Uncovering Hidden Flows of Plastic

Landscaping the Plastic Waste Management System of a City in the Global South - A Case Study of Chennai, India

MSc Industrial Ecology

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by

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An electronic version of this thesis is available at http://repository.tudelft.nl/.
All data are available in the main text or the supplementary materials in the GitHub repository (https://github.com/sowmyaravisandiran/supplementarydata.git)

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EXECUTIVE SUMMARY

Public awareness and global concern have increased for plastic littering and the impacts caused by it. The **mismanagement of plastic** is especially high in developing countries due to their inefficient waste management systems that are under increasing pressure from rapid urbanisation and population growth. Despite this, there are also high recovery rates of plastic reported for countries from the Global South – India has the highest reported plastic recovery rates, at 40-60% (Shanker et al., 2022). These **high recovery rates** can be predominantly attributed to the presence of unrecognised warriors in the Global South. These are the **informal waste workers** who work outside the conventional formal system and directly collect recyclable material from households, garbage dumps, or landfills.

Despite its indispensable contributions, the informal sector has received scant attention from the globe so far. The informal workers face several occupational hazards, and social discrimination from society, and are subject to unreliable supply chains. Thus, **developing a deeper understanding** of the system, recognising the contribution of the informal sector, and **quantifying** it will help in the efforts to integrate the informal waste sector into the mainstream. It would also highlight the problems that need to be targeted in order to reduce plastic pollution in the developing world.

There have been studies at the national level for India (Kumar et al., 2018; Nandy et al., 2015a) which describe the plastic waste management system and describe the flows of plastic in the country. However, these are top-down studies which **do not account for regional variabilities**. Due to the large population size and densities in urban India, it is interesting to see the dynamics of plastic waste management at the local and hyper-local levels by focusing on a single city. The coastal mega-city of Chennai in Southern India is chosen as the case study area for this research.

This study aims to **scope the landscape of the plastic waste management system** of the city of Chennai. First, a detailed understanding of the system is developed. Then the flows of household plastic waste in Chennai are quantified. The exchanges between the formal and the informal sectors are identified in this process. The existing data gaps encountered during the quantification are pointed out. Finally, the barriers to data collection and the barriers faced by the stakeholders of the system are highlighted.

A **mixed methods approach** is used in this study to scope the diverse aspects of the plastic waste management system of Chennai. **Qualitative interviews** with the stakeholders are conducted to develop a deeper understanding of the system. Moreover, since the lack of data due to its hidden nature is one of the main hurdles in quantifying the role of the informal sector, bottom-up data is collected from these interviews to fill in the data gaps from the literature. **15 interviews and 1 field visit** were carried out as a part of this attempt to collect local data. These interviews were analysed using the method of **qualitative content analysis** to obtain a detailed system description and to identify the barriers faced by the stakeholders in the plastic waste management system of Chennai.

Material Flow Analysis (MFA) is a useful tool to map the material flows of a sector or a specific material within a defined system boundary. Hence, the data from the interviews are combined with secondary data from literature to build an **MFA accounting model** of the plastic waste management system of Chennai. This is the quantitative aspect of the study, which presents an overview of the flows of household plastic waste in the city. From this model, the data gaps in the system are identified, and the mismanagement and recovery rates for plastic waste in Chennai are calculated.

From the model, the per capita plastic waste generated in the city of Chennai is found to be **31 kg per year**. The plastic waste management system is divided into the sub-systems of generation, collection, aggregation, recycling and end-of-life destinations and applications. The recyclable plastic stream is aggregated through the informal waste sector after collection by itinerant waste buyers, waste pickers from corporation bins and dumpsites. It is found that the conservancy workers in the formal sector sell the recyclable plastic scrap that they collect after segregation to the informal sector for a **daily cash flow** for themselves instead of giving it back to the formal sector. The informal waste sector is responsible for the **recovery of 16%** of all plastic waste generated in the city of Chennai.

The total **recovery rate** for all plastic waste in Chennai is about 27%. It was observed that these values change when recyclable and non-recyclable plastic are considered separately. There is a high recovery rate of 52% for recyclable plastic and a low rate of 15% for non-recyclable plastic. The recovery rate for PET was calculated to be about 75%. However, these rates could be inaccurate since a considerable amount of **unlabelled plastic that is potentially recyclable** ends up in mixed waste flows as non-recyclable plastic and is thus mismanaged. This fraction is not accounted for while calculating recovery rates.

The non-recyclable plastic streams are handled only by the formal sector. After aggregation, they are either processed in pyrolysis plants or cement kilns for fuel. There is also a significant portion of **uncollected waste** (30%) that ends up as litter or is openly burned. Some fractions of both recyclable and non-recyclable plastic waste end up in the landfills. The total rate of mismanagement of plastic in Chennai is 56%.

After aggregation, recyclable plastic is often sold to formal recycling facilities from the informal sector. However, due to large data gaps, the system is not described very well **beyond aggregation** in this study. Another key data gap in the system is the estimation of the number of informal workers, which could be overestimated in literature. It calls for the enumeration of informal waste workers in the city, which can be done by approaching the **self-organized associations of informal workers**.

Ambiguities in literature, like naming conventions for informal workers, lead to data quality issues. However, the **system hiding itself** from the public eye is the biggest roadblock to data collection. This happens due to multiple reasons – in the informal sector, there is a need to protect themselves from law enforcement due to their informal nature. The lack of bookkeeping in the informal sector and its decentralized nature are also data barriers. Thus, conducting **detailed quantitative surveys after gaining the trust** of the informal workers can help bridge the data gaps.

There is a lack of transparency in the formal sector, with the official statistics underestimating the quantities of plastic waste generated and collected by the formal sector. Improving data collection, and **transparently reporting the collected data** can help design more effective plastic waste management strategies.

Two different kinds of barriers in the system were identified through the qualitative research – **social barriers** faced by the stakeholders of the formal and the informal sectors (Figure 6.1), and **barriers in the technical sphere** that limits the efficiency of the plastic waste management system of Chennai (Figure 6.3). Due to social discrimination and bad working conditions in the formal sector, the workers at the lowest level prefer the informal sector over the formal sector. So, **decentralized, bottom-up integration** is needed to improve the living conditions of the workers in both sectors.

The landscape of the plastic waste management system of Chennai is thus successfully scoped in this study.

CONTENTS

LIST OF ABBREVIATIONS

Abbreviation	Definition
ABS	Acrylonitrile Butadiene
BOV	Battery-Operated Vehicles
CAG	Citizen Consumer and Civic Action Group
CMA	Chennai Metropolitan Area
EOL	End-of-Life
FS	Formal Sector
GCC	Greater Corporation of Chennai
GPPS	General Purpose Polystyrene
HDPE	High-Density Polyethylene
HIPS	High Impact Polystyrene
HM-HDPE	High Molecular High-Density Polyethylene
IWB	Itinerant Waste Buyer
IWS	Informal Waste Sector
LCA	Life Cycle Assessment
LDPE	Low-Density Polyethylene
MCC	Micro-Composting Centres
MFA	Material Flow Analysis
MLP	Multi-layered Plastics
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
NRP	Non-recyclable Plastic
PE	Polyethylene
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
RQ	Research questions
SUP	Single-use Plastics
SWM	Solid Waste Management
TV	Television

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CHAPTER 1: INTRODUCTION

Mountains of solid waste in landfills and rivers of plastic in oceans have become a symbol of modern society, more so in developing countries. Waste generation and management of plastic material have especially been a growing concern in the past two decades, with increased production and consumption of plastics worldwide. On one end, plastic is hailed as a wonderful material that has changed the face of modern consumption, with endless possibilities of its applications in different sectors due to its various properties like inertness, water resistance, electrical insulation, lightweight, and high strength. On the other end, scientists are discovering new harmful effects of plastic every day, and the pervasiveness of plastic disposed of in the environment – as microplastics that enter the soil, water, food, and our bodies.

Asia is responsible for 71% of the world's mismanaged plastics (Neo et al., 2021) with India ranking 12th in the world (Shanker et al., 2022). Sights of plastic waste littered across urban and rural environments, in open drains, rivers, beaches, and even the roads in India, paint a bleak picture of this reality. In contrast, several studies have determined that India has one of the world's highest plastic waste recycling rates, between 40-60% (Shanker et al., 2022). Moreover, around 90% of all the Polyethylene Terephthalate (PET) that is manufactured in the country is recycled or reused (Choudhary et al., 2019), the highest in the world. The success of plastic recycling on the one hand, and the grave problem of littering and mismanagement on the other, make India an interesting choice for a case study on plastic waste management in the developing context.

The mismanagement of plastic waste in India, and other developing countries is predominantly due to inefficient waste management systems (Neo et al., 2021). They often do not segregate waste properly, have insufficient capacities for collection and disposal, and have unsustainable disposal practices. These regions also face the pressure of rapid urbanisation and population growth leading to vast amounts of waste generation. Thus, there is increasing pressure on the waste management systems to adapt to the rapidly growing quantity of plastic waste generation, in terms of capacity, technology, and structural organisation.

In contrast, it is crucial to note at this point that the success of plastic recycling in India, and many other developing countries, is majorly owed to a large number of informal workers who exist outside the radar of the mainstream formal system. The informal sector is "unregulated and unregistered, low-technology manufacturing or provision of services; in which workers do not pay taxes, have no trading license and are not included in social welfare schemes" (Wilson et al., 2006). Though their operations are 'invisible', their contribution to plastic recycling in India and the rest of the developing world cannot be ignored. In fact, 70% of the recycling of PET in India is managed by the informal sector (Aryan et al., 2019).

The high efficiency achieved by the informal waste sector provides several economic and social benefits (Wilson et al., 2006). It provides employment and livelihood for marginalized communities working in the informal sector while saving costs for the solid waste management systems of the respective regions. However, several social issues in the system cannot be ignored. The informal workers are exposed to harsh working conditions, unfair compensations, and uncertain pricing (WBSCD, 2016). Nevertheless, they form the backbone of recycling in most developing countries and deserve due recognition for their contributions.

Despite being vital to the waste management system of most developing countries, the informal sector has received scant attention from the globe so far. However, the UNEP's resolution to work towards a global treaty to end plastic pollution that came into effect in 2022 is a ray of hope for the grim reality of plastic pollution. Specifically, it mentions that the world should recognize the significant contribution of the informal sector in plastic waste management, which could be the basis for a just inclusion of the informal sector in plastic management in the world (Velis et al., 2022).

One of the main challenges in estimating the contribution of the informal sector is the lack of data on the quantities managed by them. The highly decentralized and autonomous forms of operations of the informal sector make it a challenging system to study. Bottom-up data collection approaches are needed to bridge the data gaps since the informal nature of the system results in a "hidden" economy that does not come under the radar of official statistics and reports. In this study, interviews with stakeholders are conducted to collect bottom-up data.

Material Flow Analysis (MFA) is a popular and relevant choice of method used in quantitative studies of waste management sectors in both developed and developing contexts. MFA is a useful tool to map the material flows of a sector or a specific material within a particular system boundary. It is the most suitable method to estimate the flows handled by the informal sector and the interactions with the formal sector. Thus, this study also uses the tool of MFA to estimate the material flows of plastic waste and identify the data gaps in quantifying the contribution of the informal sector.

In addition to recognizing their contributions, working in tandem with the informal sector is also imperative. This would enable the waste management systems of the developing countries to tackle the problem of mismanagement of plastic by using the capacity and efficacy of the informal sector, while also helping alleviate the social barriers in the sector. An in-depth understanding of the local context and the barriers faced by the different stakeholders is necessary to enable this integration. In this study, Qualitative Content Analysis of the interview data is used to scope the plastic waste management system in a local context and develop a detailed understanding of the social barriers in the plastic waste management system.

1.1 Research Gaps

There are hardly any studies attempting to quantify the plastic waste management system in India, including the contribution of the informal waste sector. This is not very surprising because it is not an easy task, given the unorganised and informal nature of the system and the complex dynamics within it. Hence, there are large data gaps, with little to no information on the number of informal workers and the quantities managed by them. Lizner & Lange (2013) provide an extensive review of the data on the informal sectors from studies performed globally. It is observed that there are huge data uncertainties in the reported values for India.

As mentioned earlier, MFA is a useful tool that allows for the quantification of waste flows in a system. While many studies perform Life Cycle Assessment (LCA) to study the impact of waste management systems in India (Khandelwal et al., 2019; Mehta et al., 2018; Rana et al., 2019; Sharma & Chandel, 2017), there are few studies which perform an MFA. Moreover, the MFA studies in India are outdated. The most recent MFA study of waste management in India, by Nandy et al. (2015), is conducted at the national level by combining top-down and bottom-up methods of analysis using national statistics and data collected from the city of Mohali. Though performed in the year 2015, some of the data that are used in the study are from the years 2000-2008, making them outdated since there has been a steady increase in the consumption of plastic in India due to rapid urbanisation (Nandan et al., 2017). This could lead to an underestimation of the quantity of waste flows.

Additionally, all the studies assume homogeneity within India and do not capture the regional differences sufficiently. Plastic waste generation and management are not homogenous across India. Each state has different patterns of waste generation and composition, and the dynamics also vary greatly between rural and urban environments, and between multiple different cities (Kumar et al., 2018). Zooming into the system boundaries of a city shows that there is a lot of variability in the waste generation between different households within the urban environment as well, with variations in the types of plastic waste that is generated between households from different socio-economic strata (Kumar et al., 2018; Nandy et al., 2015a).

There is thus a need to evaluate the material flows of plastic waste in India, with a specific focus within a particular region to capture the dynamics that are not represented in the national averages. The city of Chennai in Southern India is chosen as the test case for this study.

There have been several studies conducted globally on the informal waste sector (IWS) that develop an understanding of its nature (Ezeah et al., 2013; Gutberlet, 2021; Medina, 2008; C. Velis, 2017; C. A. Velis et al., 2022). Several social issues that prevail in the informal waste sector regardless of the regional context have been identified by these studies. Some of them include social discrimination, like prejudice, gender-based harassment, and bribery, and occupational hazards, like health risks, unsafe working conditions and risk of unreliable supply chains (Ezeah et al., 2013).

In the Indian context, most peer-reviewed literature on the informal waste sector are either national studies (Chaturvedi, 2005; Chikarmane & Narayan, 2009; Ezeah et al., 2013; Nagarajan, 2022; R. Singh & Chari, 2014) or are focused on other cities like Delhi (Hayami et al., 2006), and Mumbai (Nagarajan, 2022; S. Singh & Chokhandre, 2015). In the case of Chennai, two reports which perform surveys on the informal waste sector in Chennai are identified (Hande, 2019a; Raj, 2019), which will provide useful inputs for this study.

Hande (2019) perform an intensive survey of the informal waste sector in Chennai. They provide valuable insights into the operations of the informal waste sector, the materials handled by them, and the demographics within. (Raj, 2019) also perform a survey of the informal waste workers where they focused on the demographics, health hazards and operation of the informal waste sector of Chennai. However, these studies do not scope the entire landscape of the plastic waste management of Chennai – i.e., they only briefly look into material-specific challenges in the system or the interactions between the informal and the formal sectors.

There has been no study that completely scopes the landscape of the plastic waste management system of Chennai, or any other city in India, which discusses both quantitative and qualitative aspects of the system and links them together to develop useful insights.

1.2 Research Objectives

This study attempts to expand the existing body of knowledge on the contribution of informal sectors in achieving high plastic waste recycling rates in India, by focusing on the test case of the city of Chennai in South India. In this regard, the research aims to estimate the material flows of plastic waste and understand the data gaps and barriers to quantifying the contribution of the informal sector in Chennai. Households are responsible for 68% of the waste generated in the city of Chennai (ENVIS Centre, 2016). Moreover, households, which are small waste generators, are the most difficult to regulate and manage in terms of improper disposal, compared to bulk waste generators like industries (Hande, 2021). Thus, household plastic waste is chosen as the scope for this study. The

study also aims to delve deeper into the plastic waste management system of Chennai and understand the barriers faced by the different actors in the system.

Based on this research objective and the chosen scope, the following is posed as the aim of this study:

Scope the landscape of the plastic waste management system of Chennai, by quantifying the flows of household plastic waste, identifying the social dynamics, and highlighting the data barriers in the system

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To achieve this research objective, the following research questions are identified:

1. What are the material flows of household plastic waste along the formal and informal sectors of the plastic recycling value chain in Chennai?
2. Where do exchanges between the informal and formal sectors of the plastic recycling value chain of Chennai occur?
3. What are the existing data gaps and inaccuracies in the quantification of the material flows of plastic waste in the city of Chennai?
4. What are the roadblocks to building a comprehensive MFA of plastic waste in the developing context?
5. What are the barriers faced by the stakeholders in the plastic waste management system of Chennai?

1.3 Relevance of the Study

Relevance to the field of Industrial Ecology

This thesis studies the dynamics of the informal sector and its contribution to plastic recycling. It would help identify systemic solutions to achieving circular economy through recycling plastic waste. Thus, it is directly relevant to the field of Industrial Ecology, which is strongly related to the concept of circular economy (Saavedra et al., 2018). The focus on data gaps in the system and the identification of barriers to building a comprehensive model of material flows through the informal sector would add value to the growing body of research in Industrial Ecology that focuses on the informal waste sector. It would help studies which aim to improve the quantitative data gaps that exist.

Relevance for the global society and the city of Chennai

The outcomes of this study will help reduce the environmental impact of plastic waste by identifying interventions to manage the waste better. Moreover, by improving our understanding of the informal sector, it would also bring about much-needed improvements in the lives of the waste pickers by giving them the recognition they deserve.

This study is especially relevant for the city of Chennai. Its coastal location makes it vulnerable to extreme weather events that can be devastating if there is a lack of a proper drainage system or waste management system (Arabindoo, 2016). This calls for increased attention to reducing littering and making the plastic management value chains more resilient in Chennai.

An MFA that is specifically focused on the city of Chennai will enable the identification of bottlenecks in plastic waste management – the obstacles faced by the informal and the formal sectors, and the potential for improvement in the collection and recycling of plastic waste.

There is a mix of low-value and high-value plastics in the waste stream, and knowing the quantities of waste generation, the recycling potential of each type, and identifying their sources and the locations to potentially separate them can help design policy interventions to:

- Reduce the amount of plastic waste in the entire system.
- Find substitutes to current plastic requirements from lower-value or non-recyclable plastics to more sustainable alternatives.
- Improve the collection of lower-value plastics by providing the right incentives.
- Close the material loop of plastic in the city of Chennai.

All of this together would help reduce the impact of plastic littering on the environment, and to improve the lives of the stakeholders involved in the waste management sector of Chennai.

1.4 Research Approach

This research study follows a mixed-method approach to answer the different sub-questions posed.

First, a detailed review of the studies which perform MFA of plastic waste in developing nations will be carried out. The data from these studies are used as secondary data wherever applicable, and the methods and assumptions followed are useful inputs for primary data collection and consequent modelling.

To account for the collection by the informal sector, data must be obtained using a bottom-up approach. Interviews, a qualitative research method, is used for this purpose. Interviews of informal waste pickers in Chennai will be designed and conducted to obtain data on the quantities of materials managed by them at different stages of the recycling value chain before the materials reach the recycling facilities. This also helps identify any interactions between the formal and informal sectors, answering the second research question. The information obtained from the interviews is supplemented by secondary data obtained through desk research – peer-reviewed literature, statistics about the formal sector that are released by the government, and reports and studies conducted by other independent bodies are used to fill in the data gaps when required.

An MFA model of the recycling value chain of plastic waste generated in the city of Chennai will then be built by combining the secondary and primary data collected. The flows of plastic waste managed by the informal sector and the formal sector are mapped, which will answer the first research question. The results of the MFA will also be used to answer the third research question by identifying the existing data gaps and inaccuracies in the quantification of the material flows of plastic waste in the city of Chennai.

For the rest of the qualitative data obtained through the interviews, the qualitative method of 'Content Analysis' is used to analyse the data and identify the barriers faced by the actors in the plastic waste management system of Chennai and the barriers to data collection, which answer the last two questions.

Finally, based on the obtained results, recommendations to improve data quality for MFA of plastic waste in the developing context and to improve the plastic waste collection and recycling capacity of Chennai are provided.

1.5 Structure of the Thesis Report

The structure that will be followed in the thesis report is given below.

Chapter 2: introduces the context for this research study by delving into the findings from previous studies, the current status of the system, and the latest developments in the field. It also describes the different aspects of the plastic waste management system in India and Chennai and defines the terms that are relevant to the study and the local context.

Chapter 3: describes the data collection method and the qualitative method used in this research. It is divided into two subsections – Data collection, and Qualitative method: Content Analysis. The first section describes the methods used for data collection from different sources – both primary and secondary. The next section describes the qualitative content analysis method.

Chapter 4: gives a detailed qualitative description of the system that was obtained through the data collected. First, an overview of the informal waste sector is given, and then the formal sector is discussed. Finally, interactions between the formal and informal sectors and exchanges outside the city of Chennai are discussed. This answers the second research question: "Where do exchanges between the informal and formal sectors of the plastic recycling value chain of Chennai occur?".

Chapter 5: discusses the quantitative aspect of this study: MFA. First, the methodological steps are discussed, and then the results are presented. The first part of the results answers the first research question: "What are the material flows of household plastic waste along the formal and the informal sectors of the plastic recycling value chain in Chennai?". The second part answers the third research question: "What are the existing data gaps and inaccuracies in the quantification of the material flows of plastic waste in the city of Chennai?". The most important data gaps that were identified are discussed.

Chapter 6: discusses the results of the qualitative analysis that identifies the barriers in the system. The first section discusses the barriers to data collection for MFA, which helps answer the 4th research question: "What are the roadblocks to building a comprehensive MFA of plastic waste in the developing context?". The next two sections identify barriers in the social system and the technical system. Together they help in answering research question 5: "What are the barriers faced by the stakeholders in the plastic waste management system of Chennai?".

Chapter 7: and Chapter 8: contextualize the results, interpret them, and discuss their implications. The limitations of the study and recommendations for future research are provided. Finally, the answers to the research questions are summarised.

CHAPTER 2: BACKGROUND

This chapter starts with an overview of the consumption of plastic in India and an overview of the plastic waste management sector in India in 2.1. The next section delves into the informal waste sector – it defines informality and describes the operations of the informal sector and the various actors involved in the sector. The area of study, the city of Chennai, is then introduced in 2.3. The current plastic waste management system of Chennai is described in this section. Finally, 2.4 gives a background of the method, Material Flow Analysis.

2.1 Overview of Plastics and Plastic Waste in India

2.1.1 Consumption of Plastics in India

The per capita plastic consumption in India is low, around 11 kg per year, which is almost 40% of the global average (Rafey & Siddiqui, 2021). It is about one-fourth of the consumption in China, and one-sixth that of Europe, with the USA having the highest per capita generation at close to 110 kg per capita per year. An overview of the types of plastics, their applications, and current recycling strategies used in India is given in Table 2.1.

Among the different types of plastics, thermoplastics (HDPE, PVC, PET, etc.) are recyclable mechanically. The others are not generally recyclable and require advanced chemical recycling technologies which are not widely followed in India (CSE, 2020; Shanker et al., 2022; Table 2.1). Mechanical and chemical recycling are among the different routes of plastic waste recycling that can be followed, which also includes biological recycling and energy recovery. Mechanical recycling involves breaking down plastics into small pieces, melting and purifying them, and making pellets or granulates from the purified plastic. It is the cheapest and easiest form of recycling. However, it causes material degradation, is sensitive to impurities and not all plastics can be recycled this way (Table 2.1). It is the most commonly used method in India (Shanker et al., 2022). Chemical recycling involves breaking down the polymers chemically into monomers, or feedstock and using the raw material obtained to make plastic again. It has a higher potential to recycle different types of plastic but is more expensive and difficult to establish.

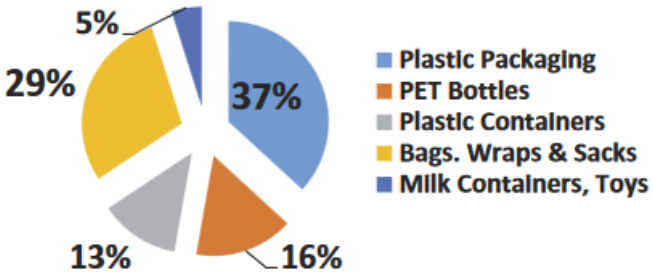

Figure 2.1: Consumption of plastic in India as various products, from Rafey & Siddiqui (2021)

Table 2.1: Plastic Types, uses and Recycling Potential in India

Plastic Type	Examples	Type of Recycling done in India
Polyethylene Terephthalate (PET)	Water bottles, textile fibre, food jars, filling for bedding	**Mechanical** – used for making apparel
Polyvinyl chloride (PVC)	Plumbing pipes, seat covers, shoe soles, cables	**Chemical/Energy recovery** – converted to feed that is used to produce new PVC products, other manufacturing processes or fuel
High-density polyethylene (HDPE)	Drink packaging, cosmetics packaging	**Mechanical** – converted to pellets and used to make new HDPE
Low-density polyethylene (LDPE)	Sheets, garbage bags, shopping bags, packaging material	**Mechanical/Energy recovery** – converted to pellets to produce new LDPE, or incinerated due to partial recyclability
Polypropylene (PP)	Food and medicine packaging, bottle caps, car batteries	Partially recycled by **mechanical** processes into new PP
Polystyrene (PS)	Pharmaceuticals, disposable cups, cutlery, packaging foam	**Not recyclable**
Other (O)	Thermosets, multilayer and laminates, nylon, melamine, etc.	**Not recyclable**

The packaging sector is the highest contributor to plastic demand in India as can be seen from Figure 2.1 and Figure 2.2. Moreover, packaging waste has a much shorter lifespan than plastic waste generated from other sectors like automobile and infrastructure (CSE, 2020).

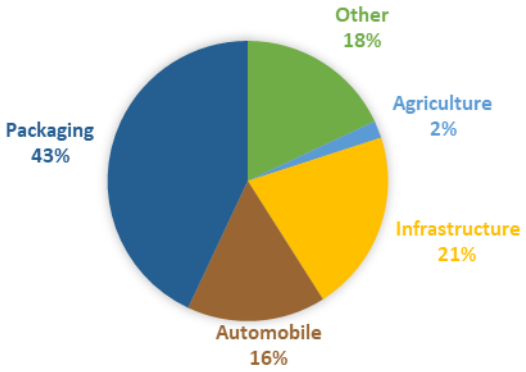

Figure 2.2: Plastic consumption by sector in India

2.1.2 Plastic Waste Generation in India

India produces a total of 3.3-5.6 million tons per annum of plastic waste (CSE, 2020; Sri Sasi Jyothsna & Chakradhar, 2020) and an average of 2.9 kg of plastic waste is generated per capita in a year (CSE, 2020). Most studies present national statistics on plastic waste generation in India. However, as mentioned earlier, there is huge variability between different states of India and even within a single city (CSE, 2020; Kumar et al., 2018). Factors like wealth and affluence affect plastic waste generation within a region. Goa, the richest state of India, stands at about 21.9 kg per capita per year, which is twice that of Delhi (CSE, 2020).

In recent years there has been a greater public awareness to manage plastic waste better. This has led to various initiatives by the central government and the regional governments. Notably, many states have banned single-use plastics, including grocery bags, cutlery, etc. (Rafey & Siddiqui, 2021).

Tamil Nadu imposed a complete ban on the manufacture, sale, storage, or use of plastic carry bags of all thicknesses in 2019 (CSE, 2020). It has also imposed a ban on single-use plastics. The effect of these policies on the quantity of plastic waste generated is not well documented.

2.1.3 End-of-Life Management of Plastics in India

In India, plastic waste is majorly collected door-to-door from households directly, by both the formal and the informal sectors (Shanker et al., 2022). A significant portion of the plastic waste also ends up in municipal solid waste (MSW) as mixed waste. Up to 60% of plastic waste is recycled in India through formal and informal sectors and the remaining 40% ends up in the environment – as litter or in landfills (Shanker et al., 2022). There remain challenges like open burning and littering, which are responsible for air and marine pollution, respectively. In Tamil Nadu, among the collected plastics, the recyclable plastic is sent for recycling and the non-recyclable plastic waste is used in road construction and co-processing in cement kilns as fuel for energy (CSE, 2020). The distinction between **recyclable and non-recyclable plastics** is important to make here. As mentioned in Table 2.1: Plastic Types, uses and Recycling Potential in India, the advanced technologies required to recycle certain types of plastics are either not present or are at their nascent stage in India, and the rest of the world, due to the requirement of large capital investments. So, it is considered that "recyclable" plastics are the types of plastic which can be mechanically recycled to be used in secondary plastic-based products and the infrastructure for the same exists in India. Everything else falls under non-recyclable plastic. This is similar to the definition adopted by Rinasti et al. (2022).

The biggest challenges to plastic recycling in India include multi-layered plastics that are difficult to separate mechanically and the difficulty to regulate the thickness of plastic bags among others. 66% of the plastic waste recovered from MSW was mixed plastics mainly used for food packaging (CSE, 2020). Ragpickers often do not collect these multilayer plastics since it is not profitable for them.

There are various end-of-life applications for non-recyclable plastics. The popular ones in India include cement kilns and building roads (Shanker et al., 2022). The Central Pollution Control Board (CPCB) recommends that non-recyclable plastics are processed in cement kilns to avoid landfilling and littering (CSE, 2020).

The recycling processes and EOL applications are not homogenous throughout the country or between formal and informal sectors. Ecoinvent database for formal and informal plastic recycling shows that there are various plastic recycling hubs across India for the formal sector, but a significant portion of the informal recycling happens in the hub in New Delhi. (WBSCD, 2016) states that 25% of all the recycled plastic in India comes from Delhi while only 5% of the plastic generated in India is from Delhi. The mechanical recycling technologies used by the informal sector are generally older and outdated (Ecoinvent v3.8). Moreover, little information is available on what happens in recycling or after in the informal sector (CSE, 2020).

As mentioned earlier, there is a high rate of mismanagement of plastics, along with a high recycling rate in India. This paints a contradictory picture of plastic waste in India. According to the plastic industry, plastic is not a problem due to the high recycling rates estimated for India (CSE, 2020). Moreover, models calculating mismanagement rates of plastic waste models majorly use World Bank data which often does not properly account for the contribution of the informal sector – due to lack of data on their 'invisible' operations and difficulty in monitoring their collection due to their autonomous, decentralized way of collection (Hoornweg & Bhada-Tata, 2012; Lebreton & Andrady, 2019).

However, the visible problem of littering and plastic pollution of soil and water cannot be ignored. In fact, estimations of plastic composition in MSW in landfills could be underestimating the share of plastics in the mixed waste, since the informal workers would have already picked out the higher-value plastics for recovery (CSE, 2020). Thus, we see that the operations of the informal sector heavily influence the dynamics of plastic waste management and properly accounting for their contribution is essential to get accurate estimates of plastic recovery and mismanagement.

2.2 The Informal Waste Sector

2.2.1 Informality and Characteristics of the Informal Waste Sector

Before going into how to estimate the contribution of the informal sector in India's plastic waste management, it is important to understand what makes the sector 'informal', how it functions, and what makes it interesting to study.

Activities that are either subsistence activities which fall below the minimum wage, or are unofficial, or even illegal activities due to tax evasion, corruption, etc., are considered 'informal' in nature (WBSCD, 2016). Both types of informal actors operate in India's informal plastic waste management sector.

Chaturvedi (2005) explains the role of informal workers in waste management systems in the developing context. In developing countries, a complex chain of workers from the informal sector contributes to recycling. They comprise waste pickers, aggregators, and waste traders. They are not recognized by the formal system and depend on recyclable material obtained directly from households and offices or scavenged from landfill and waste bins. The waste pickers scan through landfills and rejected imports to identify recyclable material (EIA, 2021). They then sell the material to aggregators who collect it and further sell it to the recycling facilities. The main source of income for the actors lies in the value of the materials they collect – this is a unique feature of developing countries where the end users, the consumers, are paid for the waste they generate (WBSCD, 2016).

The key strengths of the informal sector are its high collection and sorting efficiency and the high degree of specialization it manages to achieve (WBSCD, 2016). The informal actors are part of large collection networks with bottom-up communication channels. The communities performing waste collection, which are generally historically marginalized, contain indigenous knowledge which is highly specialized to the types and sources of plastic waste. For example, four recyclers in the informal recycling hub in Delhi only deal with motorbike seats (WBSCD, 2016). The indigenous knowledge, combined with the availability of cheap manual labour is responsible for the high efficiencies and the high degree of specialization of the downstream processes.

2.2.2 Actors in the IWS – An Overview

The hierarchy of the actors in the informal waste sector is given below in Figure 2.3.

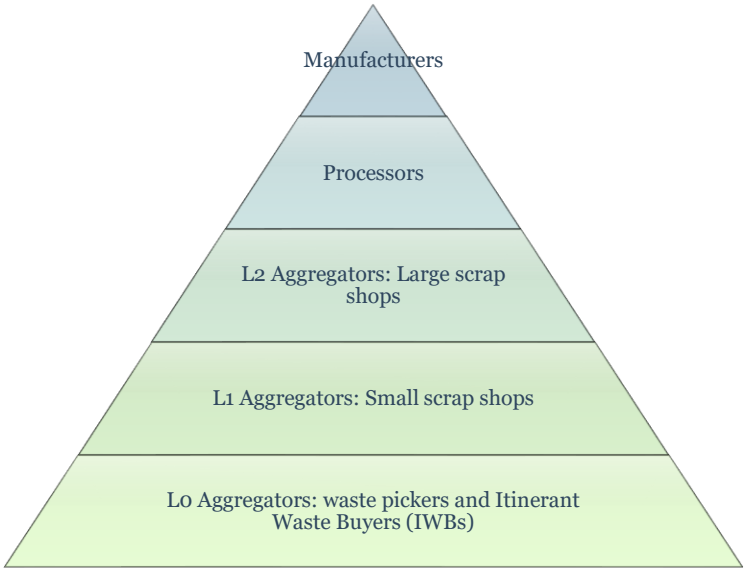

Figure 2.3: Hierarchy of actors in the informal waste sector

A description of the actors and their roles is given below.

- **L0 aggregator – Waste pickers:** Waste pickers are at the lowest of the hierarchy in the IWS. They are usually on foot and sometimes own bicycles or pushcarts, and they pick waste from landfills, and other disposal sites like garbage bins owned by the municipality, streets, open dumps, etc. They handle the waste without any safety equipment, leaving them exposed to all kinds of hazardous materials that may be present in the mixed unsegregated waste thrown by the residents. They do not have any storage capacity and generally sell the material they collect every day to the scrap shop closest to them.
- **L0 aggregator – Itinerant Waste Buyers (IWBs)**: IWBs are also scrap collectors like waste pickers. However, they buy the recyclables from the households directly by performing door-to-door collection. They are thus considered to be higher than the waste pickers in the social hierarchy. They own pushcarts or other vehicles to collect the recyclable material in, and then sell it to the scrap shop closest to them. Their incomes come from the profit margins that they have when they sell the scrap to the dealer. They do not own storage capacity either. They are material agnostic and generally collect paper, cardboard, metal, plastics, and glass.
- **L1 aggregator – small scrap shops**: Small scrap shops aggregate the scrap sold to them by waste pickers and IWBs. They also get scrap from households directly sometimes with people dropping off the recyclables at the shop themselves. They own a small space where they aggregate and sort the material they get before selling it to the large aggregators. They are material agnostic as well and deal with plastics, paper, cardboard, metal, and glass.
- **L2 aggregator – large scrap shops**: Large scrap shops typically own warehouses or have larger storage capacities than small scrap shops. They could be performing just sorting, or some basic level of processing like baling or crushing as well (Hande, 2021). They could also belong to different categories such as stockists, wholesalers, and retailers (Raj, 2019). A major portion of the L2 aggregators only deals with a specific material (metal, paper, plastic, or glass) – 69% of the large scrap dealers in Chennai were found to deal with only one material (Hande, 2021). They also typically have many employees who perform manual sorting for them from the material they buy from small scrap shops or collect directly from bulk waste generators. Depending on their

capacity, and the agreement with the small scrap shops they sometimes provide transportation by directly collecting the scrap from the small scrap dealers themselves.

- **Processor/Recyclers**: Informal recycling facilities get unprocessed or pre-processed scrap from the large aggregators, which they process into plastic pellets or flakes. They typically perform mechanical recycling and have the infrastructure to crush and grind the scrap before processing them into pellets using extruders. The recycled plastic that they produce is sold to manufacturers – either formal or informal.
- **Manufacturers**: As the name suggests, they manufacture the final products from recycled plastic for consumption by final users.

Figure 2.4: Waste picker in Chennai, from (Radhakrishnan, 2022)

Figure 2.5: Small scrap shop in Chennai , from (Justdial, n.d.)

It should be noted here that the naming convention that is used here is from Hande, (2019b), where the scrap collectors are termed L0 aggregators, the small scrap shops as L1 aggregators and the large dealers as L2 aggregators. Figure 2.6 shows the different terms used to describe actors in the recycling value chain in literature based in India. Some of the local terms used to describe scrap dealers and IWBs are “Kabadiwala”, “Kabadi”, etc.

Figure 2.6: Word cloud showing the use of naming conventions in literature to describe the informal waste sector in India, (Hande, 2019b)

2.2.3 Interactions between the Formal and the Informal Sectors

Despite the differences in the formal and informal recycling value chains, there are high linkages between the sectors. Within one loop of EOL plastic waste management, the ownership of the material can switch many times between informal and formal actors (WBSCD, 2016).

There are various challenges in the interactions of the formal sector with the informal sector. Formal actors find it difficult to compete with the low cost of operation of the informal sector which avoids taxes and pays its workers below minimum wage. There are also risks due to unstable supply chains that would be difficult for the formal sector to absorb. Violation of human rights in the informal sector is a challenge that remains unconquered.

There are some novel companies which aim to build cooperative relationships in the informal sector. An example is Banyan Nations, which is a start-up that serves as an intermediary between informal collection systems and global brands. Nevertheless, the nature of these interactions is hardly captured in the different studies and is only qualitatively described, if at all.

2.3 Area of Study: Chennai

The area of study for this research is the city of Chennai. It is a coastal mega-city in the Southern Indian state of Tamil Nadu. It has a population of 6.4 million as of 2023 (Census of India, 2011). The city covers an area of 426 square kilometres (Welcome to Greater Chennai Corporation, n.d.). However, the definition of city limits is expanding due to rapid urbanization.

The city of Chennai falls under the jurisdiction of the Greater Chennai Corporation (GCC). The GCC is a part of the Chennai Metropolitan Area (CMA) which comprises 5 municipalities, and 179 villages apart from the GCC (Chennai Metropolitan Development Authority, Government of Tamil Nadu, India, n.d.). The CMA covers an area of 1189 square kilometres. However, this study focuses only on the Greater Chennai Corporation.

As per the last expansion of the city limits in 2011, the GCC is divided into 15 zones headed by zonal officers, which are further divided into 200 wards, headed by councillors. Wards are the lowest level of administrative boundaries at which waste management occurs in the city of Chennai. Figure 2.7 is a map of the GCC, with the zonal boundaries.

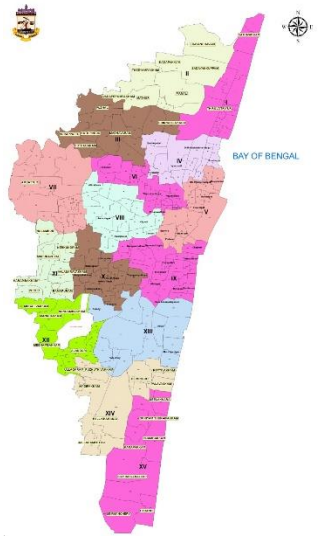

Figure 2.7: Map of Chennai with zonal boundaries, from (*Welcome to Greater Chennai Corporation*, n.d.)

2.3.1 Plastic Waste Generation in Chennai

Chennai is one of the top three plastic waste generators among cities in India, after Delhi and Mumbai, at 0.13 million tons per annum (CPCB, 2015). Thus the per capita generation of plastic waste according to these reported values is around 20 kg per year. This is almost twice the national average for per capita plastic waste generation. It is comparable to quantities generated by entire small countries, for e.g., the Netherlands generates 1.3 million tons per annum of plastic waste, even though the per capita generation is much higher (Lobelle et al., 2022).

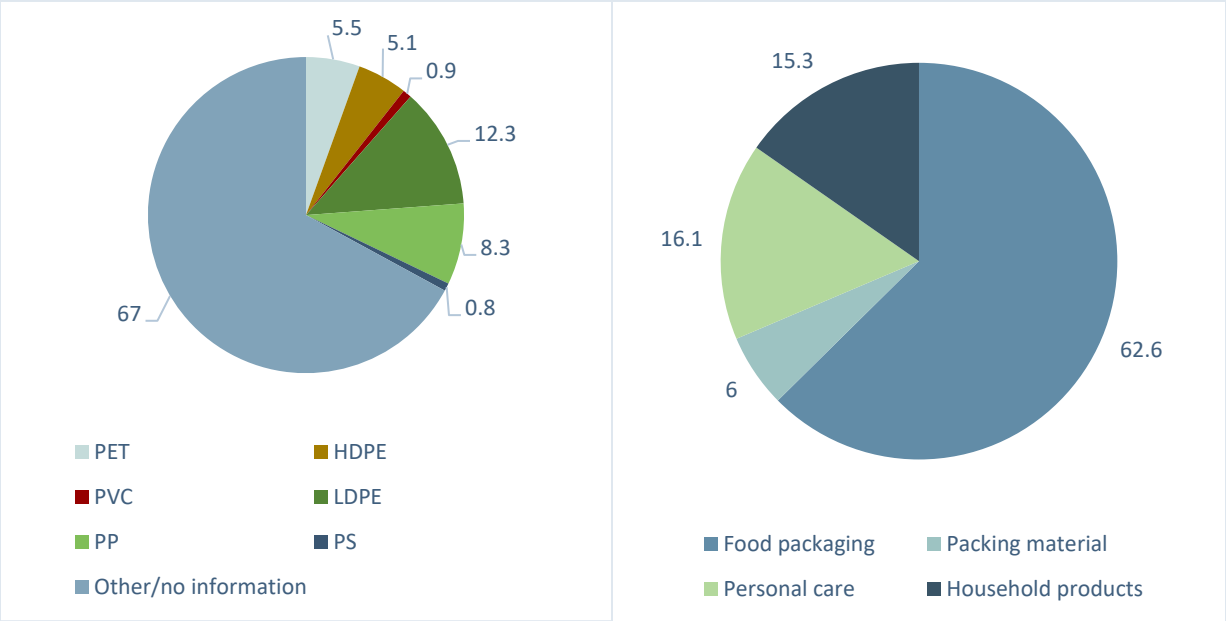

Figure 2.8: (a) Composition by polymer type, (b) Composition by product type; data from (Narayanan & Kapilavai, 2021)

Waste generators in Chennai are divided into bulk generators, which consist of large factories and industrial establishments, medium generators, which consist of commercial establishments, apartment complexes, etc., and small generators which are households and small shops (Hande, 2021). In Chennai, 68% of all solid waste generated comes from households, and hence this study focuses on household plastic waste generation in Chennai.

In the years 2021 and 2022, a non-profit group in Chennai called Citizen Consumer and Civic Action Group (CAG) conducted brand audits of post-consumer plastic waste to determine the contribution of different brands to plastic pollution in Chennai (Narayanan & Kapilavai, 2021; Narayanan & Rajkumar, 2022). In 2021, samples of plastic waste generated by households were collected to perform the audit. From Figure 2.8 (b), it is seen that food packaging is the highest contributing sector to household plastic waste production at 62.6% for indoor audits, followed by personal care products and household products. It was also found that 60% of the plastic waste produced was multi-layered plastic (MLP), which is not recyclable. MLP falls under the category of "Other" in Figure 2.8 (a). Among other polymer types, LDPE contributes the highest at 12.3%.

Chennai is also a site of import of plastic waste since it is a coastal city. India is one of the countries in the Global South that imports waste from the developed countries in the Global North (EIA, 2021). The exported waste is sent on the pretext of being recycled abroad, but most of it ends up in landfills polluting the environment and affecting the human population there (EIA, 2021). However, since the

volume of waste produced domestically is so large in India, the contribution of imported waste to the overall quantity of plastic waste generation is quite low (Cook & Velis, 2022). Specifically, the percentage contribution of imports to the total plastic waste that needs to be managed in India is around 3-4% (WBSCD, 2016). Thus, this study does not account for the imported plastic scrap that the city must manage.

2.3.2 Plastic Waste Management in Chennai

Plastic waste in Chennai is managed by both the formal and the informal sectors as shown in Figure 2.9.

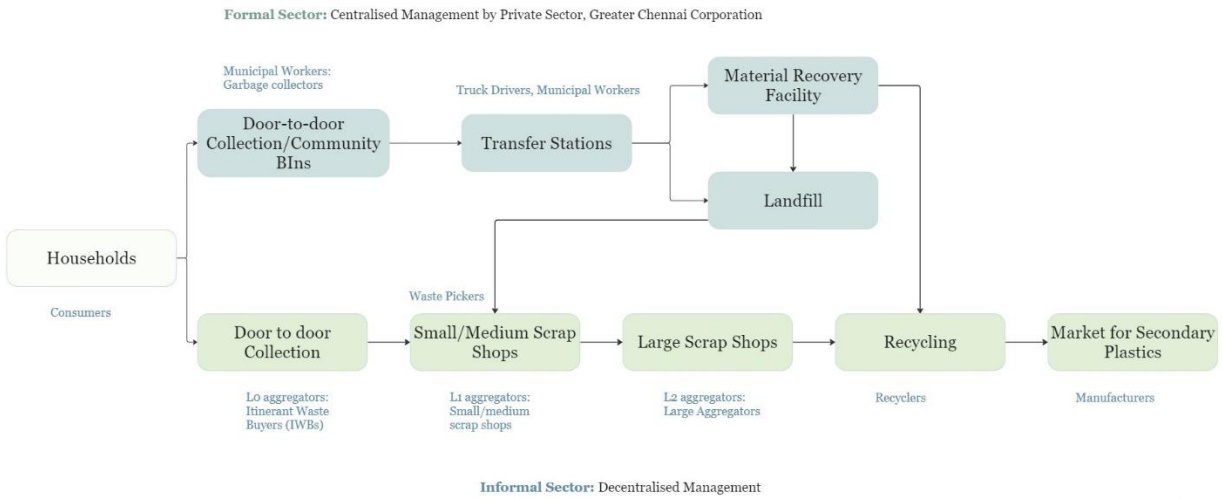

Figure 2.9: Overview of actors in the plastic waste management system of Chennai

The informal actors in India and their roles are described in Section 2.2.2. It applies to Chennai as well. The formal waste sector in Chennai is described below.

In Chennai, the Solid Waste Management (SWM) Department of the GCC is responsible for collecting and managing plastic waste (Welcome to Greater Chennai Corporation, n.d.). However, the GCC has privatized SWM by giving out tenders for the collection and disposal of waste to two companies – Urbaser Sumeet and Ramky Enviro Engineers Ltd. Urbaser Sumeet handles 7 zones, Ramky handles 4 zones while the GCC directly manages the remaining 4 zones (Bureau, 2021; 'Progress Cards for Waste Management Launched by Urbaser Sumeet', 2022).

Solid waste is collected by the formal sector through two routes. One of them is through door-to-door collection directly from the source, after segregation by the households, in tricycles or Battery-Operated Vehicles (BOVs) as shown in Figure 2.9. In this system, the waste is segregated into organic waste that can be sent to Micro-Composting Centres (MCCs) for composting, and other dry waste, which includes plastic, which will be processed separately according to the material. The other form of collection is mixed waste in corporation bins.

The collected waste is then transported to Transfer stations. The source-segregated waste is transported to Material Recovery Facilities (MRF). The rest of the waste is transported to landfills from the transfer stations directly. From the MRF, the segregated dry waste is either taken to recycling facilities for processing or to landfills for disposal.

There are two landfills in the city of Chennai – Perungudi and Kodungaiyur. Perungudi has an extent of about 200 acres, and Kodungaiyur has an area of around 269 acres (Welcome to Greater Chennai

Corporation, n.d.). The landfills are not scientifically managed and are responsible for various environmental issues due to leakage into water and soil. Recently, the corporation has initiated efforts to bio-mine the landfills in Chennai by removing the waste and processing the plastic waste through waste-to-energy plants, cement plants, etc. ('Legacy Landfill in Chennai to Be Biomined', 2023).

2.4 Background on Material Flow Analysis

This section gives an overview of the terms and definitions used in MFA, the reason for the choice of MFA as the method of study, and some background on the latest developments in the field.

2.4.1 Why MFA

MFA is a versatile tool that can help support decision-making in waste management. This is because of many reasons. The waste sector is severely data-limited compared to other sectors due to a lack of economic incentives in tracking waste flows. The mass balancing principle of MFA allows the determination of amounts and compositions of the generally data-insufficient waste flows by connecting with the waste generation or treatment processes (Brunner & Rechberger, 2016). It can also be useful to determine the concentration of hazardous substances, or other substances of interest in waste flows, that are otherwise difficult to calculate (Brunner & Rechberger, 2016). Thus, MFA is the most suitable choice of method for the quantitative aspect of this study.

2.4.2 Description and Some Basic Terminologies

MFA is one of the core methods of Industrial Ecology (Hond, 2000). It is an analytical method that can be defined as "a systematic assessment of the state and changes of flows and stocks of materials within a system defined in space and time" (Brunner & Rechberger, 2016, p. 3). The defined systems can be of different scales spatially and temporally. Some of the important terms used in MFA and their definitions are given below (Brunner & Rechberger, 2016).

- ***Substance***: The term 'Substance' refers to chemical elements or compounds that are homogenous and composed of identical units. They can be atoms, like Nitrogen (N), Phosphorous (P) or molecules like ammonium (NH_3).
- ***Good*****:** Goods or products are economic units which describe merchandise and ware. They are composed of different substances and can have positive or negative economic values.
- ***Material*****:** Material can be used to refer to any kind of 'matter' and typically refers to both substances and goods.
- ***Process*****:** Processes refer to the stage at which materials undergo transformation, storage, or transport.
- ***Stocks***: Sometimes some materials are stored in a process for a fixed duration of time. This accumulation of materials in processes is referred to as 'stocks'.
- ***Flow***: Flow refers to the rate of mass flow, i.e., the amount of mass that flows from or is exchanged between one process/location to another process/location within a system per unit of time.
- ***System***: The system contains all processes with the stocks in them and the flows between them. It is the object of study in an MFA. It is distinguished from its surroundings and can either interact with it (open system) or not have any interaction outside (closed system).
- ***System boundaries***: The system boundaries of a system are defined in both time and space. The spatial boundaries distinguish a system from its surroundings and generally refer to the geographical area under study. The temporal boundaries refer to the time period over which the system is studied.

The convention used while visualising MFA models is given below in Figure 2.10.

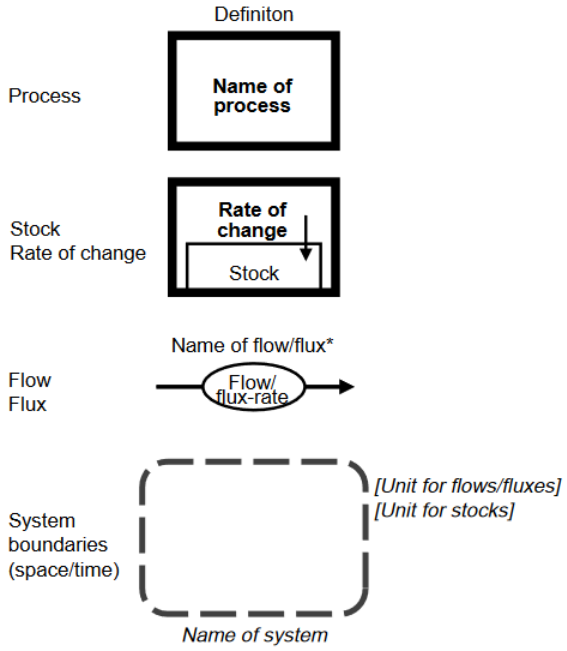

Figure 2.10: Labelling convention in MFA, from (Brunner & Rechberger, 2016)

2.4.3 Latest Developments in the Field

Literature review is used to understand the latest developments in the field of plastic and waste MFAs in the developing context and discern the knowledge gaps. Upon scoping the literature for quantitative studies on the waste management sector, it is found that some studies also combine MFA with LCA (Van Eygen et al., 2018) to evaluate the environmental impacts of the system. Studies mapping the material flows especially plastic waste flows, through the waste management systems of India, and other countries are identified.

Nandy et al. (2015) present an MFA for paper, glass, and plastic waste flows in India and include the informal sector's contribution. This is the latest MFA study of waste management systems in India that was found. The data is sampled from a small city in North India, Mohali, and is extrapolated to the rest of the country by combining collected data with data from peer-reviewed literature and other sources. This study also looks at the waste contribution of households from different socio-economic groups.

Mutha et al. (2006) perform a plastic MFA for India and includes the informal sector's contribution. They estimate the flows from secondary data and make modelling assumptions for unavailable data. This is a useful reference to validate modelling assumptions and for a framework for performing plastic MFA in India. However, it is an outdated study.

Siddique et al. (2022) is the latest study of a plastic MFA in a developing context that was found. It is based in the country of Bangladesh and provides sectoral perspectives of the plastic industry for the first time. Data is collected by a field survey of 17 informal stakeholders, as well as manufacturers and households.

Apart from the studies discussed above, several other studies have used MFA, or a combination of MFA and LCA, to study waste management systems from both developed and developing contexts. While they could be useful for the methodology followed, the most relevant ones are those from developing nations. For example, Putri et al. (2018) evaluate the material flow of plastic waste and the recycling scheme in Indonesia and include the contribution of the informal sector. Aslam et al., (2022) and Sembiring & Nitivattananon, (2010) perform MFAs on the municipal solid waste management system in Karachi, Pakistan, and Indonesia respectively and survey informal actors to include the quantities managed by them. These studies are referred to at a later stage to inform best modelling practices.

CHAPTER 3: QUALITATIVE METHODS AND DATA

This chapter introduces the data collection process and the qualitative method used in this research. 3.1 goes through the processes of data collection for secondary data and primary data. 3.2 describes the steps that need to be followed for qualitative data coding.

A mixed methods approach is used in this study to answer the research questions (1.2) owing to the diverse aspects of the system that the questions are trying to answer. Figure 3.1 gives an overview of the research methodology followed in this study.

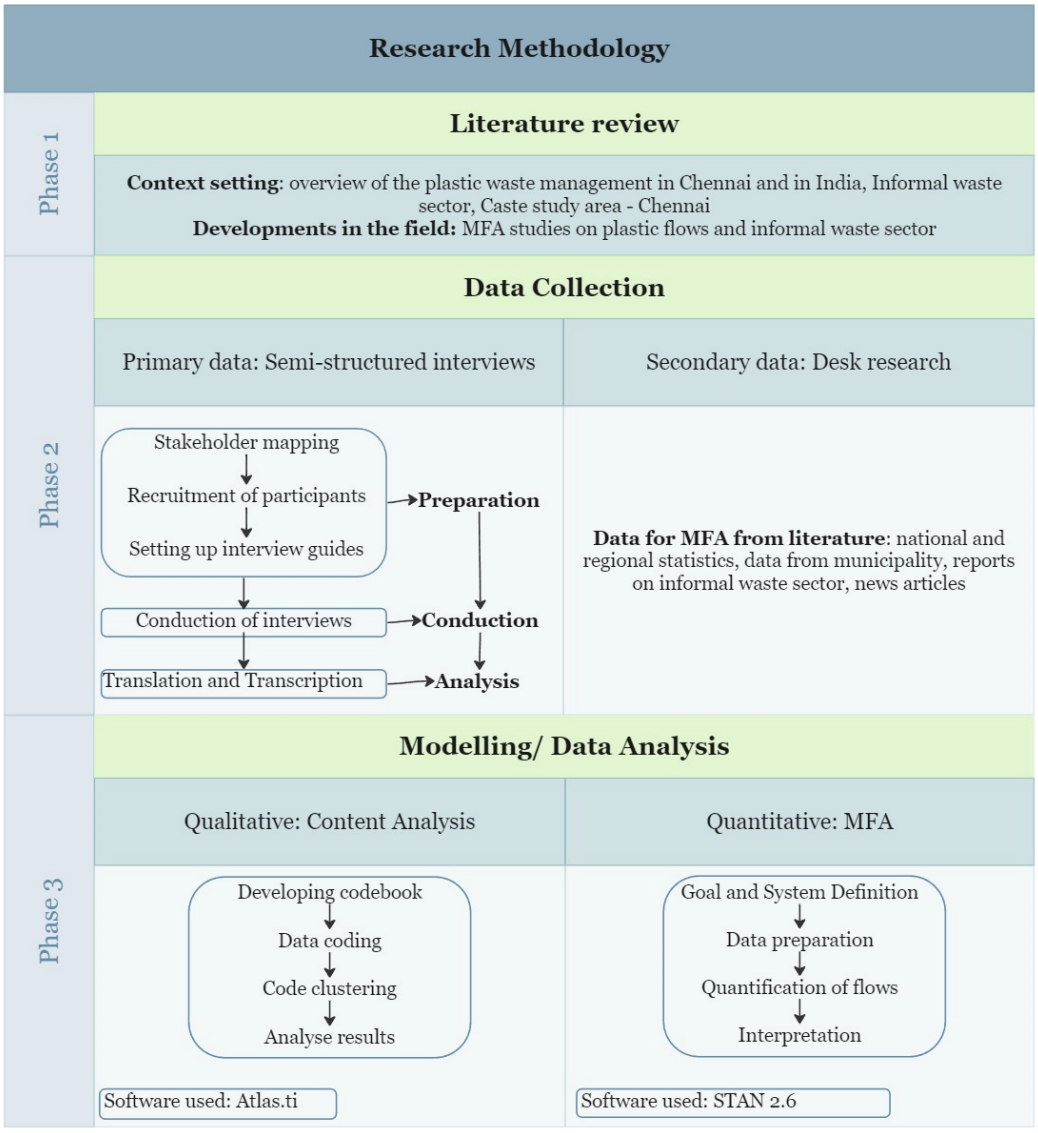

Figure 3.1: Overview of Research Methodology

The quantitative tool, Material Flow Analysis (Chapter 5:) is used to estimate the flow of plastic waste in the system, the contributions of the informal and the formal sectors in the recycling value chain of plastics, and the interactions between the two sectors.

However, due to the informal nature of the system, there are large data gaps, with little to no information on the number of informal workers and the quantities managed by them which would make building a comprehensive MFA difficult. There are also many gaps in the literature in the overall understanding of the informal plastic recycling value chain in Chennai. Thus, it is necessary to augment the already available data on the plastic waste management system by collecting primary data. Interviews are conducted to collect qualitative data for this purpose. The data collected will also help corroborate the secondary data available and identify inconsistencies in them.

Finally, to understand the data barriers and the barriers in the socio-technical system, the qualitative data collected is analysed through the method of Content Analysis. Thus, qualitative research methods are used for a deeper understanding of the system and the barriers within, while quantitative methods are used to develop a broad systemic overview of the plastic recycling value chain of Chennai.

3.1 Data Collection

3.1.1 Desk Research

Desk research is used to obtain secondary data on the formal and informal sectors in the plastic recycling value chain of Chennai from the available literature. Since there are very few sources of peer-reviewed literature with data specific to Chennai, grey literature, like industry reports, news articles, or government publications, is used to fill data gaps. This compromises the data quality to some extent. Additionally, data from studies in other Indian cities, and nationwide studies about India are used as a sanity check to verify the validity of the ranges of data used for Chennai. The obtained data is stored in an Excel file (Supplementary Data 1) according to different categories in different sheets and is finally used to build the MFA data table. Table 3.1 gives an overview of the data categories in Supplementary Data 1, and what they contain.

Table 3.1: Overview of Data Table for MFA

Sheet name	What it contains
Waste generation	Household waste MSW and plastic waste generation estimates for the national and regional levels, and city-level data specific to Chennai; Findings from plastic waste audits conducted in Chennai
Informal sector	Statistics for the number of informal waste workers at the national and city levels, estimations for total waste handled by the informal sector and waste handled per worker, and data from focused surveys conducted on the IWS in Chennai
Formal sector	Data about the infrastructure, number of workers and waste handled by the formal sector from reported values by the government and news articles
Primary data	Data that was obtained from interviews and used to fill in data gaps in MFA
Downstream data	Data from the report, Kabadiwalla Connect (2023), regarding uncollected waste and openly burned waste
Other	Other data including monetary information, capacity, and number of employees in scrap shops, information on the import of plastic waste, inter-state exchanges, population, and other national statistics
Global Statistics	Estimated proportion of waste pickers for countries of different income groups

3.1.2 Interviews

Interviews are a useful qualitative data collection method that is widely used in different fields to obtain a deeper understanding of a particular system from the participants or the stakeholders in the system (Qu & Dumay, 2011).

Interviews can either be structured, unstructured, or semi-structured (Qu & Dumay, 2011; Ryan et al., 2009). Structured interviews are rigid, with the use of a strict questionnaire with no room for deviations from it. They are used when it is very clear to the researcher what data they are looking for and already have a good understanding of the system under study. Unstructured interviews are more explorative in nature, with no pre-established questionnaire to guide the interviewer. They are used in cases when the researcher does not know what exactly they are looking for and is relying on the informal nature of the conversation to come up with relevant questions to probe the participant further. Between the two ends of this spectrum lies semi-structured interviews. It offers some level of structure in the form of interview guides while leaving room for flexibility and exploration depending on the answers given by the participants.

Semi-structured interviews are used in this study, to provide some structure while allowing for flexibility to explore issues based on the interviewees' responses during the interview process.

The entire interview process consists of the following three stages: Preparation (before the interview itself), Conduction of the interview, and Analysis of the collected data (Ryan et al., 2009; Turner, 2014). The steps followed within each stage of the interview process are elaborated in this section.

Preparation

Preparing for the interviews involves multiple different aspects – first, the stakeholders in the system are identified to help choose relevant participants for the research. Stakeholder mapping is used for this purpose to come up with a useful stakeholder list. Then, the recruitment of interview participants is done. Finally, interview guides must be set up for the different participants who will be recruited.

Stakeholder mapping

The first step towards preparing for interviews is developing the list of stakeholders relevant to the plastic waste management system of Chennai and choosing the scope of interview participants from the list. Stakeholder mapping is used for this purpose (K. Singh, 2007), and a list of stakeholders with their roles and characteristics is made. Figure 2.9 in 2.3.2 gave an overview of the plastic waste management system in Chennai and the actors involved. The stakeholder mapping with the roles and sectors of the different actors is presented in Table 3.2 below.

Table 3.2: Stakeholder mapping of the plastic waste management system in Chennai

Stakeholder	Role	Formal/Informal
	Experts	
NGOs	NGOs work with informal workers, raise awareness about SWM issues and social issues prevalent in the system, and work in collaboration with the municipality to improve the SWM system in Chennai	NA
Private service providers	Provide private waste management services for household, and bulk waste generators	Formal

Citizen initiatives	Resident associations which have mobilised support within the community and organised waste collection for the community	NA
Journalists	Report on SWM issues that the government is not transparent about and have some knowledge about the system through ground-level experience	NA
SWM department of GCC	Responsible for the collection, management, and disposal of solid waste generated in the city of Chennai. It is also responsible for implementing Policies, building infrastructure, and managing the budget for SWM	Formal
Ward-level and Zonal-level officers	Implementation of SWM at the ward and zonal levels respectively	Formal
Collection		
Itinerant waste buyers	Perform door-to-door collection service for recyclables such as plastic, paper, metal, etc.	Informal
Waste pickers	Collect recyclable waste that is discarded among unsegregated waste from corporation bins, streets, and landfills. Are also employed by small businesses or households to perform door-to-door waste collection informally	Informal
Conservancy workers	Operating the BOVs, sweeping the streets and managing corporation bins. They are employed by the government or the private companies that have the waste management contract from the government	Formal
Transportation		
Drivers of garbage trucks	Responsible for transporting waste from corporation bins to transfer stations, and then to material recovery facilities and landfills	Formal
Aggregation		
Workers in the MRFs, transfer station	Responsible for managing the facilities, loading and unloading waste, and sorting the waste where necessary	Formal
Small scrap shop/L1 aggregator	Own scrap shops to which the IWBs, waste pickers and households sell their recyclable waste	Informal
L2 aggregator of recyclable plastic	Own large warehouses where the recyclable plastic waste that they get from different scrap shops is aggregated and sorted with the help of employees. Sometimes perform pre-processing of plastic scrap	Informal
Aggregator of Non-recyclable plastic	Own large warehouses where the non-recyclable plastic waste that they get from the formal waste collection is sorted and pre-processed with the help of employees to be sent to their EOL applications	Formal
Processors		
Recyclers – formal	Registered facilities which process the plastic scrap through mechanical recycling processes to produce recycled plastic pellets/granules	Formal
Recyclers – informal	Unregistered facilities which process the plastic scrap through mechanical recycling processes to produce recycled plastic pellets/granules	Informal
Cement plants	Co-process non-recyclable plastic scrap in cement kilns for fuel	Formal
Pyrolysis plants	Waste-to-energy plants that process non-recyclable plastic scrap	Formal

Recruitment

Based on the stakeholder analysis, interview participants are then recruited for the study (Magnusson & Marecek, 2015). The **population that needs to be represented** for MFA is the total number of workers involved in dry waste management – including garbage collectors, waste-pickers, itinerant waste buyers, small, medium, and large-scale aggregators and recyclers as shown in Table 3.2.

Due to time and resource constraints, only **a selected number of stakeholders can be interviewed**. Since there is some data available about the formal sector through secondary sources, this is mostly used to represent the formal part of the recycling value chain. The interview process is restricted to conservancy workers, informal workers, and a few experts who work with them. Experts are interviewed to get a deeper understanding of the challenges in the system – the data barriers, the social issues, and the barriers in the recycling value chain. The validity of the secondary sources is also explored in the interviews with experts.

Time and willingness to participate are the biggest obstacles for the study, so the **number of participants** for the identified stakeholders to be interviewed is kept flexible depending on the response of the contacts that are established in Chennai. Chain referral is used to contact potential research participants (Magnusson & Marecek, 2015) – a case study expert is first contacted, and with their help, the rest of the contacts in the SWM network of Chennai are established. Interviews with the informal sector are established through this network.

Due to the nature of the study, an ethical review of the interview process is done to ensure that there are no risks involved for the participants. Informed consent forms are used to convey the details of the research – the purpose, format of the interview, terms of confidentiality, duration of the interview, and contact details of the researcher (Turner, 2014) – and obtain the consent of the participant. The signature of the participant is obtained at the beginning of each interview. A Data Management Plan is made and submitted to the Ethical Review Committee of the Faculty of Science, Leiden University for their approval.

Setting up the interview guide

Even though all interviews are semi-structured, the nature of the interviews would slightly differ based on the actors who are to be interviewed. Thus, the interview guides should be able to reflect this. The format of the interviews with the experts – heads of organizations, journalists, etc. – would be less structured to explore different topics and get an idea of how the system works. Interview guides are prepared based on the expertise of the individuals interviewed. The format of the interviews with the workers themselves would be more structured with different interview guides prepared for waste pickers, conservancy workers, itinerant waste buyers, and scrap shop owners. This is to allow for room for exploring the differences between the different types of organisational structures, and for me to explore topics that the interviewee might bring up during the interview, while also covering the basic information that I need from them.

To help develop the interview guides, the information required from the different actors in order to fill in data gaps is identified (Ryan et al., 2009):

1. **The organizational structures**:
    - Who is responsible for handling what in both formal and informal sectors, and what are the differences in organisation in the formal sector between different zones of Chennai.

- Exchanges between the formal and the informal sector – how do the two sectors work in harmony, where in the value chain do these exchanges occur, and what is the nature of these interactions?

2. **Material quantities and destinations**:
   - How much is collected by each actor (formal/informal), and where do they end up?
   - What types of plastic do they refuse to collect and why?
   - How do they sort the different plastic types?
   - Do they have any wastage while sorting, and if so, how much?
3. **Enumeration of workers:**
   - Any available information on the enumeration of formal and informal workers, scrap shops, and recyclers in the city.
4. **Social issues:**
   - Faced by formal workers and informal workers.
   - Challenges in achieving segregation in the formal sector.
   - Obstacles faced by the informal workers while collecting plastic.
5. **Data barriers:**
   - Barriers to data collection, including reasons for certain data gaps.

The interview guides that were prepared for the workers are given in Appendix A: Interview Guides. Siddique et al. (2022) is used as a reference for preparing the interview guides. Due to the semi-structured nature of the interviews, questions are updated throughout the interview process depending on the responses being received, or information needed.

Conduction

After preparation, the next stage is the actual conduction of the interviews. There are many things to keep in mind during this stage as well (Magnusson & Marecek, 2015) which are explained in this section.

A total of 17 interviews were conducted by the end of the interview process. Due to some data barriers that are identified in the research, it was not possible to get in touch with recyclers. One of the interviews was in the format of a field visit to the housing area of a certain community of waste pickers and interacting with a few of them to get an idea of their jobs and their lives.

An overview of the interviews conducted is given in Figure 3.2.

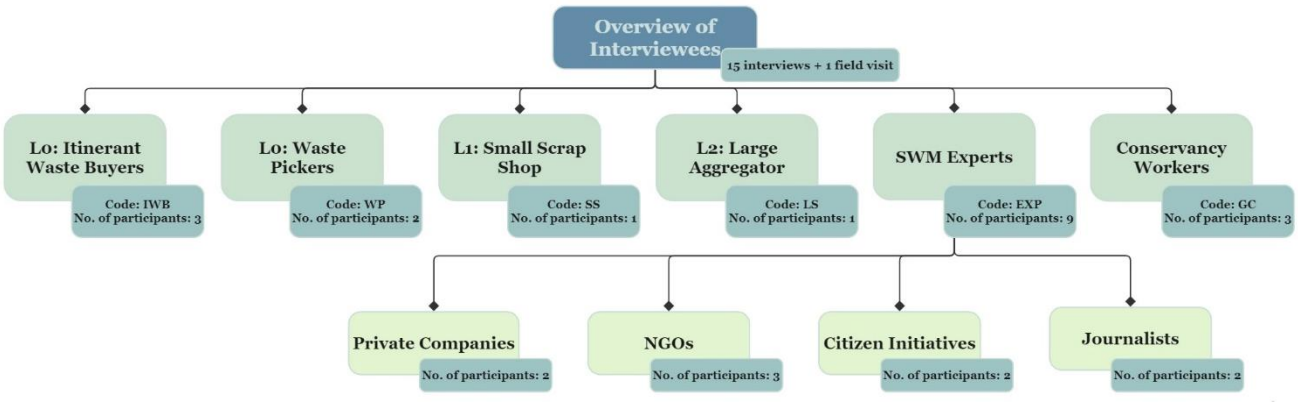

Figure 3.2: Overview of interviews conducted

The average interview duration with the workers was between 10-25 minutes each. The average duration with the experts was between 25 minutes – 1 hour. This is because the experts had more insights to share about the overall functioning of the plastic waste management system.

The language of the interviews with the workers was Tamil, the local language, which is also my first language, while the experts gave interviews in either Tamil or English depending on what they were comfortable with. I travelled to Chennai to facilitate the conduction of interviews in person. Different mediums of conduction were used – face-to-face, telephone, and video calls. For the conduction of video interviews, the software Zoom was used. The experts were sometimes more comfortable with telephonic or video interviews for ease of time while most of the workers were interviewed in person.

The interviews were audio recorded using the 'Recorder' app on a smartphone. The recordings are transferred to the OneDrive storage of the Leiden University account, and deleted from the app, with no third-party access to the interviews other than the primary researcher and the supervisors.

Analysis

Following the conduction of the interview, the data obtained must be analysed. The first step of analysis involves transcription of the audio data, and the second step involves analysing the transcripts. This section describes these processes.

Transcription

The audio recordings are translated into English for interviews in Tamil and transcribed. The voice-to-text software of Teams is used to generate automated transcripts when the interviews are in English. The transcripts are then checked once again by listening to the recording. The transcripts are stored using anonymized codes as identifiers for the participants to prevent their identification. These codes are given in Figure 3.2. Any information in the interviews that could potentially be used for the identification of the participants is removed. Following transcription, the recordings are deleted to further prevent the identification of the participants.

Qualitative analysis

The finished transcripts are then analysed and data from them is extracted. This is done by using the qualitative data analysis method, Content Analysis which is described in 3.2. The software Atlas.ti is used for this purpose. First, the data that is relevant to MFA is extracted separately by using codes relevant to MFA and using the code group 'MFA' (Figure 3.3). Then the rest of the data is analysed again for qualitative information.

3.2 Content Analysis

As mentioned above, the method of content analysis is used to analyse the qualitative data that is collected. Content analysis is a popular tool that can be used to analyse textual data like interview transcripts (Hsieh & Shannon, 2005). In content analysis, the textual data is analysed by 'coding' them by classifying quotations, sentences, phrases or words from the data into "codes" that represent the data (Columbia University Mailman School of Public Health, 2016). The codes are then further classified into "code groups" or "code categories" that categorize several codes into specific categories that can be used for analysis.

Many different types of content analysis exist. They can be broadly classified into deductive approaches, like Directed content analysis, or inductive approaches, like Conventional content analysis (Delve et al., 2023; Hsieh & Shannon, 2005). Deductive approaches follow a pre-defined

codebook – which is a set of codes and code groups – that is derived from theory. The data is classified using this codebook for analysis. Inductive coding approaches, also called open coding, on the other hand, do not have a pre-defined codebook and the codes and code categories. Instead, the codes are developed from the data itself and then updated throughout the coding process.

In this study, a mix of deductive and inductive coding is followed. Following the aim of the research some code groups are defined at the beginning, but more codes and code groups are added during the process of coding. As mentioned above, the data relevant to the MFA is extracted first by going over all the transcripts before analysing the data for qualitative information. The code groups that are determined at the beginning of the process are MFA, Barriers to Data collection, and social issues in the formal and informal sectors. Further codes and code groups are developed during the process. The software Atlas.ti is used for data coding and clustering. Three hierarchical levels of coding are used – data is first classified into "codes" which are later grouped into "category codes" and then classified into "code groups" that signify the major themes for analyses.

The steps that were followed for content analysis are explained below (Columbia University Mailman School of Public Health, 2016; Delve et al., 2023):

- ***Data collection***: This step involves the actual interview process and transcription explained in the previous section.
- ***Developing codebook***: The codebook consists of codes, category codes, and code groups. As mentioned in the previous paragraph I start with the code groups for MFA, Barriers to Data Collection, and Social Issues. Most of the codes for MFA are predefined – the volume of material, price, number of workers, etc. (see Supplementary Data 2 for the complete codebook), since it is already clear what data I am looking for to build an MFA model. The other codes, category codes, and code groups however are developed from the data in an inductive manner.
- ***Determine units of analyses and coding rules***: This step is more important when following a deductive approach. The units of analysis in the case of this study are flexible due to a combination of inductive and deductive approaches – they could be sentences, quotations or phrases, but all of which contain a unit of information corresponding to the code applied. Coding rules are flexible as well.
- ***Code rest of the data***: The rest of the data is coded according to the developed code book. While coding, quotations or phrases from the transcripts which correspond to a particular unit of information that is represented by a data code are matched to the corresponding code. In case there is a quotation that conveys some information that was not previously present as a code in the code book, a new code is created. Thus, there are many processes of iteration during coding where more codes are added, and the codes and code group are realigned and re-clustered. After completion of coding, the code groups and categories are revisited and re-clustered when necessary to build a coherent narrative for the qualitative results and to answer the research questions.
- ***Analyse result***: The code hierarchy that is developed is then used to obtain findings and the qualitative results are analysed. The results obtained through this process are given in Chapter 4: and Chapter 6:.

Figure 3.3 gives the top two levels of the code hierarchy – the code groups and category codes. The full codebook can be accessed in Supplementary Data 2.

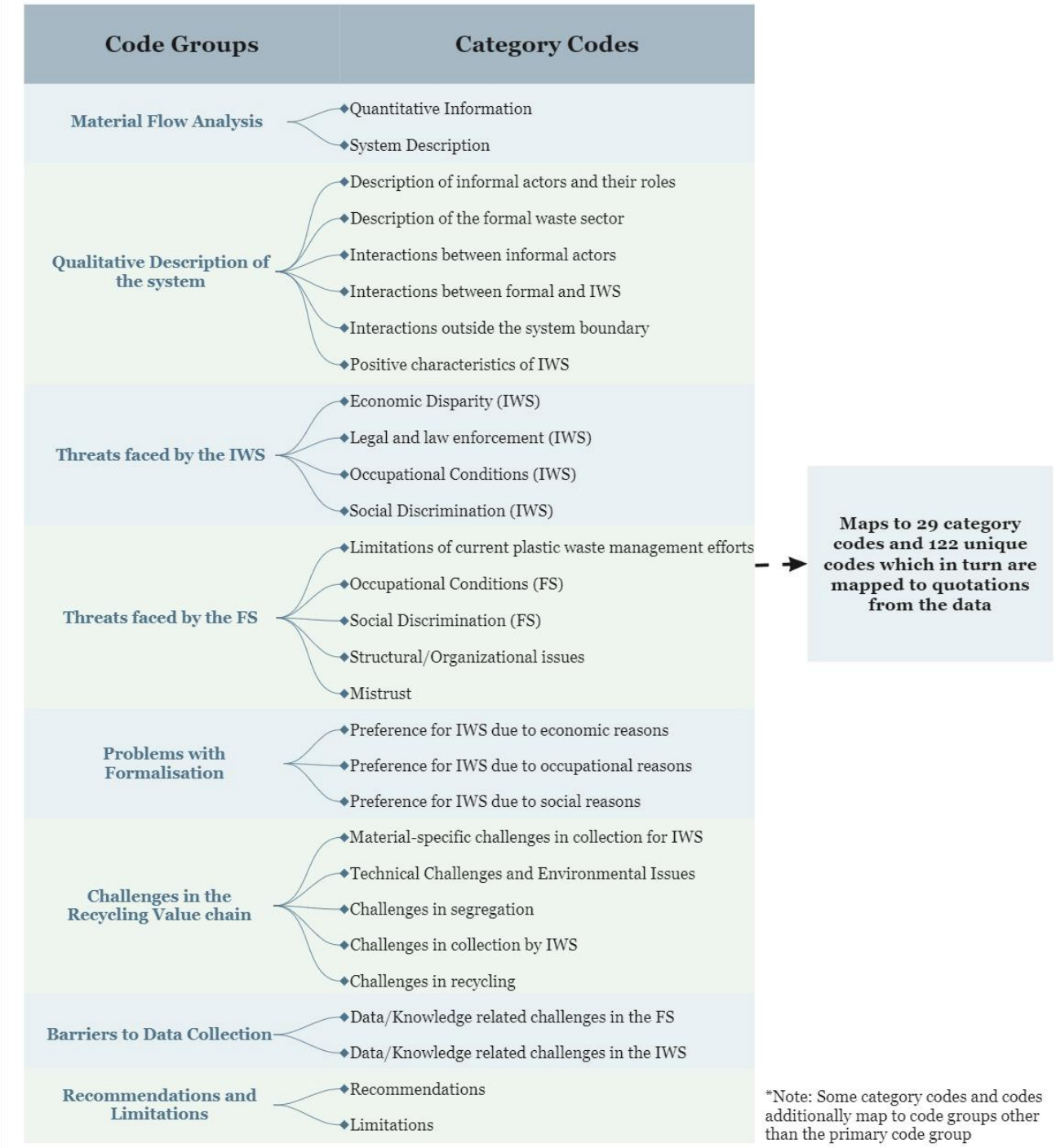

Figure 3.3: Clustering of qualitative data – code groups and category codes

The higher-level code group "Qualitative System Description" corresponds to Chapter 4:. All the information from the primary data that helps develop a qualitative description of the plastic waste system of Chennai is classified in this code group. It corresponds to information specific to the actors

in the city of Chennai, that is not available in literature elsewhere. The code group contains category codes pertaining to the description of the informal and formal waste sectors of Chennai, interactions between the formal and informal sectors, and interactions extending outside the limits of the city of Chennai.

The information clustered under the code group "Barriers to Data Collection" is discussed in 6.1. Based on the data clustering, answer to the last research question, the barriers faced by the stakeholders of the plastic waste management system of Chennai are divided into barriers in the social sphere and barriers in the technical sphere. The code groups "Threats faced by the informal sector" and "Threats faced by the formal sector" correspond to the social sphere, discussed in 6.2. As the names suggested, different threats faced by the formal and informal sectors are identified and classified into different categories (denoted by the category codes). "Problems with Formalization" is also discussed in this section. "Challenges in the recycling value chain" corresponds to the technical sphere, discussed in 6.3. It is divided into different category codes that correspond to challenges in collection, segregation, recycling, material-specific challenges in the informal waste sector, and technical challenges and environmental issues.

CHAPTER 4: QUALITATIVE SYSTEM DESCRIPTION

The plastic waste management system of Chennai is qualitatively described in this chapter. First, an overview of the informal waste sector (IWS) is given in 4.1, and then the formal sector is discussed in 4.2. Finally, interactions between the formal and informal sectors and exchanges outside the city of Chennai are discussed in 4.3.

A detailed qualitative description of the system is obtained through the process of content analysis. In addition to the information available in literature about the plastic waste management in Chennai, the interviews revealed several details specific to the local system that helped in mapping out the system qualitatively and identifying the flows of plastic waste within. It also helped in gaining a better understanding of the functioning of the system and the actors.

The results of this section serve as the input for the quantitative aspect of the research – MFA. The qualitative system description is used to define the system boundaries, sub-systems, processes and flows for the MFA model.

Figure 4.1 presents the qualitative mapping of the system, with the relevant processes and flows.

4.1 Informal Waste Sector

4.1.1 Characteristics of the IWS

Some important characteristics of the informal waste sector were observed through the interviews. Most of them corroborate what is already present in literature – like the highly decentralized nature of collection in the informal waste sector and the availability of cheap manual labour. A few of the interesting observations are mentioned here.

Objective of the IWS

One important distinction between the formal and the informal sectors is that while the objective of the formal sector lies in "waste management", i.e., providing the services of collection and disposal of waste for the citizens of the city of Chennai, for the informal sector **the objective is purely economic** – they recognise the value of the scrap and see business potential in them. The livelihood of the informal workers depends on this, and there is no governing body for the informal sector whose objective is to provide waste management services. This distinction is important since many of the behaviours of the actors in the informal sector can be explained by this. For instance, there were reports that the small scrap shop owners and the IWBs sometimes close their shops and leave early for the day if they feel like they already made enough money for the day.

This was similarly observed among the waste pickers – they preferred being in the informal sector since the hours they work, and the area they must cover solely depends on themselves. The waste picker community that I interviewed also performed other professions seasonally, like bead-making by the women and selling cheap goods made from recycled plastic seasonally for additional income. Some of them are also employed as "freelancers" to collect unsegregated waste from small establishments and dispose of them in corporation bins. Due to this and several other reasons, **the number of people performing waste picking at a given point in time is dynamic** (Sudhir et al., 1997).

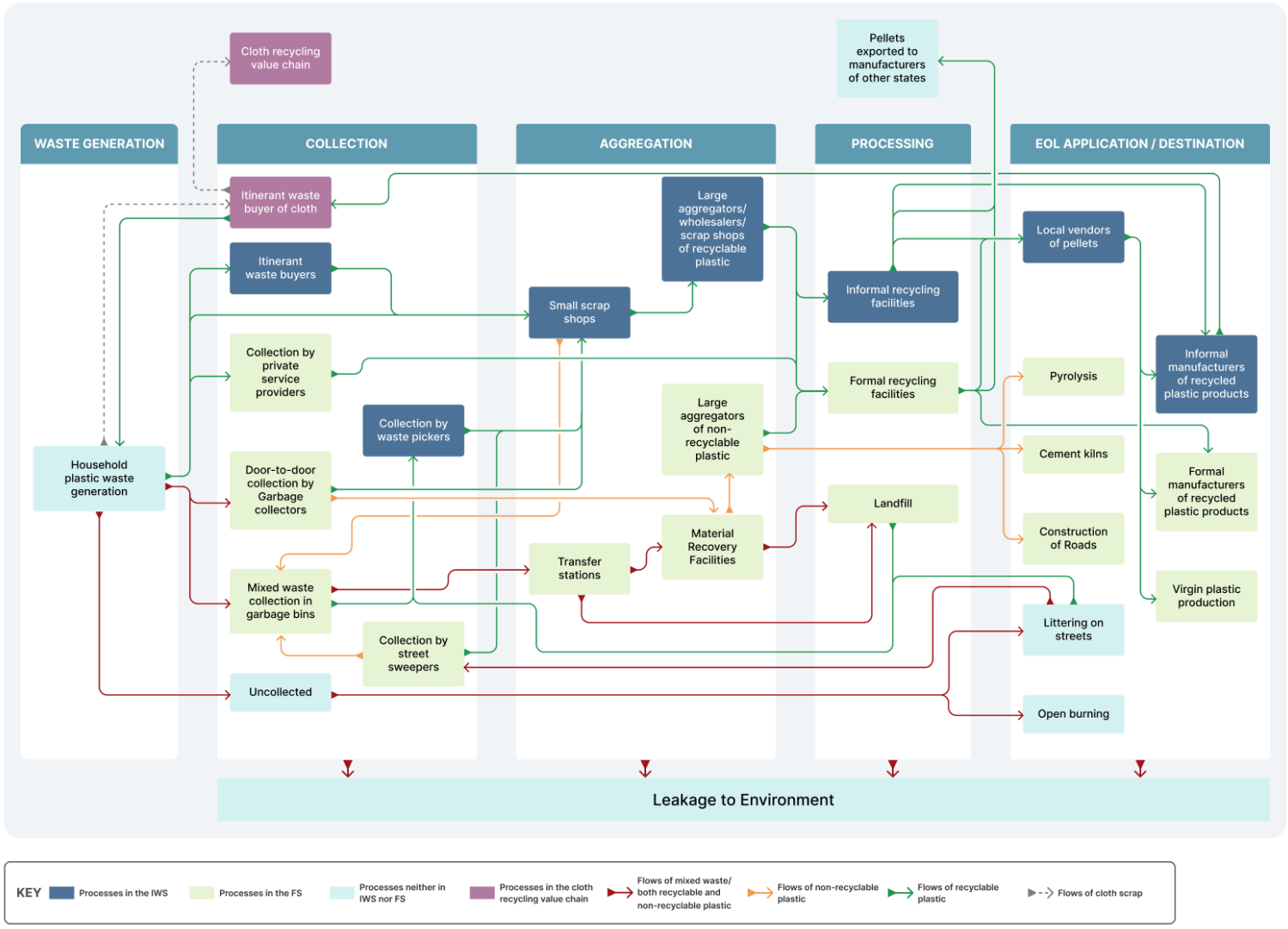

Figure 4.1: Qualitative model of the plastic waste management system of Chennai

Generational Involvement

Some of the communities performing waste picking, among other roles in the IWS, have been doing this for generations due to caste-based discrimination in society which restricts their social mobility and considers the profession as the "role" of these communities. However, it was also observed that there were many workers from other communities who entered the waste profession post-COVID since they lost their earlier jobs in other sectors due to the pandemic.

Many small scrap shops are owned by families, and the entire family contributes by working as IWBs or helping manage the shop. I observed that sometimes the owner of a scrap shop ropes in his family or his relatives from the village and helps them set up a scrap shop of their own. This phenomenon is also described in (Hande, 2019a).

Material Agnostic

The L0 and L1 aggregators are usually material agnostic – they will collect any material that is recyclable and profitable for them (paper, plastic, glass, and metal). One of the reasons that they are material agnostic is that they cannot afford to focus on only one material. The prices of the materials are dynamic and change every day. Thus, focusing on a range of materials improves their profits.

It should be noted that this also means that the actors generally tend to refuse to collect non-profitable streams of plastic – the low-value recyclable plastics and the non-recyclable plastics. This can be seen in Figure 4.1 where only the recyclable plastic flows are aggregated through the informal recycling value chain. Sometimes the IWS ends up receiving non-recyclable plastic that they cannot sell for a profit. In that case, they either discard it in the corporation bins or **reuse** the bigger plastic bags and containers within the IWS itself.

4.1.2 Description of Actors

Some interesting observations about each actor are given below.

L0 Aggregator: Waste pickers

There are clusters of waste pickers present in different areas. Various factors influence the presence and the number of waste pickers in each ward. They are more prevalent in the outskirts of the city where open dumping is present and around landfills. Around the centre of the city, their collection is restricted to corporation bins. Some waste picker communities live in housing clusters reserved for them by the government. Before formalisation in some areas, the waste pickers were also performing door-to-door collection of solid waste for households and throwing the waste in corporation bins after removing potentially recyclable scrap from the mixed waste. This has significantly reduced in areas where waste management has been privatised.

The waste pickers collecting from bins either directly sell the scrap they collect to the informal scrap shops nearby or store them in their houses/housing colony if they have space and then sell them. Regardless of whether they have storage space, the waste pickers sort the scrap into major plastic types themselves. They do this manually by differentiating based on visual characteristics like colour, and by texture. The plastic types that the scrap is sorted into are described below in Table 4.1.

The waste pickers in the landfills often have a direct connection with the scrap dealers. The scrap dealers send in their trucks to load the scrap that the waste pickers have already sorted and packed for them.

L0 Aggregator: Itinerant Waste Buyers

The IWBs own tricycles to pick up scrap. Every scrap shop has a few IWBs working for it, who perform door-to-door collection from households. They typically work only half days or at specific times of the day (between 11 pm and 3 pm) when the women have finished their household work. Many of them also share their phone numbers with customers and go to households when they are called for pick-ups.

They are also knowledgeable with manual sorting of plastic types and directly classify the plastic types in their pick-up vehicles. They also help with the sorting at the scrap shops.

L1 Aggregator: Small scrap shop

The scrap shops mostly source their scrap from small waste generators – the households. They get their scrap either by direct drop-off by households or through IWBs and waste pickers.

The scrap that is brought by the IWBs and waste pickers is further sorted and classified into different plastic types at the scrap shop since they would get lower prices from the L2 aggregator if they do not sort it. The informal workers use local terms to classify the plastic types. The sorting for these categories is done visually based on the quality of the plastic and using features like colour, product, quality, etc. Table 4.1 gives an overview of the terms used at the L0 and L1 levels, their meanings in Tamil, and the plastic types they refer to. This is adapted from Hande (2019a) and from observations during the interviews.

Table 4.1: Local terms used to describe the sorted plastic types

Term	Meaning of the term	Explanation of plastic types
Bommai	Toy	Aggregate of various plastic types that are commonly available, typically contains HDPE, PP, and PE
Masala		Like "Bommai", it is an aggregate of various plastic types and sometimes also contains low-value metals. It is used when the quantity of each material is too little to sort into more types at the lower levels. It can be further sorted into "Bommai", "Odappu", etc. at the higher levels of aggregation
Odappu (Black, white, colour, glass, television (TV), fridge etc.)	Broken goods	Contains plastic types like ABS[1], HIPS[2], and GPPS[3], which are further classified into various categories based on source (TV, fridge, etc.), appearance (Black, white, glass, etc.) or other characteristics. The lower-level aggregators classify it into sub-categories if enough scrap is available, otherwise, they are sorted into sub-categories at the L2 level.
PET	-	PET is sorted into a category separately.
Hard piece/pipe	-	This refers to PVC goods like pipes.
Kodam	Pitcher	This category refers to buckets and pitchers that are either made from virgin or recycled plastic. They are collected separately.
Colour	-	Black, white and clear plastic are collected separately. But sometimes there are small quantities of coloured plastics which are either classified separately as "colour" or in "Bommai".
Cover	-	This category refers to milk covers or other plastic covers. They are typically made of LDPE or HM-HDPE[4].

[1] Acrylonitrile Butadiene
[2] High Impact Polystyrene
[3] General Purpose Polystyrene
[4] High Molecular High-Density Polyethylene

The most common categories that the L0 and L1 aggregators reported getting from households are "Bommai", PET, "Kodam", and Black "Odappu". The other categories are generally lower in volume. Typically, black "Odappu" is the lowest value material they get but it was reported to have some demand in the market due to its use by the formal sector in laying roads.

The sorted scrap is then picked up by the L2 aggregators in the trucks that they own, since very few L1 aggregators own trucks. All the plastic scrap is typically sold to one large aggregator of plastic scrap. The other materials are sold to their respective aggregators.

L2 Aggregator: Large scrap dealers

There were no interviews conducted with large aggregators of recyclable plastic (6.1). However, some information was obtained from other stakeholders. Large aggregators have warehouses where they employ people, mostly women, to manually sort the scrap they receive into further plastic types. Hande (2019a) discusses the plastic types that they sort into, but it is out of the scope of this study.

Recyclers

There were no interviews or field visits to the informal recycling facilities (6.1), but some information was obtained from an expert.

The informal recycling facilities are mostly located in North Chennai, which is a lower socio-economic area compared to the south of the city. The facilities are present around the fringes of the city in a way that the public does not have easy access to them. They are present in clusters of 50-100 small facilities in what were described as "huts". Around two to five people work in the small facilities. They are mostly old women working without any safety equipment.

The recyclers have an association with connection to ports, from where they source imported plastic scrap. Since the quantities they manage are low, they mostly supply to small informal manufacturers of recycled plastic products.

Manufacturers

Even though manufacturers are outside the scope of this study, some interesting flows were identified through the interviews. The informal manufacturers of recycled plastic products sell their goods to itinerant waste buyers of cloth scrap. The IWBs of cloth scrap are independent of the other IWBs who collect paper, plastic, and metal. They exchange recycled plastic products for cloth scrap from households. This is an example of how the recycled plastic goes back to the source through the informal recycling value chains.

4.2 Formal Waste Sector

A brief description of the formal sector is already given in 2.3.2. Here some important highlights from the interviews with conservancy workers and large aggregators of non-recyclable plastic, that are not available in the literature, are provided.

Conservancy workers

All the workers who are directly involved in handling waste, or cleaning the streets in the formal sector are called conservancy workers. The conservancy workers who operate the BOVs are responsible for collecting source-segregated plastic. It was reported that sometimes they have to manually segregate the waste at the point of collection since some households refuse to segregate their waste before giving it to them. The waste is segregated into organic waste, recyclable plastic,

non-recyclable plastic, e-waste, clothes, etc. All types of plastic (including single-use plastic (SUPs) and MLPs) are collected by the conservancy workers, which contrasts with the informal waste collectors. The recyclable plastic collected is sold by the workers to the informal scrap shops, which is described in further detail in the next subsection. The non-recyclable plastic is given back to the supervisors from Urbaser Sumeet or the GCC.

Large Aggregator of non-recyclable plastic

Data for the large aggregator for non-recyclable plastic is obtained through an interview. The non-recyclable plastic, including MLPs and SUPs, is aggregated in warehouses of large scrap dealers. The large aggregator owns some machines like conveyors and baling machines to process the scrap and a shed to perform sorting. Thus, the plastic is sorted, baled, and sent to the final destinations.

While sorting, some recyclable plastic (around 5-10%) which is mixed with the non-recyclable plastic is removed and sent to recycling facilities. It was reported that sometimes these recyclable plastics are added to virgin streams of plastic production to reduce production costs, as is shown in Figure 4.1. However, this claim cannot be verified.

The rest of the plastic scrap is sent to cement plants (around 10%) and pyrolysis plants (around 80-85%). It was learnt that the EOL application for the construction of roads is not significant compared to cement plants and pyrolysis plants. The plastic is sorted differently for pyrolysis plants and cement plants. Everything except hazardous materials like batteries, lighters, etc. is sent to cement plants. Additionally, clothes, footwear and school bags are removed from the supply to pyrolysis plants.

The sources for the large aggregator are municipalities (70%) and bulk waste generators (30%). An insignificant amount of scrap is received from small informal scrap shops. It was also reported that they receive orders from other cities in Tamil Nadu that they directly send to cement plants for processing. These plants are typically located outside the city's boundaries.

4.3 Interactions

Interactions between the formal and the informal sector

The waste management system is complex, with ownership of plastic scrap switching many times between formal and informal actors in one loop (WBSCD, 2016). In the qualitative model, some key interactions between the formal and the informal actors are identified.

Plastic waste collected by the formal sector can end up in the informal recycling value chain in two ways – by waste pickers removing recyclable material from the corporation bins or landfills and selling them to informal scrap shops, and by conservancy workers selling recyclable scrap they collect in their BOVs or while sweeping the streets to the informal scrap shops. The latter flow occurs because the conservancy workers get an extra source of income by selling the recyclable plastic themselves to the informal scrap shops instead of throwing the material away (in the case of sweeping) or handing the material over to the supervisors (in the case of BOVs). From the interviews it was learnt that after privatisation many waste pickers were formalised and employed by the private companies working for the GCC. Initially, these conservancy workers were not allowed to take the recyclable plastic with them to sell at an informal scrap shop. Since this affected the cash flow they get every day, many of them refused to go to work, forcing the private companies and the GCC to allow them to sell the recyclable to the informal recycling value chain. In the small sample size interviewed, it was observed that this was the case for all recyclable plastic collected by the BOVs.

Hence while quantifying the system, it is assumed that all recyclable plastic collected by BOVs is processed through the informal recycling value chain.

It was observed that the aggregators in the IWS often sold their scrap to formal recyclers. They described their customers as having warehouses (L2 aggregators) and paying taxes. It was also learnt that for the formal recycling facilities, the large aggregators of recyclable plastic are dependable sources of a steady supply of scrap. However, as mentioned earlier, it was not possible to get data directly from recyclers. Thus, it is difficult to determine the dynamics beyond this stage of the recycling value chain.

From experts it was also learnt that the informal recycling facilities sell the plastic pellets at the local market, and this could enter the formal manufacturing chain. There were reports of recycled plastic being added into virgin plastic production to reduce production costs. But due to lack of data, these flows cannot be identified, and these claims cannot be corroborated.

Interactions outside Chennai

There were reports of plastic scrap coming by road from the neighbouring South Indian states of Andhra Pradesh and Karnataka. There were also reports of plastic scrap produced in Chennai being transported to these states for processing. However, these flows are not documented by official statistics or other literature.

Moreover, it was learnt that private service providers operating out of multiple states often collect and aggregate plastic scrap from the different states before processing it at a single location. It was also observed that the large aggregators of non-recyclable plastic send the baled scrap to pyrolysis and cement plants which are outside Chennai – sometimes within Tamil Nadu and sometimes outside Tamil Nadu. It was not possible to get more information on these flows through the interviews.

CHAPTER 5: MATERIAL FLOW ANALYSIS

This chapter discusses the quantitative aspect of the research study – Material Flow Analysis. First the methodological steps – Goal and System definition, and Quantification of flows are discussed. Then the results of the MFA are presented and interpreted. Finally, the existing data gaps in the system that were identified through the MFA are discussed.

5.1 Methodology

Material Flow Analysis (MFA) is introduced earlier (2.4) as an analytical method that can be used to study the flows and stocks of materials in a system. This section describes the methodology of MFA.

Three different types of MFA modelling exist – Accounting (or "book-keeping"), static and steady-state modelling, and dynamic modelling. Accounting, as the name suggests, involves collecting data on the flows and stocks of the material under study. It applies the principle of mass balance to trace the unknown flows and stocks and balance the flow of materials in the system. Static modelling involves establishing causality, i.e., the relationship between inflows and outflows of a process. It starts with flow data, process data and mass balance and translates them into a coherent set of equations. It is a snapshot in time and assumes that the system remains unchanged over the time period of the study. Dynamic modelling includes time as a modelling variable and identifies the developments of flows and stocks over time.

This study follows an accounting approach and aims to estimate the flows of post-consumer plastic scrap from households through different processes among formal and informal actors, identify the data gaps in the system, and make informed suggestions about filling in the data gaps.

MFA follows three basic methodological steps: Goal and system definition, Quantification, and Interpretation. This section describes the first two steps and the methodological choices that are made.

5.1.1 Goal and System Definition

Goal of the MFA

The goal of the MFA is to identify the material flows of household plastic waste along the formal and the informal sectors of the plastic recycling value chain in Chennai. The data gaps in the system that were realized during modelling are also identified.

System Boundaries

The city of Chennai, including the 15 zones and the wards within them, is considered as the geographical boundary for this MFA. Any exchanges of plastic scrap with cities outside Chennai, whether within or outside the state of Tamil Nadu, are considered to be import/export. Import or export of plastic scrap with other countries is not modelled in this study.

The time frame of the model is an average month, in the year 2023. Processes from the waste generation of plastic from households until their EOL destinations are included within the system boundary. However, EOL applications and manufacturers of recycled plastic are outside the system boundary. The environment, where littered plastic ends up, is also outside the system boundary.

The material considered is all post-consumer plastic scrap. Where there is data available, plastic scrap is divided into recyclable plastic scrap and non-recyclable plastic scrap (2.1.3). The units of measurement are tons per month for flows and tons for stocks.

Sub-systems and Processes

The qualitative model presented in Figure 4.1 is adapted to the system boundaries defined for MFA and simplified according to the availability of data. The system is divided into the sub-systems and processes given in Table 5.1.

Table 5.1: Processes included in the system boundary

Process number	Process name
Subsystem: Generation	
P1	Household plastic waste generation
Subsystem: Collection	
P2	L0 – Collection by IWBs
P3	Door-to-door collection by formal sector (FS)
P4	Collection of unsegregated waste by FS in bins
P5	Uncollected
P6	L0 – Collection by waste pickers
Subsystem: Aggregation	
P7	L1 – small scrap shop
P8	Material recovery facilities
P9	Transfer stations
P10	L2 – Large aggregator
P11	L2 – Aggregator of non-recyclable plastic
Subsystem: Recycling	
P12	Recycling facilities (formal/informal)
Subsystem: EOL Destination	
P13	Landfill
P14	Littering
P15	Open burning

The simplified base model of the system is given in Figure 5.1. When comparing Figure 4.1 and Figure 5.1, it is apparent that many flows and processes are not modelled in the MFA. These are discussed in detail in 5.2.2.

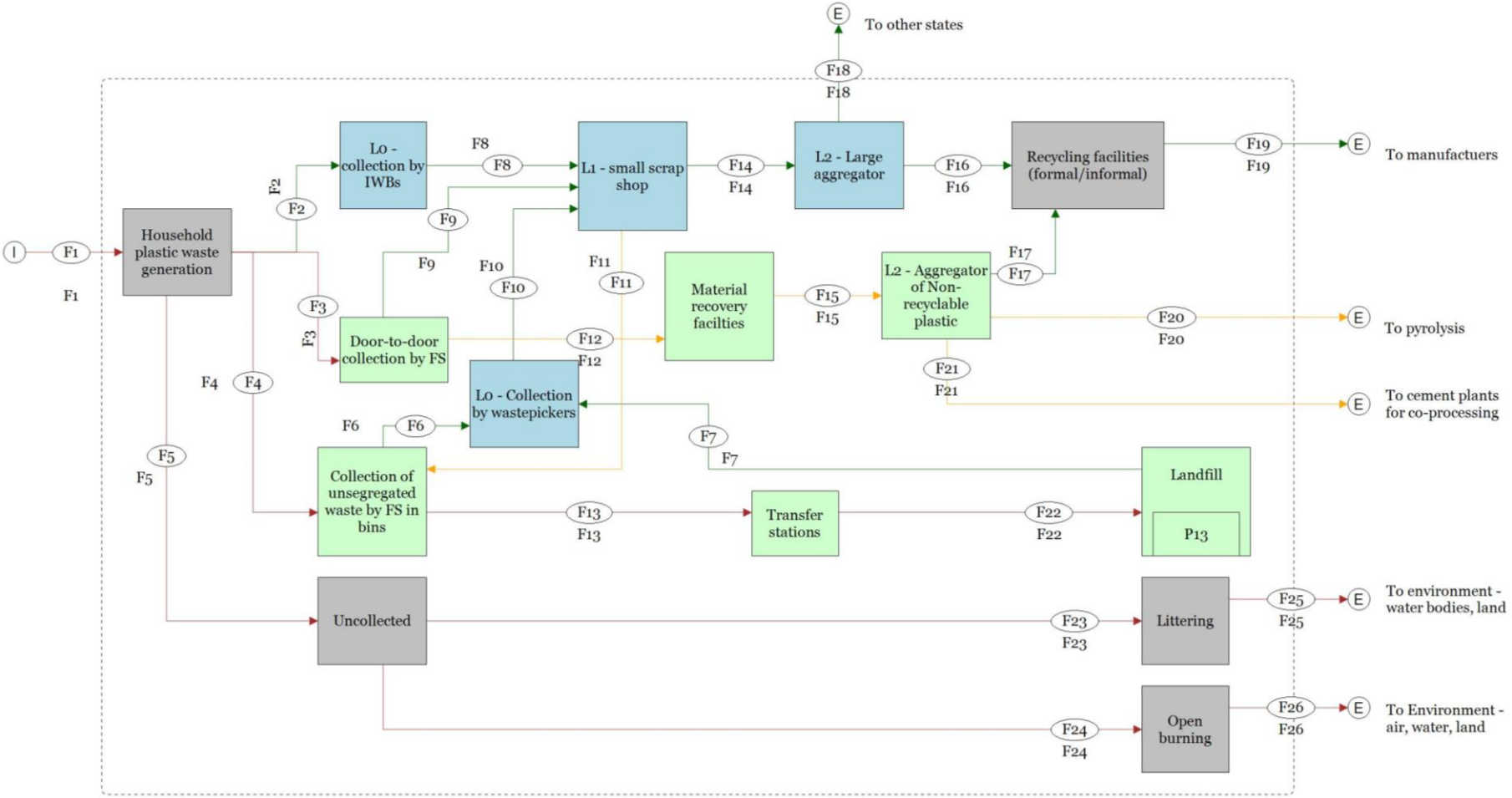

Figure 5.1: Base Model for MFA of household plastic waste in the city of Chennai, for a month in the year 2023. Processes in blue refer to the informal sector, processes in green refer to the formal sector, and the other processes are either ambiguous or belong to neither formal nor informal sectors. The flows in green refer to recyclable plastic, flows in orange refer to non-recyclable plastic, and the flows in red are either mixed waste or flows containing both recyclable and non-recyclable plastic.

5.1.2 Quantification

The approach followed for quantification, data sources, data reliability, and the actual calculation steps for each flow are described below.

Approach

Data is collected for the flows identified, according to the qualitative description of the system. Table 5.2 gives an overview of the flows that are quantified in this model. The data collected is stored according to the format described in Table 3.1 and can be accessed in Supplementary Data 1. Using this data, each flow, described in Section 3.3.1 is quantified by following both top-down and bottom-up approaches, wherever possible. Top-down data refers to the values reported at the macro-level – for a country, or group of countries – that is used to infer the dynamics at the local level. Bottom-up estimates, on the other hand, use data from individual workers, at the local or hyper-local level and use this to infer the dynamics of a higher level of system – city, region, or country.

Since the main objective of this study is to capture the dynamics at the city level, bottom-up estimates are preferred wherever available. However, top-down estimates can be used to check the validity of the obtained data ranges for the flows. Ranges of values are obtained for each flow, and two scenarios are developed in STAN – Scenario 1: Minimum value and Scenario 2: Maximum value – where the minimum and maximum possible values are used to build the model. A reconciled model is built following this, in which the most reasonable data value for the flows is chosen from the obtained ranges by observing the agreement between the data for different flows and the agreement between top-down and bottom-up approaches. The approach used for every flow is given in Table 5.2. The final model that is obtained through this process is given in 5.2.1. It should be noted that the quantification of flows is an iterative process, and the model is developed after several rounds of data collection, modelling, and reconciliation.

Data Sources

Table 5.2 also gives an overview of where primary data is used to fill in data gaps during the process of quantification.

Calculations for Flows 4, 5, 6, 7, 18, and 24 use estimates available in the literature. Flows 5 (uncollected waste), and 24 (openly burned waste) use percentages available from a study conducted in Chennai to estimate downstream flows of plastic waste (Kabadiwalla Connect, 2023). Flow 18 uses national statistics from literature. Estimation of Flow 6 uses official statistics reported by the government. Flows 6 and 7 use national and global statistics from the literature on waste pickers.

Flows 11, 17, 20, and 21 are purely estimated from primary data. Interviews with L0 and L1 aggregators provide data for Flow 11, while an interview with an L2 aggregator provides data for the other flows.

Estimations for Flows 2, 9, and 12 combine secondary data and primary data. The rest of the flows are calculated by the principle of mass balance. For a detailed explanation of how different data sources are combined, see Appendix C: Detailed Explanation of MFA Calculations.

Table 5.2: Overview of quantified flows, including the approach used for quantification, data uncertainty, and sources of data for each flow.

Flow number	Flow Name	Approach for Quantification	Data uncertainty	Data Source
F1	Plastic waste generated from households	Mass Balance	-	Calculated
F2	Plastic scrap collected door-to-door by IWBs from households	Bottom-up	High	Primary + Secondary
F3	Plastic scrap collected door-to-door by the formal sector using BOVs	Mass Balance	-	Calculated
F4	Plastic waste collected with MSW as unsegregated waste from corporation bins	Top-down	High	Secondary
F5	Uncollected waste	Unknown	Unknown	Secondary
F6	Plastic scrap recovered by waste pickers from MSW in corporation bins	Bottom-up	High	Secondary
F7	Plastic scrap by waste pickers from unsegregated waste in landfills	Bottom-up	High	Secondary
F8	Plastic scrap sold by IWBs to small scrap shops	Mass Balance	-	Calculated
F9	Recyclable Plastic scrap sold by formal workers to small scrap shops	Bottom-up	Medium	Primary + Secondary
F10	Recyclable Plastic scrap sold by waste pickers to small scrap shops	Mass Balance	-	Calculated
F11	Discarded (non-recyclable) plastic from small scrap shops	Bottom-up	Medium	Primary
F12	Non-recyclable plastic collected by formal workers to MRFs	Bottom-up	Medium	Primary + Secondary
F13	Plastic waste in unsegregated MSW that is transported from corporation bins to Transfer stations	Mass Balance	-	Calculated
F14	Sorted recyclable plastic scrap sold by small scrap shops to large aggregators	Mass Balance	-	Calculated
F15	Non-recyclable plastic transported from MRFs to L2 aggregators	Mass Balance	-	Calculated
F16	Sorted plastic scrap to recyclers	Mass Balance	-	Calculated
F17	Plastic with recycling potential recovered from non-recyclable plastic stream	Bottom-up	Low	Primary
F18	Plastic scrap exported to other cities in India for recycling	Top-down	High	Secondary
F19	Recycled plastic sent for manufacturing	Mass Balance	-	Calculated
F20	Non-recyclable plastic sent for pyrolysis	Bottom-up	Low	Primary
F21	Non-recyclable plastic sent to cement plants for co-processing	Mass Balance	Low	Primary
F22	Plastic in unsegregated MSW dumped in landfills	Mass Balance	-	Calculated
F23	Uncollected waste that ends up in litter	Mass Balance	-	Calculated
F24	Uncollected waste that is openly burned	Unknown	High	Secondary
F25	Plastic entering natural environments (water bodies or land)	Mass Balance	-	Calculated
F26	Particles entering environment (air, water, and land) after burning	Mass Balance	-	Calculated

Data Uncertainty

The uncertainties of the flows are classified into low, medium and high uncertainties, as followed in (Rinasti et al., 2022). This is presented in Table 5.2.

Flows 6 and 7 which signify the collection by waste pickers have high uncertainty since the obtained data ranges are large. Flow 4 has high uncertainty since there were reports of official statistics grossly underestimating waste collection. Flow 2 has a high uncertainty since there are issues with both estimating the number of IWBs and the average amount collected by them. Flow 24 is obtained from secondary data and a high uncertainty was reported in the study. Flow 18 has high uncertainty since there was no data at the regional level, and national statistics are used here.

Flows 9 and 12 have medium uncertainty since the primary data used to fill in the data gaps is not statistically significant. However, the data on the number of BOVs is close to the exact value. Flow 11 has medium uncertainty since primary data was used to fill in the data gaps, and it is not statistically significant. However, the data ranges obtained were not large.

Since the data from a large aggregator of non-recyclable plastic was obtained through interviews as percentages, and since there are only 5 such aggregators in the city, Flows 17, 20, and 21 have low uncertainty.

The data gaps are discussed in detail in 5.2.2.

Calculations

Detailed explanations of the calculations, assumptions made, and limitations of the assumptions can be found in Appendix C: Detailed Explanation of MFA Calculations. Below, an overview of the calculations for all flows is given, along with the equations for each flow.

Generation

Flow 1: Plastic waste generated from households

The total quantity of plastic waste generation is estimated using the principle of mass balance from the collected quantities of plastic scrap by different actors.

$$F1 = F2 + F3 + F4 + F5$$

Collection

Flow 2: Plastic scrap collected door-to-door by IWBs from households

A bottom-up approach is used to estimate the collection quantities of IWBs. Data from the interviews and from (Hande, 2019b) are used to an idea of the quantities of plastic waste collected by an IWB on average (125 kg/month - 323 kg/month). Then the number of IWBs in the city is estimated. The obtained range for the number of IWBs is 2050-3566 in the city of Chennai.

Finally, the two ranges are multiplied to get a minimum probable value of 256.26 tons/month and a maximum probable value of 1151.8 tons per month. The maximum value is chosen as the reasonable estimate to reconcile with the data on plastic scrap managed by the entire IWS. It should be noted that since most of the collection for IWBs comes from households, as earlier mentioned in 4.1.2, it is reasonable to assume that the bottom-up estimate refers completely to the collection from households.

*F2 = Total number of IWBs * Plastic collected in a month per IWB = 1151.8 tons/month*

Flow 3: Plastic scrap collected door-to-door by the formal sector using BOVs

The principle of mass balance is used to calculate this particular flow by calculating Flows 9 and 12 using a bottom-up approach (refer to Flows 9 and 12 for explanation).

F3 = F9 + F12

Flow 4: Plastic waste collected with MSW as unsegregated waste from corporation bins

A top-down estimate of unsegregated waste collected by the formal sector is used. First, the total plastic waste collected by the formal sector from households is calculated. This is done by using the reported quantity of MSW collected by the municipality (and the private companies it has leased the waste management tenders to) and multiplying it by the percentage contribution of households and the percentage composition of plastics in MSW as shown in the equation below.

*Total plastic waste collection by FS = Total MSW collection * % contribution of Households * % composition of plastics in MSW*

Next, the total plastic waste collected by the formal sector with the unsegregated MSW is estimated by subtracting the reported quantities of segregated plastic waste collected separated by the formal sector through the BOVs (top-down estimates for Flow 3). It ends up at around 7641 tons per month.

F4 = Total plastic waste collection by the FS - Plastic waste collected by the BOVs in a month = 7641 tons/month

Flow 5: Uncollected waste

The percentage of uncollected waste from the total waste generated is fixed at 29.9%. It is obtained from (Kabadiwalla Connect, 2023). The value was determined for a sample of 66 wards that exist around rivers in Chennai and is applied as an average for all wards of Chennai in this study.

*F5 = 0.299 * F3*

Flow 6: Plastic scrap recovered by waste pickers from MSW in corporation bins

The waste collected by waste pickers from corporation bins is calculated using a bottom-up approach.

First, the number of waster pickers in the city is estimated from multiple different sources (Hande, 2021; Lau et al., 2020; Sudhir et al., 1997) to obtain 22780-40,000 as the data range. The other national estimates for the percentage of waste pickers per population, compiled by (Lizner & Lange, 2013) are not used since the variation in the data is very high (8330 - 174911 waste pickers).

Then, the number of workers operating within the city and collecting plastic scrap from garbage bins is estimated by subtracting the number of waste pickers in landfills (Flow 7) from the total number of waste pickers.

The average amount of plastic waste collected by waste pickers on foot is estimated by using two approaches – by directly collecting data on the average amount of plastic scrap collected per day by

waste pickers and by using the average quantity of all materials collected per waste picker and the composition of plastic in it. This gives a range of 1.38 – 10.7 kg/day.

Finally, the two ranges are multiplied to get a range of total plastic collected by waste pickers from corporation bins. The obtained values are 903.76 tons/month as the minimum and 12535.05 tons/month as the maximum. The minimum value of 903.76 tons/month is chosen in order to reconcile with data for Flows 8 and 14 as explained below.

*F6 = (Total number of waste pickers in the city - Number of waste pickers in landfills) * Average amount of plastic waste collected by a waste picker in a month = 903.76 tons/month*

Flow 7: Plastic scrap by waste pickers from unsegregated waste in landfills

The plastic recovered by waste pickers from landfills is estimated by a bottom-up approach similar to Flow 6.

A drive conducted to enumerate waste pickers in landfills by providing ID cards for them had about 950 waste pickers registering for identity cards (IDs) (*Report on ID Card Camps for Waste Pickers*, 2015). It is assumed there was 100% registration of waste pickers at the landfills.

The average amount of plastic waste picker per waste picker is in the range of 1.38 kg/day to 10.7 kg/day as explained above in Flow 6.

The two ranges are multiplied to get a minimum value of 39.45 tons/month and a maximum value of 304.95 tons/month. 304.95 tons/month is chosen to mitigate the limitation of underestimation of the number of waste pickers operating in landfills.

*F7 = Total number of waste pickers in landfill * Average amount of plastic waste collected by a waste picker in a month = 304.95 tons/month*

Aggregation

Flow 8: Plastic scrap sold by IWBs to small scrap shops

This flow is calculated using mass balance by assuming that there is no loss of material during transportation by the IWBs from the households to the scrap shops.

F8 = F2

Flow 9: Recyclable Plastic scrap sold by formal workers to small scrap shops

While top-down estimates were available for plastic scrap recovered by formal workers, bottom-up estimates were attempted to resolve data quality issues in official statistics. From the interviews, it was found that conservancy workers operating BOVs get about 5-10 kg of recyclable plastic in a day. This combined with the reported number of BOVs (5863) leads to a range of 879.45 - 1758.9 tons per month of recyclable plastic recovered. The value on the lower end is used to reconcile with other data of the IWS.

*F9 = Number of BOVs in the city * Average amount of recyclable plastic scrap that is collected by a BOV in a month = 879.45 tons/month*

Flow 10: Recyclable Plastic scrap sold by waste pickers to small scrap shops

It is assumed that all the plastic collected by waste pickers from corporation bins and landfills is sold to informal scrap shops with no leakages.

$$F10 = F6 + F7$$

Flow 11: Discarded (non-recyclable) plastic from small scrap shops

From the interviews, it was observed that around 10-20% of plastic collected from households is non-recyclable through the informal value chains and is discarded in corporation bins as waste.

$$F11 = 0.2 * (F8 + F9 + F10)$$

Flow 12: Non-recyclable plastic collected by formal workers to MRFs

Like Flow 9, bottom-up estimates were attempted to estimate this flow. It was found that conservancy workers get about 10-15 kg of non-recyclable plastic in a day that they must return to their supervisors. This combined with the reported number of BOVs (5863) leads to a range of 1758.9 - 2638.35 tons per month of non-recyclable plastic recovered. The value on the lower end is used to reconcile with data on the non-recyclable plastic (NRP) aggregators.

$$F9 = \text{Number of BOVs in the city} * \text{Average amount of non-recyclable plastic scrap that is collected by a BOV in a month} = 1758.9 \text{ tons/month}$$

Flow 13: Plastic waste in unsegregated MSW that is transported from corporation bins to Transfer stations

The principle of mass balance is used to calculate this value. It is assumed that there is no leakage of material during transportation.

$$F13 = F4 - F6 + F11$$

Flow 14: Sorted recyclable plastic scrap sold by small scrap shops to large aggregators

Mass balance is used to quantify this flow. However, all three approaches are followed to estimate this flow and improve validity. The bottom-up approach is used by multiplying the estimated range of the number of scrap shops in the city (1970-2524) with the average quantity of plastic waste managed in scrap shops per month (0.8 - 1.52 tons/month). Since most of their supply comes from households, it is assumed that all the scrap they get is post-consumer plastic scrap. The obtained range of values for the total quantity is then 1576 tons/month - 3828.9 tons/month. The top-down approach data on the quantity of plastic managed by the entire informal waste sector of Chennai. The obtained range of values for this approach is 1600 tons/month - 2307 tons/month. Thus, the quantity estimated by the model falls within the ranges of both the top-down and bottom-up estimates.

$$F14 = F8 + F9 + F10 - F11$$

Flow 15: Non-recyclable plastic transported from MRFs to L2 aggregators

Mass balance is used to estimate this flow. It is assumed that there is no loss of material during transportation from MRFs to the large aggregator of non-recyclable plastic.

$$F15 = F12$$

Recycling

Flow 16: Sorted plastic scrap to recyclers

The recyclable plastic processed by the informal sector is sent to both formal and informal recycling facilities, but the distinction between formal and informal facilities is not made in this model due to lack of data. Mass balance is used to estimate this flow.

$$F16 = F14 - F18$$

Flow 17: Plastic with recycling potential recovered from non-recyclable plastic stream

The data obtained from the interview with a large aggregator of non-recyclable plastic is used to estimate this flow. The percentage of plastic with recycling potential recovered from the material is reported as between 5-10%. An average of 7.5% is used.

$$F17 = 0.075 * F15$$

Flow 18: Plastic scrap exported to other cities in India for recycling

(WBSCD, 2016) reports that 13% of all plastic scrap in India is transported to Delhi for recycling. The same value is assumed for the city of Chennai, but the destination of scrap is unknown and beyond the scope of this study.

$$F18 = 0.13 * F14$$

Flow 19: Recycled plastic sent for manufacturing

Mass balance is used to estimate the value of this flow. In reality, the plastic pellets are sent to the market, i.e., retailers and wholesalers who supply the secondary material to the manufacturers. However, this part of the supply chain is outside the system boundary.

$$F19 = F16 + F17$$

EOL Application and Destinations

Flow 20: Non-recyclable plastic sent for pyrolysis

Data from the interview is used to determine that 10% of the non-recyclable plastic is sent to pyrolysis plants for waste-to-energy recovery. Pyrolysis plants are outside the system boundary.

$$F20 = 0.2 * F15$$

Flow 21: Non-recyclable plastic sent to cement plants for co-processing

This flow is estimated by mass balance – the non-recyclable plastic that is not sent to pyrolysis or recycling facilities is sent to cement plants, as reported in the interview. Cement plants are outside the system boundary.

$$F21 = F15 - F17 - F20$$

Flow 22: Plastic in unsegregated MSW dumped in landfills

Mass balance is used to estimate the value of this flow and all mixed waste is assumed to be directly dumped in landfills. This assumption is made since through the interviews with experts it was found

that most of the waste collected by the formal sector is dumped in landfills, with a negligible amount of material that is being recovered and diverted from the landfills.

$$F22 = F13$$

Flow 23: Uncollected waste that ends up in litter

All the uncollected waste that is not openly burned is assumed to end up as litter by the principle of mass balance. They could either end up in water bodies or be retained on land.

$$F23 = F5 - F24$$

Flow 24: Uncollected waste that is open-burned

From Kabadiwalla Connect (2023), it is assumed that 6.98% of uncollected waste is openly burned. The approach used in the study to derive this estimate is not given.

$$F24 = 0.0698 * F5$$

Flow 25: Plastic entering natural environments (water bodies or land)

The destination of littered plastic is beyond the scope of this study as discussed in Flow 23. All of them are assumed to end up in the environment, which is outside the system boundary.

$$F25 = F23$$

Flow 26: Particles entering environment (air, water, and land) after burning

Open burning causes toxic fumes and ash that enter the air, water and soil. All particles after the stage of open burning are assumed to enter the environment which is outside the system boundary.

$$F26 = F24$$

5.2 Results

The results of the MFA are given in this section. This is the third step of MFA – Interpretation. The data gaps that were identified are also highlighted in this section.

5.2.1 Reconciled model

The final reconciled model is given in Figure 5.2. Several interesting observations can be made from the model.

The total plastic waste generated, as estimated by this model is 16,307 tons per month. This comes to about 543.6 tons per day of plastic waste generated in the city.

In this model, all recyclable plastic (flows in green) is aggregated through the informal recycling value chain. Even the segregated plastic that is collected by the formal sector is recycled through the informal recycling value chain (Flow 9). From 4.3 we know that this is because the conservancy workers sell the recyclable plastic to the informal scrap shops for extra cash flow for themselves.

The non-recyclable plastic (flows in orange) is only managed by the formal sector. While some of it is collected as segregated waste and processed in pyrolysis and cement plants (Flows 12, 15, 20 and 21), a large portion is collected as unsegregated waste (flows in red) and ends up in the landfills.

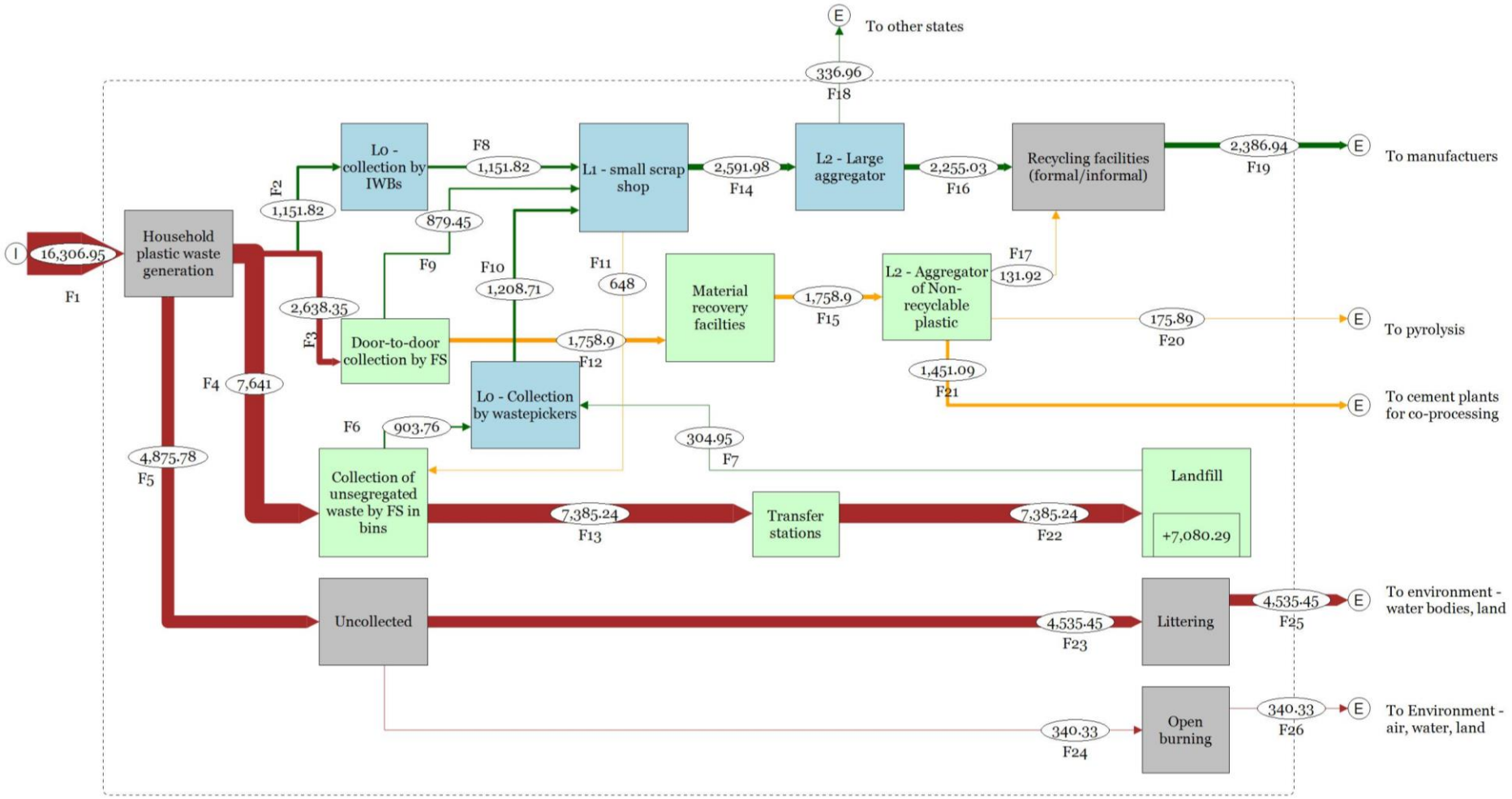

Figure 5.2: Reconciled quantitative model of household plastic waste in the city of Chennai, for a month in 2023. Processes in blue refer to the informal sector, processes in green refer to the formal sector, and the other processes are either ambiguous or belong to neither formal nor informal sectors. The flows in green refer to recyclable plastic, flows in orange refer to non-recyclable plastic, and the flows in red are either mixed waste or flows containing both recyclable and non-recyclable plastic.

There is also some amount of recyclable plastic that ends up in the mixed waste stream (Flows 4, 5) which is apparent since the waste pickers remove recyclables from the corporation bins and the landfills.

There is a small quantity of recyclable plastic that ends up in the non-recyclable plastic stream due to improper segregation (Flow 17). This is removed by manual sorting at the warehouse of the L2 aggregator of non-recyclable plastic and sent back to recycling facilities for processing.

It can also be seen that the model cannot estimate the flows of plastic going into informal and formal recycling facilities due to a lack of data beyond aggregation. This is discussed in the next subsection (5.2.2). However, as mentioned in 4.3, there are links from the informal sector to the formal sector at this stage: a significant portion of plastic scrap processed by the formal sector is sourced from the informal recycling value chain.

The collection by different actors is identified from the model and presented in Figure 5.3. This represents Flows 2, 3, 4 and 5. It is seen that a high percentage of the plastic waste from the waste generator is collected by the formal sector with the mixed waste collection of MSW. There is also a significant portion (about 30%) of plastic waste that is uncollected and ends up as litter or is openly burned.

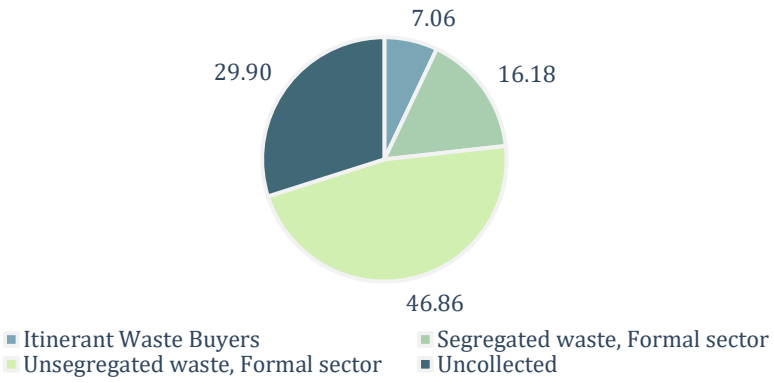

Figure 5.3: Collection by different actors from waste generators

Mismanagement, Recovery, and Recycling Rates

From the model, the mismanagement and recovery rates of plastic in the city of Chennai can be calculated. Table 5.3 gives the calculations for the different rates.

Table 5.3: Mismanagement, recovery, and recycling rates

Rates	Flows considered	Amount in tons/month	% of total plastic waste generated
Mismanaged rate	F23 + F24 + 0.6*(F22-F7)	9123.95	56%
Managed rate	F14 + F15 + 0.4*(F22-F7)	7183	44%
Managed in Landfills	0.4*(F22-F7)	2832.12	17.4%
Recovery rate	F14 + F15	4350.88	26.6%
Waste-to-energy	F20 + F21	1626.98	9.9%
Recycling rate	F18 + F19	2723.9	16.7%

The mismanagement rate is calculated by dividing the total quantity of mismanaged plastics by the total plastic waste generated in the city. It includes plastic waste that is openly burned, littered, and

not properly managed in landfills. Borrelle et al. (2020) assume that 60% of all landfill waste is mismanaged in lower-middle-income countries, including India. Thus, it is assumed that 60% of landfilled plastic waste is mismanaged in Chennai. It should be noted that this rate includes both recyclable and non-recyclable plastic. Table 5.3 gives the calculation for the mismanagement of plastics.

Mismanagement Rate = 56%

The rate of plastic waste that is managed includes everything that is recovered (non-recyclable and recyclable plastic) and the portion of plastic waste that is managed properly in landfills. The calculation for the total management rate is given in Table 5.3.

Management Rate = 44%

The total amount of plastic that is sent for recycling includes the recovery by the informal waste sector and the small quantity of recyclable plastic is recovered by the large aggregator of non-recyclable plastic in the formal sector. The calculation for the total recycling rate is given in Table 5.3.

Recycling Rate = 17%

To calculate the total recovery rate of the entire system, the non-recyclable plastic that is sent to pyrolysis plants and that is co-processed in cement kilns for fuel is also included. The calculation for the total recovery rate is given in Table 5.3.

Recovery Rate = 26.6%

From the recovery rate, the total recovery of plastic waste by the informal waste sector can be calculated separately. It is estimated by dividing the total amount of waste processed in small scrap shops (Flow 14) by the total amount of household plastic waste generated in the city of Chennai. This gives about 16% as the recovery percentage of the IWS.

% of Recovery by the IWS = F14/F1 = 16%

Plastic Types and Composition

The mismanagement, recovery, and recycling rates for all plastic are calculated together earlier. The model does not have a higher material resolution than "recyclable plastics" and "non-recyclable plastics". Thus, it can be interesting to see what plastic types are processed within these streams by looking at the data from literature and the qualitative system description that was obtained from the interviews (Chapter 4:). It is also interesting to see the individual recovery rates for recyclable plastic and non-recyclable plastics.

Table 5.4: Calculation for Recovery Rate of PET

Flows	Percentage of total plastic waste	Source	Amount in tons/month	Recovery Rate of PET
Generated in Households (F1)	5.50%	(Narayanan & Kapilavai, 2021)	896.88	75.5%
Processed by the IWS (F14+F17)	24.86%	(Hande, 2019a)	677.16	

Table 5.4 gives the calculation of the recovery rate for PET. 5.5% of all plastic waste generated from households is made of PET and 24.86% of all recyclable plastic processed through the informal waste sector is PET. This gives a recovery rate of 75.5% for PET. This is close to values reported in literature – Choudhary et al. (2019) report a recovery rate of 90% for PET in India.

As mentioned in earlier sections, this model assumes that all recyclable plastic is aggregated through the IWS. Calculating the percentage of recyclable plastic that is recovered by the IWS can help identify the potential for improving recyclability by estimating the quantity of recyclable plastic in the uncollected and mixed waste streams. Table 5.5 gives the calculations for the recovery of recyclable plastic. Chennai has a high recovery rate of recyclable plastics at 52.04%. The calculated recovery rate also implies that there is about 48% of recyclable plastic that is not recovered, that either ends up in landfills or as litter and is thus likely mismanaged.

Table 5.5: Calculation for Recovery Rate of recyclable plastic

Flows	Percentage of total plastic waste	Source	Amount in tons/month	Recovery Rate of recyclable plastic
Generated in Households (F1)	32.1%	Narayanan & Kapilavai (2021)	5234.43	52.04%
Processed by the IWS (F14+F17)	100%	-	2723.9	

The recovery rate of non-recyclable plastic can also be determined as shown in Table 5.6.

Table 5.6: Calculation for Recovery rate of non-recyclable plastic

Flows	Percentage of total plastic waste	Source	Amount in tons/month	Recovery Rate of recyclable plastic
Generated in Households (F1)	67.9%	Narayanan & Kapilavai (2021)	11072.42	14.69%
Processed by the FS (F15-F17)	100%	-	1626.98	

Only 14.69% of all non-recyclable plastic waste is recovered. Thus, the use of non-recyclable plastic is one of the major causes of plastic pollution.

5.2.2 Existing Data Gaps in the System

This section discusses some of the important data gaps in the system that were identified through the process of building the MFA. The flows that are not modelled in the MFA are also highlighted. For a detailed description of assumptions, limitations, and discussion on the data gaps for each flow, refer Appendix C: Detailed Explanation of MFA Calculations.

Exclusions in the Model

As mentioned in 5.1.1, the system described in the MFA is a simplified version of the qualitative system description (Figure 4.1). Due to the limited availability of data, several flows and processes from the qualitative model are not modelled in the MFA (Table 5.7).

Table 5.7: Exclusions in the model

Sub-system	Exclusions
Collection	Collection by private service providers, dropping off plastic scrap in scrap directly by households, and collection from the streets are not estimated in this study.
Aggregation	Flows in the formal sector – discarding some non-recyclable scrap from MRF to landfill, and aggregation of recyclable plastic by the formal sector (by private service providers and the MRF) – are not modelled. The reuse of plastic scrap in the informal sector is not modelled.
Recycling	The flows going through formal and informal recycling facilities are not identified.
EOL Application and Destinations	Leakages to the environment from different stages of the recycling value chain and the destinations of littered plastic are not addressed in the MFA.

In the collection sub-system, collection by private service providers is assumed to be negligible and is not modelled in this system. Moreover, the drop-off of recyclable plastics by households directly to scrap shops is not estimated separately due to lack of data – everything is assumed to be included within the door-to-door collection by IWBs. Due to lack of data and difficulty in estimating waste-picking from streets, both collections from streets by street-sweepers and by waste pickers are also left out of the model. This means that there is some recovery from littered plastic that is not modelled, thus leading to an underestimation of recovery rates.

At the aggregation stage, several flows are not modelled. The aggregation of recyclable plastic by the formal sector is not modelled, even though MRFs and private service providers perform this task in the formal sector. Moreover, some material is discarded from the MRFs to the landfills, which is not modelled in the system due to lack of data. There is a small amount of reuse of plastic in the informal waste sector for packaging purposes, which is not included in the quantitative model.

Due to large data gaps after aggregation in both secondary and primary data, this model does not differentiate the streams going through the formal and informal recycling facilities. This is because of several reasons like the system "hiding-off" (6.1). The processes beyond that are out of the system boundary as well due to the same reasons.

It was not possible to obtain interviews of pyrolysis plants and cement plants, due to time constraints and other reasons discussed in 4.1.2. Transparency in this stage of the recycling value chain is needed to evaluate the efficiency of the EOL applications of non-recyclable plastic that is currently used in the city of Chennai.

The end destinations of littered plastic are beyond the scope of this study and are thus not modelled here. They could end up in storm drains, eventually ending up in water bodies, or retained on land – by river banks or in other public places (Kabadiwalla Connect, 2023). Sometimes waste pickers and street sweepers could remove the plastic retained on land as mentioned earlier, thus putting them back in the recycling value chain or causing them to end up in landfills. This is not accounted for in this model due to lack of data.

There are also leakages of plastic from every stage of the recycling value chain to the environment (Figure 4.1). Only the losses from the L1 aggregators (Flow 11) are accounted for in this model. The other leakages are not quantified.

Finally, the material resolution of the flows is restricted to mixed streams of plastic and recyclable and non-recyclable plastic. The composition of plastic waste by polymer types at different stages of the recycling value chain is not modelled. However, there was some data collected through the

interviews (Table 4.1) and from literature (Hande, 2019a) about the polymer types handled by the informal waste sector, as discussed in the previous section.

Inaccuracies in the Model

The following data gaps exist in the flows that are identified and modelled in the system (Table 5.8). The limitations and implications of these identified data gaps are discussed in detail in 7.2.3.

Table 5.8: Data gaps in the modelled flows

Sub-system	Flow	Data Gap
Generation	Household Plastic waste generation	Generation quantities are not available from the literature and are not estimated directly in this study
Collection	Collection by IWBs	Number of IWBs operating in the city and the average amount of plastic recovered per worker
Collection	Collection by waste pickers	The data uncertainty is very high, indicating that the number of waste pickers operating in the city is overestimated in the literature
Collection	Collection by formal sector	Underestimation of collection quantities by official statistics
Aggregation	Export of plastic scrap	Inter-state movement of plastic scrap is not documented

CHAPTER 6: QUALITATIVE RESULTS

The results from the qualitative methodological approach of content analysis are discussed in this chapter. As explained earlier, the higher level of code clustering – code groups – are used to organize the information according to the different 'questions' that they answer. This chapter is divided according to those themes. First, the roadblocks to data collection are identified in 6.1. 6.2 discusses the barriers that the different actors – formal and informal – face in the social sphere. Finally, 6.3 gives a detailed assessment of the barriers in the technical sphere that limit the recovery and recycling of plastic waste that were identified in the interviews.

6.1 Roadblocks to Data Collection

Due to the complex and informal nature of the system, there is hardly any quantitative data available on the informal waste sector of Chennai, and the rest of India. While this study preliminarily attempts to quantify the system and identify existing data gaps in the system, identifying the factors limiting data collection can be useful for future studies, in both Chennai and other regions with informal waste economies. Knowing the barriers that they could face can help researchers plan for and navigate them better.

Results from the qualitative data analysis and personal experiences from the process of interviewing are used for this. First, the phenomenon of the system hiding off which limits data collection is described. Then some factors specific to the informal sector and the formal sector that were obtained through content analysis are described. Finally, barriers I identified through my personal experiences as a researcher are discussed.

6.1.1 System hiding-off

One of the biggest barriers to data collection that I faced is due to what I observed as the "**system hiding off**" from the public eye and not sharing any information outside. Due to the importance of this barrier and the likelihood that this is prevalent among informal waste economies in other regions as well, it is discussed in detail here.

In this study, the phenomenon of the system's unwillingness to share information – by giving interviews or any access to the facilities – and the mistrust of any outsider (in this case, the researcher) who tries to get any information about the system, is described as the "system hiding-off". This is especially encountered among both the informal and formal sectors at the downstream processes of the recycling value chain – large aggregators, recyclers, and EOL applications like cement plants. In this study, no recycler, cement plant, or informal large aggregator was interviewed.

In my experience, both the informal workers – IWBs, and small scrap shop owners – and formal actors like private service providers refused to share information on the recyclers/large aggregators to whom they supply plastic scrap. The informal workers also said that the recyclers they supply to are "registered", implying connections to the formal sector. Even when the recyclers are formal, they were reluctant to share any data due to several reasons. The informal workers felt that the recyclers/large aggregators would not be willing to share any information and may not be happy about having their information shared by them. Among the formal service providers, even when they depend on the formal recycling value chain to process the scrap they collect from households, there

is a huge lack of information that they have on what happens to the scrap after they sell it to the aggregator or the recycler. Their only contact with the recyclers is while sending the scrap to them, and they are not allowed to visit the recycling facilities either.

The formal actors stated several reasons as to why this was the case – some of them suggested that recycling is a lucrative business and hence, the recyclers do not want to share **proprietary information**. Another reason suggested was that even the formal recycling value chain is "shady" at some level – with either no proper regulations in place or recyclers not following the existing ones, recyclers burning material that is not profitable to recycle, mixing recycled plastic into virgin production to reduce costs of primary production, etc. The recycling industry was described as "territorial" and "mafia-like" with possibilities of corruption in the formal industry as well.

The informal waste sector hides from the public in different ways. For instance, the scrap from the small (L1) aggregators would be loaded up in the trucks owned by the L2 aggregators in the middle of the night, further making the system "invisible" and difficult to study. Most of the informal recycling facilities are on the fringes or outskirts of the city as mentioned in 4.1.2, or in places which the public does not have access. One of the experts I interviewed had to establish contact with the informal recycling facilities as a manufacturer interested in buying recycled plastic because they would not share information otherwise.

In the informal sector, this phenomenon of "hiding off" primarily arises out of the **need to protect themselves from law enforcement** due to their informal nature. They are afraid of being shut down in case information about them reaches the public or law enforcement. There are several reasons why the informal sector could potentially get into conflicts with legal and law enforcement. For example, many of them are not registered and do not pay taxes. Moreover, they do not follow environmental regulations, and the workers are exposed to hazardous fumes without any safety equipment – they could be penalised for this. There were also reports of recycling facilities sourcing plastic scrap from the port – implying illegal imports of plastic scrap.

There exists a **fear of law enforcemen**t among the other levels of informal workers too, due to reasons other than avoidance of tax. For instance, it was observed from the interviews that scrap shops used public spaces for the storage of scrap due to the limited capacity of their shops – some of them occupy sidewalks for storing bundles of scrap. They could be paying bribes to avoid penalisation (Ezeah et al., 2013).

The informal workers form "associations" to protect themselves from law enforcement. From the interviews, it was learnt that there exist local associations of itinerant waste buyers and small scrap shop owners that are headed by local politicians. The recycling facilities have their own associations too. Establishing the trust of associations such as these and going through them can help researchers get data on informal waste workers.

6.1.2 Informal Sector

Apart from the system being hidden, there are other factors due to the informal nature of the system, that make it difficult to quantify the flows of plastic waste in the system.

Due to the **decentralized nature** of the informal waste sector, it is highly complex and difficult to track. For example, it is difficult to quantify the collection by the waste pickers since the number of waste pickers and the amount they collect is **dynamic**, and even one waste picker could be working seasonally (4.1.2). Even within the city, there are many differences in the number of workers and the amount of waste generated between different zones.

There is a **lack of bookkeeping** due to the informal nature of the system. The small scrap shops and the IWBs had no proper records of their previous sales and could not give me an accurate estimate of the quantities of plastic scrap that they managed. There is also a **risk of unpredictability** in the supply chain due to dynamic pricing and irregular supplies.

Thus, these issues call for bottom-up approaches to quantifying plastic waste management systems, especially when the informal sector is involved. Detailed quantitative surveys would be needed to collect data on the informal sector.

6.1.3 Formal Sector

There are several data-related challenges in the formal sector. There is an extreme **lack of transparency** about the waste collection and generation quantities with reports of more waste being discarded in landfills than what is reported by official statistics. At the EOL stage, it is unclear if the formal sector can effectively process the non-recyclable plastic waste in cement plants by co-processing in cement kilns, or the construction of roads. There are reports of huge amounts of plastic scrap waiting to be processed by cement plants since the supply of plastic scrap is way higher than the capacities of the plants. While there is no way of corroborating this due to the lack of transparency, it should also be noted that the issue of lack of capacity to handle EOL application of plastic waste is not a problem that is unique to Chennai, or India.

The lack of transparency goes hand-in-hand with the **lack of a data-driven approach** by the formal sector. There is no evidence-based data available on the performance of the SWM collection system in different wards and there are only anecdotal records to where segregation is happening and where it is not. There is also a mismatch between how much is being generated and the capacity of the formal system to process it – but there are no studies or reports on the same. Currently, there is no attempt by the formal sector to enumerate or work with the informal sector.

Finally, there are reports of **interstate exchange** of plastic scrap, often undocumented, which makes it difficult to quantify what is generated and processed within the city. There is plastic scrap that is sent from the city of Chennai to other states for processing, but there were also reports of plastic coming into the city of Chennai from other states for processing here. Unfortunately, there is no data on these flows, and it was not possible to verify these claims within the scope of this study. The large aggregator of non-recyclable plastic who was interviewed reported that plastic scrap is sold to pyrolysis plants in the nearby states, and cement plants that are outside the city of Chennai. However, it was hard to get interviews with the pyrolysis plants and cement plants, with experts stating that there would be a reluctance to share any kind of data by these facilities as mentioned earlier.

6.1.4 Personal Experiences

Apart from the issues discussed above, I faced some barriers as a researcher attempting to collect data on the informal waste sector. As a woman, I did not feel safe going to many areas to establish contact and collect data through interviews, which limited the scope of my data collection. I was also told by some experts to be careful and not to go alone, or to take a male friend along with me to some areas that I was planning to visit.

It was also necessary to establish the confidence of the interview participants to get more data from them, and more time was necessary to do the same. Since this is a master's thesis, the data collection process was spread over three weeks for me, and it was not sufficient time to establish contacts and trust in the informal waste sector. This severely limited my data collection process as well.

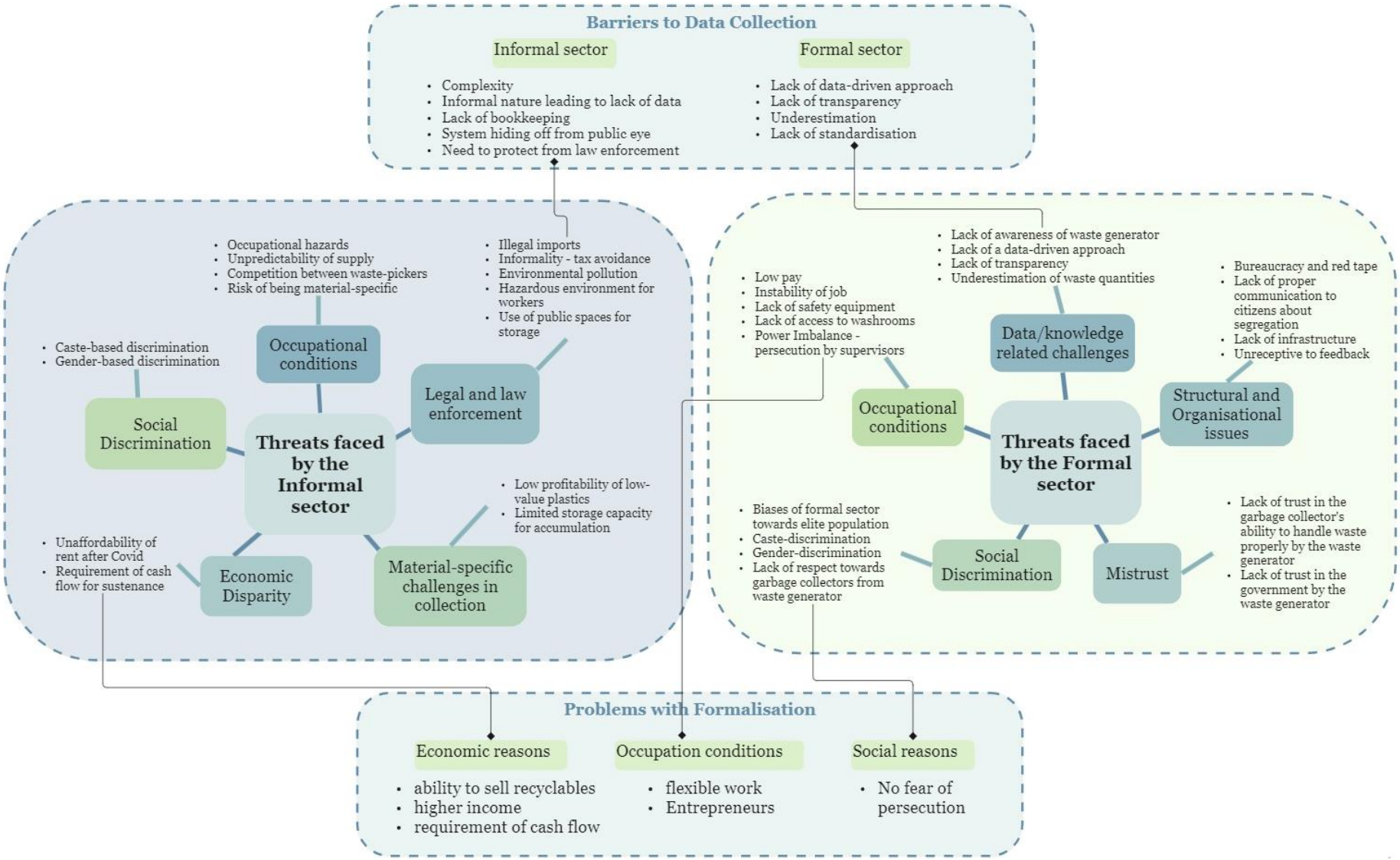

Figure 6.1: Qualitative results - Barriers in the social sphere and the barriers to data collection

6.2 Barriers in the Social Sphere

This section discusses the various barriers that the different actors face – either due to other actors, or systemic issues. It also includes barriers that the entire system faces due to social, cultural, or organizational factors. These generally affect the quality of life for the actors but could also reduce the efficacy of the system and the actors in the system, in managing the plastic waste generated in the city of Chennai. Figure 6.1 visually represents the identified barriers and their categories.

6.2.1 Threats Faced by the Informal Sector

Informal waste workers face threats due to multiple reasons – they face potential conflicts with the legal and law enforcement due to their informal nature, are subject to social discrimination in society, have severe occupational conditions, and also belong to the lower-economic strata of society which hinders them further as found in this study. Several of these issues are identified at the global and national levels in literature (Ezeah et al., 2013). But this section explores the dynamics at the local and hyper-local levels through interviews with stakeholders and experts. Figure 6.1 gives an overview of the different categories of barriers that were identified, and some of the important barriers in those categories. Each category of barriers is then discussed in detail below. Material-specific challenges faced by the informal waste sector are discussed in 6.3.2.

Economic Disparity

The informal workers are typically among the **lower socio-economic strata** of society. Many of them are in this profession as this is a source of livelihood for them, not because they chose the profession (C. Velis, 2017). It was observed that they are **heavily dependent on cash flow** for their income, which causes difficulties in formalisation (6.2.3). This also means that sudden changes in the supply chain which could disrupt their cash flow would have a huge impact on them. For instance, during the COVID pandemic, many of them had to shut down their scrap shops and go back to their villages due to loss of income. It was also observed that many of them could no longer afford the rent to retain their scrap shops post-pandemic.

Legal and Law enforcement

Due to the informal nature of their operations, informal workers often find themselves in situations which could lead to a potential conflict with law enforcement. In Chennai, informal recycling facilities are mostly present in the outskirts of the city, or somewhere that is not easily accessible by the public. The reason that the recycling facilities **'hide off'** in this way from the public eye is to avoid conflicts with law enforcement, as discussed earlier in 6.1.1 as well. Figure 6.2 gives an overview of the issues that could lead to potential conflicts with law enforcement for the informal waste sector, which was discussed in the previous section.

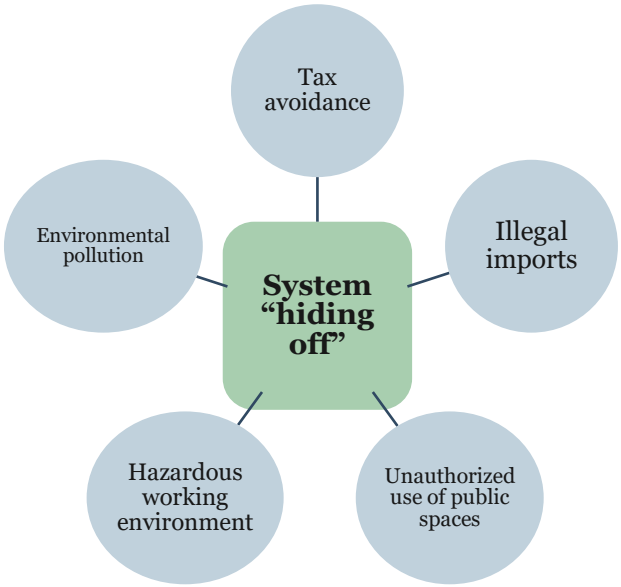

Figure 6.2: Overview of factors leading to system hiding-off

Occupational conditions

Informal workers face different kinds of barriers that are due to their occupational conditions. The ones identified through the interviews are discussed here.

There are several **occupational hazards** that informal workers face – especially the ones that are in the lower level of the hierarchy. Waste pickers use bare hands to dig into waste, which exposes them to hazardous materials, bio waste, and other harmful substances like needles, sharp objects, etc. The workers in the recycling facilities were reported to have no safety equipment and to be exposed to hazardous fumes. Waste pickers often face competition among themselves – whoever comes early to a dumpsite gets a higher share of high-value recyclables. This means that they often have to show up very early to pick up waste – around 4 a.m. sometimes – and that exposes them to risks as well.

Informal workers are also subjected to the **risk of unpredictable supply chains**. They are subject to dynamic pricing – the prices of the different materials change every day, and they would have to sell their material accordingly. They cannot afford to be material-specific, and the lower-level workers – waste pickers, IWBs, and small scrap shops are often material agnostic due to this reason.

Finally, I explored in my interviews if **seasonal differences** affect the informal workers. Some of them reported no seasonal differences in the amount of scrap that they get. But one of the IWBs reported that the collection during monsoon season is higher due to a couple of reasons – 1. During summer, the IWBs find it hard to travel longer distances in the heat, and even their customers, i.e., the waste generators, prefer staying at home to avoid the heat; 2. During the rainy season, people are more eager to get rid of plastic scrap lying around to avoid the breeding of mosquitos in the water that accumulates in littered plastic.

Social Discrimination

Informal workers face **social stigma** in general society due to the nature of the work that they do. While they perform important services of waste management for the city which the city would not

be able to survive without, they are not recognised for their services and are rather discriminated against for the same. In Chennai, and the rest of India, the informal waste workers are typically from lower caste communities which have been historically associated with this profession. This leads to them additionally facing **caste-based discrimination**. In this context, caste-based discrimination refers to prejudice faced by individuals based on the caste that they are born into. Discrimination can be in the form of limited access to resources like education and employment, social segregation, etc. During the interviews, I learnt that there were reports of informal workers finding it difficult to obtain housing due to their social status.

There exists social discrimination within the community of informal workers as well, with **women being especially vulnerable**. For example, women typically do not own collection vehicles, the way that men do. While women help in running the scrap shops owned by their male family members, they hardly own scrap shops themselves (Hande, 2019a). During my field visit with waste pickers, I observed that the women from the community were not allowed to talk as freely with me by the men in the community. Women also have to navigate the social hierarchy in their households. For instance, some communities follow a custom where the women are not allowed to go to the upper floors of the houses and be "above" the men – and are restricted to the lower floors of the houses.

6.2.2 Threats Faced by the Formal Sector

Structural and Organisational issues

The formal sector faces several structural and organisational barriers that limit efficient plastic waste management by the formal sector. It was observed that the system is very **bureaucratic**, with reports of multiple actors being unwilling to share data without approval by the corporation, and the corporation itself being uncooperative in sharing data and being transparent.

There is a severe **lack of infrastructure** that limits the formal sector – there are reports that there is not enough capacity in the formal sector to handle the plastic waste generated by the city, both in terms of segregated and unsegregated waste. Some areas in the outskirts of the city were provided proper waste collection services only recently – the waste was being dumped in open plots and openly burned before. Open dumping and burning still happen to some extent in certain parts of the city which do not have proper waste collection services. There were reports of workers from the formal sector burning the waste themselves, instead of collecting the waste from these dumpsites.

The formal system is also **disorganised**, with improper dissemination of information. There were reports from citizens that they were not sufficiently informed by the formal sector about how to segregate, and that the formal sector was unreceptive to feedback from the citizens. These factors, combined with the fact that the focus of waste management by the formal sector is on "collection and disposal" and not on "management" or "material recovery", lead to an inefficient plastic waste management system in the formal sector in Chennai.

Mistrust

There is **mistrust among waste generators** about the formal sector's efficiency to manage waste. For instance, there were reports that the citizens do not trust that the conservancy workers would collect the segregated waste properly and would end up mixing it later – hence they do not feel incentivised to segregate waste themselves. There is also mistrust of the government to efficiently manage the waste collected.

Occupational conditions

There are severe occupational conditions that the lowest level of workers in the formal sector – the conservancy workers – face as well. The data from the interviews include information about all conservancy workers – the workers who collected segregated waste in BOVs, and the workers who clean the streets and other public spaces.

Privatisation of the SWM system of Chennai has led to a **reduction in job security** and stability. The number of permanent employees is less, and contract jobs are more, with about 7000 permanent workers out of a total of around 19,000 workers employed (*Welcome to Greater Chennai Corporation*, n.d.). Apart from less pay and longer working hours in contract jobs, there are also reports of increased power imbalance – with supervisors being able to fire the contract workers easily. Moreover, they can no longer avail the benefits of a permanent government job.

Formal workers face **occupational hazards** which are as bad as, if not worse than, the hazards faced by informal waste pickers. It was reported that they are not given proper safety equipment to protect themselves while handling waste and they must often handle waste with their bare hands. There are reports that they are only given safety equipment while there is media coverage, which is then taken back later. Even in areas where they do have safety equipment, there were reports that the quality of the equipment is not sufficient to protect them from occupational hazards. Another **health risk** that the workers face is the lack of access to washrooms with clean water during their shifts. This disproportionately affects women and other gender minorities, who must go for long hours without access to washrooms even during menstruation.

Social Discrimination

Just like the informal workers, the formal workers in the lower level of the hierarchy also face **caste-based and gender-based social discrimination**. Most of the waste workers in the formal sector who directly handle waste are typically from lower-caste communities. They face caste-based discrimination from both their supervisors and the waste generators. There were reports of workers being mistreated by waste generators who refuse to segregate their waste properly because they think that it's the 'job' of the waste collector to handle their waste, and do not want to be 'told what to do' by the waste collectors. There were also reports of conservancy workers being denied drinking water by the waste generators who still treat them as "untouchables". The supervisors on the other hand overexploit workers who are especially from the lower caste communities. There were reports that the workers from the lowest castes are sometimes targeted by the supervisors and expected to work harder than the rest. There were also reports of workers who are not from lower castes being discriminated against since they are assumed to belong to the lower castes due to their profession.

Women and other gender minorities are especially vulnerable. As discussed earlier, they do not have access to washrooms. They also face sexual harassment and other forms of harassment by their supervisors. There were also reports that the women would be repeatedly assigned to clean the worst areas since the men would have more power than the women to refuse to handle something.

Data/Knowledge-related challenges

There are several data-related and knowledge-related challenges in the formal sector. The data-related challenges are already discussed in 6.1.3. The key data challenges in the formal sector are a lack of transparency and a lack of a data-driven approach to SWM in Chennai.

There is also a **lack of knowledge transfer** in the formal sector – while there are efforts to collect segregated waste, there is still a lack of awareness among waste generators on how to segregate waste properly, and this has not been sufficiently addressed by the formal system.

Limitations of current plastic waste management efforts of the formal sector

Apart from the identified barriers, the interviewees, especially the experts, also reported on limitations in the current plastic waste management efforts of the local government. This can be used to inform recommendations to improve the system. Apart from a lack of a data-driven approach that was discussed earlier, there is also a **lack of standardisation** that limits the performance of the formal sector. For example, there are no regulations on the recycling and manufacturing industry of secondary plastic products, and the existing regulations are not enforced properly.

There is a ban on all single-use plastics in the city. However, the **enforcement of the ban is not efficient** – with a focus on the retail side of the supply chain but no enforcement on the manufacturing of single-use plastics. There are monthly raids of warehouses and shops of wholesale and retail vendors of single-use plastic, with some fines imposed on them. But there is no proper information on where the SUPs are being produced and transported into the city, and no attempt to curb the production. The plastic ban was also reported to be disproportionately affecting the lower socio-economic strata, with small informal vendors, like meat and flower vendors, having no affordable alternatives to SUP bags.

Finally, the focus of the government's plastic waste management efforts has been on the disposal of garbage and not the management or reduction of garbage. For instance, the payment for the waste collection services for the private companies, according to their tender, is based on the tons of waste they collect – so, the more waste they collect, the more money they get. The tenders are also only focused on the collection and disposal of waste, with no effective policies on diverting waste from landfills. There was criticism among the experts that there is no incentive to reduce the waste produced or to divert waste from landfills. Moreover, all existing efforts are majorly focused on elite areas, with reports of minimal collection services in the outskirts of the city, and in areas with lower socio-economic demographics.

6.2.3 Problems with Formalization

As mentioned briefly in Sections 4.1 and 6.2.1, there is a preference for remaining in the informal waste sector owing to actors in the formal sector facing several of the barriers identified above. This preference was observed among the workers at the lowest levels of the hierarchy – specifically, the conservancy workers who were waste pickers before getting formalized. The reasons for this preference are grouped into different categories (Figure 6.1) and explained in detail below. In Figure 6.1, these categories are also mapped to specific barriers faced by actors in the formal and informal sectors.

Economic Reasons

As discussed in 4.1.2, the formal sector initially prevented the conservancy workers from selling the recyclables to the informal scrap shop which affected their daily cash flow. Many of the waste pickers refused to be formalised for this reason. Even after this changed, there is still some perception among the workers that they had higher incomes before being formalised and/or privatised. One of the reasons for this is that they used to work as "freelancers" for households and small businesses by collecting and disposing of their mixed solid waste in corporation bins for a small fee.

Social Reasons

The workers in the formal sector, who were previously informal, felt that they preferred the time they were informal since they didn't have to live in "fear" then. As discussed in Section 6.2.2, due to the power imbalance between supervisors and the workers, the workers have little power to exercise their rights and face caste-based discrimination from their supervisors. There were reports that they are asked to come to work even when they are sick, and they are in constant fear of being fired or persecuted if they refuse to comply. Women are especially vulnerable to workplace discrimination (6.2.2). There exists discrimination in the informal sector as well; as mentioned in 6.2.1 workers find it difficult to find housing due to their social status. However, the decentralized nature of the informal system gives them more independence and "dignity", according to some of them.

Occupational Conditions

In addition to fear of persecution by the supervisors, the occupational conditions offered by the formal sector also make it less appealing than the informal sector. While there are harsh working conditions for waste pickers, it does not seem to get better enough for the conservancy workers for them to prefer being formalised. Moreover, there are long working hours in the formal sector over which they do not have control over. For example, there was a report from a woman preferring to remain informal since the working hours in the formal sector prevented her from managing her household chores and taking care of her children. Similarly, during the interviews both the male and the female conservancy workers preferred being informal due to more flexible working hours (4.1).

6.3 Barriers in the Technical Sphere

Several barriers in the technical sphere are identified. These are the barriers that prevent efficient management of plastic waste at different stages of the recycling value chain – source segregation, collection, recycling, or EOL application – and in both the formal and the informal sectors. Figure 6.3 visually represents the barriers at different stages and sectors in the recycling value chain. They are discussed in detail below.

6.3.1 Source Segregation

There is a **lack of awareness** among waste generators on how to segregate with limited efforts by the formal sector to improve awareness, as discussed earlier. Thus, even where systems are in place to collect segregated waste, not all waste generators segregate their waste in those areas. There is no data, however, to evaluate the performance of source segregation in different wards since there hasn't been any attempt by the formal sector to collect data and report this.

There is also a **lack of capacity** to manage segregated waste in the formal sector. There were reports that even if the waste is segregated at source by the waste generators, in many areas they do not have the capacity to collect segregated waste and end up mixing it. There were also reports that waste that was collected after segregation was dumped in the landfill as mixed waste. In the latter scenario, however, the recyclable plastic would have been removed by the formal workers and sold to the informal waste stream, and only the lower-value plastics would end up in landfills. The fact that even source-segregated waste is not managed properly disincentivizes the waste generators from performing source segregation, as mentioned earlier.

Finally, some experts suggest that the presence of alternative mixed waste collection systems enables people to throw unsegregated waste and does not enforce source segregation of waste.

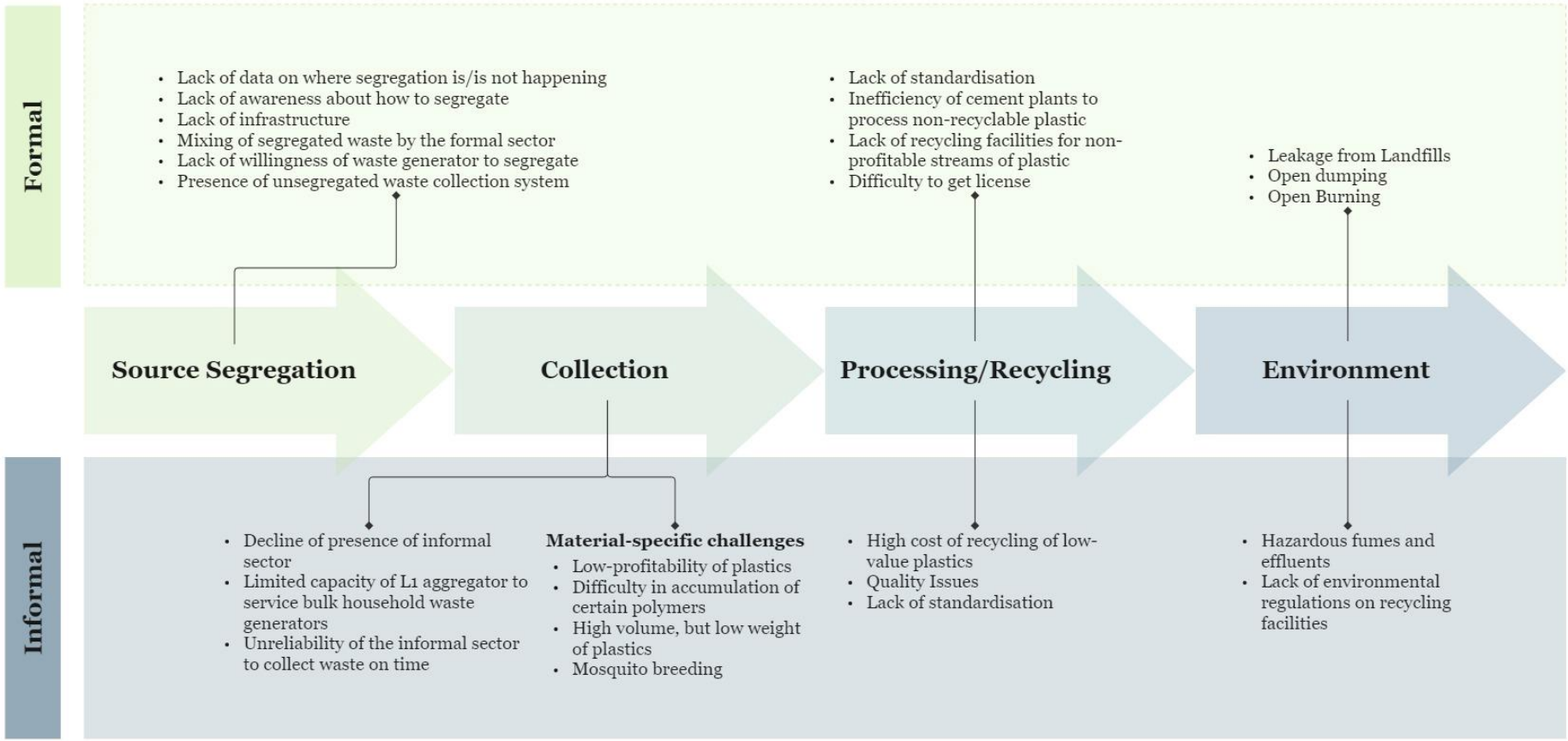

Figure 6.3: Barriers in the Technical Sphere

6.3.2 Material-specific challenges for the IWS

There are difficulties that the informal workers face that are specific to plastic, or certain types of polymers. For plastic scrap in general, the key barrier is that it is a **lightweight** material – the volume is very high, but the weight would be very low. So even if the workers manage to collect a truckload full of plastic, their profits would be much lower than other materials for the same volume.

It is difficult to accumulate certain polymers due to **irregular supply** of those scraps or their low profitability – e.g., it takes a long time to accumulate a profitable quantity of thin plastics like LDPE polybags. So, the informal sector generally does not collect these types of plastics since they have limited capacity to store the plastics for accumulation. The more profitable polymers – like HDPE cans – are sent in a "mixed" category ('Masala'/'Bommai' – 4.1.2) to the large aggregators even if the supply is irregular at the L0 and L1 levels of aggregation.

The informal sector refuses to collect the low-value plastic due to **low profitability** – these typically include thin covers as mentioned before, single-use plastics (SUPs) and multi-layered packaging materials (MLPs), secondary plastics, LDPE milk covers, etc. Milk covers are a special case since some reported that they do collect it, while some reported that they do not. One of the barriers in the collection of milk covers is that if the waste generator does not properly dry the covers before giving them, there is a risk of **breeding of mosquitos**, for which the informal scrap shops would get penalised by the corporation. It was also reported that despite the reluctance of the IWS to collect certain types of plastic, the waste generators give it to them nevertheless since they do not have other ways of disposing of it. In this case, it was observed that the IWS sometimes **reuses** the bigger plastic bags and containers that cannot be recycled, for packaging the scrap or for personal purposes.

6.3.3 Collection by the IWS

Apart from challenges faced by the workers in the informal waste sector which were discussed in 6.2.1, and the material-specific challenges faced by the informal sector, which is discussed above, there are some challenges in the system because of its dependence on the informal waste sector for the collection and aggregation of recyclable plastic.

There are reports of the **decline of the informal sector** in the city due to multiple reasons, like shutting down of scrap shops post-COVID, upward social mobility of the informal workers, etc. However, these reports are not verified. Another challenge that was mentioned in the interviews is that the small scrap shops have **limited capacity** to service bulk generators of household waste like high-rise apartments and big apartment complexes that are increasing in number in the city. These complexes could consist of 1000-2000 households at times, but one small scrap shop has the capacity to serve only around 50-100 households a month. So, there is a rise of private service providers for the collection of recyclable waste. There were also reports of citizens finding the door-to-door collection by the informal waste sector unreliable, and hence increasingly prefer using private service providers.

6.3.4 Recycling and EOL Processing

While it was very hard to get any data on the recycling and EOL processing stage (6.1.1), some barriers were identified in the recycling and processing stage through the interviews with experts. They are discussed here.

In the informal sector, the infrastructure in recycling facilities is outdated and not organised. They are generally older technologies, and they do not follow any standards or regulations. This implies that the quality of recycled products obtained from these facilities might be low. There is a **high cost**

of recycling for low-value plastics, like food packaging, SUPs, LDPE films etc., which renders them non-profitable for the informal sector. So, there is no infrastructure in the informal sector to manage these kinds of plastics.

In the formal sector, there were reports of difficulties in getting licenses for recycling facilities due to a **lack of proper standardisation and regulation**. This results in people with links to politicians and other kind of lobbying power who can secure these licenses through other means, dominating the sector.

The other issues reported in the formal sector were the **inefficiencies of EOL applications** of non-recyclable plastic. As mentioned earlier, there were reports of cement plants not having the capacity for all the plastic scrap they get, with tons of plastic scrap waiting to be processed, due to a mismatch in the demand for plastic scrap in the cement plants and the supply of plastic scrap. There were also reports of inefficiencies in the co-processing itself – with the current technology of cement kilns being unequipped to process plastic scrap. However, these reports cannot be corroborated due to reasons discussed in 6.1.3.

6.3.5 Environmental Issues

There are several environmental issues in both the formal and the informal sectors that were already covered briefly in other sections but are mentioned here.

There is a high prevalence of **open dumping and open burning** by the formal sector itself, due to its incapacity to provide collection services throughout the city. This leads to toxic fumes in the air and leakage of hazardous materials in water and land. Openly dumped plastic ends up as litter in water bodies and blocks storm drains. The plastic that ends up in landfills is also harmful to the environment due to leakages from landfills.

There are also environmental issues due to the informal recycling facilities as discussed in the earlier section. The informal recycling facilities do not follow environmental regulations and there are **hazardous fumes** and effluents released into the environment.

CHAPTER 7: DISCUSSION

In 7.1, this chapter ties together the interpretations from the results obtained. It then discusses the limitations of this research in 7.2.

7.1 Interpretations

The results from Chapters 4, 5 and 6 are interpreted in this section. First, some of the interesting insights from the qualitative system description are revisited and their implications are discussed. Then, the results of the MFA are further interpreted and compared with findings from other studies. Finally, the results from the qualitative analysis are interpreted.

7.1.1 Insights about the system

The objective of the informal waste sector is purely economic, with no social responsibility to provide the service of waste management. The informal workers at the lower level are also material agnostic for this reason – they will collect any type of recyclable material that is profitable for them. This corroborates what is described in other literature on the informal waste sector (Ezeah et al., 2013; Wilson et al., 2006). These, combined with the fact that the capacity of the IWS is under-utilised (Hande, 2019b), can be used to **incentivise the IWS to improve the collection of plastic waste**. Apart from increasing the recovery of recyclable plastic, they can also be incentivised to collect non-recyclable streams of plastic waste, which will reduce littering. Due to the problems with formalisation that were identified earlier (6.2.3), instead of conventional formalisation, a combination of monetary incentives for the IWS, and strict enforcement of source segregation by the waste generator should be used to achieve this improved collection.

A significant portion of the recyclable plastic that is collected by the formal sector after source segregation is aggregated by the IWS since **the conservancy workers sell the scrap to informal scrap shops** for extra cash flow for themselves. Moreover, after aggregation this scrap is often sold back to the formal recycling facilities from the informal sector. Thus, the ownership of material changes many times between the formal and the informal sectors within one loop of the recycling value chain.

7.1.2 Insights from MFA

The model estimates that 543.6 tons per day of plastic waste is generated in the city. With a population of about 6.4 million people in Chennai, this gives a per capita plastic waste generation of about 85 grams per day, or **31 kg per year**. This is about **50% more than the reported values for per capita plastic waste** generation (CPCB, 2015). This corroborates the finding from the qualitative analysis that the estimations of plastic waste generation in official statistics are underestimated since they do not include the plastic scrap collected by the informal waste sector and the uncollected plastic waste.

There is a high quantity of plastic waste that is either uncollected or not segregated and ends up in landfills with mixed waste. Thus, improved segregation and collection can reduce the amount of plastic waste going into landfills and litter.

Mismanagement vs Recovery Rates

The calculated rates of mismanagement and recovery for different plastic types in Chennai are discussed below in the context of the quality of data used to make those estimates and compared with national averages reported in the literature.

Mismanagement rate

In this study, it is found that the **mismanagement rate of plastics is high, at about 56%**. It should be noted that the assumption that 60% of landfilled waste is mismanaged is from global statistics and not local data. From qualitative analysis, it was determined that both the landfills in Chennai are not scientifically managed and there is some leakage to the environment. There is also biomining of the landfills to improve the management of the waste. However, it is not possible to quantify the exact percentage of mismanagement of landfilled waste.

Recovery by the IWS

The **recovery rate by the informal waste sector was calculated to be about 16%**. This value agrees with some findings from the literature – Hande (2019b) reports that the recovery of post-consumer plastic by the informal waste sector lies between 11%-20%. However, Neo et al. (2021) report that the collection of the informal waste sector in India is 59.4% which does not agree with these estimates.

When compared to the previous result on collection by different actors from the waste generator – we can see that the recovery by the informal waste sector increases from 7.06% (which is the collection by IWBs) to almost 16% due to the operations of waste pickers and the sale of recyclable plastic by conservancy works in the formal sector to the informal waste sector. Nandy et al. (2015b) found that more than 70% of the plastic that ends up in mixed waste collection streams is removed by the waste pickers. In this study, however, only about 15% of the plastic from mixed waste streams is removed by the waste pickers. This relates to the finding that there are large data gaps in the literature, with the possibility of overestimation of the number of waste pickers in the cities.

Recovery and Recycling Rates

The recovery rate is calculated to be about 27% and the recycling rate is about 17%. It should be noted that these recycling and recovery rates include both recyclable and non-recyclable plastic. While calculating recycling rates, the model does not account for losses beyond the stage of aggregation or for recycling efficiencies either. Despite this, the rates calculated in this study are lower than the high recovery rates and recycling rates of plastic for India that are reported in the literature. Shanker et al. (2022) report that 60% of the total plastic waste generated in India is reprocessed or recycled. Nandy et al. (2015b) estimate through a nationwide material flow analysis for plastics that 60-80% of plastic waste generated in India is recycled.

Next, recycling rates for the individual streams of polymer types, and recyclable and non-recyclable plastic are explored.

Recovery for Polymer Types

The recovery rate for PET is found to be 75.5%, based on the sampling of plastic waste generated by households (Narayanan & Kapilavai, 2021). In this sampling, it was found that 5.5% of the plastic waste generated was PET. But other reports state that the composition of PET in household plastic varies from 7.4% (CSE, 2020) to 9% (Rafey & Siddiqui, 2021). When these values are used, it is found

that the recovery rate for PET varies from 46% - 56%. Thus, there is a high sensitivity of the PET recovery rate to the values of the composition of PET in household plastic waste. Despite this, the recovery rate for PET is still very high. However, other studies report up to a recovery rate of 90% for PET in India (Choudhary et al., 2019), which could be overestimated.

It was not possible to calculate the recovery rate for other plastic types (HDPE, PE, PP, etc.) due to lack of data on the composition of household plastic waste and the composition of plastic waste managed by the IWS. For the latter, the values are available in the local terms used by the informal waste sector ('Bommai', 'Odappu', etc.) in Hande (2019a) which is not easily convertible to the distinct polymer types. For the former, most plastic waste composition studies are done on MSW that enters landfills (CPCB, 2015), which does not account for plastic scrap removed by the IWS in landfills, corporation bins, or directly from households. Moreover, (CPCB, 2015) includes non-recyclable multi-layered plastic (MLPs) along with recyclable fractions in the values reported for HDPE and LDPE, thus making it difficult to distinguish between the recyclable and non-recyclable fractions of HDPE and LDPE.

Recovery of recyclable and non-recyclable plastic

Finally, the recovery rates for recyclable plastic and non-recyclable plastic are estimated to be about 52% and 15% respectively.

When compared with the total recovery rate of all plastics (27%), it can be seen that the recovery rates drastically improve when only recyclable plastic streams are considered. This is probably why the recovery and recycling rates for plastic for India that are reported in India are so high. Literature is ambiguous about how the recovery rates and mismanagement rates of plastic are calculated, and where plastic is distinguished as recyclable and non-recyclable in the calculations. It is not possible to ignore the impact of mismanagement of non-recyclable plastics with over 75% of it not being recovered. Thus, this distinction needs to be communicated clearly.

Another interesting observation is that the estimate for the composition of recyclable plastic in household plastic waste used in this study only considers the products which have labels on them, while the fraction of potentially recyclable plastic could higher. This is because the source where the data for the fraction of recyclable plastic is obtained from (Narayanan & Kapilavai, 2021) classifies all products which do not have labels, in the category 'other'. Thus, the high recovery rates for recyclable plastic could be because a significant portion of recyclable plastic that ends up in mixed waste streams is accounted for as non-recyclable plastic due to the absence of labelling. While some of this could have been recovered by the IWS, it still suggests that **proper labelling of plastic products in India can improve data quality and help improve segregation and collection**.

7.1.3 Insights from the Qualitative Results

Roadblocks to Data Collection

The phenomenon of the system hiding-off is one of the biggest barriers to data collection. As discussed in 6.1.1, in the informal sector, this is because of the fear of conflicts with law enforcement due to multiple reasons. Combined with the lack of bookkeeping in the informal sector, this entails the **need for quantitative surveys** to collect data in the informal sector. Recording the quantities of scrap received by the scrap shops over a fixed duration of time might be required to collect information on the quantities managed by the informal sector. This necessitates that a considerable amount of trust is built with the informal actors, and there is reassurance of no threat to their livelihoods. Collaborating with the municipality and going through official means could help gain

some access to the informal sector in this case. The other recommendation that was obtained through the qualitative research, is to approach the associations, or self-formed organizations of waste pickers, IWBs, and recyclers and establish their trust. This will help gain access to most of the informal workers, which will help enumerate them. These associations are sometimes headed by local politicians (6.1.1), which reinforces the need to gain the approval of the local government for such detailed surveys.

In the formal sector, recycling facilities are reluctant to share data due to multiple reasons like bureaucracy, proprietary information, etc. (6.1.3). There is also a lack of transparency in official statistics. Thus, there is a need to improve data collection in the formal sector and to transparently publish them.

Barriers Faced by the Stakeholders

The barriers faced by the stakeholders are divided into the social barriers that affect the quality of life of the people or the functioning of the entire system, and the barriers that affect the technical sphere, i.e., the collection, processing, and disposal of plastic waste. Some interesting insights for both spheres are discussed below.

Social Sphere

The barriers identified for the stakeholders in the formal and informal sectors are grouped into different categories like social issues, occupational conditions, economic disparity, and structural and organizational issues (Figure 6.1). From these results, and the interviews, it was concluded that there is a **preference for the IWS over the formal sector** among the workers in the lower levels of the hierarchy (waste pickers, conservancy workers, and itinerant waste buyers). The decentralized nature of the IWS gives some autonomy to the informal workers that protects them from several social barriers, like caste-based discrimination, and power imbalances. Thus, as mentioned in 7.1.1, **instead of conventional formalisation, decentralized, bottom-up integration with the IWS** could provide the informal actors the social benefits of being in the formal sector, while protecting them from the social issues in the formal sector. This would involve recognising the contribution of the informal sector, integrating their capacity for the management of plastic waste while the workers retain their autonomy, enforcing laws that would protect their interest, but also ensuring that the actors at the lowest levels have access to knowledge about their rights and the benefits they can receive.

One of the key issues identified in the current plastic waste management efforts of the formal sector is the **focus on the collection and disposal of plastic waste**, instead of reducing plastic waste generated and managing it. Hence, changing this focus by providing the right incentives for the private companies, the actors, and the IWS can improve plastic recovery rates. There should also be a mindful implementation of the plastic ban to ensure that the effects of the ban are not disproportionately borne by the people in the lower socio-economic strata of society. This can be done by making sure that affordable alternatives are available, and that the production of single-use plastic is limited.

Technical sphere

Several barriers in the technical sphere were identified for different stages of the recycling value chain. At the source segregation stage in the formal sector, it was observed that **mistrust in the government and lack of awareness** prevent waste generators from properly segregating dry and

wet waste. The possibility of the formal sector **mixing the source segregated waste**, and not efficiently handling the waste after collection deters the waste generator even more.

Improper source segregation also leads to issues like mosquito breeding, as identified in 6.3.1. When plastic waste that is discarded is not properly dry, it serves as a breeding ground for mosquitos, which leads to the spread of diseases.

There is also the issue of inefficiency of the current plastic waste management solutions, like co-processing in cement plants. This, however, is an issue that is not restricted to Chennai, or India.

Thus, the formal sector needs to invest significant efforts towards establishing the trust of the waste generator and improving the efficiency of plastic waste management. At the recycling stage, the formal sector also needs to enforce standardisation and environmental regulations to ensure that the quality of recycled plastic is maintained, the workers have safe working conditions, and the pollution from the recycling plants is minimised.

7.2 Limitations

Several limitations in this research study must be acknowledged in order to critically analyse the results obtained and to propose recommendations for future studies to minimise them. Limitations in each stage of the research process are identified below.

7.2.1 Data Collection

As stated at the beginning of the report, the biggest limitation of this study and all other studies on the informal waste sector is the lack of data. While this study has contributed to significantly bridging some of these data gaps, there remain limitations in the modelling. Due to a lack of quantitative data, several simplifications are made while modelling which could lead to inaccuracies. For example, it is assumed that plastic waste generation within Chennai is homogenous. However, we saw that the amount and types of plastic waste generated vary between households within a city based on socio-economic demographics (Kumar et al., 2018). This heterogeneity within the city is not accounted for in this study. Modelling the heterogeneity can provide targeted solutions to reduce plastic waste generation for different demographics within the city.

The process of primary data collection through semi-structured interviews had many limitations as well:

Time and resource constraints severely limited the scope of the study. Since this is a master's thesis, I only had three weeks for conducting interviews and building a network of contacts in the formal and informal sectors. More interviews with the formal actors, and coverage of actors beyond the aggregation stage would help improve the results.

As mentioned earlier more time is also needed to **establish trust** with the interviews participants in the informal sector (7.1.3). Due to the phenomenon of the system hiding off (6.1.1), establishing trust in the informal sector is one of the biggest constraints for researchers attempting to study the informal waste sector and collect data on them.

The current sample size is very small and thus the data obtained is **not statistically significant**. Moreover, the sampling used was convenience sampling which was dependent on the contacts established. Thus, the information collected can only be used to fill in data gaps but cannot be representative of the entire system. Due to the informal nature of the system leading to a lack of bookkeeping, a quantitative survey method would be a more appropriate process for data collection,

if the time and resources for the same are available. This would increase the sample size and provide more quantitative data on the quantities managed by the different actors.

There are also limitations to the process of interviewing itself. Interviews are not immune from **researcher bias** and **social desirability bias** (Nederhof, 1985). Researcher bias exists because my perceptions and opinions as a researcher are likely to influence the processes of interviewing, even when I tried to be as unbiased as possible. Moreover, there is a lot of distance that I have from the reality faced by the actors, which might have been difficult to bridge in the short span of time that I had to interview them. Social desirability bias is when the interview participants alter their responses to answers that they consider to be more socially acceptable or desirable. Finally, since many of the interviews were in Tamil, translating the information might have led to missing interpretations. However, knowing the local context and language helped mitigate some of this.

7.2.2 Qualitative Content Analysis

The major limitation I faced as a researcher while data coding and clustering is not being an expert in qualitative research methods. The limitation associated with the process of data coding and clustering is that there is no one right way to do it, and **researcher bias** could play a role in the way the clustering is done. It is not clear if the same clustering would be reproduced if another researcher attempted the content analysis. Since inductive methods are also used in content analysis, it is not possible to have a strict codebook and set of coding rules that researchers can follow to improve reproducibility. Having more than one analyst work on the data analysis can improve robustness.

7.2.3 Material Flow Analysis

As mentioned in 5.2.1, the **material resolution of this study is limited** to recyclable and non-recyclable plastic. Apart from the lack of data, and lack of time and resources to conduct quantitative surveys, the use of local terms to sort the plastic types is a contributing factor to the difficulty in identifying the quantities of each polymer type across different flows. Thus, there should also be efforts to integrate the local context and terms into the scientific classifications of polymer types.

A combination of top-down and bottom-up approaches is used to estimate the flows of the MFA. Top-down data are both used to verify the bottom-up estimates and used to fill in data gaps when bottom-up estimation is not possible. However, **there isn't always an excellent agreement between the top-down and the bottom-up estimates**, thus leading to low reliability of the calculation made. This is primarily due to the lack of transparency in official statistics that was discovered in the qualitative aspect of the research.

Data Gaps

There are **several data gaps in the system**, leading to some flows being excluded from the model (Table 5.7) and some flows having data quality issues (Table 5.8). There is little to no information on the system beyond aggregation due to the system trying to remain hidden from the public eye. It also makes the data collection process extremely difficult and time-consuming. The obtained data ranges for some flows, like collection by waste pickers were very high, indicating that data from the literature is not accurate. There is a lack of transparency among official statistics on waste generation and collection which makes the modelling difficult. All these data gaps are identified in Table 5.8. The limitations and implications of some of the data gaps are discussed in detail below.

Household Plastic waste generation

There is no study which estimates plastic waste generation in the city of Chennai, by accounting for the heterogeneous generation patterns of households from different socio-economic strata. This study estimates the generation of household plastic waste by the principle of mass balance.

The limitation of this calculation is that it is estimated in a backward fashion – by going from the collection values and percentage of uncollected waste to the generation of plastic waste. The plastic waste generated from households in the city of Chennai **needs to be verified with a bottom-up approach** which is not performed in this study due to time constraints. There is a risk of propagation of errors that could be present in the estimation of collection flows to the estimates of plastic waste generated from households.

Collection by IWBs

One of the major limitations of using a bottom-up approach for estimating quantities managed by IWBs is that there is a **lot of ambiguity in the literature** about the naming conventions for informal workers. For example, Hande (2019b) refers to both waste pickers and IWBs as L0 aggregators and does not distinguish between them. Agarwal et al. (2005) refer to waste pickers on foot, cycles, and pushcarts, whereas waste pickers on pushcarts could imply itinerant waste buyers according to the definition used in this study. The values of average waste collected by IWBs that are obtained from literature or extrapolated from primary data are close to the quantities of waste managed by the waste pickers, while it should be more than the quantities collected by the waste pickers due to the ownership of vehicles (Agarwal et al., 2005). This raises questions about the validity of this data.

There was also **hardly any data on the number** of IWBs in the city from the literature. Hence estimates from single wards (from primary data and from (Hande, 2021)) are extrapolated to the entire city. The estimations of the number of IWBs based on primary data are not statistically significant, but they agree with the data from the literature (Sudhir et al., 1997).

The lack of data combined with ambiguities in naming conventions **calls for a standardised approach in academic studies on the IWS** and efforts towards **the enumeration of IWBs**.

Collection by waste pickers

The plastic waste collected by waste pickers is estimated using a bottom-up approach. There are various limitations in this estimation:

(1) The range of values that are obtained for Flow 6 is very high (903.76 tons/month - 12535.05 tons/month), with the **maximum value of total collection by waste pickers being too high** compared to the plastic waste collected by the informal waste sector in total.
(2) The minimum value corresponds to a **low estimate of the average plastic waste collected by a waste picker** of 1.38 kg/day per waste picker. This does not agree with the values reported in most studies; for example, Lau et al. (2020) report a value of 2.1 tons per year (6.85 kg/day) of plastic recovered per waste picker from the streets in lower-middle-income countries (Here I am making the assumption that "waste picking from streets" also refers to waste picking from corporation bins).
(3) Despite using low values for plastic recovery per waste picker, the estimation of the number of waste pickers is so high from some sources (Lizner & Lange, 2013; Sudhir et al., 1997), that the final quantity of plastic recovered by waste pickers **does not reconcile with the quantity of plastic managed by the entire IWS** as mentioned in (1). This forces the usage of the minimum possible value of scrap recovered by waste pickers. Thus, either the number of waste pickers is grossly overestimated, or the total quantity of waste managed by the entire IWS has been

underestimated. Given the high range of uncertainty in the estimation of the number of waste pickers, it is highly likely that the number of waste pickers operating in the cities is overestimated. This calls for the **need to perform an enumeration of waste pickers** in the city of Chennai.

(4) It should also be noted that the percentage of waste pickers per population is not the same in all wards, as assumed in this model. The population of waste pickers is dynamic, with different factors influencing the movement of people in and out of the profession as described in 4.1.2. Thus, using national statistics to estimate the number of waste pickers can be erroneous, due to variability at the local and hyper-local levels. This could also be a reason contributing to the data inaccuracies related to plastic waste recovered by the waste pickers.

Collection by the formal sector

From the interviews, it is suggested that there is a gross underestimation of unsegregated MSW collected by the formal sector in the official statistics. While the MFA accounts for this partially by assuming a significant portion of uncollected waste (Kabadiwalla Connect, 2023) that is not reported in official statistics, the reported value for what is collected could be even more.

The reported values for the collection of segregated plastic in the BOVs by the formal sector have data quality issues too. The bottom-up and the top-down values for this flow do not agree with each other which suggests that there could be an underestimation of segregated plastic collected by the formal sector in the official statistics.

Export of Plastic scrap

There is a lot of inter-state movement of plastic scrap (6.1.3), with plastic scrap in Chennai being sent to nearby Southern Indian states, which is not quantified in this model due to lack of data. This model uses national statistics of the percentage of plastic scrap being processed in Delhi that comes from the rest of India as the percentage of plastic scrap exported to other states. It is not representative of the dynamics of this specific region, thus lowering the validity of the assumption.

Uncollected Waste

Data uncertainty of the quantity of uncollected waste is unknown (Table 5.2). Uncollected waste is assumed to be a fixed percentage (30%) of the total plastic waste generated (Kabadiwalla Connect, 2023). It is not clear from this study how this was estimated or what is the reliability of this data. Kabadiwalla Connect (2023) only considers 66 wards which are around the rivers in Chennai. This is extrapolated to all the wards in Chennai in this study. This could lead to inaccuracies since the littering could be different in wards bordering the rivers and the wards in the interior of the city. Neo et al. (2021) report an average value of 39% of uncollected waste in India. This indicates that the estimate used in this study is reasonable. Neo et al. (2021) also report that 10% of uncollected waste is openly burned on average in India. In this study, about 7% of the waste is openly burned (Kabadiwalla Connect, 2023) which is close to the estimates from the literature.

CHAPTER 8: CONCLUSIONS

In this chapter, the answers to the research questions are summarised in Section 8.1. In Section 8.2, recommendations for future research and for improving the plastic waste management system of Chennai are presented.

8.1 Summarising the Findings

This study scoped the landscape of the plastic waste management system of Chennai and answered the research questions posed. They are summarised below.

RQ1. What are the material flows of household plastic waste along the formal and informal sectors of the plastic recycling value chain in Chennai?

A quantitative model of the system is developed using the MFA accounting method. Bottom-up estimates are used to quantify the different flows in the system wherever possible. Data from the literature and interviews conducted by the primary researcher are used to fill in data gaps and model the system.

Household plastic waste goes through the sub-systems of generation, collection, aggregation, recycling and EOL destination and applications. The recyclable plastic stream is aggregated through the informal waste sector after collection by itinerant waste buyers, waste pickers from corporation bins and dumpsites, and drop-off by households. There is also some recyclable plastic that is processed by the formal sector, by both private service providers and by the local governing body in material recovery facilities. These flows are, however, not quantified. There is a significant portion of uncollected waste (30%) that ends up as litter or is openly burned. The non-recyclable plastic streams are handled only by the formal sector. After aggregation, they are either processed in pyrolysis plants or cement kilns for fuel. There is also a significant portion of both recyclable and non-recyclable plastic waste that ends up in the landfills.

By including hidden flows, like the contribution of the informal waste sector and the proportion of uncollected waste in the model, it was observed that the per capita plastic waste generated in the city of Chennai is 31 kg per year, which is about 50% higher than the reported values from official statistics. There is a high rate of mismanagement of plastic in Chennai (56%) and a recovery rate of about 27%. It was observed that these values change for recyclable and non-recyclable plastic. There is a high recovery rate of 52% for recyclable plastic and a low rate of 15% for non-recyclable plastic. It should be noted, however, that the consideration of all potentially recyclable plastic instead of plastic that is labelled as recyclable would change these figures. The recovery rate for PET was calculated to be about 75%. However, the sensitivity of this estimate is high.

The informal waste sector is responsible for the recovery of 16% of all plastic waste generated in the city of Chennai. There are data quality issues in this figure, which are identified in the third research question, below.

RQ2. Where do exchanges between the informal and formal sectors of the plastic recycling value chain of Chennai occur?

There are many points of exchange between the formal and the informal sector. The key ones that were identified include the selling of plastic scrap by conservancy workers of the formal sector to the informal scrap shops and the selling of aggregated and sorted scrap from the informal scrap shops to formal recycling facilities. The conservancy workers sell the scrap to the informal sector for a daily cash flow for themselves. This leads to most of the recyclable scrap being aggregated through the informal sector. There are also exchanges between the two sectors in the interactions between recycling facilities and manufacturers of secondary and primary plastic and plastic products. But these flows are not identified due to lack of data.

RQ3. What are the existing data gaps and inaccuracies in the quantification of the material flows of plastic waste in the city of Chennai?

Several flows that were identified in the qualitative system description were not quantitatively modelled due to a lack of data. These include collection by private service providers, collection of scrap from littered plastic streets by waste pickers and conservancy workers, aggregation of recyclable plastic by the formal sector, and leakages from different stages of the recycling chain. However, the most important data gap is the description of the system beyond aggregation – flows through the formal and informal recycling facilities and their interactions with the market for secondary plastics.

Among the flows modelled, the bottom-up estimates for collection by waste pickers and by itinerant waste buyers are inaccurate due to the lack of enumeration of informal waste workers in the city. There is an overestimation of the number of waste pickers in the city in top-down data sources obtained from the scientific literature.

Finally, there are also plenty of data gaps in the official statistics, with reported values of waste generation and collection being lower than what is modelled in this study. They do not account for uncollected waste, collection by the informal waste sector, and movement of plastic scrap to and from other states.

RQ4. What are the roadblocks to building a comprehensive MFA of plastic waste in the developing context?

The system hiding itself from the public eye is the biggest roadblock to data collection for MFA. This happens due to multiple reasons in the formal and the informal sector – in the informal sector, there is a need to protect themselves from law enforcement due to their informal nature. In the formal sector, the lack of standardisation, and proprietary information leads to the recycling facilities not being willing to disclose information easily. The lack of bookkeeping in the informal sector and its decentralized nature are also data barriers.

RQ5. What are the barriers faced by the stakeholders in the plastic waste management system of Chennai?

Two different kinds of barriers were identified through the qualitative research – social barriers faced by the stakeholders of the formal and the informal sectors, and barriers in the technical sphere that limits the efficiency of the plastic waste management system of Chennai. The barriers faced by the informal actors include social discrimination, occupational hazards, economic disparity, and potential conflicts with law enforcement, which corroborates findings from the literature. The barriers in the formal sector include social discrimination, and occupational hazards for the conservancy workers, structural and organisational issues in the formal sector, lack of awareness of the waste generators about source segregation, and mistrust in the government for the waste

generators. The key finding was that there is a preference to remain in the informal waste sector among the workers at the lowest level of the hierarchy due to the social issues in the formal sector.

8.2 Recommendations

The outcomes of this study contributed to the knowledge about the informal waste sector, specifically in the local context of Chennai. Based on these outcomes, and the limitations of this study, several recommendations are made for future studies and for the formal sector to improve the plastic waste management system.

8.2.1 Recommendations for future studies

Bottom-up data collection is a useful approach to estimate flows when there are 'hidden flows' due to the involvement of the informal economy, as shown in this study. The data gaps identified also suggest that the enumeration of the informal waste workers can improve the quality of the information about them. This can be done by using quantitative survey methods which have already been used in similar studies (Bureecam et al., 2018; Siddique et al., 2022). However, these methods may not be able to circumvent the problem of lack of bookkeeping in the informal sector. Gaining the trust of the informal workers, spending more time with them, and recording the quantities handled by the informal workers over a fixed period of time can help address this problem. Another recommendation that was obtained is to approach the self-organized associations of informal workers and establish their trust. Approval of the local governing body, or their involvement, can help in gaining this access. These associations can help in enumeration of the informal workers.

There are several ambiguities in literature, like naming conventions for the roles of informal workers, and the methodology used to calculate recovery rates of plastic, which lead to data quality issues. Establishing standardised naming conventions, and transparently reporting the assumptions in the calculations of recovery rates of plastic can help solve these issues. The local context and the terms used in the local languages of each region of study also need to be considered and integrated with scientific literature. This would help identify the relative fractions of each polymer type at each location, which in turn can help improve the data quality.

The heterogeneity of plastic waste generation is not considered in this study. Given the high population density, incorporating demographic factors while making bottom-up estimates of plastic waste generated in the city can help identify the different quantities and types of plastic generated from households of different socio-economic strata. This can be used to design targeted solutions for the reduction and recovery of plastic waste generated at each socio-economic level.

8.2.2 Recommendations for the formal sector

There is a lack of a data-driven approach and a lack of transparency in the formal sector. Improving data collection, and transparently reporting the collected data can not only enable the citizens to remain well-informed but also design more effective plastic waste management strategies. Standardising plastic recycling and implementing environmental regulations in the recycling industry are needed as well.

There is a large amount of uncollected plastic waste that ends up as litter or is openly burned. Source segregation and collection need to be improved to reduce this. MLPs and SUPs are the highest contributors to the mismanagement of plastic. Designing policy interventions to reduce their production and consumption is needed. However, it is also seen that such measures need to be taken after addressing the possible consequences, like finding affordable alternatives to SUPs. Moreover, care should be taken so that the policy measures do not disproportionately affect disadvantaged

communities. Changing the focus of the plastic waste management efforts from collection and disposal towards reduction and management of waste is needed to provide the right incentives for the stakeholders to reduce the amount of plastic waste generated.

Improper labelling of plastic products and packaging leads to potentially recyclable plastic ending up in mixed waste streams or non-recyclable plastic streams. While the informal sector is capable of picking and visually sorting these plastic types, labelling plastic types could help improve source segregation, and consequently the collection of recyclable plastic.

Integration with the informal sector can improve the recovery of recyclable plastic waste. Given proper incentives, the informal sector's capacity can also be utilised to recover a large portion of the plastic waste, including less profitable plastic types. However, decentralized, bottom-up integration is needed to improve the living conditions of the informal sector. Due to social discrimination and occupational issues in the formal sector, informal workers prefer retaining their autonomy. Undoubtedly, there should also be longer-term efforts towards eradicating social discrimination and reducing workplace harassment in the formal sector. Steps like access to washrooms while on duty, better working hours, and better pay and benefits need to be taken urgently.

Finally, educating the waste generators about source segregation and strictly enforcing the same can not only improve the recovery of recyclable plastic but also vastly improve the working conditions of the waste workers, especially in the formal sector.

REFERENCES

Agarwal, A., Singhmar, A., Kulshrestha, M., & Mittal, A. K. (2005). Municipal solid waste recycling and associated markets in Delhi, India. *Resources, Conservation and Recycling*, *44*(1), 73–90. https://doi.org/10.1016/j.resconrec.2004.09.007

Arabindoo, P. (2016). Unprecedented natures? An anatomy of the Chennai floods. *City*, *20*(6), 800–821.

Aryan, Y., Yadav, P., & Samadder, S. R. (2019). Life Cycle Assessment of the existing and proposed plastic waste management options in India: A case study. *Journal of Cleaner Production*, *211*, 1268–1283. https://doi.org/10.1016/j.jclepro.2018.11.236

Aslam, S., Ali, F., Naseer, A., & Sheikh, Z. (2022). Application of material flow analysis for the assessment of current municipal solid waste management in Karachi, Pakistan. *Waste Management & Research*, *40*(2), 185–194.

Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G. H., Hilleary, M. A., Eriksen, M., Possingham, H. P., De Frond, H., Gerber, L. R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., & Rochman, C. M. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science*, *369*(6510), 1515–1518. https://doi.org/10.1126/science.aba3656

Brunner, P. H., & Rechberger, H. (2016). *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers, Second Edition*. CRC Press.

Bureau, O. (2021, February 23). *Ramky Enviro in 7-year waste management contract in Chennai*. https://www.thehindubusinessline.com/news/national/ramky-enviro-in-7-year-waste-management-contract-in-chennai/article33916236.ece

Bureecam, C., Chaisomphob, T., & Sungsomboon, P.-Y. (2018). Material flows analysis of plastic in Thailand. *Thermal Science*, *22*(6 Part A), 2379–2388. https://doi.org/10.2298/TSCI160525005B

Chaturvedi, B. (2005). InFormal–formal–Creating opportunities for the informal waste recycling sector in Asia. *CHINTAN Environmental Research and Action Group, Delhi*.

Chennai Metropolitan Development Authority, Government of Tamilnadu, India. (n.d.). Retrieved 12 July 2023, from https://www.cmdachennai.gov.in/

Chikarmane, P., & Narayan, L. (2009). *Rising from the Waste*. Committee For Asian Women (CAW). https://swachcoop.com/pdf/CAWAsianWastepickersPCLN.pdf

Choudhary, K., Sangwan, K. S., & Goyal, D. (2019). Environment and economic impacts assessment of PET waste recycling with conventional and renewable sources of energy. *Procedia CIRP*, *80*, 422–427. https://doi.org/10.1016/j.procir.2019.01.096

Columbia University Mailman School of Public Health. (2016, August 3). *Content Analysis*. Columbia University Mailman School of Public Health. https://www.publichealth.columbia.edu/research/population-health-methods/content-analysis

Cook, E., & Velis, C. (2022). Plastic waste exports and recycling: Myths, misunderstandings and inconvenient truths. *Waste Management & Research*, *40*(10), 1459–1461. https://doi.org/10.1177/0734242X221132336

CPCB. (2015). *Assessment and quantification of plastic waste generation in major cities*. CENTRAL POLLUTION CONTROL BOARD (CPCB).

CSE. (2020). *Managing Plastic Waste in India: Challenges and Agenda*. Centre for Science and Environment (CSE). http://www.cseindia.org/content/downloadreports/10352

Database on Solid waste management in Tamil Nadu. (2016). ENVIS Centre, Department of Environment, Government of Tamil Nadu. http://www.tnenvis.nic.in/WriteReadData/UserFiles/file/swm.pdf

Delve, Ho, L., & Limpaecher, A. (2023, March 24). *The Practical Guide to Qualitative Content Analysis*. Delve. https://delvetool.com/blog/guide-qualitative-content-analysis

EIA. (2021). *The Truth Behind Trash: The scale and impact of international trade in plastic waste*. Environmental Investigation Agency (EIA).

Ezeah, C., Fazakerley, J. A., & Roberts, C. L. (2013). Emerging trends in informal sector recycling in developing and transition countries. *Waste Management*, *33*(11), 2509–2519. https://doi.org/10.1016/j.wasman.2013.06.020

Gupta, A. K., & Nair, S. S. (2010). Flood risk and context of land-uses: Chennai city case. *Journal of Geography and Regional Planning*, *3*(12), 365.

Gutberlet, J. (2021). Grassroots waste picker organizations addressing the UN sustainable development goals. *World Development*, *138*, 105195. https://doi.org/10.1016/j.worlddev.2020.105195

Hande, S. (2019a). *Leveraging the informal waste ecosystem for better management of post-consumer recyclable waste in Urban India—A case study in Chennai*.

Hande, S. (2019b). *The informal waste sector: A solution to the recycling problem in developing countries*.

Hande, S. (2021). *Increasing Waste Recycling Through Better Informal Sector Data*.

Hayami, Y., Dikshit, A. K., & Mishra, S. N. (2006). Waste pickers and collectors in Delhi: Poverty and environment in an urban informal sector. *Journal of Development Studies*, *42*(1), 41–69. https://doi.org/10.1080/00220380500356662

Hond, F. den. (2000). Industrial ecology: A review. *Regional Environmental Change*, *1*, 60–69.

Hoornweg, D., & Bhada-Tata, P. (2012). *What a waste: A global review of solid waste management*.

Hsieh, H.-F., & Shannon, S. E. (2005). Three Approaches to Qualitative Content Analysis. *Qualitative Health Research*, *15*(9), 1277–1288. https://doi.org/10.1177/1049732305276687

Kabadiwalla Connect. (2023). *Down The Stream: A baseline study report to identify hotspots of plastic waste and open drains along the Adyar and Cooum Rivers in Chennai*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Kumar, A., Samadder, S. R., Kumar, N., & Singh, C. (2018). Estimation of the generation rate of different types of plastic wastes and possible revenue recovery from informal recycling. *Waste Management*, *79*, 781–790. https://doi.org/10.1016/j.wasman.2018.08.045

Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., Velis, C. A., Godfrey, L., Boucher, J., Murphy, M. B., Thompson, R. C., Jankowska, E., Castillo Castillo, A., Pilditch, T. D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., … Palardy, J. E. (2020). Evaluating scenarios toward zero plastic pollution. *Science*, *369*(6510), 1455–1461. https://doi.org/10.1126/science.aba9475

Lebreton, L., & Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, *5*(1), 1–11.

Legacy landfill in Chennai to be biomined. (2023, January 22). *The Times of India*. https://timesofindia.indiatimes.com/city/chennai/legacy-landfill-in-chennai-to-be-biomined/articleshow/97214496.cms

Lizner, R., & Lange, U. (2013). Role and size of informal sector in waste management – a review. *Proceedings of the ICE - Waste and Resource Management*, *166*, 69–83. https://doi.org/10.1680/warm.12.00012

Lobelle, D., Shen, L., van Huet, B., van Emmerik, T., Kaandorp, M., Iattoni, G., Baldé, K., Law, K. L., & van Sebille, E. (2022). Mapping managed and mismanaged Dutch plastic waste flows. *Available at SSRN 4050390*.

Magnusson, E., & Marecek, J. (2015). *Doing Interview-based Qualitative Research: A Learner's Guide* (1st ed.). Cambridge University Press. https://doi.org/10.1017/CBO9781107449893
Medina, M. (2008). *The informal recycling sector in developing countries*.
Mutha, N. H., Patel, M., & Premnath, V. (2006). Plastics materials flow analysis for India. *Resources, Conservation and Recycling*, *47*(3), 222–244. https://doi.org/10.1016/j.resconrec.2005.09.003
Nagarajan, A. (2022). The governance of plastic in India: Towards a just transition for recycling in the unorganised sector. *Local Environment*, *27*(10–11), 1394–1413. https://doi.org/10.1080/13549839.2022.2084721
Nandan, A., Yadav, B. P., Baksi, S., & Bose, D. (2017). Recent scenario of solid waste management in India. *World Scientific News*, *66*, 56–74.
Nandy, B., Sharma, G., Garg, S., Kumari, S., George, T., Sunanda, Y., & Sinha, B. (2015a). Recovery of consumer waste in India – A mass flow analysis for paper, plastic and glass and the contribution of households and the informal sector. *Resources, Conservation and Recycling*, *101*, 167–181. https://doi.org/10.1016/j.resconrec.2015.05.012
Nandy, B., Sharma, G., Garg, S., Kumari, S., George, T., Sunanda, Y., & Sinha, B. (2015b). Recovery of consumer waste in India – A mass flow analysis for paper, plastic and glass and the contribution of households and the informal sector. *Resources, Conservation and Recycling*, *101*, 167–181. https://doi.org/10.1016/j.resconrec.2015.05.012
Narayanan, S., & Kapilavai, V. S. (2021). *The Plasticene Epoch and the brands behind it*. CAG. https://www.cag.org.in/sites/default/files/database/The%20Plasticene%20Epoch%20and%20the%20brands%20behind%20it.pdf
Narayanan, S., & Rajkumar, M. (2022). *PACK IT IN: CAG's 2022 BRAND AUDIT*. CAG. https://www.cag.org.in/sites/default/files/database/CAG_BA_2022_Digital%20View.pdf
Nederhof, A. J. (1985). Methods of coping with social desirability bias: A review. *European Journal of Social Psychology*, *15*(3), 263–280. https://doi.org/10.1002/ejsp.2420150303
Neo, E. R. K., Soo, G. C. Y., Tan, D. Z. L., Cady, K., Tong, K. T., & Low, J. S. C. (2021). Life cycle assessment of plastic waste end-of-life for India and Indonesia. *Resources, Conservation and Recycling*, *174*, 105774. https://doi.org/10.1016/j.resconrec.2021.105774
Progress cards for waste management launched by Urbaser Sumeet. (2022, November 8). *The Hindu*. https://www.thehindu.com/news/cities/chennai/progress-cards-for-waste-management-launched-by-urbaser-sumeet/article66111822.ece
Putri, A. R., Fujimori, T., & Takaoka, M. (2018). Plastic waste management in Jakarta, Indonesia: Evaluation of material flow and recycling scheme. *Journal of Material Cycles and Waste Management*, *20*, 2140–2149.
Qu, S. Q., & Dumay, J. (2011). The qualitative research interview. *Qualitative Research in Accounting & Management*, *8*(3), 238–264. https://doi.org/10.1108/11766091111162070
Rafey, A., & Siddiqui, F. Z. (2021). A review of plastic waste management in India – challenges and opportunities. *International Journal of Environmental Analytical Chemistry*, 1–17. https://doi.org/10.1080/03067319.2021.1917560
Raj, G. (2019). *Informal Waste Dynamics: Mapping Waste Trails*. CAG.
Report on ID card camps for Waste Pickers. (2015). https://www.cag.org.in/sites/default/files/database/id%20camp%20report_final.pdf
Rinasti, A. N., Ibrahim, I. F., Gunasekara, K., Koottatep, T., & Winijkul, E. (2022). Fate identification and management strategies of non-recyclable plastic waste through the integration of material flow analysis and leakage hotspot modeling. *Scientific Reports*, *12*(1), Article 1. https://doi.org/10.1038/s41598-022-20594-w
Ryan, F., Coughlan, M., & Cronin, P. (2009). Interviewing in qualitative research. *International Journal of Therapy and Rehabilitation*, *16*, 309–314. https://doi.org/10.12968/ijtr.2009.16.6.42433

Saavedra, Y. M. B., Iritani, D. R., Pavan, A. L. R., & Ometto, A. R. (2018). Theoretical contribution of industrial ecology to circular economy. *Journal of Cleaner Production*, *170*, 1514–1522. https://doi.org/10.1016/j.jclepro.2017.09.260

Sembiring, E., & Nitivattananon, V. (2010). Sustainable solid waste management toward an inclusive society: Integration of the informal sector. *Resources, Conservation and Recycling*, *54*(11), 802–809.

Shanker, R., Khan, D., Hossain, R., Islam, Md. T., Locock, K., Ghose, A., Sahajwalla, V., Schandl, H., & Dhodapkar, R. (2022). Plastic waste recycling: Existing Indian scenario and future opportunities. *International Journal of Environmental Science and Technology*. https://doi.org/10.1007/s13762-022-04079-x

Siddique, S., Roy, B. B., Zaman, S., Khan, A., Al Alam, Md. A., Chowdhury, R. B., Biswas, K. F., Hossain, M. M., Murakami, S., & Sujauddin, M. (2022). Discerning the circularity of the plastic industry in Bangladesh through the lens of material flow analysis. *Sustainable Production and Consumption*, *33*, 700–715. https://doi.org/10.1016/j.spc.2022.08.001

Singh, K. (2007). *Quantitative Social Research Methods*. SAGE Publications India Pvt Ltd. https://doi.org/10.4135/9789351507741

Singh, R., & Chari, K. R. (2014). *Socio-Economic Issues in Waste Management by Informal Sector in India*.

Singh, S., & Chokhandre, P. (2015). Assessing the impact of waste picking on musculoskeletal disorders among waste pickers in Mumbai, India: A cross-sectional study. *BMJ Open*, *5*(9), e008474. https://doi.org/10.1136/bmjopen-2015-008474

Sri Sasi Jyothsna, T., & Chakradhar, B. (2020). Current Scenario of Plastic Waste Management in India: Way Forward in Turning Vision to Reality. In S. K. Ghosh (Ed.), *Urban Mining and Sustainable Waste Management* (pp. 203–218). Springer. https://doi.org/10.1007/978-981-15-0532-4_21

Sudhir, V., Srinivasan, G., & Muraleedharan, V. R. (1997). Planning for sustainable solid waste management in urban India. *System Dynamics Review*, *13*(3), 223–246. https://doi.org/10.1002/(SICI)1099-1727(199723)13:3<223::AID-SDR127>3.0.CO;2-Q

Turner, D. (2014). Qualitative Interview Design: A Practical Guide for Novice Investigators. *The Qualitative Report*. https://doi.org/10.46743/2160-3715/2010.1178

Van Eygen, E., Laner, D., & Fellner, J. (2018). Integrating high-resolution material flow data into the environmental assessment of waste management system scenarios: The case of plastic packaging in Austria. *Environmental Science & Technology*, *52*(19), 10934–10945.

Velis, C. (2017). Waste pickers in Global South: Informal recycling sector in a circular economy era. *Waste Management & Research*, *35*(4), 329–331. https://doi.org/10.1177/0734242X17702024

Velis, C. A., Hardesty, B. D., Cottom, J. W., & Wilcox, C. (2022). Enabling the informal recycling sector to prevent plastic pollution and deliver an inclusive circular economy. *Environmental Science & Policy*, *138*, 20–25. https://doi.org/10.1016/j.envsci.2022.09.008

WBSCD. (2016). *Informal approaches to circular economy*. WBSCD.

Welcome to Greater Chennai Corporation. (n.d.). Retrieved 3 March 2023, from https://chennaicorporation.gov.in/gcc/department/solid-waste-management/

Wilson, D. C., Velis, C., & Cheeseman, C. (2006). Role of informal sector recycling in waste management in developing countries. *Habitat International*, *30*(4), 797–808. https://doi.org/10.1016/j.habitatint.2005.09.005

APPENDIX A: INTERVIEW GUIDES

The interview guides that were prepared for the waste pickers, IWBs, aggregators, conservancy workers, and experts are given below. This is a preliminary guide focused on collecting data for the MFA – due to the semi-structured nature of the interviews, I also asked questions depending on the responses received, or information needed. (Siddique et al., 2022) is used as a reference for preparing the interview guides.

A.1 Guide for Waste Pickers

The interviews with the waste pickers were less structured than other interviews, even though the guide below was followed since data was collected through a field visit. Many times, information that was not initially included in the guides came up. Information about their lives, and social issues that they face were discussed which is not included in the guide below.

1. What types of plastic do you generally collect?
2. How much plastic waste (of each type of scrap) do you collect in a day (in kg)?
3. Are there any types of plastic you do not collect, and why?
4. Which areas/wards do you majorly cover (in case this information is not available before the interview)?
5. Whom do you sell your sorted/processed scrap to? (Amount in kg/ton or percentage)

Destination	Amount (in kg/ton or % of total)

A.2 Guide for IWBs

Part 1: Collection

6. What types of plastic do you generally collect/buy from households?
7. How much plastic waste (of each type of scrap) do you collect from households (in kg or tons/ day or month)?

Name of scrap type	Amount collected (in kg/ton per day/month/year)

8. Are there any types of plastic you do not collect/buy from households, and why?
9. What is your mode of transport?

10. Which areas/wards do you majorly cover (in case this information is not available before the interview)?
11. How does the season (monsoon/summer) affect your collection?

Part 2: Sorting/Processing and linkage to scrap shops

12. What do you do after collecting/buying the scrap (explain sorting/processing steps if any)?
13. If any sorting/processing is done: what types and quantities of waste are generated during the sorting step (what is rejected)?

Name of scrap type	Waste generated amount (in kg/ton per day/month/year)

14. Where do you dispose of them?
15. Whom do you sell your sorted/processed scrap to? (Amount in kg/ton or percentage)

Destination	Amount (in kg/ton or % of total)

A.3 Guide for Aggregators

Part 1: Collection and linkages to IWBs

1. What types of plastic do you generally collect/buy?
2. How much plastic waste (of each type of scrap) do you collect (in kg or tons/ day or month)?

Name of scrap type	Amount collected (in kg/ton per day/month/year)

3. What are the sources for your plastic scrap and how much is obtained from each source?

Source	Amount (in kg/ton or % of total)

4. Are there any types of plastic you do not collect/buy from IWBs, and why?

Part 2: Sorting/Processing and linkage to recyclers

5. What do you do after collecting/buying the scrap (explain sorting/processing steps if any)?
6. What is the storage capacity that is available to you at your scrap shop?
7. If any sorting/processing is done: what types and quantities of waste are generated during the sorting step (what is rejected)?

Name of scrap type	Waste generated amount (in kg/ton per day/month/year)

8. Where do you dispose of them?
9. Whom do you sell your sorted/processed scrap to? (amount in kg/ton or percentage)

Destination	Amount (in kg/ton or % of total)
Recyclers/export, etc	

10. In case you export any scrap - what type of plastic and what amount?

Name of scrap type	Amount exported (in kg/ton per day/month/year)

11. According to you, how many scrap shops are operating in Chennai?

A.4 Guide for Experts

A relatively less structured guide is prepared for the experts, as given below. Based on the role of the organization they belong to, their expertise, and the response received these questions are for each expert.

1. An overview of the work they have done in dry waste management.
2. Any interactions they had with formal/informal workers through the work in their organization.
3. Exchanges between formal and informal systems (formal sector selling/buying recyclables to the informal sector, or employing informal sector, companies working with a portion of the informal sector)
4. Overview of the plastic waste (and packaging waste) management in Chennai – which materials are collected and by whom, where they go, what happens at their EOL, etc.
5. About source segregation happening in households, and challenges for the same.
6. Social issues faced by formal and informal workers.
7. Any idea they may have about: the quantities of plastic waste generated by households and managed by informal workers, the number of informal workers in a city (or per population, per ton of waste)
8. Any contact they know who may be able to help with this.

A.5 Guide for Conservancy Workers

The following guide is used for the conservancy workers who drive the BOVs to collect source-segregated solid waste.

1. What types of plastic do you generally collect?
2. How much plastic waste (of each type) do you collect in a day (in kg)?
3. Which areas/wards do you majorly cover (in case this information is not available before the interview)? How many households do you cover?
4. Do people segregate the waste before they give it to you?
5. If not, where/how do you segregate the mixed waste?
6. Whom do you sell/give your sorted scrap to? (Amount in kg or percentage)

Destination	Amount (in kg or % of total)

APPENDIX B: INTERVIEW CONSENT FORM

The following consent form is signed by all interviewees. Translated forms in Tamil are used for the interviews in Tamil.

Dear participant,

First of all, thank you for accepting to be interviewed for my master's thesis titled "Plastic Packaging Waste Collection and Recycling in Chennai, India". The interview is expected to last between 30 – 45 minutes. I do not anticipate that there are any risks associated with your participation, but you have the right to stop the interview or withdraw your participation from the research at any time.

The research aims at estimating the flow of plastic packaging waste from households to recycling or landfills, in the city of Chennai. We will particularly try to estimate the contribution of the informal sector in plastic waste management in Chennai and identify the potential for improvement of waste collection and recycling. To be able to conduct the interview with you, and use the data in my research, I must ask for your consent to do so. If you accept, you agree to the following:

1. You are voluntarily taking part in this project. You understand that you do not have to take part and that you can stop the interview at any time.
2. You do not expect to receive any benefit or payment for participation.
3. The interview will be recorded, and translated to English (if conducted in Tamil), and a transcript will be generated.
4. If requested, you will be sent the transcript and given the opportunity to correct any factual errors.
5. Access to the interview transcript will be limited to the researcher, Sowmya Ravisandiran, and academic supervisors and researchers with whom she might collaborate as part of the research process.
6. Any summary of the interview content, or direct quotations from the interview, that can be made available through academic publications or other academic outlets will be anonymised so that the participant can in no way be identified, and care will be taken to ensure that other information in the interview that could identify yourself is not revealed.
7. All or part of the content of the interview may be used in academic papers.
8. The actual recording of the interview will be deleted at the end of this project.
9. You can ask any questions you might have, and you understand that you are free to contact the researcher with any questions that you may have in the future.

Name and signature of the participant:	
Date:	

If you have any further questions or concerns about this study, please contact:

Name of researcher: Sowmya Marriyapillai Ravisandiran

Email: s.marriyapillai.ravisandiran@umail.leidenuniv.nl / sowmya.ravisandiran@gmail.com

APPENDIX C: DETAILED EXPLANATION OF MFA CALCULATIONS

This appendix contains detailed explanations of the approaches used to quantify each flow and the limitations of the approaches.

Table C.1: Approach and explanation of estimations of flows in MFA

Flow number	Flow name	Approach	Explanations and Assumptions made	Findings and Limitations
Flow 1	**Plastic waste generated from households**	Mass balance	The total quantity of plastic waste generation is estimated using the principle of mass balance from the collected quantities of plastic scrap by different actors - thus the estimate is a combination of top-down and bottom-up approaches. The steps followed for this calculation are: • First, total segregated plastic waste collected by formal workers in BOVs is estimated using a bottom-up approach (Flow 3) • Next, the total plastic waste collected by the formal sector with the unsegregated MSW is estimated (Flow 4). • Percentage of uncollected waste from the total waste generated is fixed at 29.9% (Flow 5). • Total plastic scrap collected by IWBs is estimated using a bottom-up approach (Flow 2). • Finally, the total plastic waste generated is estimated by the model using a mass balance technique	There isn't always an excellent agreement between the top-down and the bottom-up estimates, thus leading to low reliability of the calculation made. Since it is estimated in a backward fashion - by going from the collection/uncollected values to generation, the validity could be low. It needs to be verified with a bottom-up study of plastic waste generation from households in Chennai which is not performed in this study due to time constraints. There is a risk of propagation of errors that could be present in the estimation of collection flows to the estimates of plastic waste generation from households. Refer to output flows (2, 3, 4, and 5) for data gaps.
-	**Plastic waste collected by private service providers**	-	Collection by private service providers is assumed to be negligible	Limitation: Do not have a full picture of the system
-	**Recyclable plastic dropped off by households at small scrap shops**	-	Dropping-off of recyclable plastics by households directly to scrap shops is not estimated separately due to lack of data – everything is assumed to be included within the door-to-door collection by IWBs	Limitation: Do not have a full picture of the system

Flow 2	**Plastic scrap collected door-to-door by IWBs from households**	Bottom-up	A bottom-up approach is used to estimate the collection quantities of IWBs. • Data from the interviews and from (Hande, 2019b) are used to an idea of the quantities of plastic waste collected by an IWB on average (125 kg/month - 323 kg/month). • There is hardly any data on the number of IWBs in the city. Hence this data gap is filled by extrapolating data from interviews and from (Sudhir et al., 1997). The calculations for these are found in Supplementary Data 1). The obtained range for the number of IWBs is 2050-3566 in the city of Chennai. • Finally, the two ranges are multiplied to get a minimum probable value of 256.26 tons/month and a maximum probable value of 1151.8 tons/month. The maximum value is chosen as the reasonable estimate to reconcile with the data on plastic scrap managed by the entire IWS.	• The values for average waste collected by IWBs are not statistically significant. Moreover, the values are close to the quantities of waste managed by the waste pickers, while they should be more than the quantities collected by the waste pickers due to the ownership of vehicles. • The estimations for the number of workers based on primary data are again not statistically significant, but they agree with the data from the literature (Sudhir et al., 1997). Hence these values are assumed to be reasonable estimates. • One of the major limitations of using a bottom-up approach for estimating quantities managed by IWBs is that there is a lot of ambiguity in the literature about the naming conventions for informal workers (7.2.3). E.g., Hande, (2019b) refers to waste pickers and IWBs as L0 aggregators and doesn't distinguish between them. Agarwal et al. (2005) refer to waste pickers on foot, cycles, and pushcarts, where waste pickers on pushcarts could imply itinerant waste buyers according to the definition used in this study. This raises questions on the validity of the values used for average quantities of plastic recovered per IWB. The lack of data combined with ambiguities in naming conventions calls for a standardised approach in academic studies on the IWS and efforts towards the enumeration of IWBs.
Flow 3	**Plastic scrap collected door-to-door by the formal sector using BOVs**	Mass balance	The principle of mass balance is used to calculate this flow by calculating Flows 9 and 12 using a bottom-up approach (see Flows 9 and 12 for an explanation)	The reported (top-down) data for the average quantity of plastic scrap segregated by the formal workers in BOVs is much less than the bottom-up estimates. The top-down value is used for the estimation of Flow 4, thus leading to a disagreement between Flow 4 and Flow 3. However, it was important to use the bottom-up estimates here to reconcile with data of Flow 15, quantities managed by the L2 aggregator of NRP. See Flow 15 for the explanation.
Flow 4	**Plastic waste collected with MSW as unsegregated waste from corporation bins**	Top-down	Top-down estimate of unsegregated waste collected by the formal sector is used to quantify this flow. The steps followed for the calculation are given below: • First, the total plastic waste collected by the formal sector from households is calculated. This is done by using the reported quantity of MSW collected by the municipality	From the interviews, it is suggested that there is a gross underestimation of MSW collected in the top-down value. Uncollected waste is not reported by official statistics, but even the reported value for what is collected could be even more. Thus, there could be two scenarios - the total waste generated is much higher, while either the quantity of uncollected waste remains the same, or the percentage of

			and multiplying it by the percentage contribution of households and the percentage composition of plastics in MSW. • Next, total plastic waste collected by the formal sector with the unsegregated MSW is estimated by subtracting the reported quantities of segregated plastic waste collected separately using the BOVs (top-down estimates for Flow 3). • Final estimate is around 7641 tons/month.	uncollected waste remains at 30%, implying a much higher quantity of uncollected waste. • The plastic composition values are outdated. but agree with multiple different sources that are more recent. However, these are the composition of plastic in household waste and do not account for the plastic that is already removed by the informal sector by either door-to-door collection or by drop-off of recyclable plastic by the households to scrap shops. • The major limitation of using the top-down value of 599 tons/month is that it does not agree with the bottom-up estimates of the amount of plastic scrap collected by BOVs (see Flow 3, 9 and 12). While the bottom-up estimates were necessary to be used for those flows, it is not possible to do so here, because of the use of the top-down estimates of total MSW collection.
Flow 5	**Uncollected waste**	Unknown	The percentage of uncollected waste from the total waste generated is fixed at 29.9%. It is obtained from (Kabadiwalla Connect, 2023), and the approach used here is unknown. The value was determined for a sample of 66 wards around the rivers in Chennai. It is applied as an average for all wards of Chennai here.	The wards sampled are surrounding water bodies and could have a greater (or lesser) percentage of uncollected waste compared to the rest of the wards in Chennai. Apart from geographic factors, other demographic factors such as the socioeconomic status of households in these wards could influence waste generation patterns and also the waste collection patterns of the formal sector.
Flow 6	**Plastic scrap recovered by waste pickers from MSW in corporation bins**	Bottom-up	The waste collected by waste pickers from corporation bins is calculated using a bottom-up approach. • First the number of waster pickers in the city is estimated by combining data from multiple different sources. Data from Hande (2021) which enumerates the number of waste pickers in Ward 100 is extrapolated to the entire city of Chennai to obtain 22780 as the total number of waste pickers. Using the average percentage of waste pickers per population for India from Chaturvedi (2010), 26269 is obtained as the number of waste pickers in Chennai. Sudhir et al. (1997) report 40,000 as the number of waste pickers in Chennai. The other national estimates for the percentage of waste pickers per population, compiled by Lizner and Lange (2013) are not used since	• The percentage of waste pickers per unit population is not the same in all wards. Various factors like proximity to landfills, waste collection system in the specific wards, socio-economic level of the ward, etc., influence the number of waste pickers in each ward. Similarly using national statistics to estimate the number of waste pickers can be erroneous as well, due to regional variability. Moreover, the population of waste pickers is dynamic, with different factors influencing the movement of people in and out of the profession. • The inaccuracies in Flow 7 would imply that there is an overestimation in the distribution of waste pickers operating in the city. • The estimation of average plastic waste collected per waste picker by the first approach does not correlate with the data obtained in the second approach. Lau et al. (2020) report that the plastic waste

			the variation in the data is very high (8330 - 174911 waste pickers). • Then, the number of workers operating within the city and collecting plastic scrap from garbage bins is estimated by subtracting the number of waste pickers in landfills (Flow 7) from the total number of waste pickers. • The average amount of plastic waste collected by waste pickers on foot is estimated by using two approaches: First, estimates for the average amount of all waste collected by waste pickers are obtained from various sources. This is between 9 and 17 kg/day. Then this is multiplied by the portion of plastic in the waste collected – the percentage of plastic by volume among all recyclables is assumed to be the same for waste pickers as it is for the rest of the IWS. This gives the average volume of plastic collected per waste picker to be 1.38 - 2.61 kg/day. The second approach is to directly use estimates of quantities of plastic waste collected from waste pickers from literature. This gives a range of 6.23 - 10.7 kg/day. • Finally the two ranges are multiplied to get a range of total plastic collected by waste pickers from corporation bins. The obtained values are 903.76 tons/month as the minimum and 12535.05 tons/month as the maximum value. The minimum value of 903.76 tons/month is chosen in order to reconcile with data for Flows 8 and 14 as explained below.	collected by waste pickers from streets (here corporation bins) is about 6.85 kg/day (Here I am making the assumption that "waste picking from streets" refers to waste picking from corporation bins). This indicates that the validity of the first approach is not high. • There are various limitations in this method of estimation: The range of values that is obtained is very high, with the maximum value being too high to be probable. Despite using low values for plastic recovery per waste picker, the estimation of the number of waste pickers is so high from some sources (Lizner & Lange, 2013; Sudhir et al., 1997), that the final quantity of plastic recovered by waste pickers does not reconcile with the quantity of plastic managed by the entire IWS – it is too high compared to the total volume managed by the IWS. This forces the usage of the minimum possible value of scrap recovered by waste pickers. Since the previous point suggests an underestimation in the average quantity picked by the waste pickers, this reinforces that either the number of waste pickers is grossly overestimated or that the total quantity of waste managed by the entire IWS has been underestimated. Given the high range of uncertainty in the estimation of the number of waste pickers, it is highly likely that the number of waste pickers operating in the cities is overestimated. This calls for the need to perform an enumeration of waste pickers in the city of Chennai.
Flow 7	**Plastic scrap by waste pickers from unsegregated waste in landfills**	Bottom-up	The plastic recovered by waste pickers from landfills is estimated by a bottom-up approach similar to Flow 6. • A drive conducted to enumerate waste pickers in landfills by providing ID cards for them had about 950 waste pickers registering for IDs (*Report on ID Card Camps for Waste Pickers*, 2015). It is assumed there was 100% registration of waste pickers at the landfills, and the total number of waste pickers in landfills is assumed to be 950. • The average amount of plastic waste picker per waste picker is in the range of 1.38 kg/day to 10.7 kg/day as explained above in Flow 6.	• In reality, the number of waste pickers in the landfills could be more if there was less than 100% registration. This, along with the finding that there might be an overestimation of the number of waste pickers suggests that (a) there may be much fewer waste pickers within the city than what national statistics estimate, and (b) there needs to be an enumeration of waste pickers conducted to properly understand their contribution to the waste economy. • Limitations for the estimations of average quantities of plastic waste collected by waste pickers are explained in Flow 6.

			• The two ranges are multiplied to get a minimum value of 39.45 tons/month and a maximum value of 304.95 tons/month. 304.95 tons/month is chosen in order to mitigate the limitation of underestimation of the number of waste pickers operating in landfills.	
-	**Plastic is recovered from litter from streets by waste pickers and formal workers who are responsible for cleaning the streets**	-	Due to a lack of data and difficulty in estimation of waste-picking from streets, both collection from streets by street-sweepers and by waste pickers is left out of the model. Waste picking from corporation bins is assumed to include some portion of this flow.	• Leaving out waste picking from litter – from streets, open dumps, and riverbanks, underestimates the contribution of waste pickers, and the rest of the IWS, in recovering mismanaged plastic. • There is some lack of clarity in what is meant by "waste picking from streets". In Lau et al. (2020), there is no distinction made between waste picking from garbage bins, or from litter on streets – both are referred to as "waste picking from streets". In this study, waste picked from garbage bins is treated separately. Additionally, in Chennai, and other cities depending on the context, the formal street sweepers play an important role in recovering and selling recyclable plastic they find on the streets. This is difficult to estimate as well, and it is unclear if it should be included under the term "waste picking from streets". Making this clarification and estimating these quantities is outside the scope of this research.
Flow 8	**Plastic scrap sold by IWBs to small scrap shops**	Mass balance	This flow is calculated using mass balance by assuming that there is no loss of material during transportation by the IWBs from the households to the scrap shops.	There could be some loss of material during transportation, but it is insignificant enough that it can be ignored. (Kabadiwalla Connect, 2023) reports that there is a leakage of 0.09% of material from collection services by the informal sector into unmanaged waste as litter, that could either end up in water systems or be retained on land.
Flow 9	**Recyclable Plastic scrap sold by formal workers to small scrap shops**	Bottom-up	While top-down estimates were available for plastic scrap recovered by formal workers, bottom-up estimates were attempted to resolve the data quality issues that were found in the interviews. It was found that formal workers who collect waste in BOVs get about 5-10 kg of recyclable plastic in a day that they can resell to scrap shops. This combined with the reported number of BOVs (5863) leads to a range of 879.45 - 1758.9 tons/month of recyclable plastic recovered. The value on the lower end is used to reconcile with other data on the IWS.	The sample size for the bottom-up estimation is not sufficient for the values to be statistically significant – a more detailed survey would be needed to establish validity. But this value is a reasonable estimation with the available information. However, the bottom-up value does not reconcile with the top-down estimate. Since the top-down estimate was obtained from a news article, the reliability of the data is low, and the bottom-up estimate is chosen as the more reasonable choice. Note, however, that this is not the case for Flow 4 which used the top-down estimate (see Flow 4).

Flow 10	**Recyclable Plastic scrap sold by waste pickers to small scrap shops**	Mass balance	It is assumed that all the plastic collected by waste pickers from corporation bins and landfills is sold to scrap shops with no leakages.	There could be some leakages during collection as explained in Flow 8. But they are not accounted for here.
Flow 11	**Discarded (non-recyclable) plastic from small scrap shops**	Bottom-up	From the interviews, it was observed that around 10-20% of plastic collected from households is non-recyclable through the informal value chains and is discarded in corporation bins as waste.	There are several limitations in this estimation: (1) The sample size of the interviews is not enough for the data to be statistically significant. However, this value is used to fill in the data gaps. (2) The leakage data from Kabadiwalla Connect, (2023) states that there is less than 0.1% leakage from sorting in the informal value chain which does not agree with the values used here. But since it is important to make the distinction between recyclable and non-recyclable plastic, and since the interviewees reported that they often get material from households that they do not want to collect since they can't sell it, the data from the interviews is used here.
Flow 12	**Non-recyclable plastic collected by formal workers to MRFs**	Bottom-up	Like Flow 9, bottom-up estimates were attempted to verify the available top-down data due to data quality issues that were found in the interviews. It was found that formal workers who collect waste in BOVs get about 10-15 kg of non-recyclable plastic in a day that they must return to their supervisors from Urbaser Sumeet or GCC, depending on who is responsible for MSW collection in that ward. This leads to a range of 1758.9 - 2638.35 tons/month of recovered non-recyclable plastic. The value on the lower end is used to reconcile with data on the aggregator of non-recyclable plastic.	Limitations for this estimation are the same as Flow 9. Also, refer to Flow 15 for further explanation of the validity of this choice.
Flow 13	**Plastic waste in unsegregated MSW that is transported from corporation bins to Transfer stations**	Mass balance	The principle of mass balance is used to calculate this value.	It is assumed that there is no leakage of material during transportation.
Flow 14	**Sorted recyclable plastic scrap sold by small scrap**	Mass Balance	Mass balance is used to quantify this flow. However, all three approaches are followed to get data for this flow and improve validity. The bottom-up approach is used by multiplying the estimated range of the number of scrap shops in the city (1970-2524) with the average quantity of plastic waste	Mass balance approach is chosen since the other approaches cannot differentiate between waste from households or from other sources (industry, retail, etc.) which also dispose of their recyclables through the IWS. The value obtained by mass balance is 2255 tons/month which lies in between the ranges obtained through both approaches

	shops to large aggregators		managed in scrap shops per month (0.8 - 1.517 tons/month). The obtained range of values for the total quantity is then 1576 tons/month - 3828.9 tons/month. The top-down approach uses statistics on the entire IWS of Chennai. It is assumed that the total plastic waste handled by the Informal sector in the city of Chennai goes through all the small scrap shops and directly uses this number. The obtained range of values for this approach is 1600 -2307 tons/month.	thus corroborating the sum of the estimates at the previous level – collection by IWBs and waste pickers.
Flow 15	**Non-recyclable plastic transported from MRFs to L2 aggregators**	Mass balance	Mass balance is used to estimate this flow. It is assumed that there is no loss of material during transportation from MRFs to the large aggregator of non-recyclable plastic. In reality, the supply chain is more complex, with the large aggregator getting supplies from different sources. But that is out of the scope of this model.	In the iterative process of modelling, data obtained through the interview with a large aggregator of non-recyclable plastic was used to adjust the values of Flows 3 and 12. The aggregator states that they can process 300 tons of non-recyclable plastic in a month. A total of 5 such facilities exist in Chennai (according to GCC), suggesting a total of around 1500 tons per month (assuming that all the aggregators have similar capacities). This necessitates the use of the value in the lower end of the range for Flow 12 (1758.9 tons per month).
Flow 16	**Sorted plastic scrap to recyclers**	Mass balance	The distinction between formal and informal facilities is not made due to lack of data.	There is a huge data gap in the system after aggregation. This is because of several reasons as discussed in 6.1. Thus, this part of the system is not modelled effectively in this study.
Flow 17	**Plastic with recycling potential recovered from non-recyclable plastic stream**	Bottom-up	The data obtained from the interview is used to estimate this flow. The percentage of plastic with recycling potential recovered from the material is reported as between 5-10%. An average of 7.5% is used.	There is a small quantity of recyclable plastic that ends up in the non-recyclable plastic stream due to improper segregation. This is removed by manual sorting and sent back to recycling facilities for processing. The limitation of using this percentage is that it is not statistically significant.
Flow 18	**Plastic scrap exported to other cities in India for recycling**	Top-down	WBSCD (2016) reports that 13% of all plastic scrap in India is transported to Delhi for recycling. The same value is assumed for the city of Chennai, but the destination of scrap is unknown and beyond the scope of this study.	There is a lot of inter-state movement of plastic scrap 5.2.2, with plastic scrap in Chennai being sent to nearby Southern Indian states as well. It is unclear how much of it actually ends up in Delhi. Moreover, the use of a national estimate is not representative of the dynamics of this specific region, thus lowering the validity of the assumption.
Flow 19	**Recycled plastic sent for manufacturing**	Mass balance	Mass balance is used to estimate the value of this flow.	In reality, the recycling value chain is more complex but is not modelled in this study due to lack of data, as explained earlier in Flow 16.

Flow 20	**Non-recyclable plastic sent for pyrolysis**	Bottom-up	Data from the interview is used to determine that 10% of the non-recyclable plastic is sent to pyrolysis plants for waste-to-energy recovery.	As mentioned earlier in Flow 17, the data from 1 aggregator is used to represent the entire system and this may not be accurate
Flow 21	**Non-recyclable plastic sent to cement plants for co-processing**	Mass balance	The rest of the non-recyclable plastic is sent to cement plants.	There is a small portion of non-recyclable plastic that is used in the construction of roads, but through the interviews, it was discovered that this is not a significant quantity. In addition to this, the limitation of Flow 16 is applicable here as well.
Flow 22	**Plastic in unsegregated MSW dumped in landfills**	Mass balance	Mass balance is used to estimate the value of this flow since all mixed waste is directly dumped in landfills.	
Flow 23	**Uncollected waste that ends up in litter**	Mass balance	All the uncollected waste that is not openly burnt is assumed to end up as litter by the principle of mass balance.	The end destinations of littered plastic are beyond the scope of this study and are not modelled here. They could end up in storm drains, eventually ending up in water bodies, or retained on land - by riverbanks or in other public places (Kabadiwalla Connect, 2023). Sometimes waste pickers and street sweepers could remove the plastic retained on land thus putting them back in the recycling value chain or causing them to end up in landfills. This is not accounted for in this model due to lack of data.
Flow 24	**Uncollected waste that is openly burned**	Unknown	From (Kabadiwalla Connect, 2023) it is assumed that 6.98% of uncollected waste is openly burned. It is not known how this estimate was determined in the study.	This estimate was obtained for a sample of 66 wards around the rivers in Chennai and may not apply to all of Chennai. From the qualitative data, it is also seen that open burning is more prevalent in the outskirts of Chennai and not within the centre, in the more densely populated areas. This could also skew results.
Flow 25	**Plastic entering natural environments**	Mass balance		The destination of littered plastic in the environment is beyond the scope of this study as discussed in Flow 23. All of them are assumed to end up in the environment, which is outside the system boundary.
Flow 26	**Particles entering environment after burning**	Mass balance		Open burning causes toxic fumes and ash that enter the air, water and soil. The effects of this are not discussed in this study.