
Electricity generated (KWH/plant/day)	420	Calculation
Electricity generated yearly (KWH/plant/yr)	138600	Calculation
Standard N Solid Fertilizer (%)	0.1	Biogas company
Standard P Fertilizer (%)	0.26	Biogas

				company
Standard K Solid Fertilizer (%)	0.26			Biogas company
Standard N Solid Fertilizer (ppm)	100000			Calculation
Standard P Solid Fertilizer (ppm)	260000			Calculation
Standard K Solid Fertilizer (ppm)	260000			Calculation
Slurry N Content (ppm)	4486			Biogas company
Slurry P Content (ppm)	3469			Biogas company
Slurry K Content (ppm)	1100			Biogas company
Concentration rate N	22.29			Calculation
Concentration rate P	74.95			Calculation
Concentration rate K	236.36			Calculation
Limiting Nutrient concentration factor	236.36			Calculation
Biogas to CNG conversion	0.00410			Biogas company
CNG density (kg/m^3)	160			Biogas company
Chemical Properties	**Inlet Slurry Feed (Input)**	**Fertilizer**	**Waste Water**	
COD (mg/L)	160169	106355	33541	Biogas company
BOD (mg/L)	5900	6000	10500	Biogas company
pH	4.26	7.5	6.92	Biogas company
Total Solids (mg/L)	67292	53944	17376	Biogas company
Total dissolved solids (mg/L)	33540	6147	5665	Biogas company
Total Suspended Solids (mg/L)	33752	47797	11711	Biogas company
Total Volatile Solids @ 550 C (mg/L)	58488	39748	12072	Biogas company
Total Organic Carbon (mg/L)	146690	52109	13598	Biogas company
Total Kjeldahl Nitrogen (mg/L)	4330	4486	-	Biogas company
C:N ratio	33.88	11.62	-	Biogas company
Total Phosphorus (mg/L)	-	3469	-	Biogas company
Total Potassium (mg/L)	-	1100	-	Biogas

				company
Humic Acid (mg/L)	-	2551	-	Biogas company
Capital Costs for a 5 ton plant				
Capital Cost of building the facility (Rs)	9000000			Biogas company
Labor for a 5 ton plant				
Salary for 4 operators and 1 supervisor (Rs/yr)	676000	1		Biogas company
Salary per manager (Rs/yr)	184364			Assumption
Salary per operator (Rs/yr)	122909.0909			Assumption
Number of operators	4			Biogas company
Number of managers	1			Biogas company
Operations and Management for a 5 ton plant				
Laboratory testing (Rs/yr)	6000			Biogas company
Personal Protective equipment (Rs/yr)	30000			Biogas company
Room rent (Rs/yr/sq km)	96			Calculation
Room rent (Rs/yr)	48000			Biogas company
Maintenance of equipment (Rs/yr)	18000			Biogas company
Consumables and lubricants (oil and grease for engine)(Rs/yr)	18000			Biogas company
Consumables and lubricants (Rs/yr/ton of waste)	3600			Calculation
Administration for a 5 ton plant				
Overhead (computers, telephone, stationary etc) (Rs/yr)	12000		1 supervisor gets paid 1.5 operator	Biogas company
Overhead (Rs/yr/ton of waste)	2400			Calculation
Total Yearly expense to company (Rs/yr)	117696			Biogas company
Profit margin (Rs/yr)	0.12			Biogas company
Total yearly price quoted to PMC (Rs/yr)	131819.52			Biogas company

Contract price of company (Rs/yr)	14123.52	Biogas company

Anaerobic Digester Costs by Scale

Biogas Plant SIZE (tons/day)	**0.1**	**0.5**	**0.6**	**2**	**5**	**100**
Num of Operators	1	1	1	2	4	20
Num of Supervisors	0	0	0	1	1	3
Spatial Area req	9	50	55	160	500	10117
Capital Cost (Rs)	480000	640000	1541000	1925000	9000000	140000000
No. of digesters	1	1	1	1	1	2
Size each digester (tons)	0.1	0.5	0.6	2	5	50
Spatial area (m^2)	9	50	55	160	500	10117

	Plant Capacity in Tons						
Annual Costs	**0.1**	**0.5**	**0.6**	**2**	**5**	**100**	**VARIABLES DEPENDENT ON**
Transportation cost (Rs/yr)	10517	52585	63101	210338	773346	15466915	f(tons refuse, rate per ton landifll, tons degradable, rate to biogas)
Annualized capital costs (Rs/yr)	45309	60411	145459	181706	849536	13215010	f(lifetime, discount rate, capital cost)
Electricity cost operations (Rs/yr)	1155	5775	6930	23100	57750	1155000	scales linearly with capacity
Labor cost (Rs/yr)	122909	122909	122909	430182	676000	3011273	f(salary operator, num operators, salary supervisor, num supervisors)
Consumables and lubricants (Rs/yr)	360	1800	2160	7200	18000	360000	scales linearly with capacity
Maintenance of Equipment (Rs/yr)	906	1208	2909	18000	16991	264300	scales with capital cost, 2% of capital
Personal Protective equipment (Rs/yr)	7500	7500	7500	15000	30000	150000	scales linearly with number of operators
Overhead (computers, telephone,	240	1200	1440	4800	12000	240000	scales linearly with capacity

stationary etc) (Rs/yr)							
Laboratory testing (Rs/yr)	6000	6000	6000	6000	6000	6000	constant
Room Rent (Rs/yr)	864	4800	5280	15360	48000	971232	scales linearly with plot area
Contract price of Company (Rs/yr)	16792	18143	18615	62357	103769	738937	12% of company operation cost
Total Annual Costs (Rs/yr)	217502	307081	412005	1073044	2591392	35578666	sum of all above costs
	Plant Capacity in Tons						
Annual Revenue	**0.1**	**0.5**	**0.6**	**2**	**5**	**100**	**VARIABLES DEPENDENT ON**
Electricity Revenue (Rs/yr)	22638	113190	135828	452760	1131900	22638000	f(price electricity, days per yr, biogas/waste, electricity/biogas)
Fertilizer Revenue (Rs/yr)	279	1396	1675	5585	13962	279231	f(price fertilizer, npk concentration factor, quantity slurry output)
Total Annual Revenue (Rs/yr)	22917	114586	137503	458345	1145862	22917231	sum of Fertilizer and electricity revenue
	Plant Capacity in Tons						
Net Cost	**0.1**	**0.5**	**0.6**	**2**	**5**	**100**	**VARIABLES DEPENDENT ON**
Net Cost (Rs/yr)	194585	192495	274501	614699	1445530	12661436	Rev minus cost
Net Cost per ton processed (Rs/ton)	5896.5	1166.6	1386.4	931.4	876.1	383.7	net cost Divided by capacity

Costs Per Ton

Scale	**0.1**	**0.5**	**0.6**	**2**	**5**	**100**
PER TON COSTS						
Capital	1373	366	735	275	515	400
Maintenance	27	7	15	27	10	8
Labor	3725	745	621	652	410	91
Operations and Energy	217	71	65	44	39	35
Materials	238	56	49	34	29	15
Building and Land	26	29	27	23	29	29
Overhead	516	117	101	102	70	30
Transportation	319	319	319	319	469	469
Door-to-door Collection	1628	1628	1628	1628	1628	1628

Total Cost Per Ton	8069	3339	3559	3104	3199	2706
Revenue Per Ton	694	694	694	694	694	694
Net Cost Per Ton	7375	2645	2865	2410	2504	2012

Appendix H: Pelletization Cost Model and Data

Plant Size (Tons per day)	0.5	1	2	5	10	Data Source
Facility						
Days operating per year (days/yr)	330	330	330	330	330	Industry Standard
Space/Plot area needed (square feet)	500	900	1500	3000	4000	Gondhalekar, 2015
Cost of land purchase or rental (Rs/yr)	Available Free	Available Free	Available Free	Available Free	Available Free	Gondhalekar, 2015
Capital Costs						
Building /structure construction cost (Rs)	100,000	150,000	250,000	600,000	1,000,000	Gondhalekar, 2015
Building lifetime (yrs)	20	20	20	20	20	Estimate
Shredder (Rs)	300,000	400,000	500,000	900,000	1,500,000	Gondhalekar, 2015
Dryer machine (Rs) BioDrying Process	400,000	600,000	900,000	1,800,000	2,500,000	Gondhalekar, 2015
Pellet press (Rs)	400,000	500,000	700,000	1,500,000	2,000,000	Gondhalekar, 2015
Machinery lifetime (yrs)	10	10	10	10	10	Estimate
Other equipment (Rs)	100,000	150,000	250,000	600,000	1,000,000	Gondhalekar, 2015
Labor						
Employees needed at plant	2	3	4	6	10	Gondhalekar, 2015
Cost of labor (Rs/ YEAR)	200,000	300,000	400,000	600,000	1,000,000	Gondhalekar, 2015
Transportation						
Cost primary collection (Rs/ton)	148	296	592	1,479	2,958	RP Transportation Calculation
Cost TS to pellet plant (Rs/ton)	75	150	300	750	1,500	Biogas company
Operating Costs						
Energy consumption per day (KWH/day)	40	70	130	300	500	Gondhalekar, 2015
Hrs operating per day	2	2	2	2	2	Gondhalekar, 2015
Electricity cost (Rs/KWH)	7	7	7	7	7	Online statistics
Electricity cost (Rs/day)	280	490	910	2100	3500	

Input material						
Water content of incoming organic waste (%)	80	80	80	80	80	Gondhalekar, 2015
Output Material						
Output pellet mass (kg/day)	100	200	400	1,000	2,000	Gondhalekar, 2015
Sale price of pellets (Rs/kg)	5	5	5	5	5	Gondhalekar, 2015
Overhead						
Administration costs (Rs/yr)	50,000	75,000	200,000	300,000	300,000	Gondhalekar, 2015
Maintenance Cost						
Maintenance of machinery (Rs/yr)	50,000	75,000	125,000	300,000	500,000	Gondhalekar, 2015
Other Figures						
Discount Rate	7%	7%	7%	7%	7%	Estimate

ANNUAL COST PELLETIZATION	**0.5 TPD plant**	**1 TPD plant**	**2 TPD plant**	**5 TPD plant**	**10 TPD plant**
Capital	170853.0	155748.3	221823.4	453086.0	660750.5
Maintenance	50,000	75,000	125,000	300,000	500,000
Labor	200,000	300,000	400,000	600,000	1,000,000
Operations & Energy	92400	161700	300300	693000	1155000
Materials	0	0	0	0	0
Building and Land	9439.3	14158.9	23598.2	56635.8	94392.9
Overhead	50,000	75,000	200,000	300,000	300,000
Transportation	73548.75	147097.5	294195	735487.5	1470975
Total Cost	646241.05	928704.77	1564916.61	3138209.30	5181118.41
Revenue	165000	330000	660000	1650000	3300000

PER TON COST PELLETIZATION	**0.5 TPD plant**	**1 TPD plant**	**2 TPD plant**	**5 TPD plant**	**10 TPD plant**
Net cost	2917	1814	1371	902	570
Revenue	1000	1000	1000	1000	1000
Total Cost	3916.6	2814.3	2371.1	1901.9	1570.0
Cost without Transportation	3470.9	2368.5	1925.3	1456.2	1124.3

PER TON COST BY ELEMENT	**0.5 TPD plant**	**1 TPD plant**	**2 TPD plant**	**5 TPD plant**	**10 TPD plant**
Capital	1035.5	472.0	336.1	274.6	200.2
Maintenance	303.0	227.3	189.4	181.8	151.5
Labor	1212.1	909.1	606.1	363.6	303.0
Energy	560.0	490.0	455.0	420.0	350.0
Materials	0.0	0.0	0.0	0.0	0.0
Building and Land	57.2	42.9	35.8	34.3	28.6
Overhead	303.0	227.3	303.0	181.8	90.9
Transportation	445.8	445.8	445.8	445.8	445.8