Imperial College London

Department of Civil and Environmental Engineering



The Impact of Black Carbon Emissions from Open Burning of Solid Waste

Natalia Reyna-Bensusan

Supervisors: Professor Stephen Smith and Professor David Wilson

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ABSTRACT

Open burning of solid waste is widely practiced in developing countries and is a significant source of air pollution, impacting climate change and human health. Waste disposal by open burning releases emissions of black carbon (BC), a pollutant with a global warming potential (GWP) up to 5,000 times greater than carbon dioxide (CO_2). However, there are major uncertainties about the extent and impacts of BC emissions from uncontrolled burning of waste on the environment. The aim of this research is to quantify the impact of BC emissions from open burning of waste and to improve the quality of the available data on open waste combustion through field measurements and laboratory experimentation.

Some of the first field data to be reported on the uncontrolled burning of waste is presented for two representative case study areas (Huejutla and Juchitán) in Mexico. Published statistical data were also scrutinized to provide an independent assessment of the extent of open burning of waste at a national level. Health databases provided by the authorities were analysed and the results showed that respiratory diseases were increased in rural areas of Huejutla and urban areas of Juchitán, corresponding with the increased exposure of the population to emissions from open burning of waste. This suggested a possible link between the uncontrolled combustion of waste and respiratory health.

A small-scale, laboratory combustion apparatus was developed to quantify the emissions released by waste combustion and to develop BC emission factors (EFs) for waste representing the composition of the case study areas and for Mexico, using optical transmission and thermal optical analysis techniques. Black carbon EFs were also developed for single waste fractions and were used to estimate regional EFs based on the waste composition characteristics of different areas of the world. The results of this research have demonstrated that action to reduce open burning of waste would have a significant and immediate benefit to improving air quality and reducing climate change.

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ACRONYMS

AFR: Africa Region

ATN: Attenuation

BC: Black carbon

CCAC: Climate and Clean Air Coalition

CH_4: Methane

CO_2: Carbon dioxide

EAP: East Asia & the Pacific

EC: Elemental Carbon

ECA: Eastern & Central Asia

EF: Emission factor

EUSAAR: European Supersites for Atmospheric Aerosol Research

FW: Fresh Weight

GHGs: Greenhouse gases

GWP: Global warming potential

HDPE: High Density Polyethylene

INECC: National Institute of Ecology and Climate Change, by its acronym in Spanish

INEGI: National Institute of Statistics and Geography, by its acronym in Spanish

IPCC: Intergovernmental Panel on Climate Change

LCR: Latin America & the Caribbean

LDPE: Low Density Polyethylene

MENA: Middle East & North Africa

MFA: Material Flow Analysis

MFD: Material Flow Diagram

MSW: Municipal solid waste

$MtCO_2Eq$: Metric tonnes of carbon dioxide equivalent

N_2O: Nitrous oxide

OC: Organic carbon

OECD: Organisation for Economic Co-operation and Development

PET: Polyethylene terephthalate

PM: Particulate matter

$PM_{2.5}$: Particulate matter of less than 2.5 micrometre diameter

POA: Primary organic carbon

POPs: Persistent organic pollutants

PROFEPA: Federal Attorney for Environmental Protection, by its acronym in Spanish

PSAP: Particle Soot Absorption Photometer

SAR: South Asia

SEMARNAT: Ministry of the Environment and Natural Resources, by its acronym in Spanish

SLCP: Short-lived climate pollutant

SWM: Solid waste management

TOA: Thermal/Optical Analysis

TOR: Thermal optical reflectance

TOT: Thermal optical transmittance

US EPA: Environmental Protection Agency of the United States of America

WHO: World Health Organisation

1. Introduction

1.1. Background

Solid waste disposal is a worldwide issue and represents a severe risk to public health and the environment. Globally, two billion people lack access to municipal solid waste (MSW) collection services and dispose of household waste typically by open burning, burial or dumping on open ground or into watercourses (UNEP and ISWA, 2015). Providing universal access to adequate, safe and affordable MSW collection services and eliminating uncontrolled dumping and burning of waste are strategic international objectives within the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2015).

The contribution to global methane (CH_4) emissions from the landfill disposal of biodegradable MSW is well established (Bogner et al., 2007). Moreover, practices and policies to reduce CH_4 emissions from the waste sector are present in many countries. For example, CH_4 emissions from MSW in Europe have dropped between 1990 and 2010 as a result of the European Union's Landfill Directive (Global Methane Initiative, 2013). This regulation obliged Member States to reduce the amount of biodegradable municipal waste that they landfill to 35 % of 1995 levels by 2016 (some countries by 2020).

This contrasts with the lack of environmental measures related to reducing black carbon (BC) emissions from waste combustion in both developed and developing countries. Black carbon is a short-lived climate pollutant (SLCP) that contributes to climate change, and which also has direct detrimental impacts on human health (US EPA, 2012b). Bond et al. (2013) described BC as the second largest contributor to global warming after CO_2.

One of the reasons that could explain the reduced efforts to address this problem is the scarcity of information on the impact of BC emissions from open burning of waste on health and climate change. Nevertheless, open burning of solid waste in backyards and at uncontrolled dumpsites represents a significant source of black carbon (BC) (Christian et al., 2010; Yokelson et al., 2011; Wiedinmyer et al., 2014; Stockwell et al., 2016). However, BC emissions from open burning of waste are not included in most emission inventories used to model and develop national/international climate change mitigation policies, due to a paucity of evidence quantifying the extent of the emissions from this source.

Black carbon is formed during incomplete combustion of fossil fuels and biomass. It has direct radiative forcing properties caused by absorption and scattering of sunlight. Black carbon deposits on snow and ice causing it to absorb more solar radiation, accelerating the melting process. It is a component of atmospheric particulate matter (PM) with an average global warming potential (GWP) that is up to 5,000 times greater than CO_2 (Bond et al., 2013). There is also a strong link between human exposure to BC emissions and increased rates of cardiovascular diseases, respiratory illnesses and premature mortality (Janssen et al., 2012; US EPA, 2012b; Kodros et al., 2016).

The rate of atmospheric pollutant emissions produced from combustion sources, such as open burning of waste, are quantitatively expressed using emission factors (EFs), which are metrics

describing the mass of a pollutant emitted per unit mass of material burned (Zhang and Morawska, 2002; Lemieux et al., 2004). In this research, EFs refer to the mass of BC emitted per kilogram (kg) of waste burned. Published BC EFs for open burning of waste are based on very limited field measurements and therefore have high levels of uncertainty. Significant uncertainties in both the available EFs and the activity levels estimating the amounts of waste burned are major barriers to recognising the impact of this potentially significant emission source.

Wiedinmyer et al. (2014) estimated that 41 % of the total waste generated globally is disposed by burning. This was calculated using IPCC (2006) guidelines on emissions from the waste sector which assume a default value of 0.6 for the fraction of waste burned in open dumps in developing countries. According to Wiedinmyer et al. (2014), uncontrolled waste combustion releases the emission of 632 x 10^3 t y^{-1} of BC, equivalent to 11 % of the total anthropogenic BC emissions globally. However, estimations of uncontrolled waste combustion are not based on experimental or field data, and, as a consequence, this emission source is not considered in the IPCC Fourth (Bogner et al., 2007) or Fifth (IPCC, 2014) Assessment Reports on climate change. Therefore, Wiedinmyer et al. (2014) highlighted the need to improve the available data on open burning of waste and that attention should be given to developing EFs and providing better estimates of burning waste.

Waste composition and the associated impact on the combustion characteristics have a significant effect on the nature and properties of the particulate and BC emissions from burning waste. Measuring EF values for specific waste types and combining this information to generate overall EFs for mixed waste with different compositions may offer a practical tool to estimate EFs for different local, regional or national waste sources, without the need to conduct direct combustion measurements, which are complex, expensive and practically difficult.

One of the most effective ways to develop EFs for open burning sources is through laboratory simulations. However, EFs are significantly affected by the combustion conditions and therefore careful control is paramount (Zhang and Morawska, 2002; Lemieux et al., 2004; Tissari et al., 2008). To calculate the overall emissions from open burning of waste, the EF is combined with the activity level, usually in terms of waste burned per unit time in a specific area, which is measured by collecting field data in representative communities and municipalities.

Mexico has one of the most significant rates of residential and open dump burning and, therefore, is potentially amongst the leading emitters of BC from MSW disposal (Wiedinmyer et al., 2014). According to Wiedinmyer et al. (2014), between 5.0 – 10.0 x 10^6 t y^{-1} of waste (13 – 27 % of the total generated) is burned by households and between 10 - 25 x 10^6 t y^{-1} (27 - 96 % of the total generated) is burned at dumpsites in Mexico. Previous estimates published by Commoner et al. (2000) suggest that 50% of MSW generated in Mexico was disposed informally, and that the amount of waste burnt in open fires was equivalent to 14.5 x 10^6 t y^{-1}.

1.2. Aim and objectives

The aim of this research is to evaluate the impact of BC emissions from open burning of waste on the environment and public health. The goal is to improve the quality of the available data on open waste combustion through field measurements and laboratory experimentation, so that this source can be included in future IPCC emission inventories. This information is valuable to identify policies and practices to mitigate the impact of the solid waste sector on climate change. To accomplish this goal, the main objectives are to:

a) Understand the current state of knowledge on BC emissions from open burning of waste and its contribution to climate change (Chapter 2)
b) Select representative areas where open waste combustion is commonly practised and gather published information on their waste management situation and the socioeconomic characteristics of the population living in those areas (Chapter 3).
c) Calculate the activity level for open burning of waste in the country where the case study areas are located, using published information and advice from federal authorities and experts in SWM (Chapter 3).
d) Collect field information on the extent of open burning of waste in the two selected case study areas (Chapter 4 and 5).
e) Analyse respiratory health databases in the two case study areas and relate them to the characteristics of open burning of waste disposal in the region (Chapter 4).
f) Determine the composition of waste in the case study areas to calculate the quantities and type of combustible waste fractions disposed (Chapter 5).
g) Construct a waste management profile of open burning of waste in the case study areas to identify the types and quantities of MSW generated and disposed by burning by households. (Chapter 6).
h) Develop a laboratory based, combustion methodology to measure BC EFs from burning waste (Chapter 7).
i) Measure BC EFs for single waste types including: green waste, different types of plastics, textiles and paper and card (Chapter 7).
j) Measure BC EFs for mixtures of these waste types based on the waste composition in the two case study areas (Chapter 7).
k) Calculate regional EFs for BC from open burning waste based on the waste composition of the case study areas, of Mexico and different areas of the world (Chapter 8).
l) Estimate BC emissions from open burning of waste in the case study areas and extrapolate the results to different regions of the world (Chapter 8).
m) Place the BC emissions from open burning into the context of other polluting emissions from the waste sector, such as methane (CH_4) (Chapter 8).

1.3. Structure of the dissertation

Each chapter in this dissertation includes an introduction, the specific aims and objectives, methodology, results and discussion. Figure 1.1 presents a flow diagram showing the integrated

structure and flow of the research. The literature review is presented in Chapter 2 and the description of the case study areas is in Chapter 3. Chapter 4 includes the results of the interviews with key stakeholders and questionnaire surveys of households in the field case study areas. This chapter also includes an analysis of health databases provided by local authorities in the field case study areas to explore the relationship between respiratory diseases and BC emissions from open burning of waste. The information presented in Chapter 4 was used to develop critical waste characterisation profiles, presented in Chapter 5. A Material flow analysis (MFA) is presented in chapter 6 based on the information gathered through the interviews with key stakeholders and the surveys of households (Chapter 4). Specifically, information on the quantity of waste collected, areas covered by waste collection services, percentages of waste recycled, and methods of waste disposal were key to developing the MFA for each case study area (Chapter 6). Chapter 7 describes the laboratory experimentation work to determine EFs from uncontrolled burning of waste. The EFs determined in Chapter 7, together with the activity levels presented in the MFA were used to estimate the total emissions from waste combustion in the case study areas, discussed in Chapter 8. Chapter 9 is the general discussion while the conclusions and recommendations for future work are presented in Chapter 10.

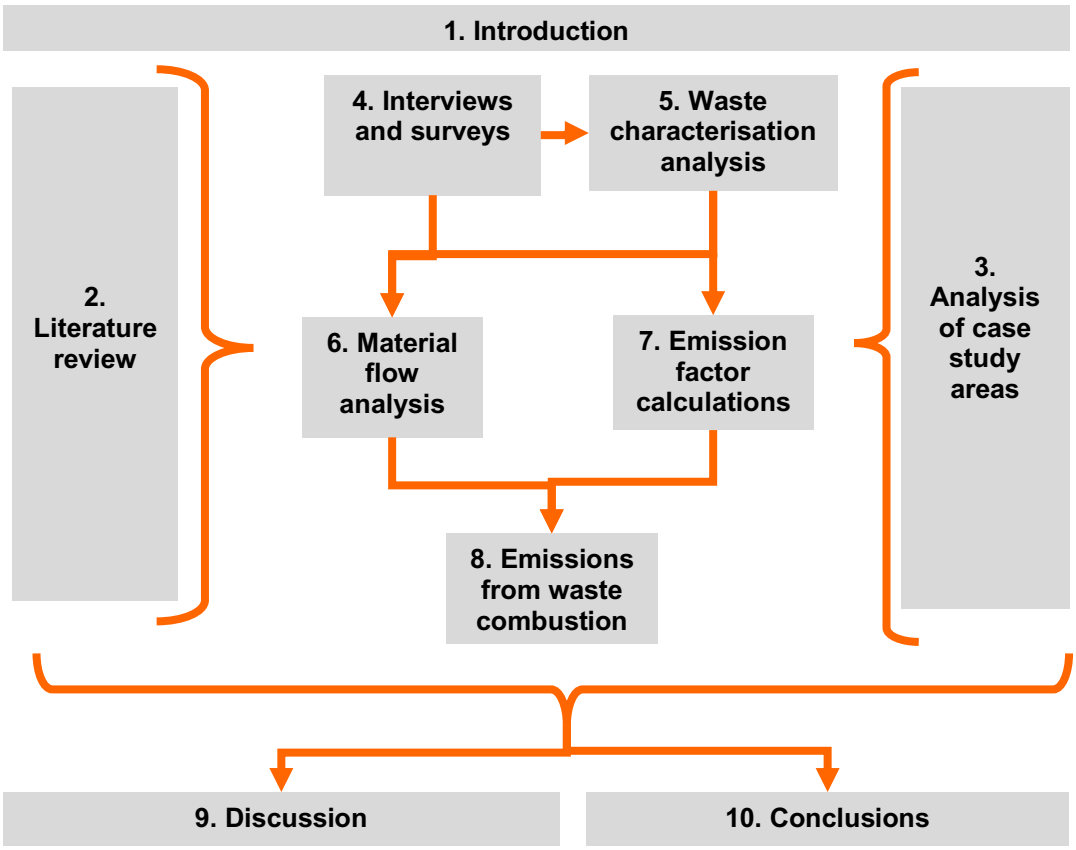


Figure 1.1 Flow chart describing the structure of the dissertation

2. Literature Review

2.1. Introduction

Globally, approximately two billion tonnes (t) of municipal solid waste are produced each year (Hoornweg and Bhada-Tata, 2012). However, an estimated two billion people lack access to waste collection services and dispose of waste typically by open burning, burial and dumping on open ground or into watercourses (UNEP and ISWA, 2015). Waste collection services are the first stage in an integrated waste management system. Following the introduction of a waste collection service it is necessary to place environmental controls on the management of the final disposal site. However, uncontrolled disposal remains a major problem internationally, and under these circumstances waste in dumpsites is commonly burned, either accidentally or deliberately to reduce the volume or to recover residual metals (IPCC, 2006; Wiedinmyer et al., 2014). Therefore, burning of waste can happen at the source of the waste production (backyard burning in households) or at legal and illegal dumpsites.

In developed countries, local authorities have the legal responsibility to implement solid waste management schemes considering the environment, public health, economics, and engineering challenges (Tchobanoglous et al., 1993). By contrast, in developing and transition countries it has been challenging to establish similar practices because municipalities often have to deal with a limited budget, lack of experience and inadequate infrastructure (Abarca-Guerrero et al., 2013).

Open burning of waste is not included in the emission inventories for climate change and, as a consequence, the municipal solid waste (MSW) sector has been underestimated as a significant contributor to air pollution. For instance, IPCC (2006) guidelines on emissions from the waste sector assume a default value of 0.6 for the fraction of waste burned in open dumps in developing countries. Nevertheless, there is a lack of experimental data available to support this and, therefore, this emission source is not considered in the IPCC Fourth (Bogner et al., 2007) or Fifth (IPCC, 2014) Assessment Reports.

This literature review will first present information on the impact of the MSW sector on climate change, including data on the estimated activity levels of uncontrolled burning of waste worldwide and in Mexico. The main areas considered include: (1) the process of open combustion of biomass and waste, and the effect of different conditions on the emissions from this source; (2) the main characteristics of BC as well as the impact of these emissions on climate change; (3) BC sampling and measuring techniques, including the advantages, disadvantages and uncertainties associated with different measuring methodologies; (4) current estimations of BC emissions from open burning of waste, including the available BC emission factors, and the uncertainty of current estimations, and (5) the health impact of BC emissions in general and of BC emissions from open burning of waste in particular.

2.2. The impact of the waste management sector on climate change

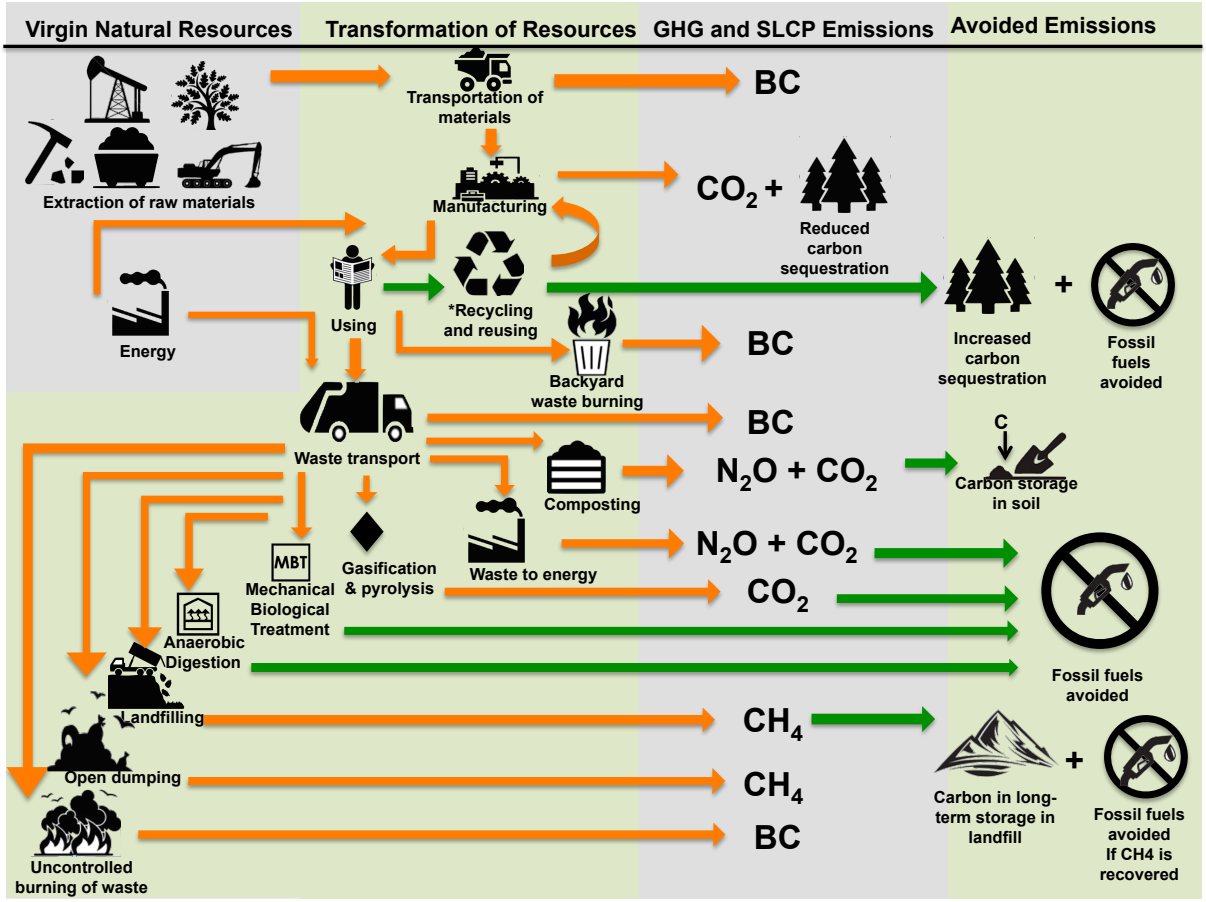
The solid waste sector is a key contributor to emissions of SLCPs, which contribute to climate change and air pollution (UNEP, 2010). The two main SLCPs emitted from the solid waste sector are

CH_4 and BC. These pollutants have short atmospheric lifetimes and a strong warming influence on the climate, with detrimental impacts on human health, agriculture, and ecosystems. Rapid action on reducing SLCPs could help to decrease the amount of global warming predicted by 2050 by as much as 0.5°C and prevent over 2 million of pollution-related premature deaths each year (CCAC, 2014).

The anaerobic decomposition of the organic fraction of solid waste in landfills results in the release of CH_4, which has a Global Warming Potential (GWP)[1] 34 times more potent than carbon dioxide (CO_2) over a 100 year horizon (IPCC, 2013). Municipal solid waste landfills are the third largest source of global CH_4 emissions accounting for approximately 11 % of estimated global CH_4 emissions, equivalent to almost 800 t of equivalent CO_2 ($MtCO_2Eq$) (CCAC, 2014). Methane emissions from landfills are generally considered to represent the primary source of climate impact from the waste sector. However, a more holistic approach would also consider the waste sector as a key contributor to emissions of other SLCPs, such as BC, which contributes to climate change and air pollution (UNEP, 2010).

Black carbon is a secondary product of incomplete combustion, which is an air pollutant that contributes to climate warming as a component of particulate matter. Several activities and processes related to SWM contribute to BC emissions, such as waste collection vehicles and waste handling equipment due to fuel combustion, as well as combustion equipment at landfills (i.e., flares and incineration). However, the most important source of BC from the waste sector is the uncontrolled open burning of waste, which can be a very significant source of BC emissions globally (CCAC, 2014). Contributions of the waste sector to climate change are summarised in Figure 2.1.

[1] The GWP is a relative measure of how much heat a GHG traps in the atmosphere compared to the amount of heat trapped by a similar mass of carbon dioxide.



***Recycling can occur in various stages of the waste management process. In this diagram, it is only represented once for purposes of simplification.**

Figure 2.1 The impact of waste management on climate change (UNEP and ISWA, 2015)

The primary processes contributing to climate change from the waste sector include:

- Emissions of CH_4 from the landfilling of organic waste (biodegradable waste including paper, food and garden refuse)
- Some minor nitrous oxide (N_2O) emissions are reported from MSW incineration, as a by-product of the adopted NO_x reduction technology (Rigamonti and Grosso, 2009). Also, N_2O is emitted during composting. However, the release from this source is minimal when sufficient aeration is supplied (Hellebrand, 1998).
- Emissions of CO_2 and BC from the collection, transportation and processing of waste (from the fuel used in these operations). There is no quantitative data to assess these emissions, however, it is suspected that they are much less important than the emissions from uncontrolled open burning of waste.
- BC from the combustion of waste in uncontrolled open fires in dumpsites and households.

The research reported in this thesis is focused on the contribution of the waste sector to climate change through open burning of waste in dumpsites and backyards.

2.2.1. Uncontrolled burning of waste in the world

Controlled combustion systems for solid waste, such as incinerators, are carefully regulated and contribute very little to polluting atmospheric emissions. However, uncontrolled burning of waste is

characteristically a form of low temperature combustion with high contaminant emissions that contributes significantly to air pollution, causing both health and environmental impacts (Christian et al., 2010; Akagi et al., 2011; Yokelson et al., 2011; Li et al., 2012; Wiedinmyer et al., 2014; Stockwell et al., 2016). Nevertheless, burning waste has been commonly ignored as an important global source of polluting emissions and omitted in most emission inventories around the world.

According to Wiedinmyer et al. (2014) domestic open waste burning is practised in both developed and developing countries. In developed regions, domestic waste is typically collected, however, burning can still occur in rural areas where collection services are expensive, unavailable, or infrequent. Waste generation is in general higher in industrialised countries and urban areas, however, the fraction burned is higher in developing countries and rural areas, where waste collection services are less frequent or do not exist. Additionally, in many developing countries, even when waste is collected and transported to dumpsites, it is a common practice to burn it in open, uncontrolled fires to reduce the volume (Wiedinmyer et al., 2014). The open burning of waste generates many atmospheric pollutants, including greenhouse gases (GHGs), reactive trace gases, particulate matter (PM), toxic compounds (such as dioxins and furans) and BC.

Wiedinmyer et al. (2014) estimated the global MSW generation was equivalent to 2.4 x 10^9 t and that 0.62 x 10^9 t was burned in the open by households, and 0.35 x 10^9 t was burned in the open at dumpsites. These estimations were developed using a default value for waste burned of 60% of the total waste available to be burned that is actually burned, as recommended by IPCC (2006). This resulted in approximately 1.0 x 10^9 t, equivalent to 41 % of the total MSW generated globally, disposed through an uncontrolled combustion process. Similarly, Christian et al. (2010) estimated that 2 x 10^9 t of waste was generated every year worldwide, and approximately half may be disposed by burning. The Waste Atlas estimated global MSW generation was consistent with this value and was equivalent to 1.9 x 10^9 t y^{-1} (Waste Atlas Partnership, 2014).

Figure 2.2 presents the global distribution of MSW burning by households and at dumpsites internationally based on Wiedinmyer et al. (2014). In Mexico, between 5 and 10 x 10^6 t of waste is burned per year in households and between 10 and 25 x 10^6 t of waste is burned annually in dumpsites (Wiedinmyer et al., 2014). Therefore, Mexico represents a region with one of the highest rates of burning waste globally. Uncontrolled open burning of waste, by households and at dumpsites, is also a significant problem in Asia and other countries in Latin America, which are regions characterised by emerging economies. The countries with the largest estimates for residential and open dump burning, and therefore, the largest emissions from this source include: China, India, Brazil, Mexico, Pakistan, and Turkey (Wiedinmyer et al., 2014).

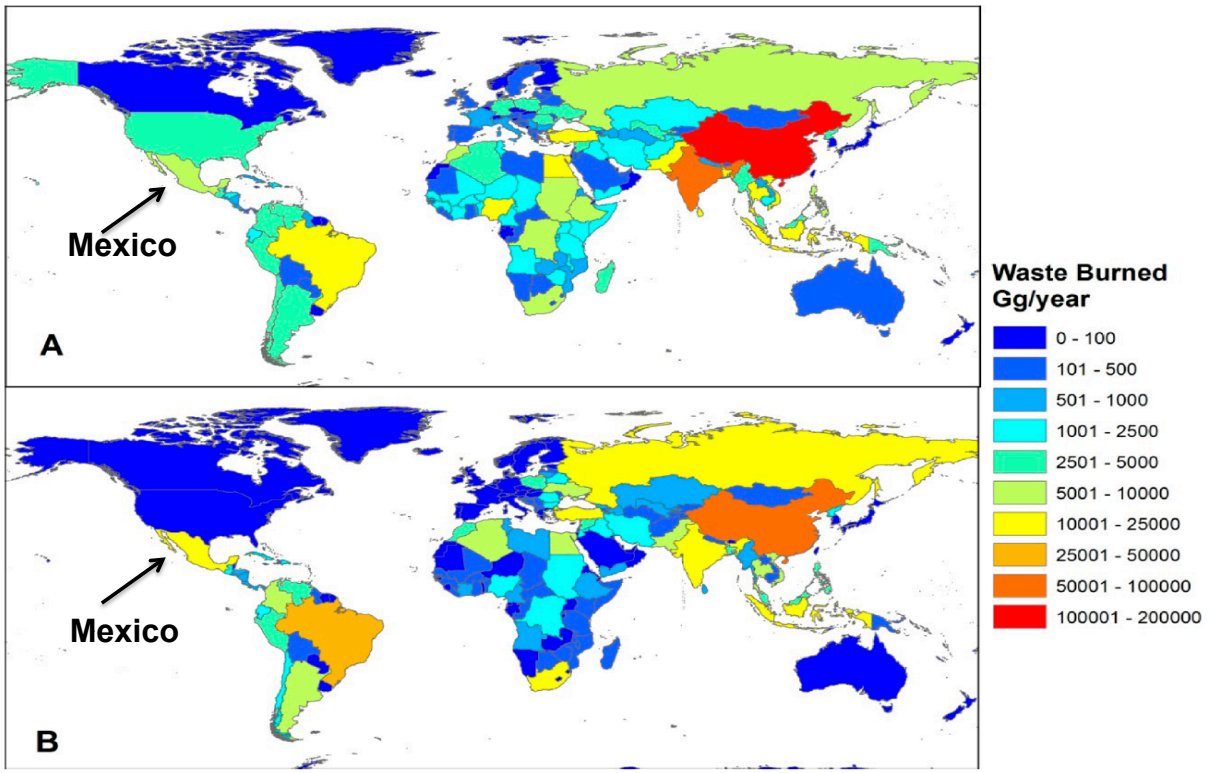


Figure 2.2 Total estimated annual waste burned (t x10^3 y^{-1}) in households (A) and at dumpsites (B) (Wiedinmyer et al., 2014)

Bond et al. (2004) assembled per capita waste generation rates from Hoornweg and Thomas (1999) and then estimated a fraction for waste disposed by open burning. However, there was considerable uncertainty (200 %) in the estimates, since the waste-burning practice is highly localised and depends on the waste management services available. Bond et al. (2004) considered the waste generation rate in rural areas of developing countries to be zero on the basis that goods in these areas are mostly recycled and packaged food is not common. Also, information for waste generation in rural areas was very difficult to obtain. The inventory did not consider combustion of industrial waste such as used tyres or electronic components, which are also important local sources of pollution. The overall value obtained for the rate of open burning of waste by Bond et al. (2004) was lower compared to estimates by Wiedinmyer et al. (2014) and Christian et al. (2010), and was equivalent to 33 x 10^6 t y^{-1}, representing 2.6 % of total waste generation globally. In general, estimates for BC emissions from waste combustion agree on the primary sources and emitting regions, however, significant uncertainties remain, such as the amounts of waste being combusted, especially in developing countries and rural areas.

2.2.2. Uncontrolled burning of waste in Mexico

Hodzic et al. (2012) estimated the impact of waste burning in Mexico City, and developed an emission inventory for this sector based on socioeconomic and emission factors measured by the 2006 MILAGRO (Megacity Initiative: Local and Global Research Observations) field project (Molina et al., 2010). This project did not include estimations for BC emissions specifically, but approximated

that 19 t day^{-1} of primary organic carbon (POA) are emitted in Mexico City. This quantity can be compared to POA emissions from fossil fuels in Mexico City, and raises the average organic aerosol concentration in the atmosphere up to 2µg m^{-3} in densely populated areas. One of the most important conclusions was that the mitigation of uncontrolled burning of waste in the Mexico City Metropolitan Area could reduce the levels of total organic aerosols by 5 % in the centre of the city, and by 15 – 40 % in the Greater Mexico City area.

There is a strong relationship between the extent of burning in the domestic setting and the socioeconomic status of households (Hodzic et al., 2012). However, there is no consistent information available for Mexico on the relationship between the amount of waste that is being burned and the socioeconomic classification of households. Hodzic et al. (2012) collected anecdotal evidence and carried out interviews, which suggested that open burning of waste might exceed 50 % in the most deprived areas, and is negligible in areas of higher socioeconomic status in Mexico City. In the richer areas, they assumed that a fraction of the collected waste was transported to landfills (or dumpsites) located in poorer areas and it was burned there. For this reason, they distributed any assumed emissions from waste generated in mid-high and high socioeconomic areas to the mid-low and low areas in equal proportions (see Table 2.1). However, the uncertainties associated with these estimates were significant. Such estimates may also apply to other metropolitan areas in Mexico, but may differ in rural areas, where waste services are less efficient or are not available.

Table 2.1 Generation of waste per capita and assumed fractions of burned waste in Mexico City Metropolitan Area

Socioeconomic classification	Waste produced per person (kg day^{-1})	% Burned
Low	0.89	60
Mid-low	0.96	60
Mid	1.04	30
Mid-High	1.05	20*
High	1.06	20*
*This waste is transported and burned in the Low and Mid-Low socioeconomic areas. **Source:** (Ojeda-Benítez et al., 2008; Hodzic et al., 2012)		

According to the National Action Planning on SLCP prepared for Mexico by the INECC and the Molina Centre for Strategic Studies in Energy and the Environment (2013), it is estimated that open burning in Mexico generates more than 20 % of the total BC emissions and 22 % of the persistent organic pollutants (POPs) in the country. Romero-Torres et al. (2009) have stated that the intentional or accidental burning of waste produces approximately 220 x 10^3 t of polluting substances per year in Mexico.

2.3. Open combustion characteristics

2.3.1. Combustion characteristics during open burning of waste

Emissions from burning processes depend heavily upon the combustion efficiency. Therefore, the main factors that determine the type and quantity of emissions from open burning are the waste characteristics (type and density) and the type of fire (flaming or smouldering). The configuration of

the burning material (in barrels, piles or laid out in the ground) also affects the nature of the emissions (Peterson and Ward, 1993). According to Peterson and Ward (1993), the phases of the combustion process during open burning comprise preheating, followed by flaming and smouldering. First, water and highly volatile hydrocarbons are volatilized during the preheating process. Subsequently, flaming combustion occurs, which is characterised by the oxidation of cellulose, lignin, and volatile hydrocarbons. During this phase there is fast fire with a good supply of oxygen and flames can be observed. When the quantity of the available oxygen decreases, flaming combustion is harder to maintain and smouldering follows. The smouldering phase has a slower rate of pyrolysis and there is no open flame (Ortiz-de-Zárate et al., 2000). Emissions from the combustion process are present during all phases, however, different pollutants are emitted during the different phases (Section 2.3.2) (Peterson and Ward, 1993).

2.3.2. Emission patterns during flaming and smouldering phases of the combustion process

According to Aurell et al. (2012) $PM_{2.5}$ emissions from uncontrolled burning are considerably higher in smouldering compared to firing combustion conditions. Ortiz-de-Zárate et al. (2000) also found that PM was mainly emitted during the smouldering stage during the combustion of cereal waste. The emission ratio (ER) for total PM was 5±3 g of total PM kg^{-1} CO_2 during the flaming phase and 65±18 g of total PM kg^{-1} CO_2 during the smouldering phase. Experimental results presented by Ortiz-de-Zárate et al. (2000) showed that cereal waste burning in fields was very similar process to savannah fires. According to Ortiz-de-Zárate et al. (2000), emission ratios should be measured both during the firing and the smouldering phases of the combustion process. For cereal waste fires, the dominant phase was flaming which was represented by a linear combination of 0.90 (flaming) + 0.10 (smouldering). The proportion of the flaming and smouldering phases during open burning of waste are likely to differ from this pattern and are probably highly variable, depending on the waste characteristics and the configuration. However, no studies specifically describing firing and smouldering proportions for open burning of waste are available.

Solorzano-Ochoa et al. (2012) analysed the emissions of polychlorinated dibenzodioxins, dibenzofurans and biphenyls (PCDD/PCDF/PCB) from open burning of waste in Mexico by setting on fire piles of household waste of approximately 100 kg. The field-based experiments showed that less compaction of the waste or active mixing during the fire (stirring) promoted combustion conditions by increasing the available oxygen. Consequently, PCDD/PCDF/PCB emissions increased during the smouldering phase of combustion, when the CO/CO_2 ratio rises. Active mixing of waste yielded the lowest EFs. Accordig to Solorzano-Ochoa et al. (2012), intermediate values for EFs occurred with piles of loosened waste. The largest EFs for PCDD/PCDF/PCBs were measured for unstirred, compacted waste.

2.4. Main characteristics of black carbon

The first major quantitative and comprehensive analysis of BC emissions was conducted by Bond et al. (2013), based on a four-year investigation led by the International Global Atmospheric Chemistry (IGAC) Project. The research quantified the complexities of BC and the impacts of co-

emitted pollutants from different sources, considering the uncertainties in measurements and calculations.

Indeed, the term “black carbon” is not used rigorously or consistently in the literature. Bond et al. (2013) described BC as a distinct type of carbonaceous material that forms only in flames during combustion of carbon-based fuels, and it is distinguishable from other forms of carbon and carbon compounds contained in atmospheric aerosols because it has a unique combination of the following physical properties:

- It has a strong capacity to absorb visible light and has a mass absorption cross section[2] of at least 5 m^2g^{-1} at a wavelength of 550nm.
- It is refractory (its basic form is not modified at very high temperatures)
- Its vaporisation temperature is near to 4,000K.
- It is insoluble in water, in organic solvents and in other components of atmospheric aerosol.
- Its lifetime ranges from 3.3 to 10.6 days.

In this research, the term BC will be used to refer to ambient aerosol material with the characteristics mentioned above. However, Bond et al. (2013) have explained that there is not a single definition of BC that has been used consistently in research studies describing absorbing aerosol and its role in the atmosphere. Figure 2.3 shows images of BC taken with a transmission electron microscope by Taketani (2016). Image (a) presents BC particles attached to the surface of non-BC material, (b) shows bare BC particles and (c) presents BC particles coated with non-BC material. According to this report, light absorption is increased by BC particles coated with non-BC material.

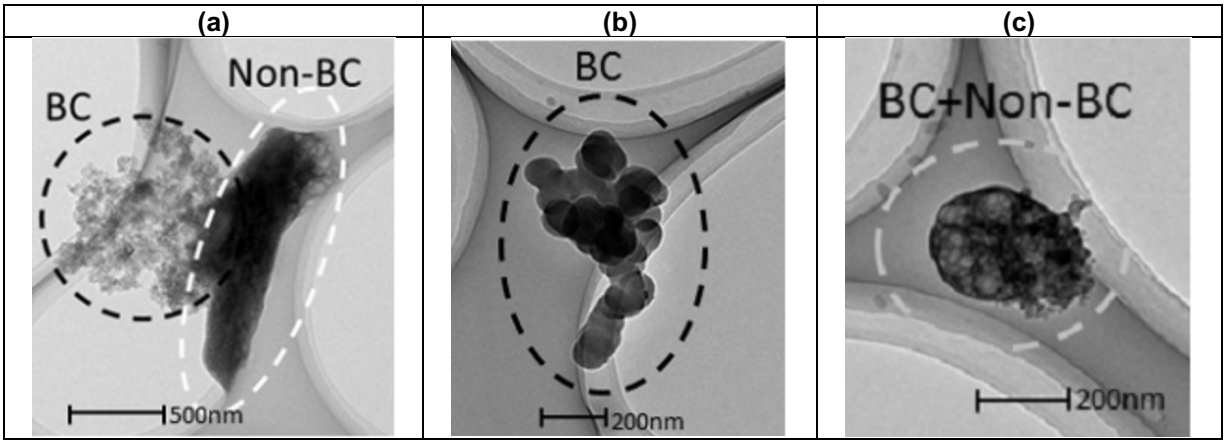


Figure 2.3 Transmission electron microscope images of BC (Taketani, 2016)

According to Bond et al. (2013), a significant fraction of atmospheric BC concentrations come from anthropogenic activities. These particles are produced during the combustion of carbon-based fuels

[2] The mass absorption cross section (MAC) is used to calculate the radiative transfer and radiative forcing caused by soot particles.

when oxygen is insufficient for complete combustion. However, BC can also form in the presence of adequate oxygen supply overall, in localised areas of high fuel content and low content of oxygen, for example, when the reactants are not well mixed. Also, BC is the substance with the strongest light absorption capacity per unit mass in atmospheric aerosols.

Black carbon properties (density, absorption coefficient, size, and morphology) are highly variable as they depend on the conditions of generation, the source of emissions, transformations due to mechanisms such as catalytic surface reactions, the degree of mixing with other constituents as well as its rate of removal due to wet and dry deposition (North et al., 2014). Black Carbon warms the atmosphere due to the interaction with sunlight. Emitted BC undergoes regional and intercontinental transport and is removed from the atmosphere through precipitation and dry deposition to the Earth's surface, with an average atmospheric lifetime of approximately one week. Consequently, BC is found in remote regions of the atmosphere at concentrations much lower than in source regions.

2.4.1. Primary sources and global estimates of BC emissions

The most important sources of BC emissions are diesel engines, industry, residential solid fuel, and open burning. On a global scale, the dominant emitters of BC depend on the location. For example, residential solid fuels contribute 60 – 80 % of emissions in Asia and Africa, whereas diesel engines contribute about 70 % of emissions in Europe and North America (Bond et al., 2013). In Africa and Central and Latin America, open biomass burning is the most significant source of BC in these regions (Grahame et al., 2014). On a local basis, open burning of waste can be a major BC source in rural and periurban areas, where waste collection services are insufficient or unavailable.

Estimates of BC emissions are sensitive to the methodology and assumptions used in the measurements and predictions. Bond et al. (2013) developed the first quantitative and comprehensive analysis of BC global emissions, summarised in Table 2.2. Global emissions of BC were estimated at approximately 7.5 (with a range from 2 to 29) x 10^6 t per year in 2000. East Asia was the largest contributing region representing 23.1 % of total global emissions, followed by Africa with 22 %. Southeast Asia contributed 10.8 % of global emissions, the United States, 3.9 %, and OECD Europe, 3.7 %. Open biomass emissions included combustion of forests, grasslands as well as open burning of waste for disposal (including crop residues and urban waste). The overall BC contribution from burning biomass was equivalent to 2.75 (ranging from 0.8 to 1.3) x 10^6 t y^{-1} (Bond et al., 2013). Other estimations by Grahame et al. (2014), suggested that worldwide BC emissions were higher than those predicted by Bond et al. (2013) and were equivalent to 8.1 x 10^6 t per year.

Table 2.2 Global BC emissions from energy and biomass combustion (t year^{-1})

Source	Modelled [a]	Scaled [b]	Current [c]	BC Range
Energy Related Emissions [d]	4,600	10,140	4,790	1,220 to 15,000
Open Biomass Emissions [e]	**3,100**	**6,810**	**2,750**	**800 to 13,800**
Total Emissions	7,700	16,950	7,540	2,020 to 28,800

a) Based on SPEW (Speciated Pollutant Emissions Wizard) emissions and GFED (Global Fire Emissions Database) 2.0 emission fields (reported as the source of open-burning emissions), which were used in many AeroCom models.
b) Modelled regional emissions adjusted by burden scale factors.
c) Best estimate Bottom-Up values for BC Emissions in 2000.
d) Includes power plants, industrial activity, transportation, and residential fuel use.
e) Includes combustion of forests and grasslands or savannah (regardless of the cause of the fire), open burning of waste for disposal, including crop residues and urban waste.
Source: Bond et al. (2013)

2.4.2. Impact of BC emissions on climate change

The main impact of BC emissions on climate warming takes place in the mid-high latitude of the Northern Hemisphere, however, Bond et al. (2013) argued that BC could also provoke changes in the precipitation patterns of the Asian Monsoon and that it has been one of the causes of Arctic warming in the twentieth century. The best estimate of the direct climate influence of BC calculated by Bond et al. (2013) is about a factor or two higher than previous estimates by IPCC (2007). According to Bond et al. (2013), the overall impact of BC on the climate could be equivalent to a warming effect of about 1.1 Watts m^{-2} with a range of +0.17 to +2.1 W m^{-2}. Thus, BC represents the second largest contributor to global warming, approximately two thirds of CO_2 (Bond et al., 2013). However, concentrations of BC can respond quickly to reductions in emissions because it is rapidly removed from the atmosphere by deposition. Thus, in contrast to CO_2, reductions in emissions of BC represent a potentially highly effective mitigation strategy that could reduce global climate forcing from anthropogenic activities in the short term (Bond et al., 2013).

The significance and impact of different climate forcers can be compared based on the Global Warming Potential (GWP), which is a measure of how much energy 1.0 t of an emitted gas or aerosol will absorb over a given time, relative to an emission of 1.0 t of CO_2. The larger the GWP, the greater the contribution to climate change compared to CO_2 over that same time scale (IPCC, 2013). Estimating a GWP value for BC is complex because of its various physical properties and because it is not well mixed or homogeneous in the atmosphere. However, many studies have attempted to estimate the GWP for BC, as shown in Table 2.3. Thus, the GWP for BC ranges from 1,200 to 5,100 in a 20-year horizon. As expected, the GWP drastically decreases if considered over a 100 or 500-year horizon, due to the short lifetime of BC in the atmosphere.

Table 2.3 Estimates of GWP values for emissions of BC for different time horizons

Source	20 year	100 years	500 years
Koch et al. (2007)	1,200 to 3,200	340 to 920	100 to 280
Naik et al. (2007)	2,000 to 5,100	580 to 1400	180 to 440
Reddy and Boucher (2007)	1,400 to 2,600	380 to 740	120 to 220
Berntsen et al. (2006)	1,200 to 2,200	340 to 640	100 to 190
Bond and Haolin (2005)	2,200	680	-
Schulz et al. (2006)	1,600	460	140

Note: the first four studies referenced evaluated GWP values for different sets of regions; the last two only produced global estimates.
Adapted from: (Fuglestvedt et al., 2010; US EPA, 2012b)

Consequently there is uncertainty about the actual impact of BC emissions on climate change relative to CO_2, nevertheless, all estimates suggest BC is an important and significant atmospheric pollutant. This is further illustrated by estimating BC emissions from open biomass burning; Table 2.4 presents the CO_2 equivalent emissions for this source (in t per CO_2 equivalent, $MtCO_2Eq$) using the estimated open biomass burning BC emissions presented in Table 2.2 and the GWP estimates for BC provided in Table 2.3.

Table 2.4 CO_2 Equivalent of open biomass burning BC emissions using different GWP ($MtCO_2Eq$)

	Open Biomass Emissions (t x 10^3)	Schulz et al. (2006) Average GWP 1600	Berntsen et al. (2006) Average GWP 1700	Reddy and Boucher (2007) Average GWP 2000	Bond and Haolin (2005) Average GWP 2200	Koch et al. (2007) Average GWP 2200	Naik et al. (2007) Average GWP 3550
Scaled[a]	3,100	4,960	5,270	6,200	6,820	6,820	11,005
Modelled[b]	6,810	10,896	11,577	13,620	14,982	14,982	24,176
Current[c]	2,750	4,400	4,675	5,500	6,050	6,050	9,763

a) Based on SPEW (Speciated Pollutant Emissions Wizard) emissions and GFED (Global Fire Emissions Database) 2.0 emission fields (reported as the source of open-burning emissions), which were used in many AeroCom models.
b) Modelled regional emissions adjusted by burden scale factors.
c) Best estimate Bottom-Up values for BC Emissions in 2000.
Adapted using information of: (Fuglestvedt et al., 2010; Bond et al., 2013)

Thus, the BC equivalent emissions range from 4,400 to 24,200 $MtCO_2Eq$ depending on the assumed extent of open biomass burning emissions and the GWP used. As a benchmark to demonstrate the relative significance of BC emissions from waste, Table 2.5 shows the global CH_4 emissions from different sectors, as well as their CO_2 Equivalents. According to the US EPA (2006), CH_4 emissions from the waste sector are approximately 5,100 $MtCO_2Eq$. As observed, estimations using the lowest GWP to calculate BC $MtCO_2Eq$ from biomass combustion are similar to CH_4 $MtCO_2Eq$ from the waste sector. However, if we use a higher GWP such as the one suggested by Naik et al. (2007) and modelled regional open biomass combustion emissions, BC $MtCO_2Eq$ could be almost five times larger compared to CH_4 $MtCO_2Eq$ from the waste sector. Using the same GWP and estimated open biomass emissions, BC $MtCO_2Eq$ from open biomass combustion could be similar to the global total CH_4 $MtCO_2Eq$ from the energy, agriculture, industrial and waste sector combined.

Table 2.5 Global Methane emissions and $MtCO_2Eq$ equivalent emissions for a 20-year horizon by sector in 2000

Sectors	CH_4 t x 10^6	CH_4 (GWP 86) $MtCO_2Eq$
Energy	78.4	6,741
Agriculture	148.2	12,749
Industry	0.3	25
Waste	**59.8**	**5,140**
Global Total	**286.7**	**24,653**
Source: US EPA (2006)		

2.5. Black carbon measurements and quantification tools

The two primary sources of BC data are based on ambient or source-based emission measurements. Both experimental methodologies require sample collection and analysis procedures, and each step of the process can have significant implications for the quality and interpretation of the measured results. Most estimates of BC classify the measured quantity as apparent elemental carbon (ECa) and apparent black carbon (BCa). The word "apparent" is used to differentiate the measurements as estimates of BC concentrations (US EPA, 2012b).

2.5.1. Methods to collect PM emission samples

Black carbon is a significant contributor to fine particle mass, or particulate matter (PM) (Yoo et al., 2011; Bond et al., 2013). The carbon concentration present in PM is commonly quantified by analysing the chemical, physical, and light absorption properties of the particles. The chemical and physical characteristics of carbon in PM vary in refractivity (the inertness of the carbon at high temperatures) and light absorption. For this reason, different carbon measurement techniques provide unique information about these properties and can significantly influence the result (US EPA, 2012b).

The available monitoring methods for PM in ambient air include both direct reading instruments, which provide continuous measurements of particle concentrations, and filter-based gravimetric samplers that collect PM on a filter, which is then analysed and/or weighed in a laboratory. The most important PM sampling methods and the advantages and disadvantages of the different techniques were examined by Defra (2005) and are summarized in Table 2.6.

Table 2.6. Advantages and disadvantages of the primary PM sampling methods

Technique	Advantages	Disadvantages	Estimated precision
Filter-based gravimetric samplers	• Reference method for PM10 specified in the EU First Daughter Directive.	• High operating costs. • Time resolution of the measurement is limited to 24-h. • Reporting requirements of the EU First Daughter • Directive cannot be met • Results can only be provided some days after the sample is collected	± 2µg m^{-3}
TEOM Analysers	• Provides real-time data with short time resolution (<1 h). • Improved precision compared to the reference method	• Preheated air stream causes a greater loss of semi-volatiles compared to the reference method. • High capital cost.	± 0.5 µg m^{-3}
ß-attenuation analysers	• Provides real-time data with short time resolution (<1 h).	• If a heated inlet is used, some semi-volatile material may be lost. • Unheated samplers may suffer from interference due to the presence of water. • Analyser contains a radioactive source.	± 3 µg m^{-3} but depends on analyser type
Optical Analysers	• Portable and often battery operated. Can measure several size fractions simultaneously.	• Depends on assumptions about particle characteristics, which may vary from place to place and time to time.	Depends on analyser type
Black smoke	• Simple, robust, inexpensive and easy to maintain. Long time series of existing data	• Measures an index rather than a gravimetric concentration. • Calibration factor not appropriate to the current mix of pollution sources. • Time resolution of the measurement is limited to 24-h.	±2 µg m^{-3}, may be higher at current typical concentrations
Personal Samplers	• Portable samplers that can easily be deployed in the field and used to determine personal exposure to particulate concentrations.	• As above, depending on measurement method used. • All personal exposure analysis is very labour-intensive.	According to technique employed, as above
Source: DEFRA (2005)			

2.5.2. Techniques for measuring BC in samples

Particulate matter samples collected from ambient air that contain BC also contain other constituents (Bond et al., 2013). Indeed, the mass fraction of BC in an atmospheric aerosol is usually less than 10 % of the total mass. Therefore, it is not possible to measure the BC mass directly by weighing the aerosol deposit collected from an air sample and the BC mass must be determined using indirect and alternative analytical methods. Furthermore, there is no standardised approach to measuring BC and the available methods are operationally defined, as shown in Figure 2.4. Measuring the optical properties or light-absorbing characteristics (optical or light absorption methods) of PM is a popular approach (Liousse et al., 1993; Watson et al., 2005; Davy et al., 2017), as it is a non-destructive method and can perform rapid BC determinations. Alternative strategies involve measuring the thermal and chemical properties (thermal-optical methods) or the morphology or microstructure (microscopy methods) of PM. There is however, a lack of standardisation of calibration materials or the definition of the characteristics or properties of the BC measured (US EPA, 2012b).

Optical methods quantify the light-absorbing component of particles as BC or apparent BC (BCa), which can be used to estimate BC concentrations and can also indicate the presence of other components that absorb light in the near-UV (brown carbon, BrC). Light absorbing carbon (LAC) is a term used to describe light-absorbing particles in the atmosphere, including BC and BrC. The second major method includes thermal or thermal-optical techniques, which distinguish refractory and non-refractory carbon as EC or apparent EC (ECa), and OC or apparent OC (OCa), respectively (US EPA, 2012b). Currently, many BC research studies are based on EC measurements; however, these two components have similar properties and therefore are commonly used interchangeably (Rao and Somers, 2010; Bond et al., 2013).

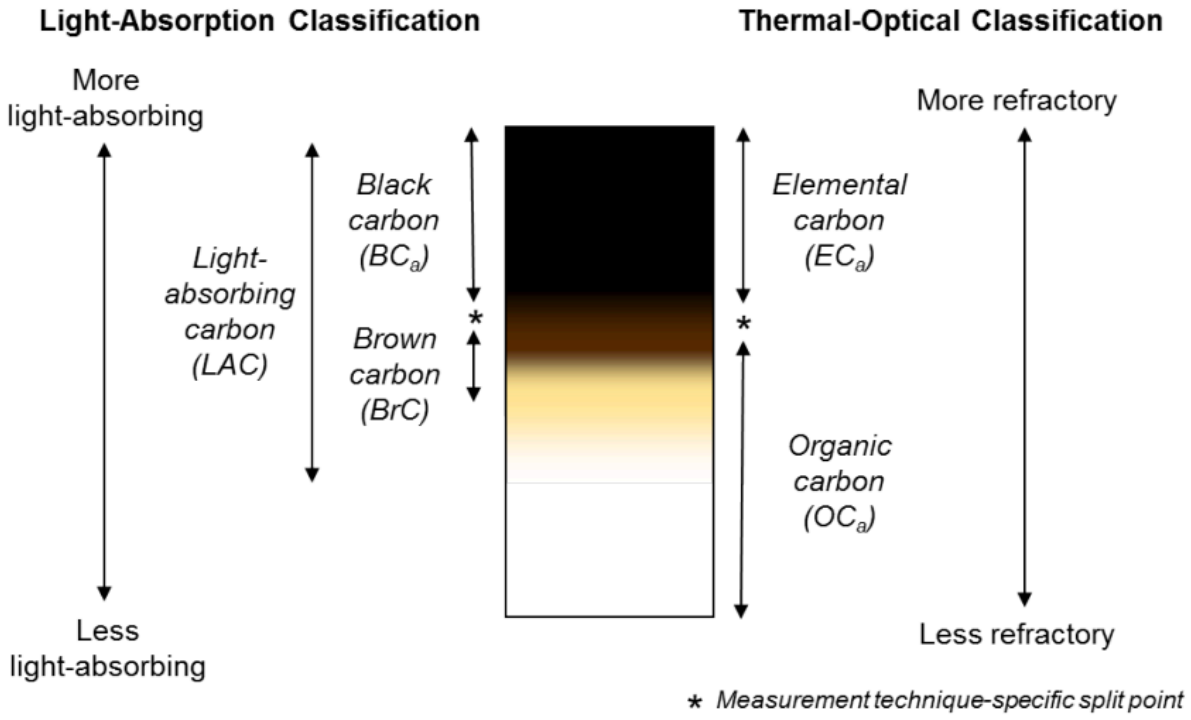


Figure 2.4 Measurements of the carbonaceous components of PM (US EPA, 2012b).

A summary of measurement techniques for BC mass was provided by Bond et al. (2013) and is shown in Table 2.7, including common terminology used and the directions and causes of bias in the measurements.

Table 2.7. Techniques for measuring BC mass, method-defined terminology for BC, and sources of systematic bias

Technique	Common name	Suggested name	Common instruments	Sources of bias	Direction of bias [a]
Optical absorption with in situ detection	BC	Equivalent BC (BC + other absorbing material)	Photoacoustic	Change in Mass Absorption Cross section (MAC) with aerosol aging [b] Presence of other absorbers (dust, organic carbon) [c]	+, - +
Optical absorption by collection on filters	BC	Equivalent BC	Transmissometer, Aethalometer; Particle Soot Absorption Photometer (PSAP); Multi-angle Absorption Photometer (MAAP)	Same as optical absorption above, plus: Optical interactions between particles and filter matrix [d] Modification of particle morphology by organic carbon	 + +
Optical absorption with heated inlet	BC	Equivalent BC	Continuous Soot Monitoring System (COSMOS)	Charring of low volatility organic species	+
Thermal heating and optical absorption	Elemental carbon (EC)	Apparent elemental carbon (ECa)	Thermal Optical Reflectance (TOR); Thermal Optical Transmittance (TOT)	Failure to accurately correct for charred organic carbon; Catalytic oxidation of BC in presence of metals or metal oxides; Absorption by charred material affects split between OC and EC [e] Detection of less volatile organic carbon	+ - - +

a) (+) = BC measured too high; (-) = BC measured too low.
b) If calibrated with fresh, unmixed BC, measurement overestimates BC mass after mixing with non-absorbing species and increase in absorption.
c) Depends on wavelength; measurements around 630 nm often are unaffected unless dust concentrations are high.
d) Positive bias if uncorrected filter-based measurements are used; otherwise, it can be either positive or negative.
e) More extreme for transmission-based monitoring of charring.

Source: Bond et al. (2013)

Light absorption by aerosols is mostly caused by BC particles (Moosmüller et al., 1998; Petzold and Schönlinner, 2004). For this reason, the measurement of aerosol light absorption is used to determine BC. The relationship between the aerosol absorption coefficient (b_{abs}) and the corresponding BC mass concentration (C_{BC}) is established by an aerosol mass-specific absorption coefficient () using the following relationship:

However, there are different values for reported in the literature. For this reason, there is no single relationship between aerosol absorption and BC mass concentration, which varies for different kinds of BC aerosols (Petzold and Schönlinner, 2004). The most common technique to quantify BC through the measurement of the absorption coefficient involves collecting aerosol on a filter and extrapolating atmospheric absorption from the resulting change in transmission of light through the filter. The Particle Soot Absorption Photometer (PSAP), the Multi Angle Absorption Photometer (MAAP), the Aethalometer and Thermal/Optical Analyser (TOT/TOR) are the most frequently used instruments to quantify BC using a light transmission approach. There are several important differences between these instruments and the algorithms used to approximate the absorption coefficient (Huffman, 1996; Bond et al., 2013).

2.5.2.1. Particle soot absorption photometer (PSAP)

This equipment quantifies the change in optical transmission of a filter as aerosol is deposited on it over time at a number of wavelengths. The change in transmission from one measurement to the next is related to the optical absorption coefficient ***bap*** m^{-1} of the deposited aerosol based on the equation:

Where ***AREA*** is the collection area of the filter, ***VOLUME*** is the volume of air sampled in a time interval, ***I*** is the current transmitted intensity, I_0 is the transmitted intensity for the previous sample and ***f(Tr)*** is the filter correction factor, which is a function of absolute transmission. This can be related to BC mass by dividing the result by the specific absorption for BC at the wavelength of the instrument.

The measurement of the absorption coefficient in aerosols is complex and influenced by the intrinsic properties of the filter and the collected aerosol material. Thus, the aerosol light extinction coefficient, σ_{ep}, is the sum of the aerosol light scattering coefficient σ_{sp} and the absorption coefficient σ_{ap}. Moreover, all filter-based measurements of absorption show some response to scattering of the collected particles (Bond et al., 1999). For this reason, it is essential to carefully calibrate and correct the PSAP based on measurements of the aerosol scattering coefficient (Bond et al., 1999; Petzold and Schönlinner, 2004).

2.5.2.2. Multi angle absorption photometer (MAAP)

The Multi Angle Absorption Photometer (MAAP type 5012, Thermo Scientific Inc.) was developed to reduce aerosol scattering and improve measurements of BC. To achieve this, the MAAP determines the optical absorption coefficient using radiative transfer considerations, which include multiple scattering effects and high absorption measurements caused by reflections from the filter. The instrument manufacturer derived a standard absorption efficiency of 6.6 $m^2\ g^{-1}$ for rural and urban aerosols, which is generally used as a default value for the conversion of the light absorption into BC mass concentration (Petzold and Schönlinner, 2004).

Comparisons between the MAAP results and a thermal reference method by Petzold and Schönlinner (2004) indicated that a constant specific absorption can be used to convert the optical absorption coefficient to BC mass. The MAAP instrument uses the following equations to calculate BC mass loading:

where ***MBC*** is the mass of BC deposited on the filter, ω_0 is the single scattering albedo (determined from the radiative transfer considerations mentioned above), ***tr*** is the transmittance, **AREA** is the area of the collection zone ($2cm^2$) and σ_{BC} is the specific absorption of BC.

2.5.2.3. Aethalometer

Aethalometry measures the BC content of aerosol samples based on the optical attenuation of a beam of light transmitted through a sample collected on a filter (Virkkula et al., 2007). The absorption coefficient of the sample is quantified by a single pass transmission of light through the sample, measured relative to an identical clean, blank reference filter. The absorption coefficient, α [m^{-1}] is calculated from the transmission, area and volume of the sample, and converted to a BC concentration, as a first approximation, using a mass extinction coefficient[3] (Quincey et al., 2009).

2.5.2.4. Thermal/optical reflectance and transmittance (TOR/TOT)

This method measures organic (OC) and elemental (EC) carbon. It is based on the principle that different types of carbon-containing particles are converted to gases under different temperature and oxidation conditions. The carbon analyser consists of a thermal system and an optical system. The thermal system has a quartz tube placed inside a coiled heater. Current through the heater is controlled to reach and maintain specific temperatures for different time periods. A quartz filter containing the aerosol sample is placed in the heating zone and heated to different temperatures under non-oxidizing and oxidising atmospheres (Chow et al., 1993) and the volatilised carbon species released at different temperatures are detected and quantified.

2.5.3. Differences and uncertainties in BC quantification

One major cause of uncertainty in estimating BC and its environmental impacts is that the term "black carbon" has been used to include other aerosol materials that do not necessarily exhibit the strict physicochemical properties of BC. Thus, adopting a more ambiguous, broader interpretation of BC creates problems when comparing results obtained between different studies on the effects and impacts of BC on climate change. Moreover, many of the methods and techniques used to measure BC can be biased by the presence of other chemical components[4]. Indeed, mass concentrations measured can differ between methods by up to 80% and as would be expected with analytical instruments, the most significant sources of error correspond with aerosols with low BC mass fractions (Bond et al., 2013).

Bond et al. (2013) critically examined the biases that occur when measuring BC. The most common sources of error occur due to three primary reasons:

1) mixing with other substances increases absorption or extinction,
2) BC is incorrectly classified as another material,
3) another material is incorrectly classified as BC.

Most techniques measure similar BC mass concentrations when they are applied to pure BC or when other aerosol components are removed by heating (Knox et al., 2009; Kondo et al., 2009), or solvent rinsing (Subramanian et al., 2006).

[3] The mass extinction coefficient is a parameter that defines how strongly a substance absorbs light at a given wavelength, per mass density.

[4] The mixing of other components with BC can take place either within ambient aerosol particles before sampling or in the sample itself if other particles are collected and measured at the same time.

Published examples of BC measurements of untreated samples are usually in closer agreement for certain types of emission sources, such as diesel exhaust, which contain little non-BC material. By contrast aerosols released from biomass burning have a high content of organic matter and other inorganic substances that potentially interfere with BC detection and quantification (Novakov and Corrigan, 1995; Reid et al., 1998). The measurement of BC from the open burning of waste would also be expected to be subject to interferences since the combustion of complex matrices releases a dynamic mixture of aerosolised by-products. Therefore, it is critical to develop a sound sampling and analytical methodology to identify BC particles and distinguish them from other interfering substances to accurately quantify BC emissions and impacts arising from this source.

2.5.4. Elaboration of BC emission inventories

Emission inventories provide critical information used by national and international agencies to assess the impacts of atmospheric emissions on the environment and human health. This data is therefore essential and underpins the development of sound air quality management strategies to regulate air pollutants and to mitigate climate change. Global BC emission inventories have high levels of uncertainty due to a lack of detailed information on source types, EFs, activities and controls, especially in the developing world.

There is no standard methodology applicable to BC inventory development. For many source categories, BC emissions are estimated through $PM_{2.5}$ inventories (INECC, 2010; Schauer and Bergin, 2016). BC inventories used for modelling purposes are commonly based on estimated activity rates (for example, mass of waste burned) combined with emission factors (for example, grams of BC emitted per mass of waste burned). Following this approach, Chow et al. (2010) described the emission of an atmospheric pollutant as follows:

where E_i is the total emission of a constituent ***i*** ($PM_{2.5}$, EC, OC, or other components) from J source types. ***Aj*** is the activity level (e.g., mass of waste burned); EF_j is the PM mass emission factor (e.g., g kg^{-1} of waste); F_{ij} is the mass fraction of constituent **i** in PM mass from source type j; and X_j and eff_j are the fraction of controlled emitters and emissions control efficiency, respectively, for source type j. If no emission controls are applied, X_j and eff_i are equal to zero. F_{ij} equals 1 for PM mass emissions. Inventories can also be developed based on emissions estimates from field or satellite measurements and modelling. One example of field measurements of source and ambient air quality were the PM Supersites Program field campaigns (US EPA, 2000). Satellite observations provide information on land cover, fires, human population settlements and infrastructure. This information is used to quantify emissions from land use and biomass burning, as well as to approximate the spatial distribution of fossil fuel combustion. This method of estimating emissions is referred to as “top-down,” in contrast to the “bottom-up” inventories that use economic and land management data (Hardwick and Graven, 2016). According to Hardwick and Graven (2016), the accuracy of emission inventories can be improved by using emission estimates (bottom-up methods) and comparisons with ambient observational data (top-down methods). However, Hodzic et al. (2012) indicated that many uncontrolled waste fires are too small to be detected by satellites.

Black carbon inventories are often developed using air pollution monitoring based on $PM_{2.5}$ and not the total particulate material in the atmosphere, therefore they may underestimate the total BC emissions (US EPA, 2012b). Most BC inventories are based on EC measurements, however, as mentioned in Section 2.5.2, these components are regarded as synonymous and are commonly used interchangeably (see Figure 2.4).

2.6. Black Carbon emissions from open burning of waste

2.6.1. Methods to collect emissions from open combustion

Characterising emissions from open fires is a technically challenging problem as there are inherent difficulties in attempting to capture and quantify the total amount of emissions from a burning source under field conditions. The collection of the emissions from open combustion involves “sampling of a wind-driven, mixing, and convective plume” (Aurell et al., 2017). There are also inherent hazards to personnel and equipment working near the fire. The high concentrations of emissions in close proximity to a fire can also lead to detector saturation of analytical instrumentation. One solution to the proximity problem is to include aerial sampling of the emissions (Yokelson et al., 2013; Aurell et al., 2017).

2.6.1.1. Collecting emissions from open combustion in the field

When collecting emission samples from uncontrolled waste combustion for risk assessment purposes (exposure limits) it is necessary to collect at least one set of samples at the receptor location and another in an upwind position in relation to the burning pit to capture background concentrations. However, ideally, multiple samples should be collected at all wind directions (Hanna-Beauregard et al., 2005). This methodology is unsuitable for measuring overall absolute emissions of a pollutant from a specific source and only provides data for point measurements relevant to localised sensitive receptor exposure.

2.6.1.2. Using a combustion chamber to collect emissions from open burning

A combustion chamber is a technique that is used to control the burning process and to facilitate emissions collection from open burning of waste. For example, Ortiz-de-Zárate et al. (2000) developed a combustion chamber apparatus to collect emissions from cereal waste burning and Park et al. (2013) employed a similar approach to evaluate open burning of solid wastes emissions in Korea. Park et al. (2013) recommended that the chamber should be constructed to allow natural air inflow to simulate the open combustion process. A ceramic insulator is also used inside the chamber to prevent thermal transfer. A combustion chamber simplifies the characterisation of emissions from open burning sources by using small amounts of representative materials in a controlled environment (Lemieux et al., 2004).

2.6.2. BC EFs for open burning of waste

Lemieux et al. (2000) and Woodall et al. (2012) measured emissions from open burning of solid waste and developed PM EFs, but did not report BC EFs. Furthermore, the waste composition and combustion conditions do not apply to developing countries. Lemieux et al. (2000) examined the

emissions from waste burned in barrels in rural areas of the US, and Woodall et al. (2012) characterised emissions from small-scale burning of solid waste from military sites. According to Woodall et al. (2012), some of the most significant differences observed between military sourced MSW and average MSW in the US are that the former include increased quantities of packaging materials, construction refuse, canvas material, food waste packaging (from ready to eat meals) and polyethylene terephthalate (PET) water bottles. Both studies used combustion chambers to characterise the emissions from open burning of waste.

Two further studies have reported BC EFs for open burning of waste for developing countries, based on landfill fire sampling near Mexico City (Stockwell et al., 2016). However, the number of test burns completed in both studies was limited. For example, Christian et al. (2010) measured emissions from four fires at a major landfill site near the Mexico City Metropolitan Area. However, open burning of waste in backyards and at dumpsites of smaller communities and rural areas, where burning of waste is more extensive and which differ significantly in composition and burning conditions, were not considered. Stockwell et al. (2016), on the other hand, measured BC EFs from two burns of mixed waste (containing food waste, paper, plastic bags, cloth, diapers and rubber shoe in the first sample and mixed waste including cardboard and food packaging in the second) at a major dumpsite; however, the specific waste fraction composition analysis of the waste samples was not provided. These studies reported significantly different EFs for BC from open burning of waste of 0.646 +/- 0.272 (sd) g BC kg^{-1} (Christian et al. (2010) and 3.30 +/-3.88 (sd) g BC kg^{-1} waste burned (Stockwell et al. (2016). Thus, the limited published results show there may be considerable variation in the extent of BC emissions from open burning and that uncertainty remains about representative BC EFs that apply to uncontrolled open combustion of waste under different conditions in developing countries.

2.6.3. Global BC emission inventories for open burning of waste

2.6.3.1. General BC emission inventories and waste combustion estimates

The main challenges to developing emission estimates for uncontrolled open burning of waste relate to the paucity of evidence concerning the activity level (when, where, and how much waste is being burned) and the EF, which are either unknown, unreliable or unrepresentative (Wiedinmyer et al., 2014). Nevertheless, the IPCC (2006) has recommended a methodology to estimate national-scale emissions of GHGs from the open burning of waste. This methodology provides guidance to estimate and report CO_2, CH_4 and N_2O emissions from open waste combustion of all types of combustible waste. In addition, Bond et al. (2013) have developed a global inventory of particulate black carbon (BC) and particulate organic carbon (OC) and include emissions from open waste combustion.

Activity data for the uncontrolled burning of waste emissions are difficult to estimate because, amongst other reasons, they are not of specific economic interest and, therefore, have not been quantified by national research authorities (Bond et al., 2013). Until now, emissions from solid waste burning are estimated using per-capita waste generation rates, the waste fraction burned and an appropriate pollutant EF. Waste generation rates and the fraction burned both differ significantly

depending on the area and the socioeconomic characteristics of the community and are therefore specific to a particular location (Christian et al., 2010).

Bond et al. (2004) developed a global tabulation for BC and primary organic carbon (OC) particles emitted from combustion, including emissions from fossil fuels, biofuels, open biomass burning, and burning of urban waste. Unlike other BC and OC ''bottom-up'' inventories that assign EFs only taking into consideration the fuel type and economic sector, this also includes combinations of fuel, combustion type, and emission controls and their prevalence on a regional basis, since emission rates are highly dependent on combustion practice (Bond et al., 2004). According to Bond et al. (2004), 393 x 10^3 t y^{-1} of BC are emitted globally as a result of open waste combustion.

The contribution of open waste combustion to BC pollutant emissions according to Wiedinmyer et al. (2014) are more substantial compared to previous estimates by Bond et al. (2004), and are equivalent to 632 x 10^3 t y^{-1} of BC. Wiedinmyer et al. (2014) also estimated that open waste combustion $PM_{2.5}$ emissions are equivalent to approximately 29% of the total global anthropogenic $PM_{2.5}$ emissions.

2.6.3.2. Published BC emissions in the USA, including burning of waste

Open burning of waste is generally associated with inadequate or lacking waste management services in developing countries. However, the practice of open burning continues to be a significant source of BC emissions in developed countries with well-founded waste management systems. For example, Battye et al. (2002) ranked the different emission sources of BC according to the contribution to US emissions, based both on the best estimate and the upper end estimate of emissions (Table 2.8). As would be expected, the largest BC emission sources in the US were non-road and on road diesel emissions. However, open burning (other) and open burning in houses were ranked as the fourth and seventh most important contributors to BC emissions, with 7.7 and 4.4 % of the total emissions respectively.

Table 2.8. Ranking of US Sources of BC Emissions and Uncertainty

Category	Contribution to total U.S. BC emissions (%)		Uncertainty of BC estimate (t y^{-1})	Rankings of importance
	Based on best estimate	Based on upper end estimate		Based on Best Estimate (Share of BC)
Non road - diesel	21	27	34	**1**
On road Diesel Vehicles	15	19	24	**2**
Prescribed forest burning	7.9	12	22	**3**
Open burning - other	**7.7**	**8.3**	**2.5**	**4**
Residential combustion - wood	4.8	6.9	9.8	**5**
Non road - gasoline	4.7	9.8	25	**6**
Open burning - residential	**4.4**	**4.7**	**1.4**	**7**
Aircraft	4	5.6	7.4	**8**
Marine Transportation	3.6	4.9	5.8	**9**
On road gasoline Vehicles	3.6	7.7	19	**10**
Source: Battye et al. (2002)				

2.6.4. Published Estimations of BC from open burning of waste in Mexico

Several studies have investigated the impact of biomass burning from wildfires on local and regional air quality in Mexico; however, the impact of open waste burning on air quality has received little attention. BC inventories for Mexico have used EFs developed for other regions, as no local data are available. The first BC inventory for Mexico was elaborated by the INECC (INECC and SEMARNAT, 2015) using two methodologies to estimate BC emissions. The EFs used in the inventory were obtained from an extensive literature review (Streets et al. (2001)[5] on BC emissions in China. Activity data were based in energy consumption values available for a previous GHG emission inventory (INECC, 2010). Following this approach, overall BC emissions for Mexico for 2006 were estimated to be in the range 52 and 454 x 10^3 t y^{-1}(INECC, 2010). The second strategy defined BC as a fraction of $PM_{2.5}$ emissions, and provided an estimated total BC emission for Mexico of 56 to 100 x 10^3 t y^{-1}. INECC intends to apply this methodology to subsequent National Inventories of GHG and "criteria" pollutant Inventories (INECC, 2010).

In 2018, the INECC published a new GHG emission inventory (INECC, 2018), which included BC emissions in Mexico from 1990 to 2015. The estimated BC emissions were 86.7 x 10^3 t for 1990 and 106.6 x 10^3 t for 2010, representing an increase of 23 % over the 25-year period. Table 2.9 shows how the distribution of emission sources has remained the same, with the energy sector contributing the largest fraction (93-95 %), followed by biomass burning (agricultural and forestry) representing 3 to 6 % of total BC emissions. Open burning of waste represented approximately 1 – 2 % of the total BC emissions for Mexico. However, only municipal solid waste from rural areas was considered and uncontrolled burning of waste in dumpsites and landfills located in urban and periurban areas were not included. Open burning of organic material, such as garden and food waste was also excluded. Consequently, BC emissions from open burning of waste are likely to be underestimated in the national BC emission inventory for Mexico (INECC, 2018). Moreover, the uncertainty in the estimates was reported to be more than 50 %, due to the high degree of uncertainty associated with the assumed EFs for BC emissions.

Table 2.9 BC emissions from different sources in Mexico (1990-2015)

Source of BC emissions	1990	1995	2000	2005	2010	2015
Energy	**86.7**	**94.7**	**95.8**	**103.9**	**109.4**	**106.6**
Agriculture and land use (biomass burning)	**3.1**	**5.8**	**5.1**	**5.4**	**4.3**	**4.4**
Open burning of waste	**1.6**	**1.8**	**1.9**	**1.7**	**1.6**	**1.2**
Total Emissions (t x 10^3)	**91.4**	**102.3**	**102.8**	**111.0**	**115.2**	**112.2**
Source: INECC (2018)						

Other estimates of BC in Mexico are the result of a campaign carried out in the spring of 2007 to measure the initial emissions of trace gases and aerosol speciation for elemental and organic carbon (EC and OC) from several waste fires in Central Mexico, obtaining EFs for trace gases and particles

[5] Their emission factors cover 37 different source types over five sectors (power, industry, residential, transport, field combustion) and 13 different fuel types, including biofuels.

from open waste combustion (Christian et al., 2010; Yokelson et al., 2011). The results included a fine particle EF for waste burning in Central Mexico of 10.5 g per kg. Li et al. (2012) also performed emission measurements from uncontrolled waste combustion in Mexico, and concluded they are an important source of $PM_{2.5}$ in Mexico, comprising about 3–30% of the total simulated $PM_{2.5}$ mass on average[6].

2.7. Open burning of waste and health impacts

The inhalation of PM has an adverse effect on human health (Janssen et al., 2012). According to the WHO (2003), exposure to fine PM is responsible for approximately 100,000 advanced deaths and 725,000 years of lost life each year in Europe. Morbidity and mortality from fine PM exposure causes lung diseases such as asthma, chronic obstructive pulmonary disease and lung cancer. There is also an important correlation between PM concentrations and cardiovascular disease (US EPA, 2012a). Ultrafine particles are capable of penetrating the lung lining and entering the bloodstream where they can have several dangerous effects on the human body. As heart diseases are more common than lung diseases, according to Highwood and Kinnersley (2006) more people die from cardiovascular than lung failure as the result of being exposed to urban air pollution. Currently, scientists around the world are performing studies to better understand the effects of BC on human health through clinical and animal testing (US EPA, 2012a).

Kumari et al. (2017) stated that open burning waste caused the release of many air pollutants, which can lead to severe health issues, especially for children, pregnant women, the elderly, and people with pre-existing respiratory or heart conditions. The most significant health risks from the open burning of waste are due to the direct inhalation of smoke when in close proximity to a fire. Health impacts also occur at greater distances from the combustion emission source depending on the distance to the fire, the amount and type of material burned, exposure duration, individual sensitivity and wind direction (Kodros et al., 2016).

Janssen et al. (2012) showed there was an association between short-term variations in BC concentrations and short-term changes in health (including eye, nose and throat irritation; bronchitis and pneumonia; asthma and emphysema; all-cause[7] and cardiovascular mortality, and cardiopulmonary hospital admissions). Cohort studies (Filleul et al., 2005; Lipfert et al., 2006; Beelen et al., 2008; Smith et al., 2009) analysed by Janssen et al. (2012) also provide evidence of associations of all-cause and cardiopulmonary mortality for individuals exposed to long-term BC contamination.

Recently, Kodros et al. (2016) reported that 270,000 premature deaths are caused through exposure to emissions from open burning of waste globally, equivalent to approximately 9% of the total deaths linked to $PM_{2.5}$. Kodros et al. (2016) used the GEOS-Chem global chemical-transport model and incorporated information from the emission inventory by Wiedinmyer et al. (2014) to

[6] The waste burning emission inventory used in that study has large uncertainties (about a factor of 2 or more), which could potentially influence the evaluation of the contribution of open waste burning to $PM_{2.5}$ in Mexico City.

[7] All-cause mortality is a term used by epidemiologists to refer to death from any cause.

estimate the impact of open burning of waste on the health of the human population. This showed that the largest mortalities from open burning of waste occurred in China, India, Pakistan and Russia. However, there was considerable uncertainty in the health response to $PM_{2.5}$ and in the emission calculations from this source, which translated to a high uncertainty in estimating the actual health impacts of between 138,000 and 518,000 premature deaths per year.

Kodros et al. (2016) compared the particulate pollution of open burning of waste with those released by solid fuel cooking stoves, and showed that both sources increased atmospheric concentrations of $PM_{2.5}$ by 10-20 % on average. This study explains that even when open burning of waste and solid fuel cookstoves are more common in developing regions, neighbouring regions lying downwind suffer from these emissions too. The study concludes that waste collection services and controlled waste disposal have not yet been a priority for many developing countries, however, research linking open burning of waste with detrimental human health suggests that improving these services could save many lives.

According to the Waste Atlas Partnership (2014), people working on dumpsites are at risk of developing respiratory diseases from open burning of waste. The smoke from burning solid waste can result in respiratory problems, headaches and dizziness, in the short-term, as well as more serious diseases such as cancer, respiratory conditions and heart disease in the long term. For instance, in a study that was carried out in Nigeria, it was found that informal waste pickers developed pneumonia while they worked in the dumpsite (Afon, 2012). Also, children living and working on a dumpsite in Kenya reported respiratory tract infections, chronic bronchitis and asthma (UNEP, 2007). Another study conducted in India showed that there is a prevalence of inflammation of the respiratory tract and decreased lung function among informal waste workers in the dumpsite (Ray et al., 2005). At the same time, data from UN Habitat (2010), shows a significant increase in the incidence of sickness among children living in households where waste is dumped and burned in the vicinities. In one small city in Egypt, 89 % of villagers living downwind of the burning dumpsite were suffering from respiratory diseases.

3. Characteristics of waste management in Mexico and in the case study areas

3.1. Introduction

Inadequate solid waste management can lead to detrimental human health and negative impacts to the environment, including climate change. Effective SWM strategies continue to represent a major challenge both in cities with high population densities as in rural and remote areas. One of the consequences of inefficient waste collection services is the disposal of waste by uncontrolled combustion. Open burning of solid waste in backyards and at uncontrolled dumpsites is a significant source of black carbon (BC). However, BC emissions from open burning of waste are not included in most emission inventories used to model and develop national/international climate change mitigation policies.

According to Wiedinmyer et al. (2014), Mexico has one of the largest rates of backyard and dumpsite burning of MSW and, therefore, could be amongst the leading emitters of BC from waste disposal (Wiedinmyer et al., 2014). Wiedinmyer et al. (2014) estimated that 18 % of the total waste generated is burned in households and 43 % at dumpsites in Mexico. This translates to approximately 32 x 10^6 t y^{-1} of waste disposed by uncontrolled combustion. Previous estimates by Commoner et al. (2000) suggested that 50 % of MSW generated in Mexico was disposed informally and that the amount of waste burnt in open fires was equivalent to 14.5 x 10^6 t y^{-1} both in backyards and dumpsites.

This chapter will present a comprehensive analysis of the current waste generation characteristics, waste management practices and regulatory framework in Mexico relevant to open waste combustion. It will also include an analysis to estimate the activity level of open burning of waste in Mexico using published data on waste composition, the proportion of households that dispose of waste by open burning, as well as information gathered through interviews with waste specialists to approximate rates of open combustion in dumpsites. An overview of the location, climate, population distribution and socioeconomic characteristics in the case study areas chosen for this research will also be presented.

The aim of this chapter is to present an overview of the case study areas investigated in this research, including the main waste management characteristics in each region, using published data. To accomplish this, the objectives of this chapter are to:

a) Describe the SWM sector in Mexico.
b) Present an estimation of the activity level of open burning of waste in Mexico using published information from the national census, reported data on waste composition, estimations of waste sent to uncontrolled dumpsites reported by environmental authorities and advice from experts in SWM on percentages of waste burned in dumpsites in Mexico.
c) Provide information on the location, climate, population, socio-demographic conditions, and published data of waste management characteristics and regulations of the waste sector in the case study areas.

3.2. Methodology for the selection of information sources and case study areas

Various factors were considered in selecting the case study areas. The most important aspect was to identify representative locations in Mexico in terms of open burning of waste activities, both at the household level and in municipal and illegal dumpsites. Federal waste management authorities in the INECC, state authorities responsible of waste management, and specialists in the sector were consulted to assist in the selection of representative candidate study areas for investigation, along with a literature review investigation. Small to medium-sized municipalities (population size <100,000) with unreliable MSW collection services, and particularly in rural areas, more frequently dispose of waste by uncontrolled burning in the open, compared to cities with larger population densities where more rigorous waste management controls may be in place (Buenrostro et al., 2009; Friesen-Pankratz et al., 2011; Encarnación-Aguilar, 2015).

Other aspects considered in the selection process was transportation accessibility from Mexico City, the willingness of local authorities to participate in the project, and health and safety conditions in the region. As a result of this analysis, the Municipality of Huejutla, in the state of Hidalgo, and the Municipality of Juchitán, in the State of Oaxaca, were selected as the case study areas (see Figure 3.1).



Figure 3.1 Case study areas chosen for this research

For consistency and relevance of information, consistent data sources were used to develop the characterisation assessment at the national and state level, which relied heavily on National Institute of Geography and Statistics (INEGI), and Mexican National Council for the Evaluation of Social Development Policy (CONEVAL by its acronym in Spanish). Other sources on the environmental situation in Mexico included the Ministry of the Environment and Natural Resources (SEMARNAT by its acronym in Spanish), and the Municipal Development Plans published by the local authorities in each case study region.

An assessment of the socioeconomic conditions in the municipalities was completed based on the multidimensional framework developed by CONEVAL (2009). The framework considered a number of variables (current per capita income, level of education, access to health services, access to social security, quality and the size of house, access to basic services in the dwelling, and access to food) to determine the poverty level of the population. To measure poverty, CONEVAL defined specific criteria for each of these components (also called social deprivations) and used a "minimum wellbeing threshold"[8] and a "wellbeing threshold"[9] to determine whether an individual's income was sufficient to meet their basic needs. Households living in ***extreme poverty*** have an income below the minimum wellbeing threshold and experience three or more social deprivations. Communities living in ***poverty*** have an income below the wellbeing threshold and experience one or more social deprivations, and those with at least one social deprivation, but with an income above the wellbeing threshold are described as ***vulnerable due to social deprivation***. Households experiencing no social deprivations, but with an income below the wellbeing threshold, are described as ***vulnerable due to income*** (CONEVAL, 2009).

3.3. Waste generation and management in Mexico

3.3.1. Availability of waste management statistics in Mexico

National waste generation data in Mexico are not based on centralised reporting and monitoring, but are estimated from population size and consumption habits. The Ministry of Social Development (SEDESOL) applied the procedure defined in regulation NMX-AA-61-1985 to estimate the solid waste generation rate.

The INECC developed the second "Baseline for the Integrated Management of Waste" in 2012 (the first version was released in 2006). This presents approximated waste generation data per capita by region, current action plans, waste regulatory frameworks, available infrastructure and treatment of waste, among other information relevant to waste management in Mexico.

3.3.2. Waste generation

The Ministry of Social Development reported that the amount of waste generated in Mexico in 2010 was over 112,300 t day^{-1}, equivalent to 0.98 kg day^{-1} per capita. Solid waste generation increased by 25% from 2003 to 2010 due to urban growth, industrial development and changes in consumption patterns (SEMARNAT, 2013a). However, waste generation patterns differ significantly between different states (Figure 3.2). As would be expected, the largest rates of waste generation are found in states with large metropolitan areas, including the Federal District (DF), Mexico State, Jalisco, Veracruz and Nuevo León. Compared to these states, waste generation in Hidalgo and Oaxaca is much lower, equivalent to 2,405 and 1,945 t day^{-1} respectively. The reduced amount of waste generation in these areas is related to a smaller population, a higher percentage of rural

[8] Minimum wellbeing threshold: Monetary value of the food basket.

[9] Wellbeing threshold: Monetary value of food, goods, and basic services basket.

population and decreased socioeconomic status of people living in Oaxaca and Hidalgo compared to Mexico City, Jalisco and Nuevo León.

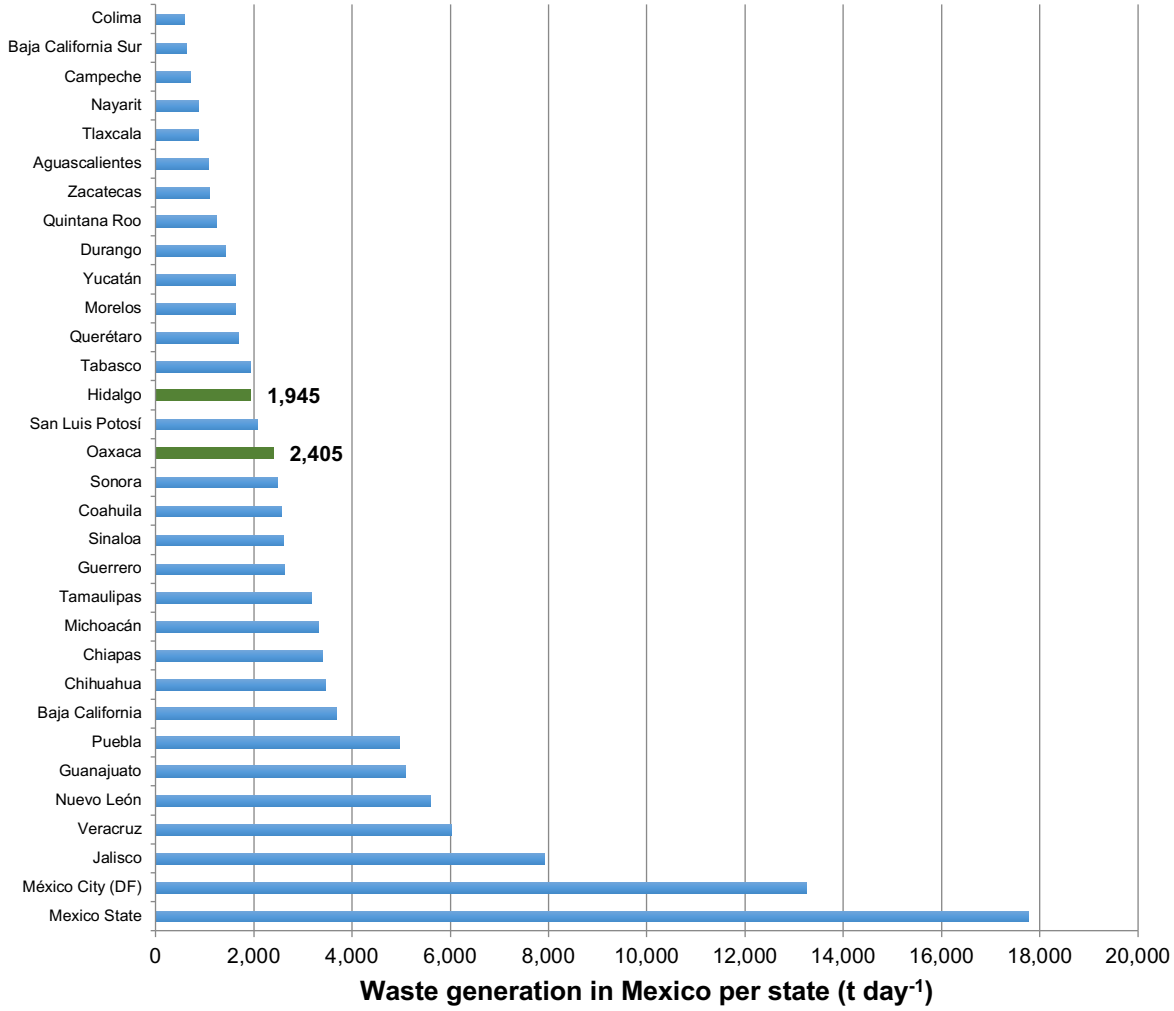


Figure 3.2 Waste generation in Mexico per state (t day^{-1}) (SEMARNAT, 2013a)

Similarly, waste generation per capita also varies significantly between states (see Figure 3.3 and Figure 3.4). The states located in the centre and south of the country (including Veracruz, Guerrero, Michoacán, Tlaxcala, Zacatecas, Hidalgo, Chiapas and Oaxaca) tend to have the lowest rates of waste generation per capita. By contrast, the states located in northern areas together with the Mexico City Metropolitan Area in the centre of the country, have the highest overall per capita waste generation rates. Major differences in the per capita generation rates are apparent, for instance the amount of waste generated per capita in Mexico City (1.5 kg day^{-1}) is 2.4 and 2.1 times larger compared to the state of Oaxaca (0.63 kg day^{-1}) and Hidalgo (0.73), respectively.

As observed in Figure 3.3, per capita waste generation rates in Hidalgo and Oaxaca are amongst the lowest in the country. Per capita waste generation estimations in Mexico are based on socioeconomic status and therefore this reflects that Hidalgo and Oaxaca are amongst the poorest states in the country.



	Very High	≥ 1kg
	High	0.90 - 0.99 kg
	Medium	0.80 - 0.89 kg
	Low	≤ 0.79 kg

Figure 3.3 Generation of waste per capita (kg day^{-1}) per state in Mexico in 2010 (compiled using data from INEGI (2010a) and SEMARNAT (2013a)

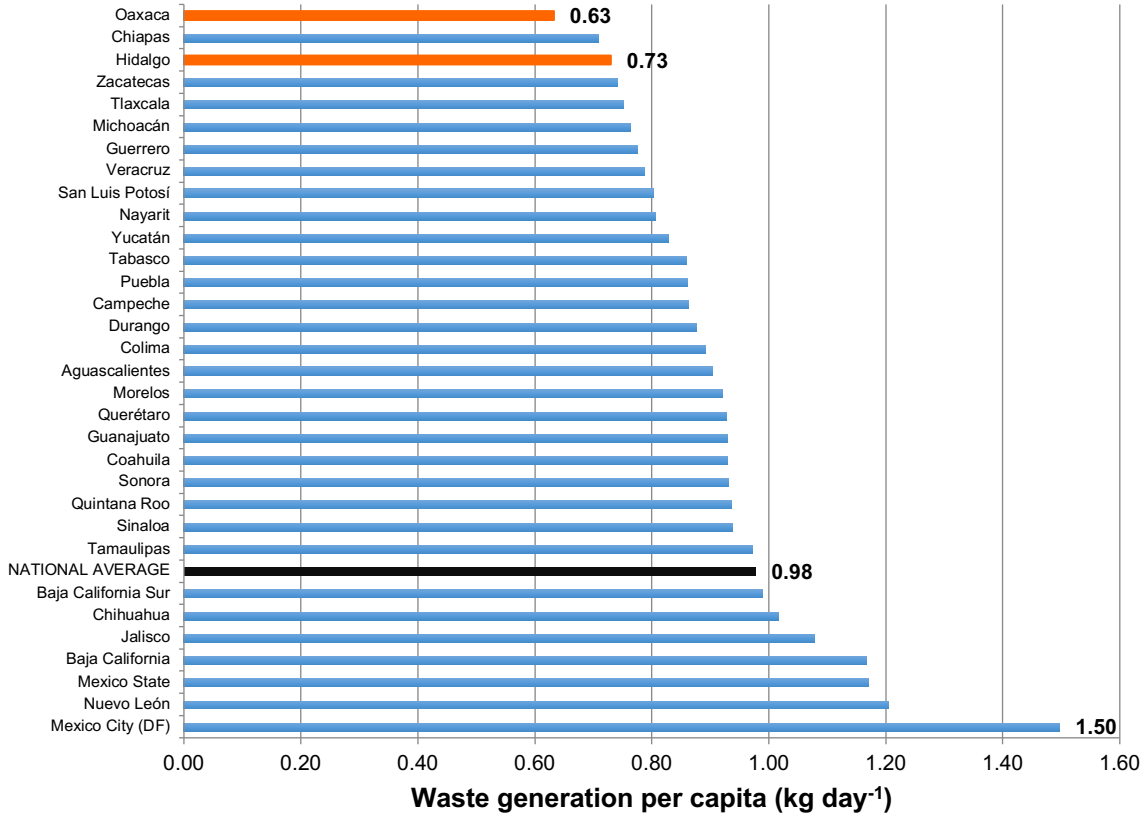


Figure 3.4 Comparison of waste generation per capita (kg day^{-1}) per state in Mexico in 2010 (INEGI, 2010a; SEMARNAT, 2013a)

There is another source of statistics reporting slightly different values on waste generation in Mexico developed by the INECC (2012) using information of the "State and Municipal Programmes for Waste Prevention and Management" (PEPGIR and PMPGIR by its acronyms in Spanish) that were available in 2012[10]. This suggests that there is a need to consolidate information sources to assist in the development of coherent policy in waste management in Mexico. These data did not cover all states and municipalities of the country and therefore statistical parameters (variance, standard deviation and the correlation coefficient) were applied to extrapolate waste generation data to the whole country. According to INECC (2012), the MSW generation in Mexico is approximately 102,895 t day^{-1} and the estimated weighted average of waste production per capita is 0.852 kg day^{-1} as shown in Table 3.1. The value presented by INECC (2012) for total waste generation and per capita waste generation are approximately 8.8 and 14 % smaller compared to estimations published by SEMARNAT (2013a) (112,300 t day^{-1} and 0.98 kg per capita day^{-1}).

Table 3.1. Average waste generation per capita in Mexico estimated from PEPGIR and PMPGIR

Units	PEPGIR and PMPGIR*
Average (kg $capita^{-1}$ day^{-1}**)**	0.852
Maximum (kg $capita^{-1}$ day^{-1}**)**	4.3
Minimum (kg $capita^{-1}$ day^{-1}**)**	0.3
Standard deviation	0.299
Variance	0.09
*PEPGIR: State Programmes for Waste Prevention and Management PMPGIR: Municipal Programmes for Waste Prevention and Management **Source:** INECC (2012)	

The national statistics for waste management (INECC, 2012) also include waste collection and handling data (Table 3.2,

Figure 3.5). Approximately 84 % of the generated waste is collected either through selective or mixed collection; 9.6 % is recycled or recovered through an industrial process. Importantly, the final disposal destination for almost 12 % of the waste generated in Mexico is unknown. It is possible that a significant portion of this fraction is disposed by burning in households or dumpsites (INECC, 2012).

[10] "State Programmes for the Prevention and Management of Waste" were available for 21 of the 32 states in Mexico. Only 33 of the 2457 municipalities had a "Municipal Programme for the Prevention and Management of Waste".

Table 3.2. National waste generation and management in Mexico

Activity	Quantity	Unit	Percentage
Generation	102,895	t day^{-1}	100
MSW Collection	86,356.9	t day^{-1}	83.93
Mixed collection	76,984.7	t day^{-1}	74.82
Selective collection	9,372.2	t day^{-1}	9.11
Transference stations	86	Units	NA
Treatment	98	Compost plants	NA
Scavenging during collection	3,823	t day^{-1}	3.71*
Scavenging in dumpsite	370.1	t day^{-1}	0.36*
Industrial recycling	4,366	t day^{-1}	4.24*
Selection Plants	17	Units	NA
	1,346	t day^{-1}	1.31*
Recycling	9,904	t day^{-1}	9.63*
Final disposal in landfills and controlled sites	62,287.7	t day^{-1}	60.54*
Disposal in dumpsites	16,395.1	t day^{-1}	15.93*
Unknown disposal	2,132.7	t day^{-1}	2.07*
Trucks with compacting devices	4,864	Units	34.01
Trucks with open box	8,829	Units	61.74
Other type of trucks	608	Units	4.25

*Estimated data
Source: INECC (2012)

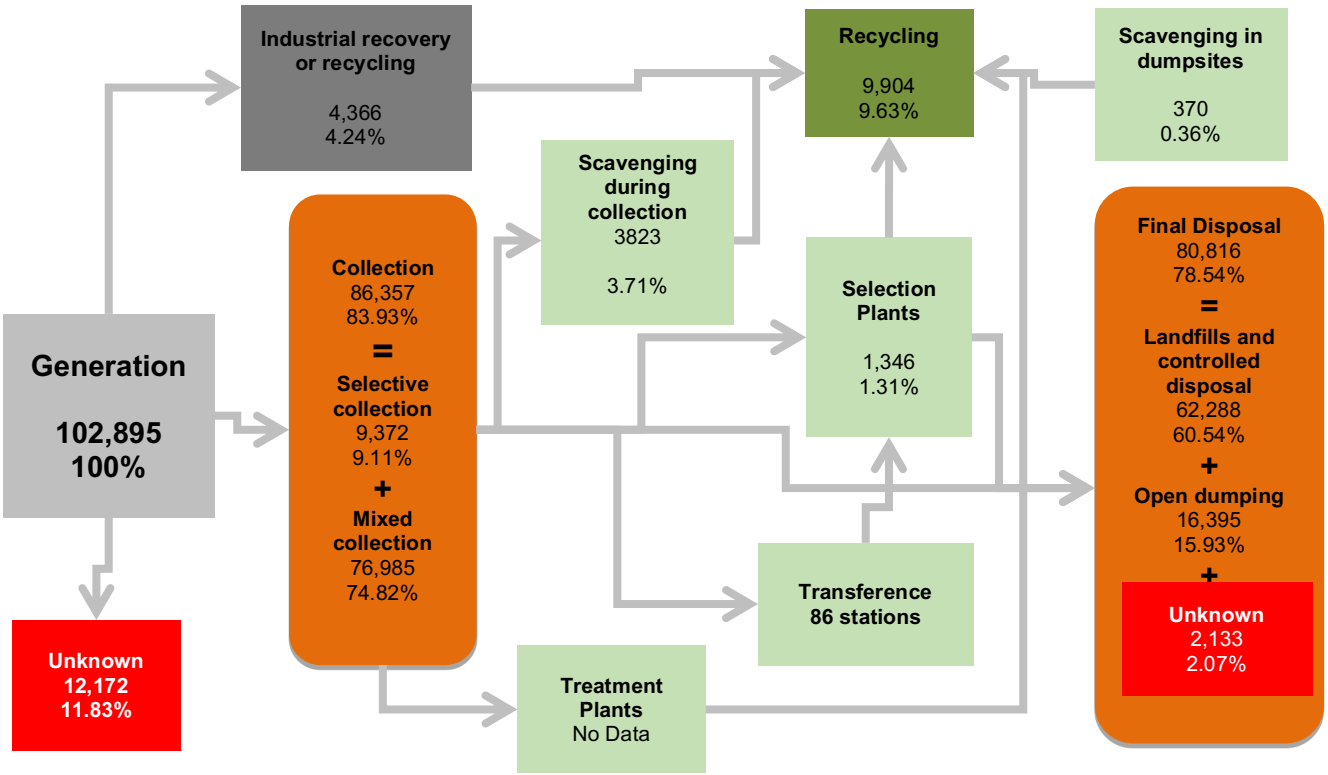


Figure 3.5 Flow diagram of MSW management in Mexico (t day^{-1}) (INECC, 2012)

3.3.3. Waste regulations

Article 115 of the Mexican Constitution specifies that municipalities are responsible for providing waste management services, including waste collection, transport, treatment and confinement (Poder Legislativo Federal, 1917). Article 100 of the "General Law for the Prevention and Integrated Management of Waste" (LGPGIR by its acronym in Spanish) (Diario Oficial de la Federación, 2003) incorporates the main elements of integrated waste management into Mexican policy. According to the LGPGIR, solid waste in Mexico is classified as follows:

- **Hazardous waste:** Corrosive, reactive, explosive, toxic and inflammable waste or waste that contains infectious agents. This also applies to containers, packaging material and soil that has been contaminated while managing waste (Article 5, fraction XXXII, LGPGIR).
- **Special Management Waste**: Waste generated by productive processes that are not considered to be hazardous, urban solid waste or generated by a source of large quantities of solid waste (Article 5, fraction XXX, LGPGIR).
- **Urban Solid Waste:** Waste generated by households, such as packaging, containers and any other waste products that result from domestic activities. Urban Solid Waste also comprises waste generated by small businesses that produce waste with similar characteristics to household waste and waste that is generated in the public spaces (Article 5, fraction XXXIII, LGPGIR).

This law (LGPGIR) also provides a more specific definition of responsibilities among the three levels of government in relation to waste management, as described in Table 3.3. The LGPGIR states that municipalities may charge a fee for waste management services and may use these resources to strengthen their waste management systems.

Table 3.3 Responsibilities of MSW management for the three levels of government

National Level (Article 7)	State Level (Article 9)	Municipal Level (Article 10)
• Formulating national policies on waste • Elaborating the National Program for the Prevention and Integrated Management of Waste (PNPGIR) • Elaborating the National Program for the Remediation of Contaminated Sites (PNRSCR) • Issuing official Mexican regulations on hazardous waste (NOMs) • Issuing official Mexican regulations on environmental performance of urban solid waste and special waste • Regulating and controlling the generation of hazardous waste that is not managed by the State Authorities • Monitoring compliance with the applicable regulations and imposing sanctions when necessary • Authorizing waste management activities including importing, exporting and transit of hazardous waste • Promoting the construction of infrastructure for Integrated Waste Management (IWM) in coordination with the State and Municipal Authorities • Publishing information on waste management at a national level • Developing joint strategies with the State and Municipal Authorities to improve the management of waste	• Formulating state policies on special waste • Designing programs for the management of special waste in compliance with the PNPGIR and the PNRSCR • Issuing legal instruments for special waste • Authorizing integrated waste management activities related to special waste • Recording management plans for special waste • Establishing obligations for waste generators and providers of special waste management services • Regulating and establishing fees for the provision of special waste services • Promoting the construction of infrastructure for the integrated management of urban solid waste, special waste and hazardous waste, in coordination with the National authorities • Promoting private and social sector participation in the design and implementation of actions to manage and prevent the generation of special waste • Assist the Federal authorities in the publication of information on waste management • Determining indicators to evaluate the application of the LGPGIR.	• Formulating municipal programs for the integrated management of urban solid waste in compliance with the State programs. • Issuing regulations and legal instruments for the implementation of the LGPGIR and State regulations • Provide urban solid waste management services (including collection, treatment and final disposal) • Give permits or concessions related to waste management services • Keep record of generators of large quantities of urban solid waste (i.e. supermarkets) • Verifying compliance of regulations on urban solid waste and imposing sanctions when necessary • Participating in the control of hazardous waste for generators of small quantities of waste and imposing sanctions when necessary • Charging for urban solid waste management services and investing these resources in the operation and strengthening of the services
Source: SEMARNAT (2003)		

The LGPGIR also states that the regulations related to the generation, management and disposal of waste include the following prohibitions:

1. Placing waste in public areas, wasteland, gullies, mountain gaps, drainage and sewage systems, electric, gas or telecommunication cabling pipes, bodies of water, underground caves, natural protected areas, environmental conservation areas, rural areas and other non-authorized areas according to the regulation.
2. The uncontrolled open burning of waste.
3. Opening new dumpsites.

Therefore, according to the LGPGIR uncontrolled burning of waste is officially an illegal practice in Mexico. There is also a series of federal regulations concerning waste and its management. Regulation NOM-083-SEMARNAT-2003 establishes the specifications for site selection, design, construction, operation, monitoring, close down and supplementary works for landfills for the final

disposal of urban solid waste and waste requiring special management. This instrument includes restrictions to reduce impacts at nearby sites and protected natural areas, establishes minimal distance to airports, roads, railroads, as well as hydrological, geological, hydrogeological aspects and the application of technologies for the management of waste.

NOM-098-SEMARNAT-2002 is a mandatory standard that applies to all facilities where waste incineration occurs, other than crematoriums and industrial furnaces. This regulation is not applicable for the incineration of radioactive waste, as there is a special regulation for this purpose. This instrument sets a limit to air pollutants that can be emitted during the incineration of waste. Hazardous waste containing persistent organic pollutants and bio-accumulative compounds cannot be incinerated.

The Office of the Federal Attorney for Environmental Protection (PROFEPA by its acronym in Spanish) is the primary environmental protection enforcement agency. PROFEPA has offices in each state, responsible for enforcing legislation applicable to the protection and restoration of the environment and natural resources.

3.3.4. General MSW management information

3.3.4.1. Waste characterisation

Figure 3.6 shows the general composition of collected MSW in Mexico (prior to disposal or recycling) (SEMARNAT, 2013a). Organic matter, including food and garden waste, represents the largest overall waste fraction equivalent to more than 50 % of generated MSW. Other major waste fractions include paper and cardboard (approximately 14 %) and plastic (approximately 11 %).

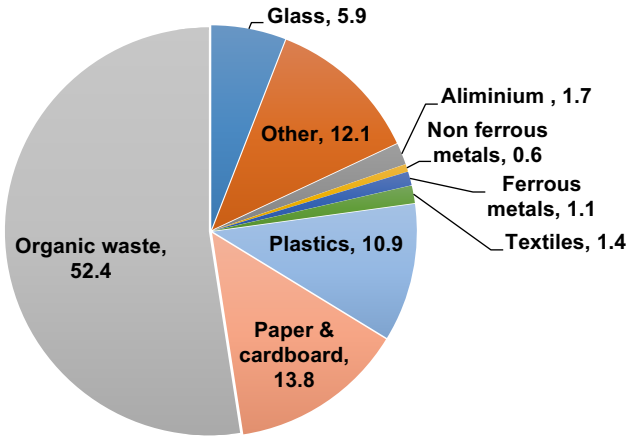


Figure 3.6 MSW composition in Mexico prior to disposal and recycling according to SEMARNAT (2013a)

The Baseline for the Integrated Management of Waste (INECC, 2012) also provides data on average waste composition for Mexico (Figure 3.7). According to these data, organic waste is 14 % lower compared to the estimation by SEMARNAT (2013a) (38 % compared to 52 %). The other fraction that differs significantly is “other” waste, which in the case of SEMARNAT (2013a) is 12 %, whereas (INECC, 2012) suggests this fractions represents more than 21 % of the total waste

generated. The amount of the remaining waste fractions reported by (INECC, 2012) and SEMARNAT (2013a) are generally similar.

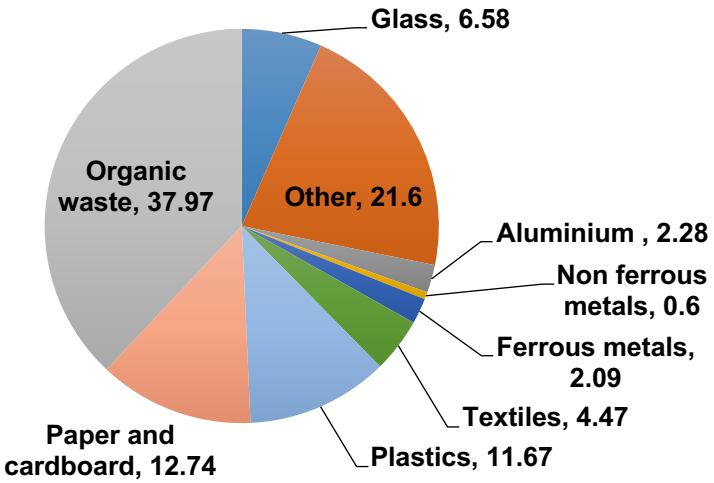
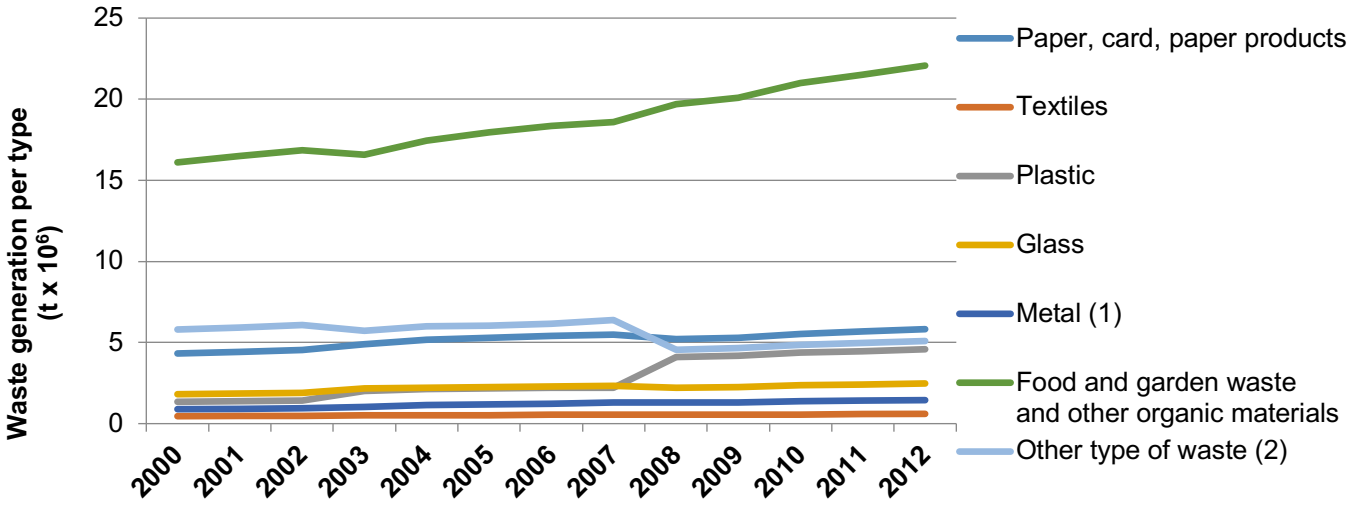


Figure 3.7 MSW composition in Mexico prior to disposal and recycling according to INECC (2012)

Figure 3.8 presents the changes in waste generation and composition from 2000 to 2012 in Mexico. During this period the size of the food and garden waste fractions have increased significantly and plastic waste generation has also increased by a factor of two.



Note: These data refers to the waste produced in cities, including that generated in houses, commerce, institutions, recreational areas and others.

1 Includes aluminium, ferrous and non-ferrous metals, copper, lead, tin and nickel.

2 Includes small pieces of waste, demolition material, rubber and nappies among others.

Figure 3.8 Waste generation by type in Mexico 2000-2012 (INEGI, 2014b)

3.3.4.2. Waste collection

According to SEMARNAT (2013a), 85 % of MSW generated in Mexico was collected in 1998 and the collection rate increased to 93 % in 2011. However, this rate varies significantly depending on the size of the community (Figure 3.9). For instance, in 2011 the waste collection rate increased to 95 % in metropolitan areas[11], 80 % in medium sized cities, but only by 26 % in small cities and 13 % in rural areas.

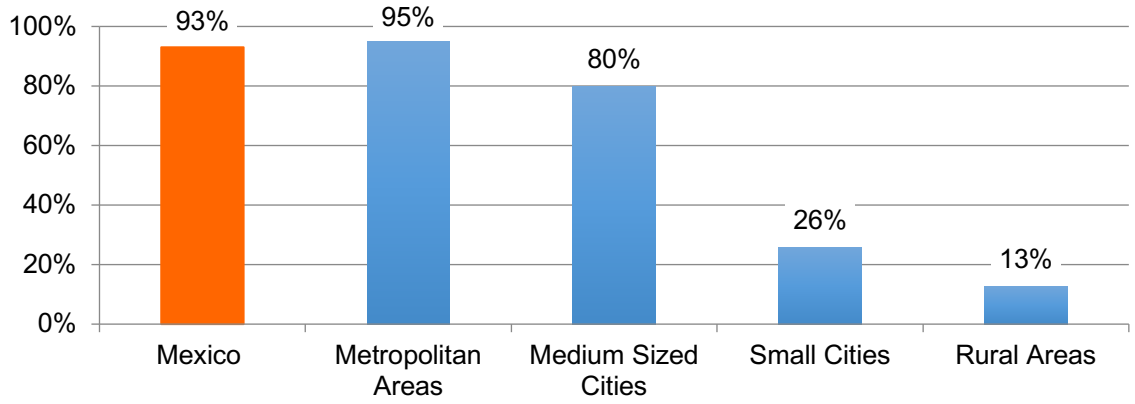


Figure 3.9 Waste collection in Mexico by size of community (SEMARNAT, 2013a)

The cost of waste collection services in Mexico varies considerably in different states, ranging from \$130 Mexican pesos (£5.9) t^{-1} to \$2,666 Mexican pesos (£121) t^{-1}. This variation may be explained because in some cases, infrastructure investments are included in the costs, whereas, in other cases, only operating costs are considered (INECC, 2012).

3.3.4.3. Role and significance of the informal sector in waste management

Informal stakeholders play an important role in providing solid waste management services all over the world (Brown and McGranahan, 2016), including waste collection, collection of recyclable materials directly from households or as waste pickers in transfer stations, landfills and dumpsites (Oteng-Ababio, 2011).

In Mexico, 58 % of the employed population (29 million people) has an informal job[12] (INEGI (2014a). The number of people working specifically within the informal MSW sector in Mexico is unknown, but it is estimated to be several hundred thousand (Wamsler, 2000). Medina (2000) suggested that up to 2 % of the population living in cities in Latin America survives by scavenging waste.

The informal waste management sector in Mexico is divided into those who pick waste during collection, called “prepepena” and those who pick waste at the dumpsites and landfills, described as

[11] According to the Ministry of Social Development, metropolitan areas include more than one municipality and have more than 1 million inhabitants. Medium cities have between 100 and 999 thousand inhabitants; small cities are those that are bigger than 15 thousand inhabitants and smaller than 99 thousand inhabitants. Rural communities are those that have less than 15 thousand inhabitants (SEDESOL, 2012).

[12] Informal jobs include: workers in informal companies or households, informal workers in formal companies, workers that do not have a stable contract, workers without social welfare (such as healthcare), domestic workers, people selling goods in the streets or informal markets, owners of micro businesses, as well as their employees or family involved in the business, either receiving a wage or not.

“pepena”. The prepepena takes place while the waste is being transported to transfer stations, dumpsites or landfills, where the waste pickers separate recyclables and sell them to commercial processing companies. Wamsler (2000) considered that these activities contributed to recycling 2 - 3 % of the solid waste generated in Mexico.

3.3.4.4. Final disposal of MSW in Mexico

Final disposal of MSW in Mexico includes: sanitary landfills, uncontrolled dumpsites and open dumping. Controlled dumpsites and sanitary landfills have partial inspection, supervision and application of necessary measures to comply with the regulations established for controlling waste disposal, which is the Official Mexican Norm, NOM-083-ECOL-1996. Uncontrolled dumpsites are sites where different types of MSW are disposed and mixed without control. Open dumpsites refer to illegal final disposal sites where waste is disposed and accumulated illegally without any technical control (INECC, 2012).

3.3.4.4.1. Methods of waste disposal by households

In this research, the term ‘household waste disposal’ refers to the different approaches employed by householders to dispose of waste. INEGI (2011) showed that open burning of waste was an important method of solid waste disposal in some regions of the country and, in the southern states, in particular, including: Oaxaca, Chiapas, Guerrero, Tabasco and Veracruz, more than 30 % of households disposed of solid waste by burning (see Table 3.4). As may be expected, the frequency of burning declared by households in the Federal District in Mexico City, was significantly smaller and equivalent to 0.11 % (INEGI, 2011).

Table 3.4 Waste disposal methods used by households according to state in Mexico (% of households)

State	Population	Number of households	Average occupants per household	Waste disposal methods (% of households)					
				Waste collection	Container or municipal dumpsite	Open burning		Other	Not specified
Oaxaca	3,783,491	936,359	4.0	51.8	4.3	40.8	Very High (>30%)	2.7	0.4
Chiapas	4,785,677	1,084,500	4.4	53.1	2.5	39.6		4.5	0.3
Guerrero	3,378,137	816,642	4.1	49.0	7.8	39.6		3.2	0.5
Tabasco	2,231,743	570,132	3.9	59.2	4.5	34.4		1.5	0.4
Veracruz	7,622,807	2,027,661	3.8	62.3	3.8	32.2		1.4	0.3
Campeche	816,867	214,072	3.8	68.4	3.9	26.8	High (21-30%)	0.8	0.1
San Luis Potosí	2,573,321	640,693	4.0	68.1	4.0	26.6		1.0	0.3
Yucatán	1,951,699	504,951	3.9	66.1	5.8	26.1		1.0	1.1
Hidalgo	2,672,904	673,159	4.0	69.4	5.3	23.9		1.2	0.2
Puebla	5,773,760	1,380,656	4.2	68.5	8.4	20.8		1.9	0.4
Zacatecas	1,493,882	377,174	4.0	69.7	8.6	20.6		0.8	0.2
Nayarit	1,075,664	294,470	3.7	78.1	3.1	17.6	Medium (11-20%)	1.0	0.2
Durango	1,624,630	407,646	4.0	76.8	4.6	16.4		1.6	0.6
Michoacán	4,342,947	1,081,827	4.0	80.8	3.7	14.1		1.0	0.4
Sinaloa	2,758,050	722,337	3.8	83.4	2.0	12.4		1.5	0.7
Quintana Roo	1,319,120	367,569	3.6	80.3	5.4	12.2		0.5	1.6
Tamaulipas	3,252,937	902,548	3.6	83.4	2.5	12.0		0.6	1.6
Sonora	2,625,590	735,695	3.6	84.7	4.3	9.3	Low (0-10%)	1.2	0.5
Guanajuato	5,472,860	1,287,875	4.2	84.7	6.3	8.1		0.6	0.4
México State	15,104,013	3,717,606	4.1	90.1	1.9	7.1		0.4	0.5
Chihuahua	3,388,957	951,205	3.6	89.6	2.5	6.8		0.7	0.5
Morelos	1,768,413	475,166	3.7	89.2	3.0	6.7		0.8	0.3
Coahuila	2,738,203	736,427	3.7	81.8	11.0	6.0		0.7	0.6
Querétaro	1,825,159	455,026	4.0	83.8	10.7	4.5		0.5	0.5
Tlaxcala	1,179,808	276,772	4.3	92.5	1.5	4.5		1.3	0.3
Baja California	3,098,948	869,565	3.6	90.1	4.5	4.3		0.4	0.9
Nuevo León	4,640,811	1,215,839	3.8	92.8	1.2	3.8		0.3	2.0
Jalisco	7,315,955	1,819,793	4.0	93.0	2.5	3.6		0.4	0.6
Baja California Sur	631,738	185,595	3.4	88.0	7.5	3.3		0.5	0.6
Colima	646,855	180,866	3.6	91.2	5.4	3.0		0.2	0.1
Aguascalientes	1,178,260	293,024	4.0	6.4	92.1	1.1		0.2	0.3
Distrito Federal	8,770,578	2,440,641	3.6	93.3	5.6	0.1		0.1	0.9

Compiled using data from INEGI (2011)

The categories (low, medium, high and very high) in Table 3.4 and Table 3.7 were introduced to illustrate the geographical distribution (based on % of households) of the frequency of open burning of waste as a disposal method in different states and regions of Mexico, shown in Figure 3.10 and Figure 3.11. The map in Figure 3.10 shows that central-northern and southern regions have the highest rates of open burning of waste reported by households. Areas where open burning is less frequently practised include the northern border region, some states in the west and the central region, in close proximity to the Federal District in Mexico City. Therefore, the states selected for this research were Oaxaca, and Hidalgo, as these represented regions with very high (41 %) or high (24 %) rates of open burning of waste by households, respectively (INEGI, 2011).

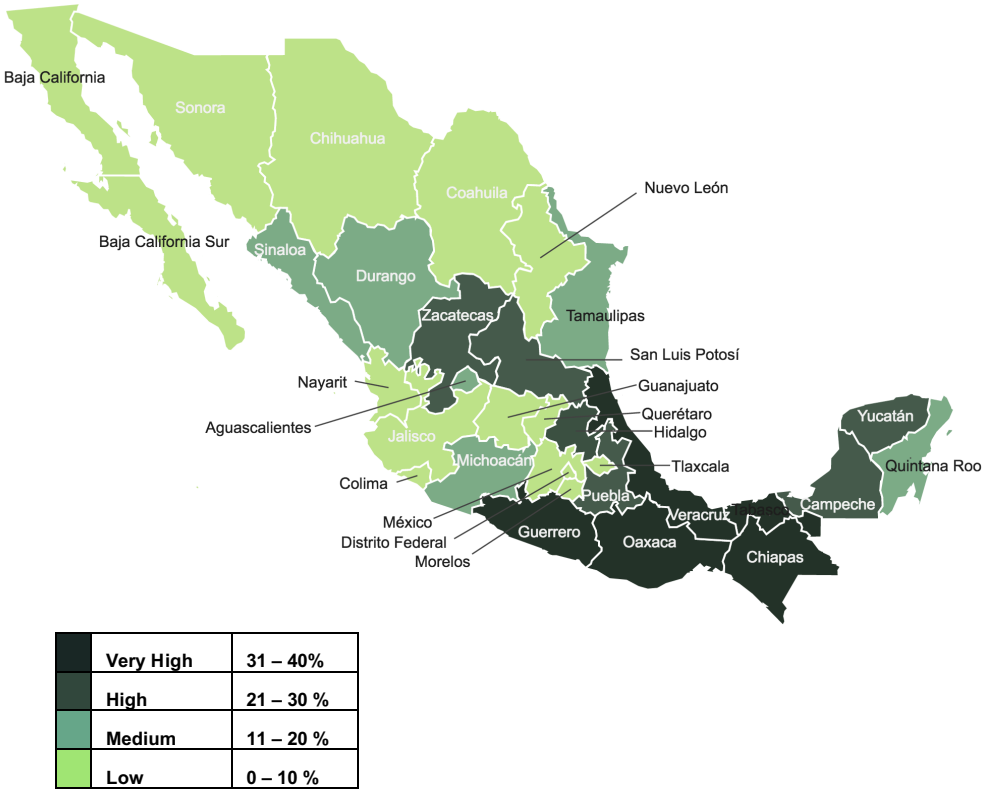


Figure 3.10 Proportion of households engaged in open burning of waste by state in Mexico (% of households) (compiled using data from INEGI (2011))

3.3.4.4.2. Final disposal of waste in landfills

It is common practice for municipal authorities in Mexico to refer to their final disposal sites as "sanitary landfill", implying that they operate according to strict environmental regulation for pollution control. However, according to an evaluation of the final disposal sites in 41 municipalities in Mexico, the majority of the sites do not have the necessary infrastructure and operation processes consistent with sanitary landfill engineering and management (Bernache-Perez, 2011). Table 3.5 shows the amount of waste that arrives to controlled and uncontrolled sites in Mexico. Approximately 30 % of the waste (32 x 10^3 t day^{-1}) in Mexico is disposed in uncontrolled sites where it is likely to be burned in open fires.

Table 3.5 Waste disposed in controlled and uncontrolled sites by size of communities in Mexico in 2010 (t day^{-1})

Size of community	Controlled sites	Uncontrolled sites
Metropolitan areas (More than 1 million)	41,289	5,831
Medium cities (> 100,000)	32,698	8,241
Small cities (15,000-99,999)	2,115	6,867
Rural areas (2,500-14,999)	1,441	11,270
Total	**77,371**	**32,379**
Source: SEMARNAT (2013b)		

MSW is burned in uncontrolled sites and in some cases also in “controlled” landfills. However, there is no information regarding the amount of waste that is burned in final disposal sites. According to interviews conducted with waste experts (Encarnación-Aguilar, 2015; Solorzano-Ochoa, 2015), between 50 % and 80 % of the waste disposed in uncontrolled sites is likely to be burned through self-ignition of methane or intentionally set on fire to reduce the volume or to uncover metals for collection and recycling. This number is consistent with the IPCC Guidelines for National Green House Gas inventories, which suggests a default value of 60 % for the fraction of waste burned in dumpsites (IPCC, 2006).

3.3.5. Waste burning activity levels in Mexico

In this section, the patterns of waste burning in households and dumpsites were further scrutinised to provide a quantitative estimate of the total mass of waste burned by households and dumpsites in Mexico. This information will be used in following chapters of this dissertation to calculate BC emissions from open burning of waste.

The combustible fraction was estimated using an average of the waste composition in Mexico combining the figures presented by SEMARNAT (2013a) and INECC (2012), as shown in Table 3.6. Information on the proportion of households that burn waste as a disposal method was published in the 2010 Census (INEGI, 2011) (see Table 3.4). Waste burned in dumpsites was estimated using information on uncontrolled dumpsites in Mexico and the proportion of the waste received and disposed by burning based on interviews with experts of MSW management in Mexico (Encarnación-Aguilar, 2015; Solorzano-Ochoa, 2015) and IPCC guidelines (IPCC, 2006).

Table 3.6 Fraction (%) of combustible waste in Mexico

Type of waste	Average SEMARNAT[1] & INECC[2]	Combustible	Fraction of combustible waste burned
Organic	45.2	0.4	18.1
Textiles	2.9	1.0	2.9
Plastics	11.3	1.0	11.3
Paper and card	13.3	1.0	13.3
Other	16.9	0.4	6.7
TOTAL fraction burned			52.3
Source: (INECC, 2012; SEMARNAT, 2013a)			

Table 3.7 shows the material mass balance for uncontrolled burning of MSW in backyards in Mexico. It was assumed that 62 % of the MSW generated in Mexico originates from households (OPS et al., 2011), and that 52 % of this is combustible waste (INECC, 2012; SEMARNAT, 2013a; INECC and SEMARNAT, 2015). This analysis showed that approximately 4.3 x 10^3 t day^{-1} of waste may be burned in backyards by households in Mexico.

Table 3.7 Potential waste disposal by open burning by households by states in Mexico (t day^{-1})

State	Waste generation per day	Domestic waste	Combustible waste	Houses that dispose by open burning (%)	Waste potentially burned	Scale
Veracruz	6,020	3,714	1,943	32%	626	
México State	17,765	10,961	5,733	7%	406	
Guerrero	2,630	1,623	849	40%	336	
Puebla	4,975	3,070	1,606	21%	334	
Chiapas	2,555	1,576	825	40%	327	**Very High**
Oaxaca	2,405	1,484	776	41%	317	**>150**
Tabasco	1,925	1,188	621	34%	214	
San Luis Potosí	2,075	1,280	670	27%	178	
Michoacán	3,325	2,052	1,073	14%	151	
Hidalgo	1,945	1,200	628	24%	150	
Yucatán	1,620	1,000	523	26%	137	
Guanajuato	5,095	3,144	1,644	8%	133	**High**
Tamaulipas	3,175	1,959	1,025	12%	123	**100-150**
Sinaloa	2,595	1,601	837	12%	104	
Jalisco	7,920	4,887	2,556	4%	91	
Durango	1,430	882	461	16%	76	
Sonora	2,480	1,530	800	9%	75	
Zacatecas	1,105	682	357	21%	74	**Medium**
Nuevo León	5,605	3,458	1,809	4%	69	**50-99**
Coahuila	3,400	2,098	1,097	6%	66	
Campeche	710	438	229	27%	61	
Baja California	3,680	2,271	1,188	4%	50	
Nayarit	875	540	282	18%	50	
Quintana Roo	1,240	765	400	12%	49	
Morelos	1,635	1,009	528	7%	36	
Colima	3,460	2,135	1,117	3%	34	
Querétaro	1,695	1,046	547	4%	24	**Low**
Tlaxcala	880	543	284	4%	13	**0-49**
Chihuahua	580	358	187	7%	13	
Baja California Sur	630	389	203	3%	7	
Distrito Federal	13,250	8,175	4,276	0%	5	
Aguascalientes	1,070	660	345	1%	4	
National	**109,750.2**	**67,715.9**	**35,418.1**	**-**	**4,327**	
Compiled using data from INEGI (2011), OPS et al. (2011) and SEMARNAT (2013a)						

This information was mapped in Figure 3.11 which shows that the highest rates of burning waste, equivalent to >150 t day^{-1}, occur in the southern (except for Campeche, Quintana Roo and Yucatán states) and central area (except from Querétaro, Morelos, Tlaxcala and Distrito Federal). In contrast, the states located in northern regions (with the exception of Tamaulipas and Sinaloa), have lower (<100 t day^{-1}) rates of waste disposal by open burning.



Figure 3.11 Classification of states by amount of waste burned in the open by households (compiled using data from INEGI (2011), OPS et al. (2011) and SEMARNAT (2013a))

Community size is an important factor to consider when assessing waste burning patterns, as larger communities tend to have access to better waste collection services and therefore are less likely to burn waste in uncontrolled fires, compared to smaller populations. Table 3.8 combines information about methods of waste disposal with waste generation rates by community size in Mexico. Waste generation per capita varies greatly depending on community size, for example, cities with >100,000 inhabitants generate 5.5 times more waste per capita than communities with <15,000 inhabitants. The estimated amount of waste burned in households (assuming that 61.7 % of MSW is domestic and 52.3% of this is combustible, refer to Table 3.6) was 2 x10^{3} t day^{-1}. This value is smaller than the estimate based on state-wide statistics for waste generation (as shown in Table 3.7, 4.3 x10^{3} t day^{-1}), which may be explained because, whilst smaller communities burn more waste, they also generate less waste per capita compared to larger cities. This analysis shows the importance of collecting waste generation and activity data at a municipality level to provide more accurate information about local and overall national waste disposal practices and of backyard burning of waste by households in particular.

Approximately 38 % of the population in Mexico live in small communities (<15,000) usually with limited or no access to waste collection services (54.5 % of this fraction have access to waste collection) and rates of open burning are higher (37.8 % dispose of their waste by burning) compared to larger communities (Table 3.8). In contrast, 48 % of the population live in cities with populations of >100,000, and in this case at least 88 % have access to waste collection and the rate of uncontrolled burning of waste is 1 %. Consequently, small cities generate a relatively modest fraction of the total

solids waste in Mexico, equivalent to 12 %, however, they are responsible for 79 % of the waste that is disposed by uncontrolled burning in households.

Table 3.8 Methods of waste disposal and waste potentially burned in households by community size in 2010 (t day^{-1} unless otherwise specified)

	Size of community	<15,000	15,000-99,999	> 100,000	Mexico
	Population	42,192,353 (38 %)	16,481,713 (15 %)	53,169,718 (48 %)	111,843,784
	Amount of households	10,158,618	4,167,533	14,317,340	28,643,491
Methods of waste disposal by housholds	Given to waste collection services	54.5 %	80.0 %	88.4 %	78.7%
	Taken to dumpsite	2.3 %	2.1 %	1.2 %	1.3 %
	Taken to container	2.5 %	2.5 %	5.7 %	3.9 %
	Burning	**37.8 %**	**4.0 %**	**1.1 %**	**14.5 %**
	Burial	0.98 %	0.30 %	0.10 %	0.38 %
	Street or illegal dumpsite	0.82 %	0.12 %	0.08 %	0.35 %
	Cliff, sea, river	0.73 %	0.10 %	0.04 %	0.30 %
	Not specified	0.33 %	0.48 %	0.85 %	0.61 %
	Waste per capita (kg day^{-1})	0.30	0.55	1.66	0.98
	Total waste generated	12,711 (12 %)	8,982 (8 %)	88,057 (80 %)	109,750
	Domestic waste	7,843	5,542	54,333	67,718
	Combustible domestic waste	4,102	2,899	28,418	35,419
	Waste potentially burned	**1,551.17 (79 %)**	**115.00 (6 %)**	**299.07 (15 %)**	**1,965.23**
	Compiled using data from INEGI (2011), OPS et al. (2011) and SEMARNAT (2013a)				

Table 3.9 combines information for open burning of waste by households and at dumpsites in Mexico. A low and a high estimate is reported for backyard burning, based on the amount of waste burnt in households by state (high estimate) or by community size (low estimate), and a high and low estimate of waste burned in uncontrolled dumpsites, was determined following interviews with experts (Encarnación-Aguilar, 2015; Solorzano-Ochoa, 2015) and using IPCC guidelines (IPCC, 2006). This suggested that between 10.4 - 17.8 x 10^3 t day^{-1} of waste is burned in uncontrolled fires in Mexico, equivalent to 10 - 16 % of the total waste generated in the country. Burning in backyards by households and at dumpsites account for 19 - 24 % and 76 – 81 % of the total amount of waste disposed in Mexico by uncontrolled open fires, respectively.

Table 3.9 Open burning of waste by households and at dumpsites in Mexico according to this research (t day^{-1})

	Estimated waste burned in houses		Waste disposed in uncontrolled sites	Estimated combustible[a] waste burned in dumpsites[b]		Total waste burned	Waste burned/Waste generated	Houses vs. Dumpsites
High estimate	**By state**	4,327	32,379	**80%**	13,549	**17,876**	**16%**	**Households:** 24% **Dumpsites:** 76%
Low estimate	**By community size**	1,965		**50%**	8,468	**10,433**	**10%**	**Households:** 19% **Dumpsites:** 81%

a) It was considered that 52.3% of the waste that was set on fire was combustible (Table 3.6)
b) According to interviews with experts on waste management in Mexico (Encarnación-Aguilar, 2015; Solorzano-Ochoa, 2015)
Compiled using data from Encarnación-Aguilar (2015), INEGI (2011), OPS et al. (2011) and (SEMARNAT, 2013b)

The First Biennial Update Report to the United Nations Framework Convention on Climate Change (INECC and SEMARNAT, 2015) has estimated the extent of open burning of waste in Mexico both by households and at dumpsites (Table 3.10). The analysis was based on the population per state, percentage of households that burn waste, per capita waste generation, quantity of uncontrolled dumpsites and the waste they receive, as well as the fraction of waste burned in houses and dumpsites according to expert opinion.

Table 3.10 Open burning of waste according to the First Biennial Update Report to the United Nations Framework Convention on Climate Change (t day^{-1})

Area	Waste burned in houses	Waste burned in dumpsites	Total waste burned
Mexico	887	66	**953**
Hidalgo State	9.2	3.1	**12.2**
Huejutla (case study 1)	0.75	0.12	**0.87**
Oaxaca State	10.7	2.6	**13.2**
Juchitán (case study 2)	0.48	-	**0.48**

Source: INECC and SEMARNAT (2015)

The results suggested that less than 1,000 t day^{-1} of waste was burned in uncontrolled fires in Mexico, and 93 % of this was burned in backyards. Thus, open burning of waste in Mexico apparently only represented 0.87 % of the total waste generated. These results differ greatly by two orders of magnitude compared to the estimate of open burning calculated here (Table 3.9), which suggested the rate of open burning was equivalent to approximately 13 % in average of the total waste generated. This emphasises the potential wide variation in outcomes that are possible depending on the assumptions used in estimating rates of open burning in the absence of high quality field measurements on the extent of open burning activity.

3.4. Characteristics of Huejutla de Reyes, Hidalgo

3.4.1. Location

Huejutla de Reyes is one of 84 municipalities in the state of Hidalgo, in the Huasteca region of central Mexico (Figure 3.12). This municipality is located inland and has an area of 395 km², occupying 1.89% of the territory of the state of Hidalgo. Huejutla is located 200 m above sea level;

however, the elevations of the municipality range from 100 to 1,400 m. Huejutla's territory is divided between agricultural land (81.45 %), urban areas (3.55 %) tropical rainforest (14 %) and forest (1 %) (INEGI, 2009).

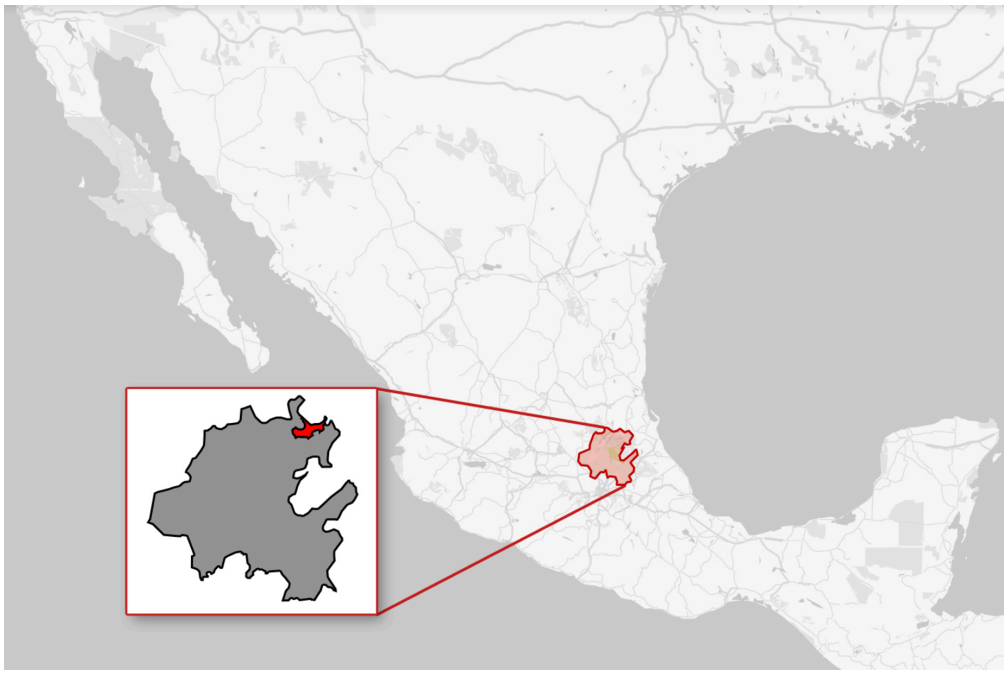


Figure 3.12 Location of Huejutla de Reyes, Hidalgo, México

3.4.2. Climate

The average annual temperature in Huejutla is 23.8ºC, with a yearly average range of 22.2 to 25.3ºC. The monthly average temperature varies from around 20ºC in the winter to 30ºC during the summer (Figure 3.13).

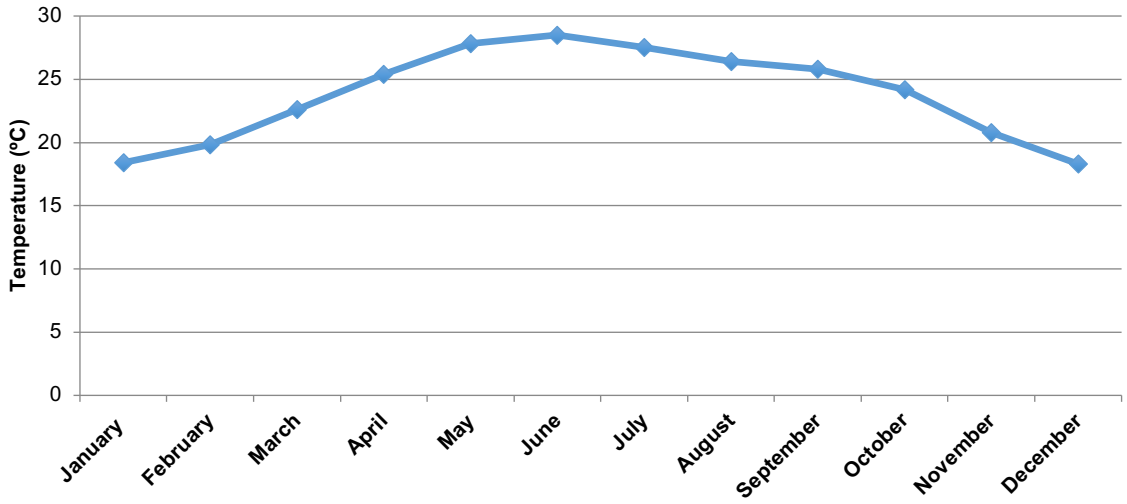


Figure 3.13 Monthly average temperature in Huejutla de Reyes (1989-2003) (INEGI, 2009)

Approximately 52 % of the territory in Huejutla is classified as humid subtropical with heavy rain in the summer, and 48 % as humid subtropical with rain all year round. The average rainfall is

approximately 1,500 mm per annum, with a typical annual range of 1,100 to 1,800 mm (INEGI, 2009). The wettest season is the summer and early autumn period (June to October), when rainfall varies between 150 and 250 mm per month. In the winter and spring, the average monthly rainfall decreases to 50 mm (Figure 3.14).

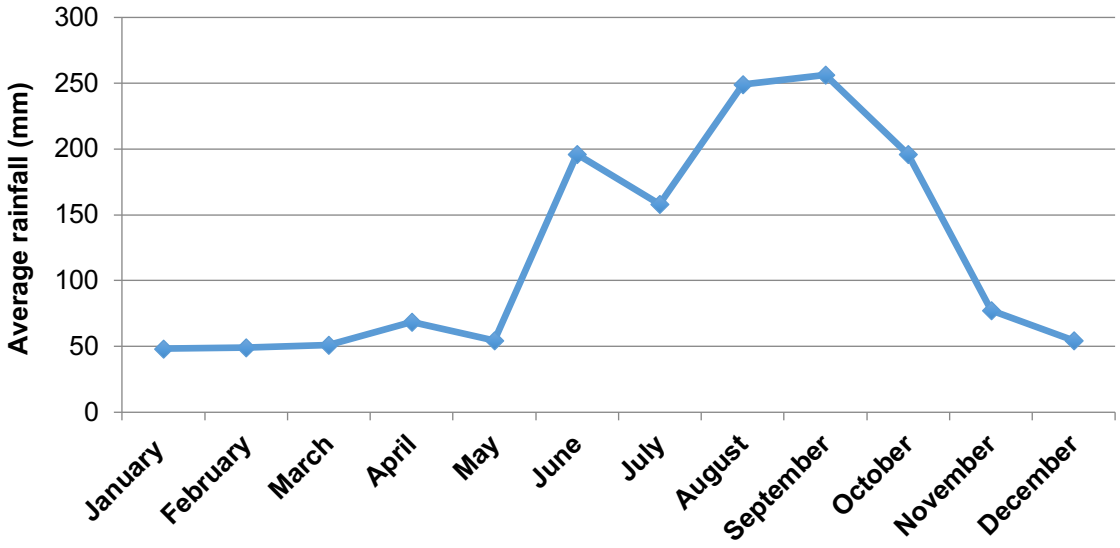


Figure 3.14 Monthly average rainfall in Huejutla de Reyes (1989-2003) (INEGI, 2009)

3.4.3. Population distribution and growth

The total population of Huejutla de Reyes in 2015 was almost 130,000 inhabitants, 4.55 % of the population of Hidalgo State. The capital of the municipality is also called Huejutla de Reyes and it is the largest community and most densely populated area of the region. The metropolitan area has a population of over 43,000 inhabitants (33 % of the total population of the municipality). Other communities in the municipality are considerably smaller with <5,000 inhabitants; approximately half of the population lives in communities with <1,500 inhabitants (Figure 3.15). The average density of the population in Huejutla is 311 inhabitants km^{-2}, and the average occupants per household is 4.7 (CONEVAL, 2016a).

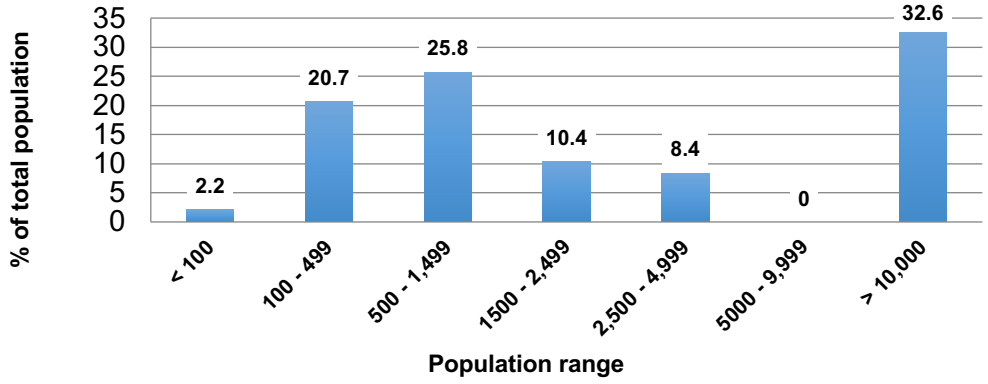
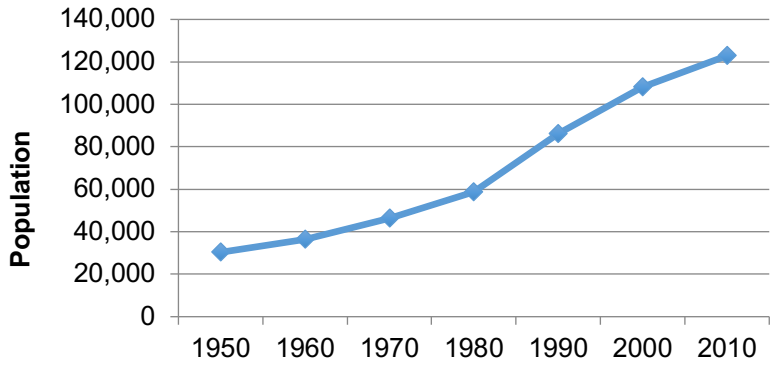


Figure 3.15 Size of communities in Huejutla de Reyes, Hidalgo (SEDESOL, 2013b)

The population in Huejutla has rapidly increased from 1950 to 2010 (Figure 3.16). The greatest population increase was observed from 1981 to 2000, when the municipality grew from 59,000 to

86,000 inhabitants (almost 50%). However, the growth rate slowed down to 14 % in the last recorded period (2000 to 2010). If this trend remains during the following decade, the projected population for 2020 in Huejutla will be in excess of 140,000.



Period	Population increase
1951-1960	20%
1961-1970	28%
1971-1980	27%
1981-1990	46%
1991-2000	26%
2001-2010	14%

Figure 3.16 Population growth in Huejutla from 1950 to 2010 (INEGI, 2002; SEDESOL, 2013b)

3.4.4. Socio-demographic indicators

The population distribution between different socioeconomic conditions (Section 3.4.3) in Huejutla is shown in Figure 3.17. A large proportion of the population (66.6 %) live in poverty (43.4 %) or extreme poverty (23.2 %). Significant numbers are also either vulnerable due to social deprivation or due to income. Only 8.3 % of the population is considered to be non-vulnerable or poor in Huejutla de Reyes (INEGI, 2009; CONEVAL, 2016a).

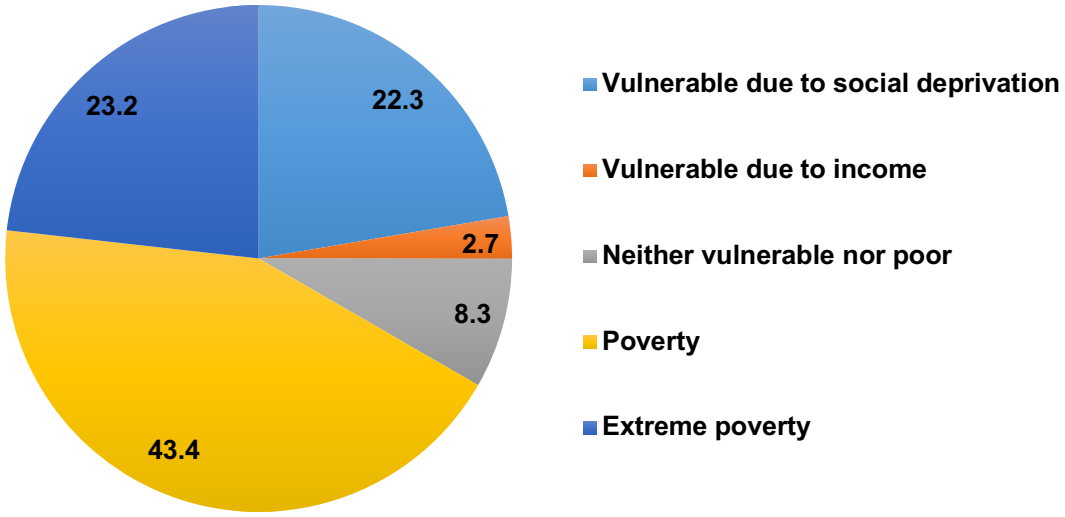


Figure 3.17 Population (%) living in poverty and vulnerability conditions in Huejutla (CONEVAL, 2015)

The proportion of the population affected by different poverty indicators is shown in Figure 3.18 for Huejutla in 2015. The indicator that scored higher is the percentage of the population who does not

have a chimney (54 %) when using coal or fire to cook in their household[13]. More than one third of the population has no access to health services and 22 % has inadequate waste collection services (CONEVAL, 2015; CONEVAL, 2016a). The term *inadequate waste collection services* refers to the percentage of households that burn, bury or dispose of their waste in open fields, streets, rivers, lagoons, cliffs or the sea (CONEVAL, 2009). It is important to mention that this indicator was calculated using information collected from one question related to the common waste disposal methods in households included in the national Household Income and Expenditure Survey (ENIGH by its initials in Spanish), therefore the numbers differ from the data obtained through fieldwork activities for this project and presented later in this dissertation.

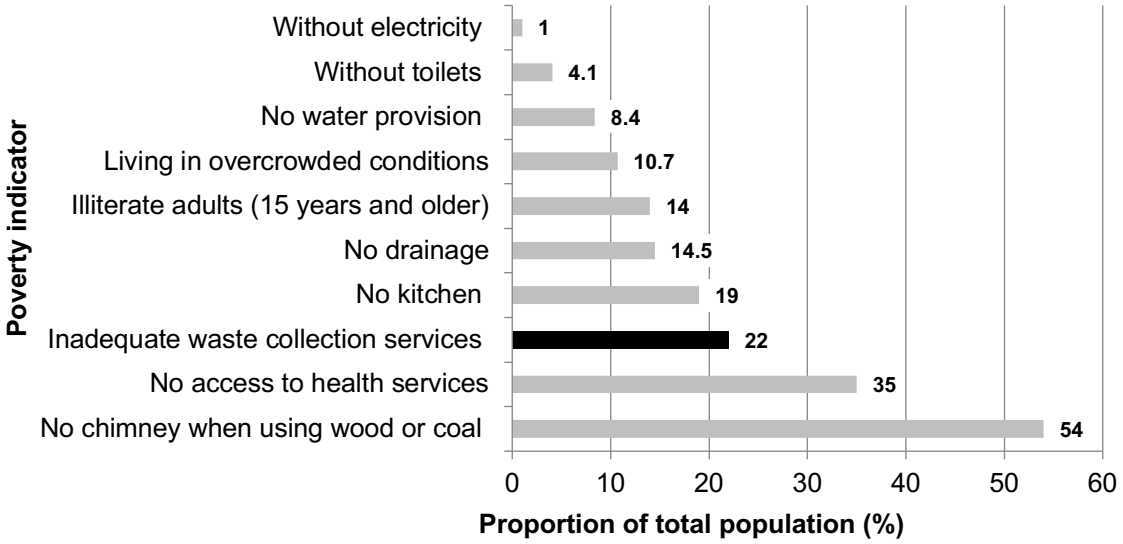


Figure 3.18 Poverty indicators in Huejutla de Reyes Hidalgo in 2015 (CONEVAL, 2015; CONEVAL, 2016a)

The spatial distribution of communities suffering from the two main categories of social marginalisation (extreme poverty and poverty) is shown in Figure 3.19, in relation to the location of urban areas in the municipality. Priority attention areas are also shown, where there is a high incidence of households with the highest social marginalization and extreme poverty conditions. The majority of communities living in such socially marginal conditions are located in rural areas (CONEVAL, 2016a). Priority attention areas are located in periurban areas, possibly in newly built neighbourhoods at the edge of the city. These areas have a higher population density compared to rural areas and therefore the concentration of families in poverty or extreme poverty conditions is larger. Overall, households within the urban area tend to have better socioeconomic status compared to periurban and rural areas.

[13] During fieldwork activities performed for this research, it was observed that most kitchens in Huejutla are located outside of the household.

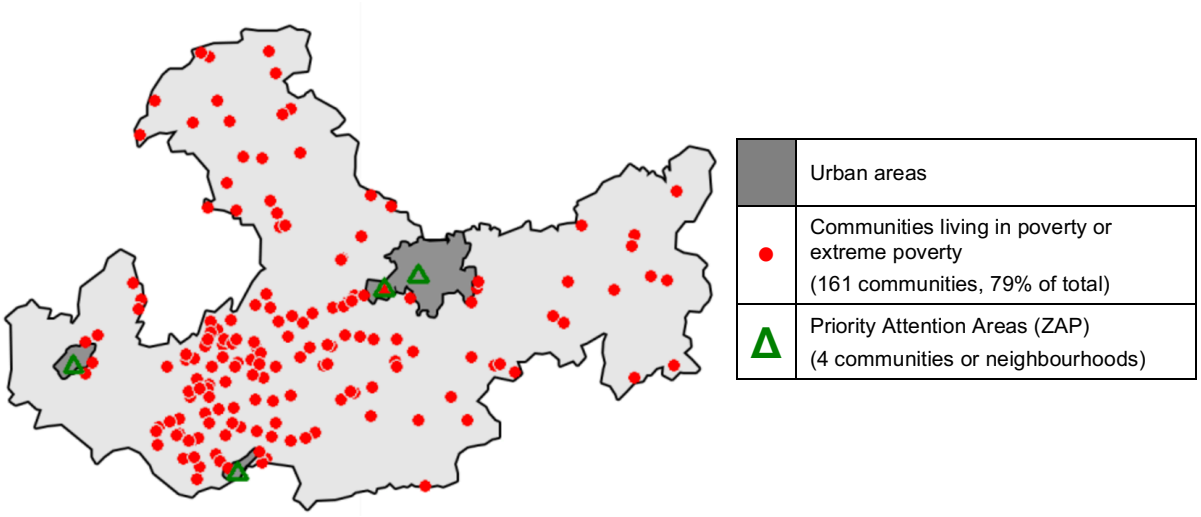


Figure 3.19 Spatial distribution of poverty and marginalisation in Huejutla de Reyes, Hidalgo (INEGI, 2009; CONEVAL, 2016a)

3.4.5. Published waste management data

Huejutla's Municipal Development Plan 2012-2016 (Ayuntamiento Constitucional de Huejutla de Reyes, 2012) states that around 50 t of MSW were collected per day in the municipality in 2010. More recent data retrieved from the national census for municipal governments and delegations (INEGI, 2014c) suggests that 55 t of waste were collected per day in 2013 in Huejutla. The Municipal Development Plan also states that the municipality owns 11 trucks for waste collection services, 6 with an open box, and 5 with waste compacting mechanisms. One of the objectives of the Municipal Development Plan was to expand the waste collection infrastructure by acquiring three compacter trucks and that promote recycling of waste, specifically of cardboard, polyethylene (PET), fabrics, glass, aluminium and bone among others. This would be achieved in collaboration with a private company and also through social communication strategies to promote waste separation in households (Ayuntamiento Constitucional de Huejutla de Reyes, 2012).

Solid waste disposal methods used by households at a state and municipal level are shown in Table 3.11 based on 2010 census data (INEGI, 2011). More than 40 % of households reported that they dispose of waste by open burning. This is higher than the overall rate of open burning for the State of Hidalgo, which is approximately 24 % (INEGI, 2011). Burning rates differ greatly within regions of the state as it depends significantly on the access to waste collection services, which tend to be better in the capital of the state and urban areas of large cities compared to smaller communities and periurban and rural areas.

Table 3.11 Methods for waste disposal in Huejutla de Reyes Municipality (% of households)

Area	Households	Household waste collection [a]	Waste container or dumpsite [b]	By burning [c]	Other [d]	Not specified
Hidalgo	673,159	69	5.3	24	1.2	0.2
Huejutla	26,952	59	0.3	41	0.1	0.2

a) Household waste collection: Includes houses where waste is collected by municipal authorities or independent collectors
b) Waste container or dumpsite: Households that dispose of their waste by taking it to a public container or municipal dumpsite
c) By burning: Households that burn waste as a disposal method
d) Other: Households that bury waste, dispose of waste in the street, cliff, river, lake or sea, or in an illegal dumpsite.

Source: (INEGI, 2011)

3.4.6. Waste regulations in the Municipality

Waste regulations for environmental protection in Huejutla were published in 2009 (Ayuntamiento Constitucional de Huejutla de Reyes, 2009). Table 3.12 describes the articles relating to the collection, transport, management and disposal of MSW. In particular, Article 5 states that burning of waste is illegal in Huejutla. Also, Article 135 bans actions that can be associated with emitting pollutants that have a detrimental impact on public health or harm the environment. This is the case of open burning of waste.

Table 3.12 Waste regulations in Huejutla de Reyes

Article	Description
5	The Municipal Government has the faculty of applying legal regulations related to the generation, transport, storage, management, treatment and final disposal of municipal and industrial solid waste, as long as it is not considered to be hazardous, following article 137 of the General Law for Ecological Balance and Environmental Protection (Congreso de la Unión, 1988). The Ecology Department of the Municipality is in charge of assigning land for the final disposal of MSW following the requirements stated in the Official Mexican Standard NOM-083-SEMARNAT-2003, about the specifications of environmental protection for the selection of the site, design, construction, operation, monitoring, closure, and complementary works of a site for final disposal of urban solid waste and wastes requiring special handling (Diario Oficial de la Federación, 2004). The Ecology Department is also in charge of the basic waste management activities at the final disposal site such as limestone covering, levelling and fumigation. It is the duty of the Department of Public Security and Civil Protection to carry out surveillance and arrest those individuals that are breaking the regulations stated in this document. **This includes burning of waste in streets, riversides, private land, households, commercial land and public spaces**, as well as dumping waste in non-authorised areas.
58	It is an obligation of those individuals that generate household solid waste to pay for the services of collection, transport, treatment and final disposal of waste. Moreover, it is mandatory to separate waste in organic and inorganic fractions and place them in plastic bags for their collection. The population should refrain from disposing of liquids, mixed organic and inorganic fractions and hazardous waste. It is an obligation of the population to participate in any programmes related to collection, separation, reduction, reuse and recycling of waste carried out by the municipal government. It is not allowed to dispose of waste in abandoned land, cliffs and riversides.
59	Commercial establishments that generate non-hazardous waste should apply for a registration with the environmental authorities of the municipality and should follow the regulations for waste disposal established by the municipal government.
101	This article establishes that Municipal Authorities of Huejutla will carry out activities for the integrated waste management of waste (collection, transport, treatment and final disposal) of households, businesses, industries and public spaces.
102	The Ecology Department of the Municipality will integrate public committees in the neighbourhoods of the city and the rural communities in collaboration with civil, education and health authorities with the purpose of encouraging the separation of waste and the determination of adequate places for its storage in order to ease its collection.
103	The Ecology Department will carry out capability building workshops for the public committees integrated into the municipality.
104	Municipal authorities will promote the participation of business owners in the installation of adequate containers for the separation of organic and inorganic waste within their premises.
126	This article prohibits the introduction of hazardous waste from other municipalities into Huejutla de Reyes. MSW will be admitted only if there is a signed agreement to do so.
127	Establishing temporary or permanent final disposal sites for hazardous waste in the municipality is not permitted.
128	Prohibits the collection, separation and transport of waste by non-authorized companies or individuals.
129	It is not allowed to dispose of waste from hospitals, automotive workshops, gas stations or construction sites in the final disposal site of the municipality.
130	This article prohibits disposing of waste in areas that are not authorised by the municipality.
135	States that emitting pollutants that have a detrimental impact on public health or harm the environment is not allowed.
Source: Ayuntamiento Constitucional de Huejutla de Reyes (2009)	

3.5. Characteristics of Juchitán de Zaragoza, Oaxaca

3.5.1. Location

Juchitán de Zaragoza is one of 570 municipalities in the state of Oaxaca in southeast Mexico, in the Tehuantepec Isthmus region (Figure 3.20). The municipality covers an area of 914 km², representing 0.43 % of the state of Oaxaca. Water bodies (lagoons connected to the sea) occupy almost half of the territory in Juchitán. The altitude of the municipality varies from 0 to 460 m above sea level. The majority of the rural areas of the municipality are dedicated to irrigated agriculture and a minor fraction to rain fed agriculture. Cultivated land in the municipality represents 20 % of the total territory. There is also pastureland and a small tropical rainforest (1.2 % of the total territory) near the northern border (INEGI, 1996; Ayuntamiento Constitucional de Juchitán de Zaragoza, 2014).

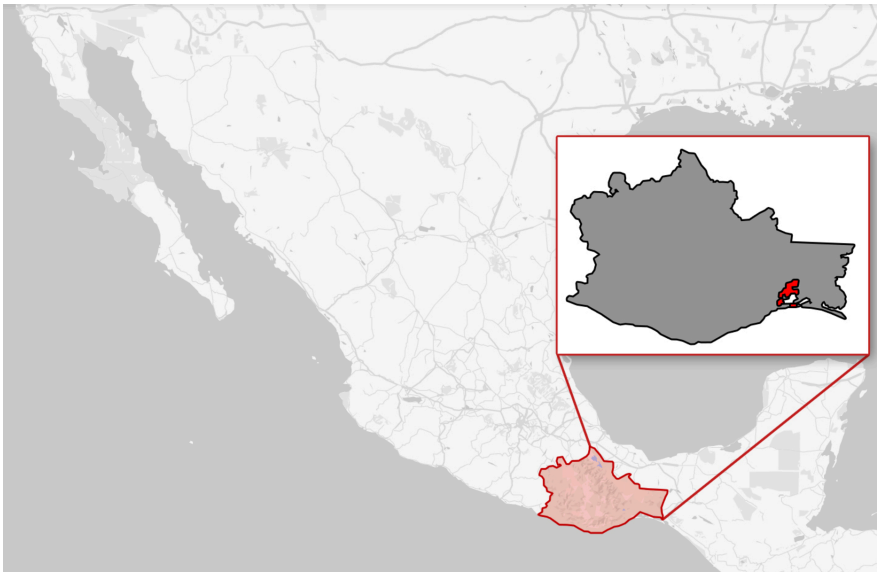


Figure 3.20 Location of Juchitán de Zaragoza, Oaxaca, México

3.5.2. Climate

The temperature in Juchitán is stable throughout the year, as shown in Figure 3.21. It goes from nearly 30ºC in the spring and summer to around 25 ºC in the winter months, with an average annual temperature of 27.4ºC. The maximum annual average temperature recorded was 32.1ºC and the lowest was 22.2ºC.

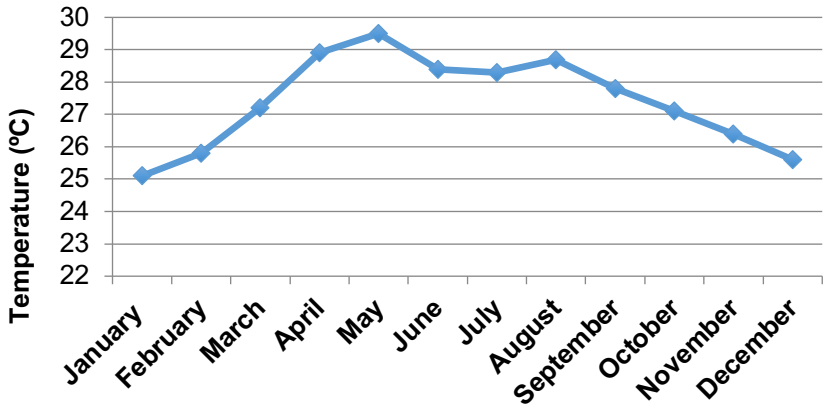


Figure 3.21 Monthly average temperature in Juchitán (1951-2010) (Servicio Meteorológico Nacional, 2011)

The weather in the municipality is classified as tropical wet-dry climate with most rains happening from May until October, as shown in Figure 3.22. There is practically no rain occcuring during the winter and early spring. The average annual rainfall in Juchitán is 986.4mm (Servicio Meteorológico Nacional, 2011).

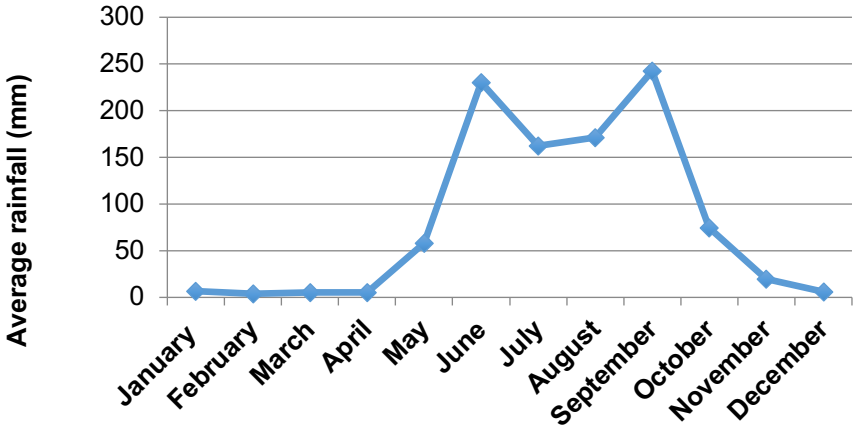


Figure 3.22 Monthly average rainfall in Juchitán de Zaragoza (1951-2010) (Servicio Meteorológico Nacional, 2011)

3.5.3. Population distribution and growth

The population in Juchitán de Zaragoza was over 98,000 inhabitants in 2015, approximately 2.5 % of the population of Oaxaca State (CONEVAL, 2016b). The capital of the municipality is also called Juchitán de Zaragoza and it is the most populated community, as 80 % of the population lives in this metropolitan area. Over 12 % of the population lives in communities with <5,000 inhabitants and around 7 % in communities with <2,500 inhabitants (Figure 3.23). The average population density in Juchitán is 101.75 inhabitants km^2 and the average occupants per household is 3.89 (SEDESOL, 2011).

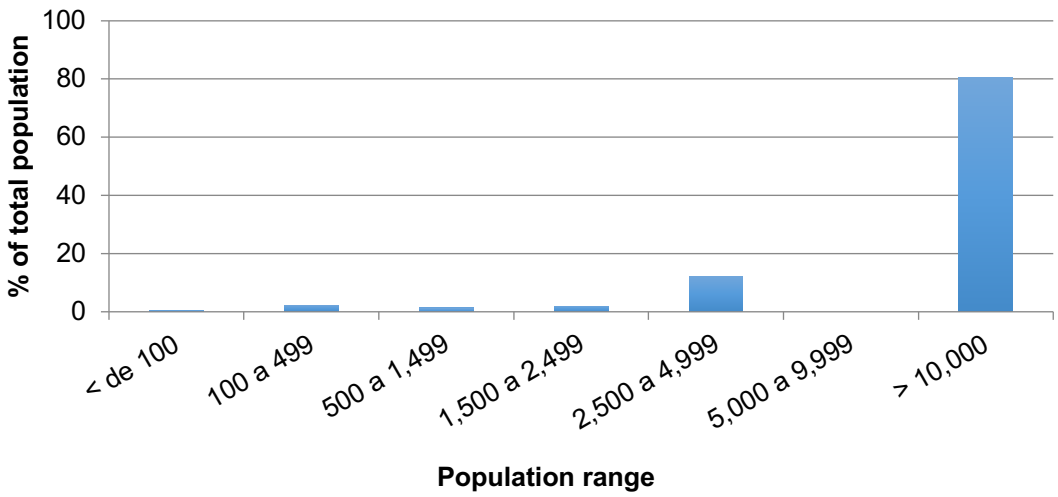
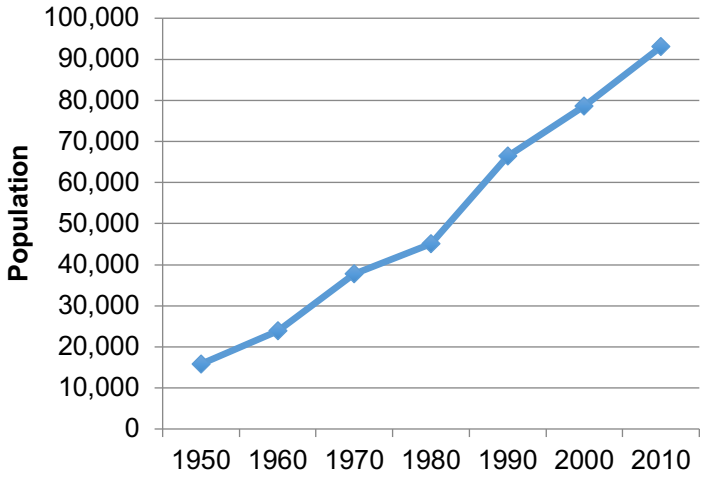


Figure 3.23 Size of communities in Juchitán de Zaragoza, Oaxaca (SEDESOL, 2011)

Figure 3.24 shows the population growth rate in Juchitán from 1950 to 2010. The population has shown a rapid growth, especially from 1951 to 1970 and 1981 to 1990, when the number of inhabitants in the municipality doubled. In the last period recorded (2001-2010), the growth rate was near to 20 %. If this trend remains during the following decade, the projected population will reach 110,000 inhabitants in 2020.



Period	Population increase
1951-1960	51 %
1961-1970	58 %
1971-1980	19 %
1981-1990	48 %
1991-2000	18 %
2001-2010	19 %

Figure 3.24 Population growth in Huejutla from 1950 to 2010 (INEGI, 1996; SEDESOL, 2011)

3.5.4. Socio-demographic indicators

The population distribution between different socioeconomic characteristics in Juchitán is shown in Figure 3.25. Almost 62 % of the population in Juchitán lives in poverty or extreme poverty conditions, around 30 % is vulnerable due to social deprivation or due to income and only 10 % of the population is considered to be non-vulnerable or poor (CONEVAL, 2016b).

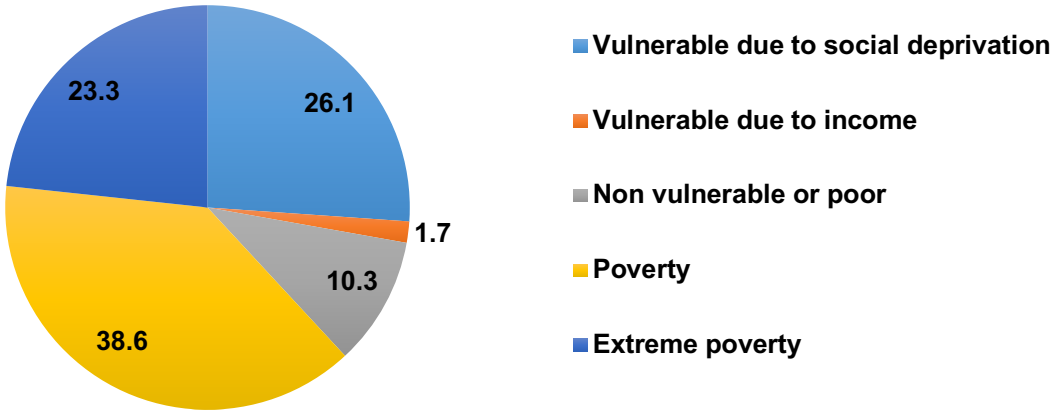


Figure 3.25 Population (%) living in poverty and vulnerability conditions in Juchitán de Zaragoza (CONEVAL, 2016b)

The framework to evaluate poverty in Juchitán shows that more than 43 % of the population has no access to public health services. Over 18 % of the population has no chimney when using wood or coal in their premises. However, similarly to the case of Huejutla, during the fieldwork activities of this research, it was observed that in Juchitán most people that use wood or coal for cooking purposes do so in the outside area of the household. This framework also reports that 12 % of the population in this municipality has access to inadequate waste collection services[14]. Just as in the other case study region, the indicator for inadequate waste collection services presented in Figure 3.26 was calculated using information collected for the national Household Income and Expenditure Survey (ENIGH by its initials in Spanish) therefore these numbers differ from the data obtained through fieldwork activities for this project and presented later in this thesis.

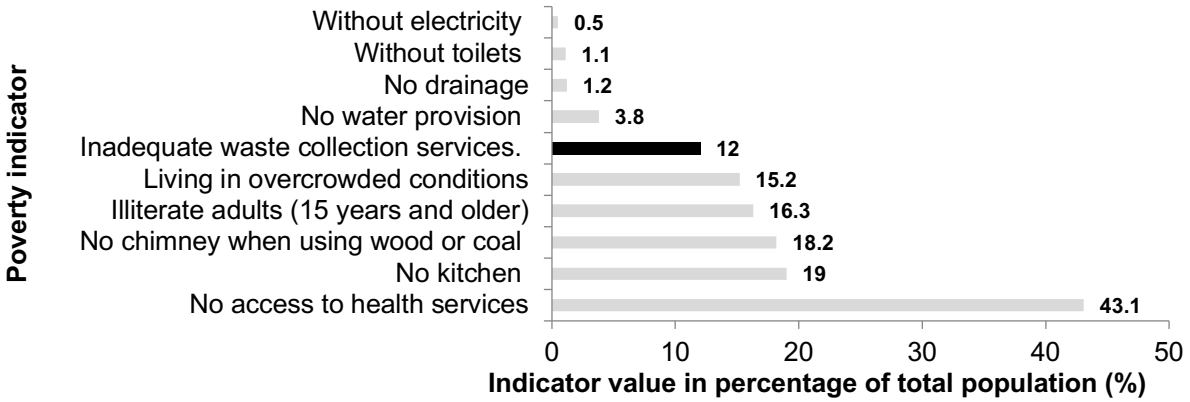


Figure 3.26 Poverty indicators in Juchitán de Zaragoza in 2015 (CONEVAL, 2013; CONEVAL, 2016b)

[14] "Inadequate waste collection services" refers to the percentage of households that burn, bury or dispose of their waste in open fields, streets, rivers, lagoons, cliffs or the sea (CONEVAL, 2009).

The spatial distribution of communities suffering from the two main categories of social marginalisation of extreme poverty and poverty in Juchitán is shown in Figure 3.27. It is observed that the majority of the communities living in poverty and extreme poverty conditions in this municipality are located outside and rather distant, of the urban areas of the municipality. Most of the priority attention areas are located in periurban areas of the municipality, where it is common to find newly built neighbourhoods with a high incidence of households with no access to basic services, and where its inhabitants are living in poverty conditions. Just as in the case of Huejutla, this map shows that households within the urban areas tend to have better socioeconomic status compared to the periurban and rural areas in the Municipality.

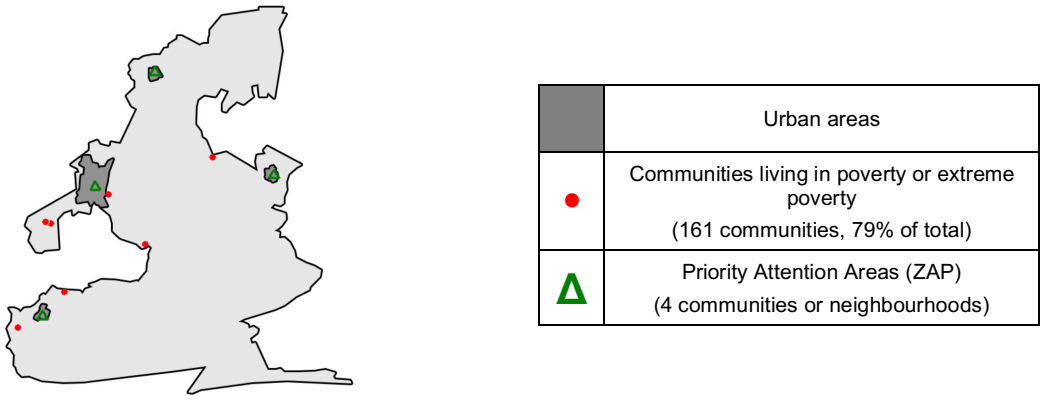


Figure 3.27 Spatial distribution of poverty and marginalisation in Juchitán de Zaragoza (INEGI, 2010b; CONEVAL, 2016b)

3.5.5. Published waste management data

The national census for municipal governments and delegations states that waste collection was around 90 tons per day in 2013 in Juchitán and that municipal authorities owned 4 compacted trucks for waste collection services (INEGI, 2014c). The municipal development plan for the 2014-2016 period states that waste generation in Juchitán was over 98 tons per day in 2014 (Ayuntamiento Constitucional de Juchitán de Zaragoza, 2014), however, they do not specify how much of this is collected. In this document, municipal authorities describe waste management services as inappropriate, as there is no treatment carried out after waste is collected and taken to the final disposal site. Moreover, authorities state that waste is burned in the final disposal site to reduce its volume, generating polluting emissions to the environment. Additionally, during the windy season (autum and winter), waste in the final disposal site is blown away to the surrounding areas, polluting agricultural fields and water bodies, severely affecting farming and fishing activities. There is no procedure in place to manage hazardous material coming from the hospitals in the municipality, and there is no census for the sources of this type of waste (Ayuntamiento Constitucional de Juchitán de Zaragoza, 2014).

Municipal authorities state that the regulation of hazardous waste management is urgent, as well as the improvement of current MSW management practices. They propose to acquire infrastructure to improve waste collection services and provide waste bins in all neighbourhoods of the urban area of

the municipality. Municipal Authorities declared to have 11 waste collection trucks (3 of them serving central public spaces and streets) and 600 waste containers in the centre of the city. The municipality employs around 180 workers for waste collection and cleaning purposes and states that 85 % of them collect waste from businesses, schools, markets, parks, streets and avenues in the centre of the city. The other 15 % collects waste from the same sources, but in periurban areas of the municipality (Ayuntamiento Constitucional de Juchitán de Zaragoza, 2014).

The extended census carried out in 2010 revealed that Oaxaca is the state with the highest incidence of uncontrolled burning of waste as a disposal method in Mexico (Table 3.13). However, it also showed that Juchitán Municipality has a much lower rate of open burning of waste compared to the average in Oaxaca state, as only around 13 % of the households use this waste disposal method in households.

Table 3.13 Methods for waste disposal in Juchitán de Zaragoza (% of households)

Area	Households	Household waste collection [a]	Waste container or dumpsite [b]	By burning [c]	Other [d]	Not specified
Oaxaca	936,359	52	4.3	41	2.7	0.4
Juchitán	21,735	78	5.5	13	3.3	0.1

a) Household waste collection: Includes houses where waste is collected by municipal authorities or independent collectors
b) Waste container or dumpsite: Households that dispose of their waste by taking it to a public container or municipal dumpsite
c) By burning: Households that burn waste as a disposal method
d) Other: Households that bury waste, dispose of waste in the street, cliff, river, lake or sea, or in an illegal dumpsite.
Source: INEGI (2011)

3.5.6. Waste regulations in the Municipality

Currently there are no published environmental or waste regulations for Juchitán de Zaragoza. However, as described previously in this chapter, the Mexican Constitution specifies in Article 115 that municipalities are responsible for providing citizens with waste management services, and the Article 100 of the "General Law for the Prevention and Integrated Management of Waste" states that the regulations related to the generation, management and disposal of waste include the prohibition of the uncontrolled open burning of waste.

3.6. Discussion

Table 3.14 presents a summary of the main characteristics of the two case study areas selected for this research. Huejutla de Reyes and Juchitán de Zaragoza share certain characteristics, such as the size of their population (98 thousand and 130 thousand inhabitants), population growth rates per decade (14 % and 19 %) and the number of people living in poverty and extreme poverty conditions (62 % and 67 %). Some of the differences include the location, as Huejutla is in Central Mexico, and Juchitán in the Southeast. Another difference is that while Huejutla is a landlocked municipality, half of the territory in Juchitán is comprised of lagoons that are connected to the sea. Published information about waste generation and management also differs between the two municipalities, the Municipal Development Plan for Huejutla (Ayuntamiento Constitucional de Huejutla de Reyes, 2012) presents a

waste generation of 50 t day^{-1} of waste, while municipal authorities in Juchitán estimate that 98 tons day^{-1} are generated (Ayuntamiento Constitucional de Juchitán de Zaragoza, 2014). Per capita waste generation in Huejutla is equivalent to 0.4 kg day^{-1}, which is less than half of the per capita waste generation in Juchitán (1 kg day^{-1}).

The annual poverty and social marginalisation report states that 22 % and 12 % of the population in Huejutla and Juchitán respectively, have inadequate waste collection services (CONEVAL, 2015), (CONEVAL, 2016b). The extended census in 2010 revealed that over 40 % of the population in Huejutla dispose of waste by burning, while in Juchitán, approximately 13 % of households use this method of waste disposal (CONEVAL, 2016a), (CONEVAL, 2016b). Nevertheless, this information differs from the data found through fieldwork activities carried out for this research and that will be discussed in further chapters of this thesis.

Table 3.14 Main characteristics of case study areas

Characteristic	Huejutla de Reyes	Juchitán de Zaragoza
Location	Central Mexico, Huasteca Region	Southeast Mexico, Tehuantepec Isthmus Region
Population in 2015 [a]	129,919	98,043
Population growth 2000 – 2010 [b]	14 %	19 %
Population living in poverty or extreme poverty [c]	66.6 %	61.9 %
Urban / Rural population [d]	33% / 67 %	80% / 20 %
Population with inadequate waste collection [e]	22 %	12 %
Published waste generation data [f]	48 t day^{-1} (in 2010)	98 t day^{-1} (in 2014)
Waste per capita according to local authorities [g]	$0.4^{(8)}$ kg day^{-1}	1 kg day^{-1}
Households that dispose of waste by open burning [h]	40.91 %	13.26 %

a) (CONEVAL, 2016a), (CONEVAL, 2016b)
b) (INEGI, 1996), (INEGI, 2002), (SEDESOL, 2011), (SEDESOL, 2013a)
c) (CONEVAL, 2015), (CONEVAL, 2016b)
d) (SEDESOL, 2013b), (SEDESOL, 2011)
e) (CONEVAL, 2016a), (CONEVAL, 2016b)
f) (Ayuntamiento Constitucional de Huejutla de Reyes, 2012). (Ayuntamiento Constitucional de Juchitán de Zaragoza, 2014).
g) Using population in 2010 (122,905 inhabitants), as the waste generation data available for Huejutla is from that year
h) (INEGI, 2011)

Waste management practices vary significantly between different regions of Mexico, and depend to a great extent on community size and socioeconomic status. In general in Mexico, smaller communities tend to be the poorest. Using information from the 2010 Census (INEGI, 2011) about methods of waste disposal in households, and waste generation data, it was possible to determine an approximate amount of waste that is disposed by open burning in Mexico. Two methods were applied for this purpose, obtaining different results: by state (8.3 $x10^3$ t day^{-1}, Table 3.7, page 61) and by community size (3.8 x 10^3 t day^{-1}, Table 3.8, page 63). This difference occurs because calculating open burning of waste by community size takes into consideration that the percentage of households that dispose of waste by burning in small communities is higher, however, the amount of waste generated by small communities is lower compared to larger urban areas with access to better waste

collection services. Specifically, small communities represent 38 % of the total population and generate 12 % of the waste, but account for 80 % of the waste that is disposed by uncontrolled burning in the country (Table 3.8).

The amount of waste burned in dumpsites in Mexico is difficult to approximate, as there are no sources reporting this method of waste disposal. However, solid waste management experts in Mexico suggest that 50 - 80 % of the waste in dumpsites is disposed by burning in uncontrolled final disposal sites. Using this information, it was possible to approximate upper and lower estimates for the total amount of waste disposed by open burning in both households and dumpsites. Specifically, it was estimated that between 18 % and 31 % of the waste generated in Mexico is disposed by burning in uncontrolled open fires. There is considerable uncertainty in the rates of open burning of waste calculated using national statistical information. Measurements of the activity rate in the field in representative communities where open burning is commonly practised are necessary to reduce this uncertainty levels. However, the information presented here exposes the extent of the problem of open burning of waste in Mexico.

4. Direct evidence collected from municipal authorities, stakeholders and householder groups on waste disposal practices in the case study areas

4.1. Introduction

This chapter will present the information obtained from 500 door-to-door surveys conducted in the two case study areas that commonly burn waste in Mexico: Huejutla de Reyes, in the state of Hidalgo, and Juchitán de Zaragoza, in the State of Oaxaca. The surveys collected information about the drivers influencing waste disposal, recycling and burning patterns in urban and rural areas, as well as respiratory disease frequencies in the household, cooking methods and smoking habits. This information will help understand the impact of the emissions from open burning of waste compared to other sources of pollution within the household.

This chapter will also present information obtained from a series of interviews carried out with waste management municipal authorities and other key stakeholders in the waste management sector of the two municipalities. The data collected through these interviews helped to understand the characteristics of the waste management process in each of the case study areas. These interviews also provided data to quantify the waste generated by non-residential sources, such as schools, hospitals and businesses.

The analysis of respiratory health databases collected from municipal authorities in the case study areas (Huejutla and Juchitán) will also be presented, with the objective of indentifying any potential link to the uncontrolled open burning of waste. Uncontrolled burning of waste releases a wide range of toxic pollutants, including CO_2, dioxins, furans, CH_4 and PM including BC (Christian et al., 2010; Stockwell et al., 2016; Jayarathne et al., 2017). Black carbon is a component of PM, and is especially dangerous to human health because of its small size with a diameter <2.5 micrometres. Black carbon particles can penetrate the respiratory system through the lungs and enter the bloodstream, causing cardiovascular and respiratory diseases, and eventually, premature death (WHO, 2003). Individuals previously affected by cardiovascular and respiratory diseases, the elderly, and children are at highest risk from exposure to BC (US EPA, 2016).

The health implications of the uncontrolled burning of waste are strongly suspected (Cogut, 2016; Kodros et al., 2016), but few data are available measuring the actual impacts on the human population. Kodros et al. (2016) estimated the extent of premature adult mortalities from chronic exposure to PM of less than 2.5 micrometre diameter ($PM_{2.5}$) from open burning of waste. Health data were incorporated into the waste emission inventory for open burning of waste by Wiedinmyer et al. (2014). The results suggested that uncontrolled combustion was responsible for 270,000 adult mortalities per year. In comparison, deaths caused by malaria infections are equivalent to 580,000 globally each year (UNICEF, 2015). The mortality rate from open burning of waste is similar to the numbers of mortalities estimated for exposure to $PM_{2.5}$ emissions from solid fuel cook stoves, which are equivalent to 300,000 to 400,000 per year (Chafe et al., 2014; Butt et al., 2016; Kodros et al., 2016). Indeed, Kodros et al. (2016) concluded that emissions from open burning of waste caused approximately 10% of the total ambient $PM_{2.5}$ mortalities.

The aim of this chapter was to identify waste disposal practices in the case study areas to better understand open waste combustion and its potential health impact in the case study areas. The objectives were to:

a) Carry out interviews with municipal authorities in the waste sector to collect information on waste disposal practices.
b) Obtain and gather reported information on the density and type of settlements in the case study areas, and to classify them into urban, periurban and rural areas.
c) Identify and interview the key stakeholders of the waste management sector.
d) Design and apply a waste management questionnaire to randomly selected householders to obtain information on waste disposal behaviours and respiratory disease frequencies.
e) Clinical databases of respiratory diseases from health authorities in the case study areas were examined and rates of infection in urban and rural populations were calculated
f) Calculate the population distribution statistics in rural, periurban and urban areas served by different medical facilities;
g) Assess the contributory factors that may be potentially important in influencing the rates of respiratory diseases in the case study areas.

4.2. Materials and methods

4.2.1. Household questionnaire design

A structured household questionnaire was designed to collect specified information on waste disposal practices by householders. The questionnaire was based on closed questions to provide uniformity of the obtained data, to simplify the analysis of the information and minimise ambiguity in the responses and therefore in the interpretation of the results. The design of the questionnaire followed a structure used by INEGI (2011) for the national extended census carried out in 2010. Answers for each question were assigned a numerical value to facilitate interpretation. For example, the approach used in the national extended census was adopted and scores between 1 and 7 applied to specific selected answer options, whereas scores of 8 or 9 were assigned when the respondant did not know or did not wish to respond the answer to the question asked, respectively.

The first section of the questionnaire was designed to collect information on the general demography of household members, including gender and age. The following section included questions on the feeding of food-waste to pets and farm animals. The next questions were about the frequency and costs of the waste collection service in the neighbourhood. The survey also included questions to gather information about waste separation and recycling patterns in the household. A critical section of the questionnaire was about the frequency of waste burning activities in the neighbourhood and in the household, and the identification of unofficial local sites where open burning of waste was commonly practised. Questions were also added to collect information about the frequency of respiratory diseases in children, adults and the elderly. The final section of the questionnaire was designed to gather information on the socioeconomic status of the family by identifying electrical and electronic device ownership, adopting the protocol recommended by INEGI (2013). In the second survey performed in Juchitán, two questions were added to collect data on

smoking habits and cooking methods, with the objective of identifying other sources of BC emissions within the household that are related to respiratory health (Lin et al., 2008). The results obtained from the questions relating to respiratory health are presented and discussed in detail in Chapter 9 on the impacts of BC from waste combustion on respiratory health. The full questionnaire is provided in APPENDIX A3.

4.2.2. Selection of surveyed households and questionnaire completion

Data were collected for a total number of 240 randomly selected properties within Municipality of Huejutla including: 100 urban, 80 periurban and 60 rural households. For Juchitán, 250 households were surveyed, 200 of them belonging to urban/periurban areas and 50 were rural households. The distribution of households selected for the questionnaire in both case study areas was based on the location of urban, periurban and rural communities in each area to ensure all community types and marginalisation characteristics were represented (Figure 4.1 and Figure 4.2).

The questionnaires were completed between 27 May – 5 June 2015 for Huejutla and between 4 – 8 April 2016 for Juchitán. A team of 4 undergraduate students in each case study area were employed, trained and supervised to help with the household visits. This significantly expanded the total number households that could be visited for data collection in the survey.

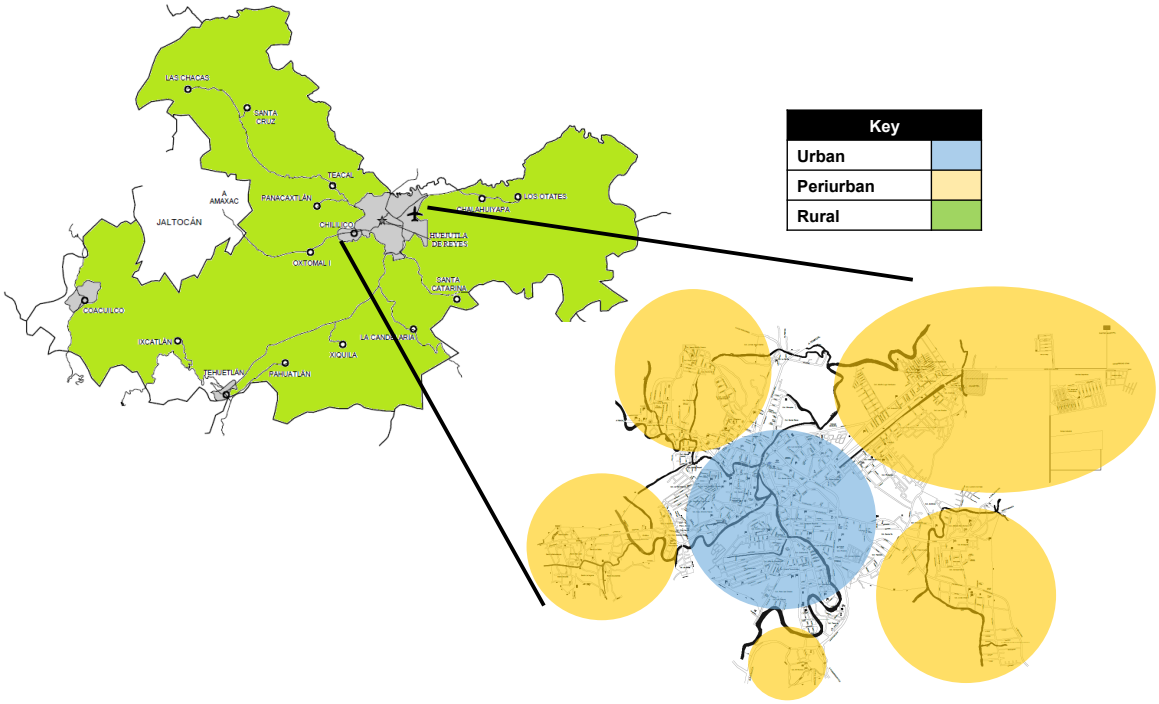


Figure 4.1 Location of urban, periurban and rural areas in Huejutla de Reyes Municipality

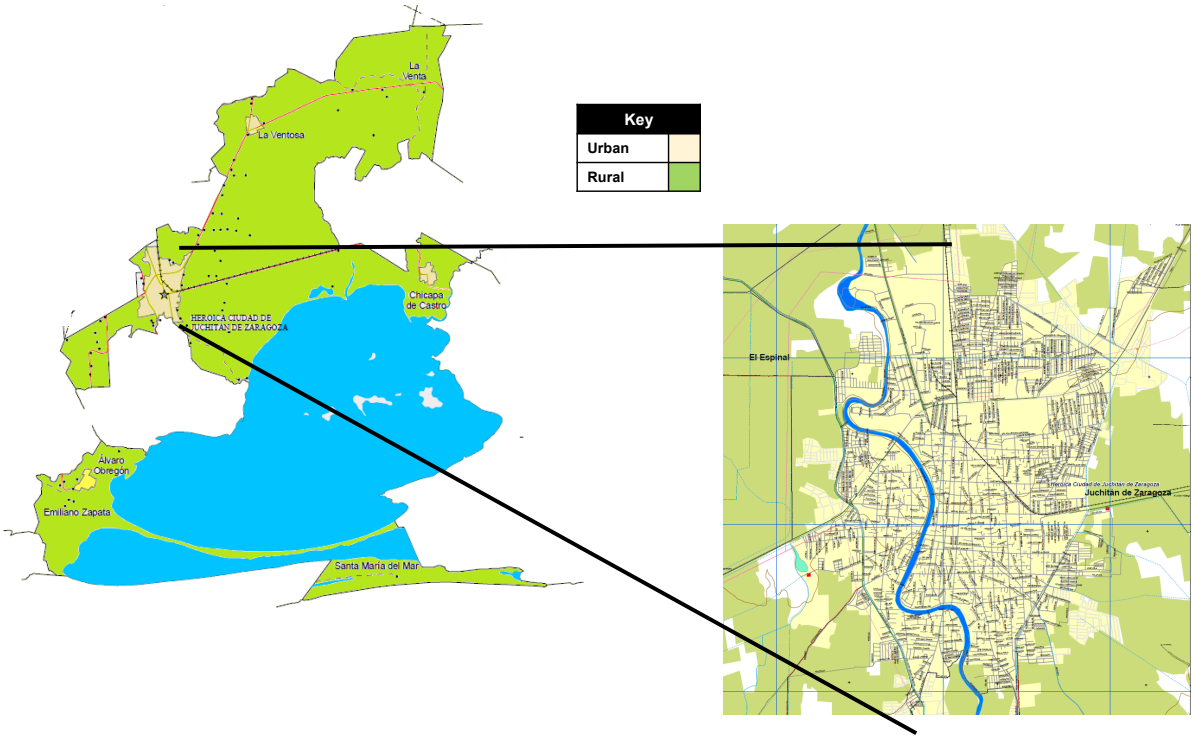


Figure 4.2 Location of urban and rural areas in Juchitán de Zaragoza Municipality

4.2.3. Interviews with key stakeholders in the waste sector

Interviews were carried out with municipal authorities responsible for environmental services and waste management activities, waste truck drivers and their helpers, waste pickers in official and unofficial dumpsites, waste recovery facilities and environmental not-for-profit organisations. The object was to obtain information about household and non-household waste generation, waste management strategies and waste recycling in the study areas. The detailed description of the interviews with key stakeholders and the data or resources gathered through this process is presented in Table 4.1 for Huejutla and in Table 4.2 for Juchitán. Contact with stakeholder communities in the case study areas was initially made with the Director of the Ecology Department in Huejutla, and the assistant to the Municipal President in Juchitán, and then subsequently by their recommendation and by word of mouth to other key individuals involved in the waste management sector.

Table 4.1 Interviews with stakeholders in Huejutla

Stakeholder	Number of people interviewed	Information/resources provided
Director of the Ecology Department in the Municipality of Huejutla	1	• Letter approving the project by the Municipal Authority, to facilitate contact with private householders, other waste stakeholders and health authorities. • A vehicle for the waste collection and characterisation assessment. • Contact with the Waste and Cleaning Services Manager and with the recycling centres in Huejutla.
Waste and Cleaning Services Manager in the Municipality of Huejutla	1	• Information about waste management practices at the municipal disposal site, quantities of waste collected from households and commercial sites, waste collection routes and frequency, capacity and number of waste trucks, number of waste truck drivers contracted by the Municipality, and number of informal waste pickers working at the dumpsite.
Waste truck drivers contracted by the Municipality	4	• Confirmation of waste collection routes and quantities of waste collected per day. • Quantity and type of waste separated informally by truck drivers and their assistants for sale to private recycling centres.
Waste pickers at the dumpsite (informal workers)	5	• Confirmation of the number of individuals picking waste at the municipal dumpsite. • Type and quantity of waste recovered. • Contact details of the commercial recycling centres that purchase collected recyclable materials.
Managers at recycling collection centres	5	• Quantity and type of waste processed by each collection centre per month. • Destinations of the recovered materials for final recycling.
Independent waste collectors (recyclables)	4	• Quantity and type of material collected, collection routes and the waste recycling centres that buy collected recyclables.
Deputy Director of Public Health Provision in Huejutla	1	• Database for respiratory diseases registered in Huejutla.

Table 4.2 Interviews with stakeholders in Juchitán

Stakeholder	Number of people interviewed	Information/resources provided
Assistant of the Municipal President in Juchitán	1	• Letter approving the project by the Municipal Authority, to facilitate contact with private householders, other waste stakeholders and health authorities. • Contact with Municipal Waste Collection Unions • Contact with project manager for the design and construction of new waste management facility
Former director of the Ecology Department in Juchitán	1	• Location of legal and illegal dumpsites • Description of the waste management system in Juchitán • Estimated data on waste generation in the Municipality
Director of the Ecological Forum (NGO)	1	• Contact with managers of Independent Waste Collection Unions • Estimated data on waste generation in the Municipality • Undergraduate dissertation on waste management in Juchitán • Provided a space for waste characterisation analysis in a small waste management facility in the Forum • Provided transportation and the help of a collaborator to visit legal and illegal dumpsites
Managers of Municipal Waste Collection Unions	3	• Quantity of waste collected per day • Areas of waste collection • Quantity of waste recovered for recycling
Managers of Independent Waste Collection Unions	2	
Managers in dumpsites	2	• Quantity of waste received per day • Information about waste management in dumpsite • Information about the number of waste pickers at dumpsite
Waste collection truck drivers	3	• Quantity of waste collected per day • Information on the type of waste and quantities recovered for recycling per day • Contacts for waste recycling facilities
Waste pickers at dumpsites	6	• Confirmation of the number of waste pickers working at dumpsites • Information on the type of waste and quantities recovered for recycling per day
Managers at recycling collection centres	6	• Type of waste and quantity recovered per month • Destiny of waste recovered by the facility
Project manager for the design of a new waste-to-energy facility in Juchitán	1	• Documentation on waste characterisation analysis for Juchitán • Information (plans and design) on waste to energy facility
Director of Public Health Provision in Juchitán	1	• Database for respiratory diseases registered in Juchitán

4.2.4. Clinical health data collection for respiratory diseases

Respiratory health data for Huejutla and Juchitán were obtained from the Municipal Health Authorities (Jurisdicción Sanitaria 10 de Huejutla de Reyes, 2015; Jurisdicción Sanitaria 2 del Istmo de Tehuantepec, 2016). The databases provided by the Health Authorities reported the number of cases of respiratory disorders in each medical facility, or clinic, per year. Databases included the number of reported respiratory cases, but not the origin of patients; therefore it was assumed that patients attending a specific medical centre also originated from that local community. The rate of

disease burden in urban and rural areas was calculated using the total population statistics obtained for each of these community types.

The respiratory health database provided by the Municipal Authorities in Huejutla included information from surrounding municipalities served under the same sanitary jurisdiction: Atlapexco, Huautla, Jaltocan, San Felipe de Orizatlán, Xochiatipan and Yahualica (Figure 4.3). The information was subdivided into medical units located in different communities in each municipality. These municipalities have similar waste management, generation and uncontrolled burning of waste characteristics compared to Huejutla, as shown in Table 5.8 and Figure 5.3. Therefore, the medical data is assumed to be representative of the whole area, which can be divided in urban and rural communities. The communities in Huejutla's surrounding municipalities were smaller than 5,000 inhabitants and were therefore considered to be rural. In this region, the only community that was categorised as an urban area was the capital of Huejutla Municipality with approximately 40,000 inhabitants. The medical units in rural areas provided services to more than 146,000 inhabitants. Health statistic data for Huejutla were available from 2005 to 2014.

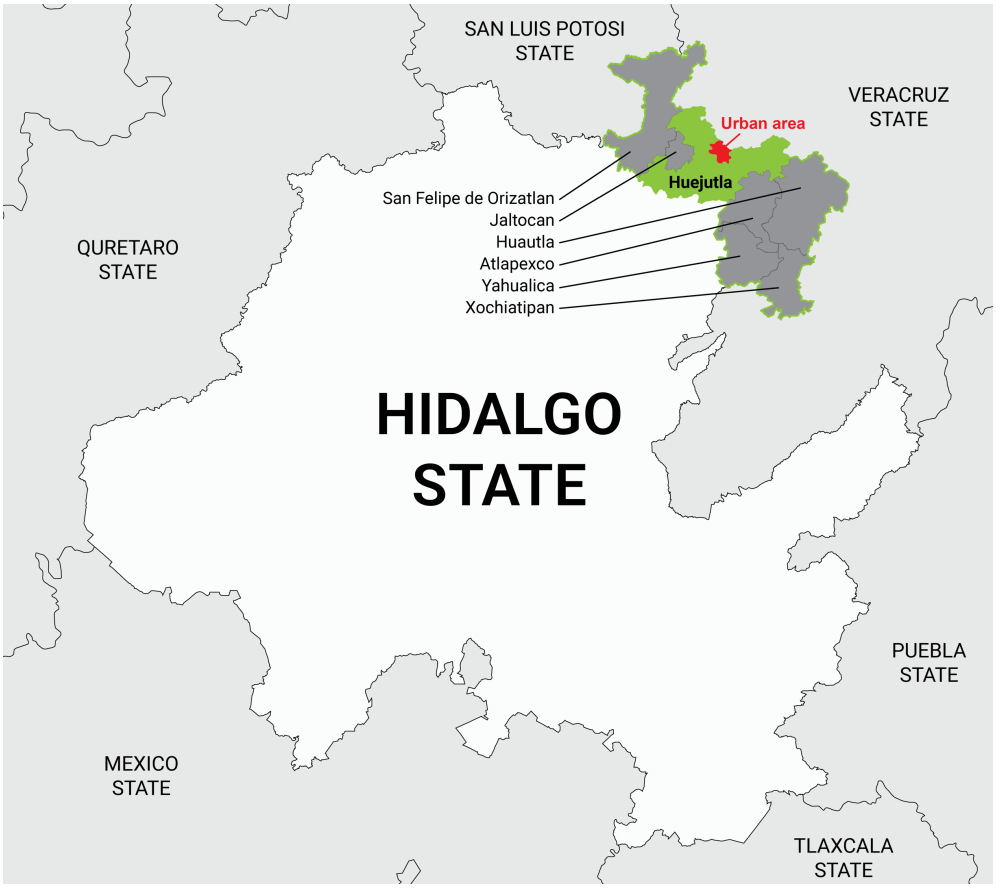


Figure 4.3 Municipalities served by the Health Authority in Huejutla de Reyes

The Health Authority in Juchitán provided respiratory health data from 2006 to 2015 (Jurisdicción Sanitaria 2 del Istmo de Tehuantepec, 2016). In this case, all the medical units in the database were located in the Municipality of Juchitán. In total, 9 medical units were located in urban areas, and

provided health services to almost 75,000 people, equivalent to approximately 80 % of the total population in the Municipality. Five medical units were located in rural areas of the Municipality, serving a population of over 18,000 inhabitants (20 % of the total population).

4.2.5. Health data from household questionnaire in case study areas

The household questionnaire conducted in the case study areas included questions to gather information about the frequency of respiratory diseases in children, adults and the elderly in urban, periurban and rural areas. In the second survey performed in Juchitán, two questions were also added to collect data on smoking habits and cooking methods, with the objective of identifying other sources of BC emissions within the household that are related to respiratory health (Lin et al., 2008).

4.3. Results

4.3.1. Data collected through interviews with key stakeholders in Huejutla

In Huejutla, the Waste and Cleaning Services Department of the Municipality operate a waste collection service and one main dumpsite, and all collected waste is disposed at this site. Approximately 30 t day^{-1} are collected at households and 40 t day^{-1} at public spaces (including streets, parks, schools and hospitals) and businesses. At the dumpsite, waste is consolidated by a mechanical compacting machine and covered with a layer of soil at intervals of 4-6 weeks. The Municipal Authority ceased burning waste at the dumpsite in 2013 and do not acknowledge the occurrence of informal open burning by households within the region where it is responsible for the collection and disposal of MSW.

Waste collection services in Huejutla are free of charge for households. The results of the household questionnaire corroborated information given by the Municipal Authority on the frequency of the waste collection services. Urban households received a daily waste collection service and waste was collected at a reduced frequency of two times per week in periurban areas. In rural areas of Huejutla, collection round data provided by the municipality indicated that 70 % of households had access to a waste collection service for bulky and non-compactable materials, such as bed mattresses or glass, but general household waste was not collected. The frequency of this more limited service to rural areas was once every 1 to 3 months. Provision of this service is not automatic and the local mayor has to be proactive and make a request to the Waste and Cleaning Services Department of the Municipality. Hence, collection services were very limited in rural communities.

The Municipality operated a fleet of 9 trucks (5 compacter trucks, 1 mini compacter and 3 carrier trucks) to collect waste, and employed 14 drivers. Truck drivers were also engaged in informal recycling activities, to provide an additional income source from the sale of high value recyclates (e.g. aluminium cans, metals, and in some cases polyethylene (PET) and high-density polyethylene (HDPE) containers. Private waste collectors (approximately 15) employed by the waste recovery facilities, also provided a recyclate collection service (mostly metals from discarded furniture or appliances) mainly in more densely populated urban areas. Interviews with the group of independent operators indicated that the collection and sale of PET and aluminium cans was commonly practised in the Municipality. Twenty informal pickers were licensed by the Municipality to collect waste at the

dumpsite for recycling. Recyclable materials collected by these different groups were taken and sold to private waste recovery facilities (5 facilities operated in the Municipality, Table 4.3) that prepare, bale and transport recycled materials for reprocessing in other municipalities. However, no recyclate processing industries operated in the Municipality of Huejutla.



Figure 4.4 Waste recovery facilities and waste collection services in Huejutla

Collectively, waste recovery facilities diverted a total of 75 t of waste per month from landfill disposal. Evidence collected during interviews with informal waste pickers, indicated that approximately 36 t of waste were recovered each month at the dumpsite. Truck drivers (and their helpers) employed by the Municipality to carry out waste collection services recovered approximately 9 t of waste each month during the waste collection process. The materials recovered by truck drivers were then sold to one of the waste recovery facilities in the Muncipality. A detailed description of the materials recovered in Huejutla is presented in Table 4.3.

Table 4.3 Recovery of waste per month by recovery facilities and at the municipal dumpsite (kg month^{-1})

Type of material recovered	Waste recovery facility 1	Waste recovery facility 2	Waste recovery facility 3	Waste recovery facility 4	Waste recovery facility 5	TOTAL
Aluminium	1,000	100	250	250	250	1,850
Steel	3,500	3,000	15,000	15,000	15,000	51,500
Plastics	5,000	1,500	300	300	300	7,400
Paper	500	3,000	-	-	-	3,500
Cardboard	30	5,000	-	-	-	5,030
Glass	500	500	-	-	-	1,000
Copper	3,000	30	100	100	100	3,330
Rubber	600	500	-	-	-	1,100
TOTAL	**14,130**	**13,630**	**15,650**	**15,650**	**15,650**	**74,710**

4.3.2. Data collected through interviews with key stakeholders in Juchitán

In Juchitán, the Municipality only provides waste collection services for households located in the city centre, from waste collection bins located in public areas, hospitals, schools and food markets (Table 4.4). These services are provided through three waste collection unions affiliated to the Municipality, which collect approximately 42 t day^{-1}. Two independent waste collection unions offer a commercial service for which they charge a fee to collect waste (depending on the amount) from other households and businesses in Juchitán; the total waste collected by the independent unions was

approximately 81 t day^{-1} of waste. The fee varies between $10 and $30 pesos per collection, which is equivalent to £0.4 to £1.2[15]. Therefore the total amount of waste collected in Juchitán by municipal and independent waste collection unions was equivalent to 123 t day^{-1}.

The Municipality operates a dumpsite for the disposal of waste by the municipal waste collection unions. The waste that arrives at this facility is burned to reduce volume and to control pests. The operator responsible for managing the facility indicated that no additional waste treatment was undertaken. Waste collected by the Isidro Morales Union was taken to an informal, unregulated dumpsite, where it was also burned in the open. The union operated by Cecilio Villalobos disposed of collected waste at a site that was previously operated as a waste transfer station, which is now used as a final disposal site where waste is also burned to reduce volume. Two other small unofficial dumpsites were also identified within the Municipality boundary. No waste was burning at these locations when visited (April 20, 2016); however, there was evidence that waste had been recently burnt at these sites.

Table 4.4 Description of waste collection unions in Juchitán

Waste Collection Unions					
Parameter	**SUTAJ**	**Victor Yodo**	**Flores Magón**	**Isidro Morales**	**Cecilio Villalobos**
Type of Union	Municipal	Municipal	Municipal	Independent	Independent
Waste collected (t day^{-1})	25	12	5	6	75
Proportion of household waste collected (%)	0	0	40	90	80
Number of workers (collectors and helpers)	21	60	15	6	200
Waste collection points	Schools, food markets, parks, hospitals	Streets, schools, jail	Street and households in the city centre	Households and businesses (mainly restaurants)	Households, businesses and the 2 main supermarkets
Infrastructure	1 large compacter truck (9 t) 3 small compacter trucks (3.5 t) 3 trucks (3 t)	1 large compacter truck (5 t) 1 small compacter truck (2 t) 1 truck (3 t)	1 small compacter truck (2 t) 1 truck (3 t)	6 horse wagons	3 large trucks (14m^3), 5 small trucks, motorbike/horse wagons

In total, approximately 200 t of waste are recovered per month in Juchitán (Table 4.5). Municipal and independent unions that collect waste in Juchitán recover different types of waste materials. These materials are transferred to a waste recycling facility in a neighbouring Municipality. Waste recovered by informal waste pickers in the municipal dumpsite is also sold to the same recycling company. Additionally, there are five waste recovery facilities that collect recyclables from households and businesses in the Municipality. One waste recovery facility is specialized in collecting recyclables from industry and the two largest supermarkets in the Municipality. Finally, the Ecological Forum, a local initiative and not-for profit organisation, receives waste from 20 to 30 families in Juchitán and recovers recyclable materials including organic waste to produce compost. Materials recovered by

[15] Conversion rate of 26 MXP (Mexican Pesos) to £1 (on 22 of January 2018).

these facilities are transported to different states of the country for further processing and recycling. A detailed description of waste recovery in Juchitán is presented in Table 4.5.



Figure 4.5 Waste collection services and recovery facilities in Juchitán

Table.1 Recovery of waste per month by recovery facilities, waste collection unions and at the municipal dumpsite in Juchitán (kg month^{-1})

	Waste Recovery Facilities							Waste Collection Unions						
Type of material recovered	**Waste recovery facility 1**	**Waste recovery facility 2**	**Waste recovery facility 3**	**Waste recovery facility 4**	**Waste recovery facility 5**	**Industrial waste recovery "Mecot"**	**Ecological Forum of Juchitán**	**SUTAJ**	**Sindicato Victor Yodo**	**Sindicato Flores Magón**	**Sindicato Isidro Morales**	**Sindicato Cecilio Villalobos**	**Municipal dumpsite**	**Total**
Aluminium	100	400	2,000	100	0	600	25	676	520	300	156	600	50	5,527
Plastics	200	400	-	0	500	20,000	100	1,040	520	200	156	7,000	1,500	31,616
Steel	5,000	13,000	8,000	15,000	15,000	15,000	0	1,586	1,040	7,500	234	10,000	600	91,960
Copper	100	500	100	50	0	300	0	0	52	50	5	100	60	1,317
Bronze	50	200	50	0	0	50	0	0	52	20	3	10	30	465
Cardboard	300	0	0	300	0	42,000	100	0	0	0	0	0	0	42,700
Glass	0	0	0	0	0	20,000	125	0	0	0	0	0	0	20,125
Compost	0	0	0	0	0	0	2150	0	0	0	0	0	0	2,150
TOTAL	**5,750**	**14,500**	**10,150**	**15,450**	**15,500**	**97,950**	**2,500**	**3,302**	**2,184**	**8,070**	**554**	**17,710**	**2,240**	**195,860**

4.3.3. Household questionnaire results for waste disposal practices in Huejutla

In Huejutla, the number of occupants per household slightly increased in the order urban < periurban < rural. However, the number of inhabitants per household was relatively consistent overall ranging from 5.1 in urban areas to 5.7 in rural areas. Householders reported that waste collection services were free of charge, and the frequency varied depending on the area of the Municipality. Urban householders received a daily waste collection service, and in periurban areas, household waste collected two times per week. Approximately 80 % of surveyed households in rural areas reported they had no access to waste collection services. All rural households provided with a waste collection service available reported that this was infrequent and only available for bulky waste such as furniture, mattresses and also for glass bottles.

Almost 78 % of rural households had pets or farm animals and food waste generated in the household was used as animal feed. The proportion of households feeding food waste to animals decreased in periurban areas (approximately 62 %) and, as may be expected, the lowest rate of using food waste as an animal feed was found for urban dwellings (46 %). Waste separation of recyclable materials was more common in rural areas, where nearly 60 % of households, approximately 15 % more than in urban areas, separated waste. The level of marginalisation was greatest in rural areas of Huejutla, where almost 60 % of households had 2 or fewer basic appliances (marginalisation level 3, Table 4.6). By contrast, this level of marginalisation was represented by 16 % and 7 % of periurban and urban households, respectively. The higher level of marginalisation observed in rural areas could explain the higher rates of waste separation observed in these communities, as recyclable materials are commonly sold to provide an additional source of income.

In Huejutla, burning of waste occurred in 22 %, 37 % and 92 % of households surveyed in urban, periurban and rural areas of the Municipality, respectively. The increase in the rate of households burning waste corresponded strongly with the reduced availability of regular and reliable collection services, as indicated by the collection service frequency data. However, burning of waste also continued in urban and periurban areas that were served with frequent, daily or twice-weekly collections.

Table 4.6 Household questionnaire results for Huejutla (% unless otherwise stated)

Huejutla											
Area	Number of surveys	Total number of people	Average people in houses	Frequency of collection[a]	Owns animals and feeds them waste	Waste separation of recyclable materials at home	Levels of marginalisation[b]			Burning of waste in neighbourhood	Households that burn waste
							Level 1	Level 2	Level 3		
Urban	102	518	5.1	Daily	46.1	45.1	41.2	52.0	6.9	57.8	21.6
Periurban	76	403	5.3	Once or twice per week	61.8	53.9	23.7	60.5	15.8	72.4	36.8
Rural	63	360	5.7	80 % has no service, 20 % once a month or less	77.8	58.7	5.0	43.3	56.7	98.4	92.1

a) Households in rural areas with access to waste collection services stated it was only for bulky and non-compactable items including furniture and glass
b) Levels of marginalisation:
Level 1: Household owns 6-8 appliances
Level 2: Household owns 3-5 appliances
Level 3: Household owns 0-2 appliances
Appliances include: fridge, washing machine, boiler, microwave oven, TV, phone (landline), cell phone and computer.

4.3.4. Household questionnaire results for waste disposal practices in Juchitán

In Juchitán the average number of occupants per households was 4.4 in urban areas and 4.8 in rural communities. The results of the household questionnaire confirmed that municipal waste collection services were only available in the urban city centre of the Municipality and were provided free of charge. Other areas of the Municipality stated that waste collection services are provided through independent unions and that a fee is charged at the point of collection. Waste was collected at a frequency of 2-3 times per week for the majority of households (85 %) in urban areas of Juchitán and the average cost for this service was £5 per month. The frequency of waste collection was reduced to an average of 1-2 times per week for the majority (66 %) of rural households and the charge was £3 per month. Approximately 14 % of households in rural areas stated that they either burn their waste or take it to a nearby dumpsite instead of paying for waste collection services. The details of the frequency and cost of waste collection services in Juchitán is presented in Table 4.7.

Table 4.7 Frequency of waste collection in Juchitán (% unless otherwise stated)

Juchitán						
Area	Daily	3 x week	2 x week	1 x week	Only burns or takes to dumpsite	Average cost (£ month^{-1})*
Urban	7	45	39.5	7.5	1	5.1
Rural	0	20	36	30	14	2.9
*Assumed conversion rate of 26 MXP (Mexican Pesos) to £1						

More households in rural areas feed organic waste to animals or pets (74 %), compared to urban households (45 %). Waste separation of recyclable materials at home was also performed by more rural households compared to urban households (26 % and 17.5 %, respectively), probably linked to

the level of marginalisation of the communities and sale of recyclable materials by rural households as a supplemental income stream. In rural areas of Juchitán, 26 % of the population had a marginalisation status equivalent to level 3, (see Table 4.8). In contrast, only 5 % of the urban population in the Municipality were represented by this level of marginalisation.

Burning of waste in Juchitán is more common in rural compared to urban areas. Specifically, 84 % of the population reported that they burn all or some of the waste generated. The rate of waste burning in urban areas was also relatively high, and 51% of households disposed of waste by open burning. The increase in the rate of households burning waste in rural areas could be linked with the high level of marginalisation of these communities, and to avoid paying direct fees and charges for waste collection. As a reference, the minimum wage in Mexico is equivalent to approximately £103 per month (Gobierno de México, 2018); therefore the typical average fee for waste collection of £3 per month is equivalent to 3% of the minimum wage. Furthermore, many rural households in Mexico receive an income significantly below the national minimum wage. Indeed, almost 62 % of the population in Juchitán (Section 3.5.4) are considered to be below the poverty or extreme poverty threshold (CONEVAL, 2016b). Consequently, under such circumstances, burning waste is the preferred option for waste disposal to avoid the cost of waste collection.

The rate of smoking is four times higher in urban (16 %) compared to rural households (4 %) in Juchitán. However, the percentage of families who cook using an outdoor woodstove is three times higher in rural (46 %) compared to urban areas (15 %). Additionally, 10 % of rural households have indoor wood stoves, compared to 1.5 % urban areas.

Table 4.8 Household questionnaire results for Juchitán (%)

Juchitán survey analysis													
Area	Number of surveys	Total number of people	Average number of people in houses	Owns animals and feeds them waste	Waste separation of recyclable materials at home	Levels of marginalisation*			Burning of waste in neighbourhood	Households that burn waste	Smoking in house	Wood stove cooking	
						Level 1	Level 2	Level 3				Outside	Inside
Urban	200	884	4.42	45.0	17.5	33.5	61.5	5.0	74.0	51.0	16.0	15.5	1.5
Rural	50	239	4.8	74.0	26.0	6.0	68.0	26.0	94.0	84.0	4.0	46.0	10.0

*Levels of marginalisation:
Level 1: Household owns 6-8 appliances
Level 2: Household owns 3-5 appliances
Level 3: Household owns 0-2 appliances
Appliances include: fridge, washing machine, boiler, microwave oven, TV, phone (landline), cell phone, computer

4.3.5. Incidence of respiratory diseases reported in household questionnaires

The rate of respiratory diseases for children, adults and the elderly in urban, periurban and rural households provided from the responses to the questionnaire survey in Huejutla is presented in Figure 4.6a. The largest frequency of respiratory disease in each age class examined (children, adult and elderly) was reported for rural areas compared to periurban and urban households. For example, the proportion of the rural population reporting a respiratory illness more than three times per year was 46, 33 and 40 % for children, adults and the elderly, respectively, compared to 13, 5 and 6 %, respectively in urban areas.

The health status statistics collected from households in Juchitán suggested the incidence of respiratory disease was similar between rural and urban areas, as shown in Figure 4.6b. Specifically, the percentage of population that presents respiratory diseases in urban compared to rural areas is 34 % and. 36 %, 10 % and 17 %, and 18 % and 22 % for children, adults and the elderly, respectively.

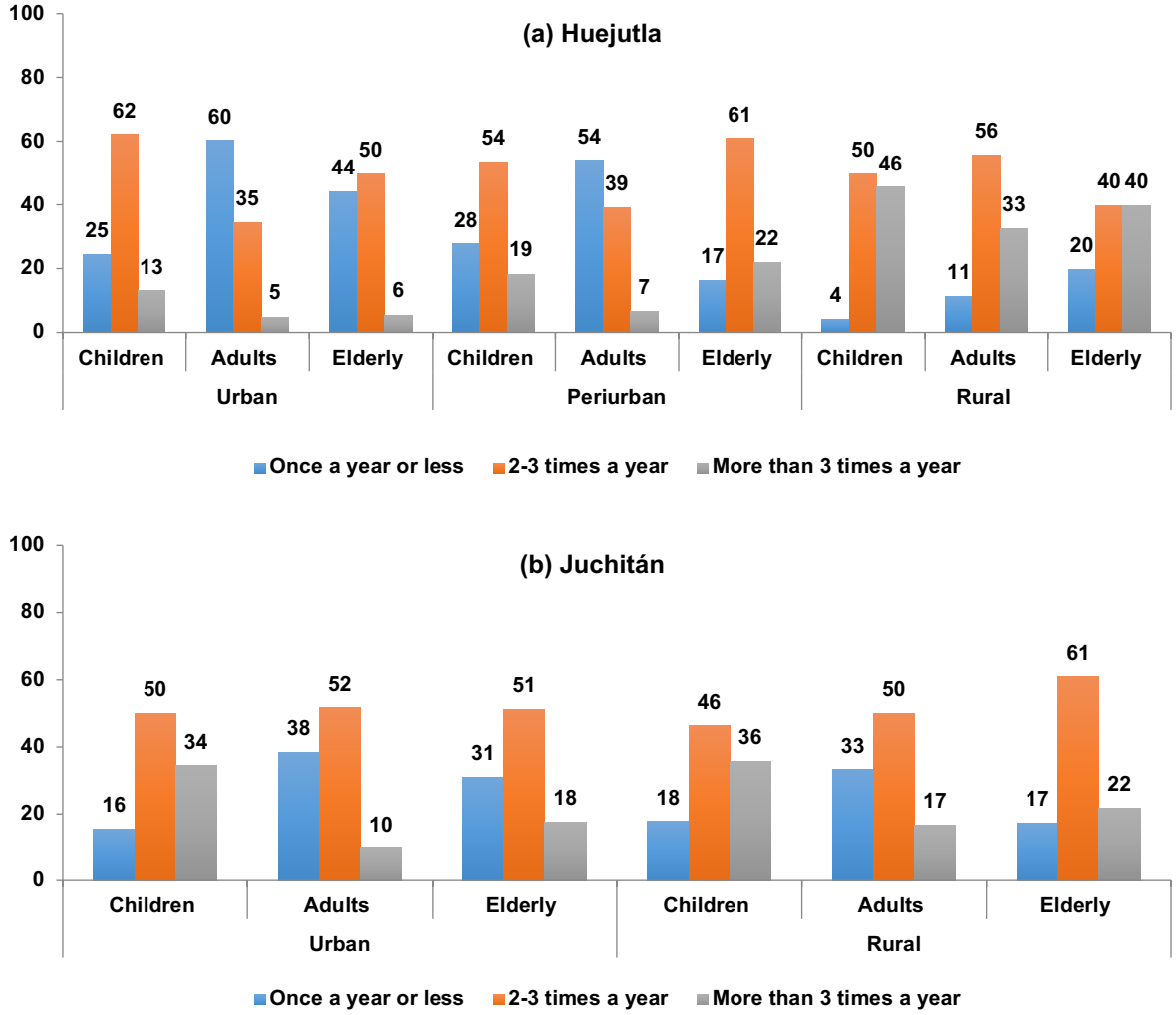


Figure 4.6 Incidence of respiratory diseases reported in household questionnaires in (a) Huejutla and (b) Juchitán (%)

4.3.6. Clinical respiratory health data

Health records gathered from medical units in Huejutla showed that respiratory diseases were more frequent in rural compared to urban areas (Figure 4.7a). In general, the results showed that between 28 and 35 % of the population per year in rural areas reported cases of respiratory disease. In urban areas, the rate of respiratory diseases was apparently smaller and equivalent to 13 to 25 % of the population per year. Thus, in some cases, respiratory diseases were reported twice as frequently in rural compared to urban areas.

In Juchitán, health records show an opposite trend to the one found in Huejutla. There, respiratory diseases were more prevalent in urban compared to rural areas, as shown in Figure 4.7b. In Juchitán,

20 to 36 % of the urban population presents respiratory diseases. In rural areas, 11 to 15 % of the population is treated for respiratory illnesses each year. Therefore, respiratory diseases in the rural population are almost half compared to those in urban areas.

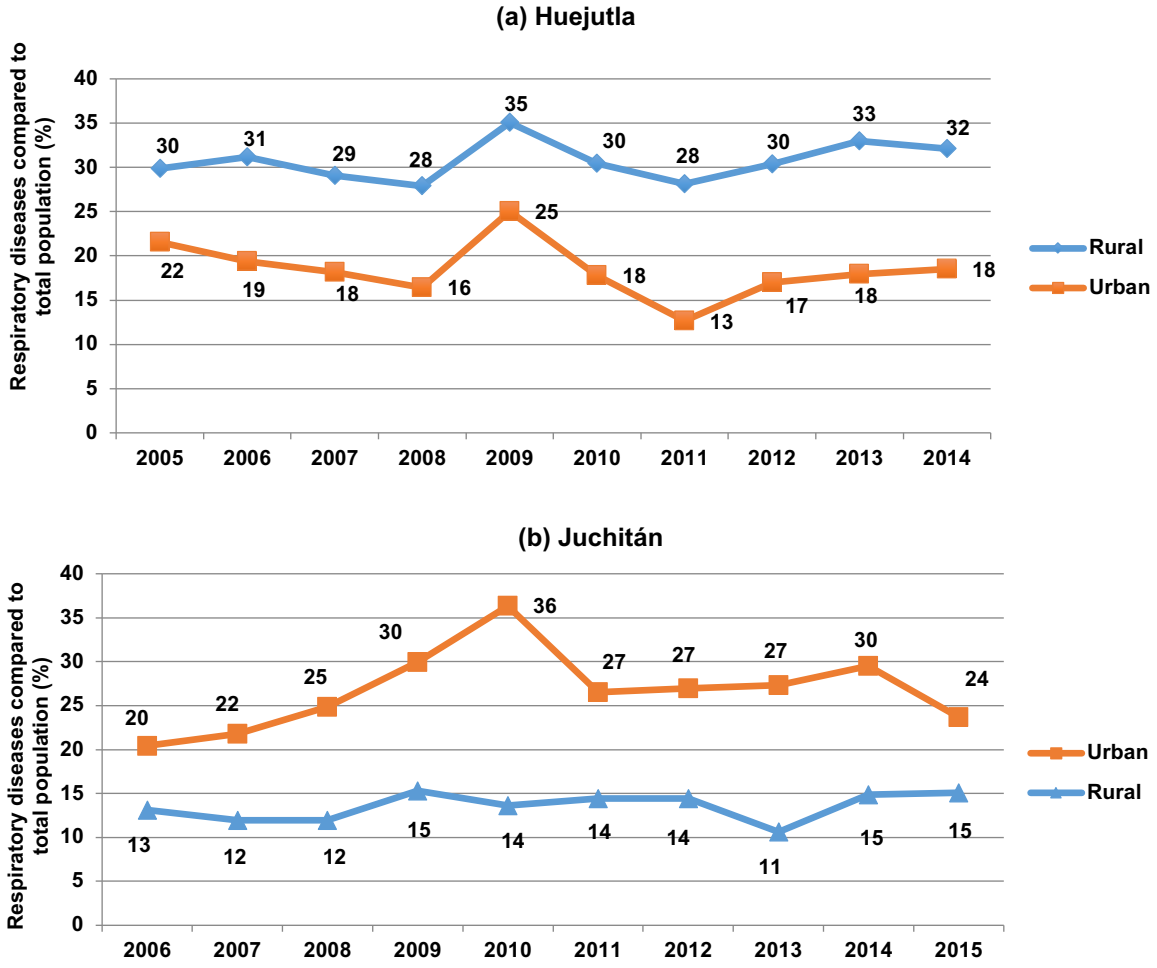


Figure 4.7 Respiratory disease in rural and urban areas in (a) Huejutla and (b) Juchitán (Jurisdicción Sanitaria 10 de Huejutla de Reyes, 2015; Jurisdicción Sanitaria 2 del Istmo de Tehuantepec, 2016)

4.4. Discussion

The fraction of households using food waste as feed for domestic animals was similar in both case study areas. For instance, the proportion of rural households feeding food waste to animals was 78 % in Huejutla and 74% in Juchitán. Similarly, the proportion of households feeding waste to animals in urban households was similar and equivalent to 46 % in Huejutla and 45 % in Juchitán. In contrast, waste separation was more common in households in Huejutla compared to Juchitán. For example, almost 60 % of rural households separated waste in Huejutla, however, waste separation only occurred in 26 % of rural households in Juchitán. Furthermore, almost three times more urban households in Huejutla (45 %) separated waste compared to Juchitán. However, overall, a larger quantity of waste is recovered in Juchitán, 200 t per month, compared to Huejutla, 70 t per month. Further analysis of the recovery rate relative to the overall waste generation is presented in chapter 6.

The results from both case study areas strongly suggested that the characteristics of the waste collection services are a primary factor controlling the extent of open burning of waste by households. In Huejutla, urban, rural and periurban areas received different levels of MSW collection service. Rural communities had a very limited or no waste collection service and therefore the majority of households (92 %) disposed of waste by uncontrolled open burning, compared to urban districts, where the Municipal Authority operated regular waste collections. Nevertheless, burning was also observed (albeit to a smaller degree compared to rural areas) in urban (22 %) and periurban areas (37 %), where frequent waste collection was conducted. A possible explanation why urban and periurban communities that receive a daily or twice-weekly collection services continued to burn waste was that the collection service was introduced comparatively recently and, although it had operated for approximately three years, the practice of burning waste was a long established and accepted, familiar disposal method. Therefore, in addition to providing regular waste collections, further support may be necessary to eradicate open burning completely, such as education programmes and providing households with a secure means of storing waste between collections. In Huejutla, the authorities ceased burning waste at the official dumpsite in 2013; however, open burning of waste is still present in backyards, streets and clandestine dumpsites.

In Juchitán, independent unions provided household waste collection services to the majority of the population, but in contrast to Huejutla, services are not free of charge. Over half of the population in Juchitán is considered to be within the poverty or extreme poverty marginalisation status and therefore the cost of waste collection fees is avoided by disposing of waste by open burning. This is particularly evident in rural areas, where 84 % of the households disposed of part or all of their waste by open burning. Open burning of waste in households was also common in urban areas, and 51 % of urban dwellings reported burning waste as a method of disposal. Additionally, all waste collected by municipal and independent unions was taken to dumpsites and burned to reduce volume and to control pests. Consequently, the rate of waste burning in Juchitán is more extreme than in Huejutla.

Respiratory health is usually poorer in urban areas due to increased exposure to air pollution from transport and industry, compared to rural areas (Iversen et al., 2005; O'Reilly et al., 2007; Gartner et al., 2008; Jang, 2012). This was the case in Juchitán, where respiratory diseases in the urban population were approximately double the number of cases reported by the Health Authority for rural areas. The impact of open burning of waste is also strongly recognised as an important contributor to respiratory disease (Hodzic et al., 2012; Li et al., 2012; Kodros et al., 2016; US EPA, 2016). Indeed, the open burning of waste in the Juchitán region at the main waste dumpsites occurred close to the urban areas and therefore, could also have a significant negative impact on respiratory health. In contrast, health records collected from medical centres in Huejutla suggested the opposite trend was apparent as the incidence of respiratory disease was greater in rural compared to urban areas. The uncontrolled burning of waste in Huejutla was increased in rural areas, where 92 % of rural households burned waste, compared to urban areas, where 22 % of households burned their waste.

The clinical health data for both case study areas was based on the location of the medical facility, and not the specific origin of patients. Since rural areas have fewer medical facilities and may offer

less extensive services, it is likely that rural inhabitants may actually use medical centres in urban areas. Therefore, it is possible that the rate of respiratory diseases estimated for rural areas may be underestimated in both Huejutla and Juchitán.

Other important factors that could explain the patterns of respiratory incidents could be linked to cooking with solid fuels and smoking. In Huejutla, for example, wood is the main cooking fuel in 49.1% of households (INEGI, 2011) and cooking on open fires is practised to a greater extent in rural compared to urban areas. In Juchitán, the national Census (INEGI, 2011) stated that 22 % of the population cook with solid fuel. However, results from the household questionnaire showed that 17 % of urban households use solid fuel as a cooking method (15.5 % outside the house and 1.5 % inside) while 56 % of the rural population (46 % outside the house and 10 % inside) used this cooking method. Therefore, as may be expected, rural populations tend to use solid fuel significantly more for cooking purposes compared to urban households. Nevertheless, rates of respiratory diseases were higher in urban areas in Juchitán, which could be potentially linked to poor air quality due to open burning of waste at the nearby municipal dumpsite. In Juchitán, strong winds generated as a result of the combination of meteorological and topographic conditions (Romero-Centeno et al., 2003) carry the emissions from open burning of waste generated in dumpsites to some of the most populated areas, especially in the autumn and winter seasons (Noriega, 2016).

Smoking represents another major cause of respiratory disease, however, smoking is much more frequent in urban compared to rural populations in Mexico; indeed, the reported rates of smoking in these areas are almost 40 % and 24 %, respectively (CONADIC, 2008). Therefore, smoking behaviour is unlikely to be a major factor explaining the increased rate of respiratory illness in the rural community of Huejutla. In the case of Juchitán, the household questionnaire indicated that the smoking population in urban areas of Juchitán (16 %) was four times larger compared to rural areas, equivalent to 4 %. Thus, smoking could also be a factor contributing to the increased number of cases) of respiratory disorders in urban areas of Juchitán.

The clinical statistical information in Huejutla was consistent with the rate of respiratory diseases reported for children, adults and the elderly in urban, periurban and rural areas from household questionnaires. The questionnaire results showed that the proportion of the rural population reporting respiratory illness was over three times larger per year in rural compared to urban areas. By contrast, in Juchitán the results obtained from the household questionnaire did not show marked differences between the rate of respiratory diseases in urban and rural areas of the Municipality.

The economical burden of respiratory diseases in the case study areas was calculated using an estimation of the cost of individual medical consultations in clinics or medical units in Mexico, and the average loss of productivity considering one day of medical leave per reported case (Table 4.9). According to these data, the annual cost of respiratory diseases in Huejutla is almost £1.5 million, while in Juchitán, respiratory diseases cost over £600,000 per year.

It is not possible to specify the actual contribution of open burning to respiratory disease in the case study areas. Nevertheless, the medical data presented here suggest that there is a strong potential link between open burning of waste and increased rates of respiratory disease. Thus, the

cost of improving waste collection services in Huejutla, and waste management services at final disposal sites in Juchitán, could be offset by the savings in medical services by reducing the rate of respiratory diseases and the associated loss of economic productivity in the case study areas.

Table 4.9 Approximated cost of respiratory diseases per year in case study areas

Cost of respiratory diseases (£)	Huejutla	Juchitán
Cost of individual medical consultation*	21.1	
Average loss of productivity*	6.9	
Average number of cases per year	52,385	22,465
Cost of medical consultations for respiratory diseases	1,106,880	474,690
Cost of loss of productivity for respiratory diseases	359,460	154,160
Total cost of respiratory diseases	**1,466,340**	**628,840**

*Source for cost of individual medical consultation ($505 Mexican Pesos) and average loss of productivity in Mexico: (IMCO, 2013)

Note: Loss of productivity is calculated considering average wages in Mexico and one day of medical leave.

The results of the controlled assessment analysis presented here do not provide direct evidence of a link between respiratory disease and the open burning of waste. However, the increased respiratory diseases in rural areas of Huejutla and urban areas of Juchitán correspond with increased exposure to atmospheric emissions from open burning of waste, suggesting there could be a strong link between the uncontrolled combustion of waste and the respiratory health of the local population. The higher incidence of respiratory disorders in rural communities of Huejutla is unexpected as these diseases are usually more prevalent in urban areas, where the population is exposed to increased emissions from transport and the industry. The only factors that could explain this trend are open burning of waste and cooking with solid fuels. Further investigation of the impacts of open burning on health is strongly recommended.

5. Household waste characterisation analysis

5.1. Introduction

A waste characterisation analysis provides an estimate of solid waste generation and its composition (WastesWork and AEA, 2010; Miezah et al., 2015). This information is necessary to design proper management strategies at different levels of the solid waste system. Waste composition is influenced by economic development, climate, geographic location and culture (Hoornweg and Bhada-Tata, 2012). In Mexico, information is available on collected MSW composition, prior to recycling and disposal. However, Mexican MSW composition data is not based on field measurements and monitoring, but is estimated from population size and consumption habits (Solórzano-Ochoa et al., 2010; INECC, 2012; SEMARNAT, 2013a). Moreover, there is a lack of information on MSW composition in areas with no waste collection services, where open burning is common. Specifically, there is no published composition or quantification data for waste that is disposed by burning in backyards or dumpsites.

Emissions from open burning of MSW strongly depend on the composition of the waste (Solórzano-Ochoa et al., 2010; Wiedinmyer et al., 2014; Stockwell et al., 2016). Therefore, understanding this relationship will enable better assessment of the extent and impact of open burning of waste. This information is essential to understand the impact of uncontrolled burning of waste on climate change and human health, to improve BC inventories, and to provide a rigorous technical basis for effective local and national policies for MSW management, health provision services and climate change mitigation. For instance, IPCC (2006) guidelines on emissions from the waste sector suggest a default value of 0.6 for the proportion of waste burned in open dumps in developing countries. Field data are necessary to determine the combustible fraction and validate the IPPC assumption. As a result of these data gap, open burning of waste is not currently included in the IPCC Fourth (Bogner et al., 2007) or Fifth (IPCC, 2014) Assessment Reports due to the paucity of scientific data quantifying this emission source.

The aim of this chapter is to quantify the composition of household waste generated by communities in Mexico where domestic open burning of waste is widely practised, and to determine the quantities and types of combustible waste materials that are disposed by uncontrolled burning. The specific objectives are to:

a) Conduct a detailed waste characterisation analysis for the study areas of Huejutla and Juchitán;
b) Analyse the results of the waste characterisation data to understand the effects of community type on the types and amount of different waste fractions disposed;
c) Calculate the specific waste generation rate per capita within the different communities in the case study areas to establish the activity level for open burning of waste;
d) Determine the effects of socioeconomic status and community type on the waste composition and per capita waste generation for both areas.

5.2. Materials and methods

The waste characterisation fieldwork took place in June of 2015 for Huejutla de Reyes and in April 2016 for Juchitán de Zaragoza.

5.2.1. Selection of houses

A sub-group of households that frequently burned waste and that agreed to participate in further stages of this research during the household questionnaire (Chapter 4), were identified and selected for further detailed investigation of household waste composition. Four waste samples were collected from each household over a two-week period for compositional analysis. In Huejutla, 20 households were analysed, 5 in each of the urban and periurban areas and 10 in the rural area. In Juchitán, there was no periurban area, as the majority of the inhabited territory was considered as urban by municipal authorities, and only a relatively small number of rural households are located on the boundary of the Municipality. In this case, 30 households were selected, 20 in the urban areas and 10 in rural areas. The number of houses in each area for both Huejutla and Juchitán was selected considering the population in urban, periurban (in the case of Huejutla) and rural areas. The sample size was increased in Juchitán, based on the experienced gained in Huejutla, to further increase the statistical validity of the analysis.

5.2.2. Methodology for waste characterisation

The methodology for the waste characterisation assessment was adapted from the Mexican regulation for waste characterisation in households (Diario Oficial de la Federación, 1992) and from UK guidance (WastesWork and AEA, 2010). Participants were asked to collect all the household solid waste generated during the assessment period, including waste that they would normally dispose of by burning, and place the material into a polyethylene waste collection bag that was provided. Waste samples for all households were collected on the same day on two occasions per week (Tuesday and Friday) and were transferred to the municipal dumpsite to complete the composition assessment.



Figure 5.1 Waste characterisation process in Huejutla

The total sample collected from each house was weighed on an electronic platform scale (Figure 5.1) to determine the total mass of waste collected per household. Waste samples were initially processed by passing over a 10mm screen to separate the fine material fraction (<10 mm), which was collected and weighed. The main residual portion was spread on a plastic sheet on the ground to reveal the different material components to enable preliminary manual sorting into major material

categories including: plastics, metals, textiles, glass, paper and cardboard, food and garden waste. These material groups were separated into individual piles on the plastic sheeting and they were further sub-divided by hand-sorting into 23 separate waste category types (Table 5.1), according to their combustible properties (Diario Oficial de la Federación, 1992). The mass of each waste fraction was measured and recorded.

Table 5.1 Waste categories

Wet waste / Waste that can be fed to animals	
1	Food waste
Combustible	
2	Garden waste
3	Wood
4	Cardboard and paper
5	High-density polyethylene (HDPE)
6	Plastic bags and plastic packaging (Low-density polyethylene, LDPE)
7	Polystyrene
8	Disposable cups, plates, cutlery (Polypropylene, PP)
9	Polyethylene terephthalate (PET)
10	Hard plastic [a]
11	Tetra pack packaging
12	Sanitary waste
13	Electrical waste, cables
14	Hazardous waste [b]
15	Aluminium lined packaging / foil
16	Textiles
17	Synthetic fibres
18	Rubber
19	Other [c]
20	Residual fraction [d]
Non-Combustible	
21	Aluminium cans
22	Metals, metallic cans
23	Glass
24	Construction waste

a) Plastic toys and non-disposable plastic containers.
b) Syringes, catheters, needles, swabs, bandages and disposable medical devices.
c) Cotton, rubber, wood, leather, shoes, products with mixed materials such as umbrellas.
d) Waste samples were processed by using a 10mm screen to separate the fine material fraction (<10 mm). This was classified as the "residual fraction".

5.2.3. Statistical analysis of waste characterisation

The sample size of houses examined in the waste characterisation analysis (20 for Huejutla, 30 for Juchitán) was relatively small and the statistical examination of the data was completed to assess the statistical significance of the results. One-way analysis of variance (ANOVA) was carried out on the mass (g) of each waste category measured to determine the statistically significant effect of household type (urban, periurban and rural) on the amount of each waste type that was generated.

Significant effects of household type were detected for various waste fractions in both case study areas. For those fractions that presented a significant difference, the least significant difference (LSD)

was calculated to compare the mean mass (g) of each waste category generated by each household group.

Two equations (Williams and Abdi, 2010) were used to calculate the LSD: Equation 5.1 for the groups with different number of houses sampled, and Equation 5.2 for groups with the same number of houses sampled.

Equation 5.1

Equation 5.2

where *t* is the critical value, taken from the t-distribution table (*t* = 2.984), *MSE* is the mean squared error calculated by ANOVA and *r* is the number of scores used to calculate the means (number of households in each area).

For Huejutla, the number of houses participating in urban and periurban areas was equivalent to n=5. However, the number of houses sampled in rural areas was larger, and in this case n=10. In Juchitán, there were n=20 households in urban areas and n=10 in rural areas.

5.2.4. Calculation of waste composition in case study areas

The proportional composition of each waste fraction in the total sample was calculated on an as received, fresh weight basis, using the following formula:

Equation 5.3

Results were calculated based on the total fraction weight and total overall weight for the houses sampled in each area of the Municipality (urban, periurban and rural) as well as for the Municipality as a whole. The waste generation per capita was determined by the following equation:

Equation 5.4

5.3. Results

5.3.1. Waste generation and characterisation in Huejutla

5.3.1.1. Compositional analysis in Huejutla

Overall, combustible materials represented a significant fraction of the collected waste, equivalent to 65.9 %, of the total household waste generated on average, across all community. Garden waste was the largest combustible fraction overall, equivalent to 22.2 % of the total waste generated. Other combustible materials including sanitary waste (17.8 %) and plastic carrier bags and packaging (3.9 %) collectively represented more than 20 % of the total waste. Combustible recyclable materials such as paper and cardboard (5.1 %), tetra packs (2.2 %), polyethylene (PET) (2.0 %), high-density polyethylene (HDPE) (1.7 %), and non-combustible recyclables, including glass (1.2 %), aluminium (1.0 %) and metals (0.9 %) collectively represented almost 15 % of the total waste generated.

The fraction of food waste in Huejutla was largest in periurban dwellings (38.9 %), followed by urban households (32.4 %). The smallest food waste fraction was generated in rural areas (24.5 %). Rural households in Huejutla generated the largest garden waste fraction, equivalent to 28.7 % of the total waste generated. Urban households also generated a large amount of garden waste (23.7 %). A possible explanation for this observation in urban areas could be that houses in the centre of the Municipality were older and built in the traditional style with large gardens and patios. In contrast, periurban houses were constructed more recently and usually with smaller outdoor spaces, hence, the rate of garden waste generated was smaller (12.1 %).

The fraction of sanitary waste generated by households in the periurban area was larger (25 %) compared to urban dwellings (17.7 %). The proportion of sanitary waste generated by rural households was reduced by more than 50 % compared to periurban dwellings (12.2 %). The total plastics fraction (HDPE, LDPE, Polystyrene, PP, PET and hard plastic) collectively represented 11.7 % of the total household waste generated in rural areas, and was equivalent to 11.1 % for periurban and 9.5 % for urban households. Nevertheless, rural households generated the smallest total mass of plastic waste compared to the other community types examined (Section 5.4.2).

Table 5.2 Household waste composition (% fresh weight) in Huejutla

Huejutla				
Waste type	Urban	Periurban	Rural	TOTAL
Waste that can be fed to animals				
Food waste	32.4	38.9	24.5	31.5
Combustible				
Garden waste	23.7	12.1	28.7	22.2
Wood	0.3	0.1	0.1	0.2
Cardboard and paper	5.1	3.3	6.4	5.1
High-density polyethylene (HDPE)	1.1	1.9	2.1	1.7
Plastic bags and packaging (Low-density polyethylene, LDPE)	3.6	4.8	3.5	3.9
Polystyrene	0.5	0.6	0.4	0.5
Disposable cups, plates (Polypropylene, PP)	1.4	1.4	1.4	1.4
Polyethylene terephthalate (PET)	1.9	1.8	2.4	2.0
Hard plastic (a)	1.0	0.6	1.8	1.2
Tetra pack	2.9	1.9	1.6	2.2
Sanitary Waste	17.7	25.0	12.2	17.8
Electrical waste, cables	0.1	0.0	0.1	0.1
Hazardous waste (b)	0.1	0.1	2.4	0.9
Aluminium lined packaging / foil	0.5	0.6	0.5	0.5
Textiles	3.4	0.8	2.3	2.3
Synthetic fibres	0.04	0.2	0.0	0.1
Rubber	0.1	0.4	0.3	0.2
Other (c)	0.6	0.5	2.3	1.1
Residual fraction (d)	2.5	2.2	2.9	2.5
TOTAL (combustible waste)	**66.4**	**58.2**	**71.7**	**65.9**
Non - Combustible				
Aluminium cans	0.0	1.2	0.4	0.5
Metals, metallic cans	0.4	1.2	1.3	0.9
Glass	0.7	0.5	2.2	1.1
Construction waste	0.0	0.0	0.0	0.0
TOTAL (non-combustible waste)	**1.1**	**2.9**	**3.8**	**2.6**
TOTAL	100	100	100	100

5.3.1.2. Statistical analysis of waste generation data in Huejutla

The statistical examination of the waste characterisation data for Huejutla is shown in Table 5.3. The amount of waste generated on a daily basis per household and per capita, as well as the size of several waste fractions decreased consistently between the different communities in the order: urban ≥ periurban > rural. This was the case for food waste, sanitary waste, plastic and tetra pack fractions. For example, the total amount of waste generated by urban households was approximately 4,600 g day^{-1} fresh weight (FW), 2.3x the amount compared to rural properties which generated 2,100 g day^{-1} FW. The rate of food waste generation by urban houses was almost three times larger, at 1,500 g

day^{-1} FW, relative to rural houses, which disposed of approximately 500 g day^{-1} FW of food waste. Households were requested to collect all the waste they would normally dispose by burning or other routes, however, feeding food waste to domestic animals is not regarded as disposal, therefore this fraction may not be as representative as other waste fractions analysed in the waste characterisation data. Indeed, rural communities have larger numbers of domestic animals compared to urban/periurban areas and waste food is used as animal feed, therefore, it is reasonable to infer that this behaviour may explain the smaller rate of food waste generation in rural compared to urban/periurban areas. However, some other fractions, such as metal waste, aluminium cans and glass showed no consistent patterns between community types. This could be explained because these materials are collected for recycling across all communities within the Municipality.

No statistically significant effect (P>0.05) of community type was detected between the urban and periurban households. Therefore, these data were pooled together for comparison with rural households by ANOVA. This confirmed that the increase in the waste generated per household and per capita, and in the amount of food waste generation, and tetra pack, aluminium foil and plastic waste by urban+periurban households compared to rural areas was statistically significant (P≤0.05). Pooled urban and periurban data showed that the overall rate of waste generation per capita was significantly increased (P=0.026), at 811 g capita^{-1} day^{-1}, compared to rural households which generated 433 g capita^{-1} day^{-1}.

No statistically significant difference (P>0.05) in waste fraction size was detected by ANOVA for the other categories of disposed waste. Nevertheless, the rates of disposal of garden waste, plastics and textiles by urban households were increased approximately by a factor of two compared to rural houses. For example, 1,100 g day^{-1} FW of garden waste was disposed by urban households, compared to 610 g day^{-1} FW by rural dwellings. Rural households are less likely to have packaged goods and food compared to urban and periurban areas and this may explain the reduced rates of disposal of plastic waste observed in rural relative to urban/periurban communities. The disposal of sanitary waste by urban and periurban houses was also approximately four times larger, equivalent to approximately 840 g day^{-1} FW, relative to rural dwellings, which, on average disposed of 260 g day^{-1} of sanitary waste. No construction waste was found in any of the samples of collected household waste.

Table 5.3 Statistical analysis of waste (mean generation rate, g per house per day) in Huejutla de Reyes, Hidalgo

Huejutla								
Parameter	Mean (+/- standard deviation)				*P1*	LSD1/LSD2 for *P1*	*P2*	LSD1 for *P2*
	Urban (n=5)	Periurban (n=5)	Urban+Periurban (n=10)	Rural (n=10)				
Occupants per house	5.80 (±1.48)	5.00 (±1.58)	5.40 (±1.51)	5.00 (±1.63)	0.629	NS	0.576	NS
Waste generated per house	4,621.8 (±1,082.5)	3,446.4 (±1,556.5)	4,034.1 (±1,407.6)	2,125.4 (±1059.4)	0.005	2.26/1.96	0.003	2.35
Waste generated per capita per house	826 (±254.6)	795.4 (±635)	810.7 (±456.3)	432.9 (±180.9)	0.088	NS	0.026	0.66
Waste that can be fed to animals								
Food waste	1,499 (±258.8)	1,339.6 (±441.6)	1,419.3 (±351.4)	521.4 (±294.3)	<0.001	0.62/0.54	<0.001	0.61
Combustible								
Garden Waste	1,096.6 (±623.7)	418 (±327.1)	757.3 (±590.2)	609.4 (±707)	0.221	NS	0.618	NS
Wood	14.8 (±24.5)	3.4 (±4.7)	9.1 (±17.7)	3 (±7.6)	0.265	NS	0.329	NS
Cardboard and paper	237.4(±159.3)	113(±75.7)	175(±134.6)	136.3(±119.0)	0.502	NS	0.239	NS
HDPE	50.8 (±23.8)	64.6 (±45.6)	57.7 (±35)	45.8 (±36.6)	0.645	NS	0.462	NS
Plastic bags and packaging (LDPE)	167 (±71.6)	165.2 (±55.1)	166.1 (±166.1)	74 (±17.5)	0.001	0.09/0.07	0.000	0.08
Polystyrene	21.6 (±6.6)	20.8 (±7.1)	21.2 (±6.5)	9.5 (±5.5)	0.002	0.01/0.01	0.000	0.01
Disposable cups, plates (PP)	64.4 (±41.7)	48.8 (±29.7)	56.6 (±35.1)	30.7 (±27.5)	0.171	NS	0.082	NS
PET	86 (±107.3)	61.2 (±35)	73.6 (±76.4)	50.1 (±40.5)	0.580	NS	0.401	NS
Hard plastic	47 (±58.9)	21.8 (±28.6)	34.4 (±45.7)	38.3 (±38.4)	0.634	NS	0.845	NS
Tetra pack	134.2 (±95)	64.2 (±36.8)	99.2 (±77.3)	35.1 (±28.4)	0.013	0.10/0.09	0.024	0.11
Sanitary Waste	820 (±836.4)	860.6 (±1,584.5)	840.3 (±1,194.6)	258.9 (±149.7)	0.354	NS	0.144	NS
Electrical waste, cables	4.4 (±4.6)	0 (±0)	2.2 (±3.8)	2.4 (±4.5)	0.267	NS	0.867	NS
Hazardous waste	3.6 (±8)	4 (±6.2)	3.8 (±6.8)	51.8 (±163.8)	0.672	NS	0.366	NS
Aluminium lined packaging / foil	21.2 (±9.3)	21.8 (±7.3)	21.5 (±7.9)	11.2 (±5.5)	0.015	0.01/0.01	0.003	0.01
Textiles	155 (±241)	26.6 (±27.9)	90.8 (±175.4)	49.2 (±70.6)	0.248	NS	0.493	NS
Synthetic Fibres	1.6 (±3.6)	6.4 (±10.8)	4 (±8)	0.6 (±1.9)	0.208	NS	0.209	NS
Rubber	5.6 (±8.3)	12.6 (±28.2)	9.1 (±19.9)	6.4 (±14.2)	0.776	NS	0.735	NS
Others	25.6 (±52.9)	17.8 (±25.9)	21.7 (±39.5)	49.1 (±43.5)	0.365	NS	0.158	NS
Residual fraction	113.8 (±64.3)	76 (±84.3)	94.9 (±73.4)	62 (±22.8)	0.241	NS	0.192	NS
Non - Combustible								
Aluminium cans	2 (±2)	43 (±85.7)	22.5 (±61.1)	7.5 (±13.3)	0.262	NS	0.457	NS
Metals	20.6 (±15.6)	40.8 (±31.6)	30.7 (±25.8)	26.9 (±24.3)	0.418	NS	0.731	NS
Glass	30 (±32)	17.6 (±13.4)	23.8 (±24)	46.7 (±42.6)	0.323	NS	0.157	NS
Construction waste	0 (±0)	0 (±0)	0 (±0)	0 (±0)	-	-	-	-

P1= Significance for urban v periurban v rural
P2= Significance for urban+periurban v rural
NS = not significant ($P>0.05$); LSD1 = Least significant difference ($P\leq0.05$) for comparing means with equal numbers of replicates (urban v periurban); LSD2 = Least significant difference ($P\leq0.05$) for comparing means with unequal replicates (urban or periurban v rural)
Shaded rows = statistically significant values ($P\leq0.05$)

5.3.2. Waste generation and characterisation in Juchitán

5.3.2.1. Compositional analysis in Juchitán

Combustible materials also represented a large fraction of the total waste generated, equivalent to 66.7 %, of the total household waste in urban and rural areas in Juchitán (Table 5.4). Garden waste was the largest combustible fraction, equivalent to 31.1 % of the total waste generated. Other significant combustible waste fractions were sanitary waste (9.3 %) and LDPE (5.2 %). Combustible recyclable materials in Juchitán, including: paper and cardboard (5.1 %), tetra packs (1.0 %), PET (2.9 %), HDPE (2.3 %), and non-combustible recyclables, including: glass (2.4 %), aluminium (0.1 %) and metals (0.8 %), represented almost 15 % of the total waste generated.

The proportion of food waste generated was slightly larger in rural (31.9 %) compared to urban areas (29.5%) in Juchitán. However, the opposite trend was observed for garden waste and, in this case, the largest proportion was generated by urban households, equivalent to 33.5 % of the total waste, and this value was 10 % larger compared to rural households, which generated 20.4 % of garden waste relative to the total waste collected. The proportion of sanitary waste in Juchitán was consistent in urban and rural households, which generated 9.3 % and 9.2 % of this waste fraction, respectively. Collectively, the proportion of plastics generated in the urban area was significantly lower (14.2 %) compared to rural households (21.5 %). However, as was the case for Huejutla, as a fraction of the total generation, plastic waste represented a larger proportion of the waste from rural dwellings, but the actual amount of plastic waste generated was smaller compared to urban areas. Although waste fraction data is a widely used metric to assess waste composition, these results emphasised that care needed to be exercised in interpreting the results as the data were strongly influenced by the different disposal patterns of other major waste fractions between the community types.



Figure 5.2 Waste characterisation process in Juchitán

Table 5.4 Waste composition (% fresh weight) in Juchitán

Juchitán			
Waste type	Urban	Rural	TOTAL
Waste that can be fed to animals			
Food waste	29.5	31.9	**30.0**
Combustible			
Garden waste	33.5	20.4	**31.1**
Wood	0.3	0.4	**0.3**
Cardboard and paper	4.8	6.3	**5.1**
High-density polyethylene (HDPE)	1.6	5.6	**2.3**
Plastic bags and packaging (Low-density polyethylene, LDPE)	5.1	5.7	**5.2**
Polystyrene	0.4	0.6	**0.4**
Disposable cups, plates (Polypropylene, PP)	2.2	3.7	**2.5**
Polyethylene terephthalate (PET)	2.7	4.0	**2.9**
Hard plastic (a)	2.3	1.9	**2.2**
Tetra pack	0.8	2.1	**1.0**
Sanitary Waste	9.3	9.2	**9.3**
Electrical waste, cables	0.3	0.1	**0.3**
Hazardous waste (b)	0.3	0.0	**0.3**
Aluminium lined packaging / foil	0.2	0.3	**0.2**
Textiles	1.3	1.4	**1.3**
Synthetic Fibres	0.0	0.0	**0.0**
Rubber	0.0	0.01	**0.0**
Others (c)	2.1	0.0	**1.7**
Residual fraction (d)	0.5	0.4	**0.5**
TOTAL (combustible waste)	**67.8**	**62.3**	**66.7**
Non - Combustible			
Aluminium cans	0.1	0.3	**0.1**
Metals, metallic cans	0.8	0.8	**0.8**
Glass	1.8	4.9	**2.4**
Construction waste	0.0	0.0	**0.0**
TOTAL (non-combustible waste)	**2.7**	**5.9**	**3.3**
TOTAL	100	100	100

5.3.2.2. Statistical analysis of waste generation in Juchitán

The statistical analysis of the waste generation for Juchitán is shown in Table 5.5. The analysis of the data for Juchitán showed that there was a statistically significant difference ($P \leq 0.05$) detected by ANOVA between urban and rural households for the following metrics examined including: waste generated per house and per capita, food waste, garden waste, LDPE and sanitary waste. However, no statistically significant difference ($P \geq 0.05$) in waste generation was identified for the other waste categories. The amount of waste generated per household and per capita, as well as the size of most waste fractions was generally larger in urban compared to rural households. Thus, the total amount of

waste generated per capita by urban dwellings was significantly (P=0.003) increased by a factor of more than 2x and was equivalent to 4,500 g day^{-1} FW compared to rural households, which generated 2,060 g day^{-1} FW. Food waste generation in the urban area was also significantly (P=0.025) increased and over 2x larger, at 1,300 g day^{-1} FW, compared with the rural communities, which disposed of nearly 660 g day^{-1} FW of food waste. Similarly to Huejutla, feeding food waste to domestic animals was also common in Juchitán. Rural households generally maintained larger numbers of domestic animals compared to houses in urban areas, which may explain the increased amount of food waste generated in urban compared to rural areas. Also, the rate of disposal of garden waste (P=0.007) was increased by a factor of 3.6 in urban compared to rural areas. The disposal rates of LDPE and sanitary waste were also significantly (P=0.02 and P=0.017, respectively) larger by a factor of two in urban compared to rural houses and the disposal of other plastics (polystyrene, PP, PET and hard plastic) was also considerably higher in urban households, albeit, in these cases not significantly (P>0.05). However, the fractions sizes of HDPE, tetra packs and glass were larger in rural compared to urban households.

Table 5.5 Statistical analysis of waste (mean generation rate, g per house per day) in Juchitán de Zaragoza, Hidalgo

Juchitán				
Parameter	Mean (+/- standard deviation)		*P*	LSD
	Urban (n=20)	Rural (n=10)		
Occupants per house	4.15 (±1.90)	5.00 (±1.70)	0.242	NS
Waste generated per house	4,513.2 (±1,755.4)	2,066.0 (±765.9)	<0.001	1.75
Waste generated per capita per house	1,259.3 (±728.1)	478.4 (±261.3)	0.003	0.71
Waste that can be fed to animals				
Food waste	1,332.4 (±820.7)	658.1 (±512.6)	0.025	0.85
Combustible				
Garden Waste	1,514 (±1,096.5)	422.2 (±602.7)	0.007	1.12
Wood	12.1 (±53.9)	9.2 (±19.5)	0.864	NS
Cardboard and paper	219 (±131.3)	129.5 (±62.7)	0.052	NS
HDPE	70.3 (±35.6)	116.3 (±132)	0.151	NS
Plastic bags and packaging (LDPE)	230.7 (±139.9)	117.7 (±48.5)	0.02	0.14
Polystyrene	17.2 (±15.8)	13.5 (±10.2)	0.491	NS
Disposable cups, plates (PP)	100 (±93.6)	75.6 (±34)	0.433	NS
PET	119.9 (±66.3)	82.5 (±38.6)	0.113	NS
Hard plastic	104.8 (±217.6)	40.4 (±61.5)	0.37	NS
Tetra pack	36.4 (±43)	43.4 (±33.3)	0.65	NS
Sanitary Waste	418.9 (±271.7)	190.9 (±112.2)	0.017	0.27
Electrical waste, cables	13.4 (±52)	2.3 (±7.3)	0.512	NS
Hazardous waste	14 (±56.9)	0 (±0)	0.447	NS
Aluminium lined packaging / foil	11.1 (±13.8)	5.7 (±9.7)	0.297	NS
Textiles	56.8 (±97.2)	29.9 (±44.9)	0.417	NS
Synthetic Fibres	0.4 (±1.7)	0 (±0)	0.489	NS
Rubber	1.9 (±4.2)	1.1 (±2.6)	0.597	NS
Others	95.3 (±101.1)	0 (±0)	0.006	0.10
Residual fraction	24 (±19.6)	8 (±8.6)	0.02	0.00
Non - Combustible				
Aluminium cans	5.5 (±10.6)	5.3 (±6.3)	0.986	NS
Metals	34.5 (±59.1)	15.8 (±25.2)	0.352	NS
Glass	83.2 (±95.4)	100.4 (±116.7)	0.667	NS
Construction waste	0 (±0)	0 (±0)	-	NS

P= Significance
NS = not significant (*P*>0.05; LSD = Least significant difference (*P*=0.05) for comparing means with unequal replicates (urban: n=20 and rural: n=10)
Shaded rows = statistically significant values (P≤0.05)

5.4. Discussion

5.4.1. Waste generation per capita

The overall weighted average generation per capita for the Huejutla Municipality was calculated considering the size of the population in each of the urban, periurban and rural areas, and the measured waste generation per capita in each area (Table 5.6). As would be expected, by taking account of the relative population sizes of the different communities, the estimated overall weighted average value for the Municipality was smaller and equivalent to 0.52 kg day^{-1} compared to the directly measured value observed here of 0.64 kg day^{-1}, which. This is explained because 70% of population in Huejutla is rural, and rural households generate less waste per capita per day compared to periurban and urban areas.

Table 5.6 Weighted average waste per capita (kg day^{-1}) in Huejutla

Huejutla				
Area	**Total population**	**Total waste collected (kg day $^{-1}$)**	**People in sample**	**Waste per capita (kg day^{-1})**
Urban	10,004	23.1	29	0.80
Periurban	30,011	17.2	25	0.69
Rural	82,890	21.3	50	0.43
Total	122,905	61.6	104	-
			Direct Average	**0.64**
			Weighted Average	**0.52**

The weighted average per capita waste generation in Juchitán (Table 5.7), considering the population distribution in urban and rural areas, and their respective waste generation rates per capita measured here, was equivalent to 0.96 kg day^{-1}. The direct average was lower, at 0.75 kg day$^{-1.}$ In this case, the higher weighted average rate for waste generation per capita reflected the predominantly urban characteristics of the Juchitán district compared to Huejutla, where waste generation is considerably higher relative to rural areas, equivalent to 1.09 kg day^{-1} and 0.41 kg day^{-1}, respectively. Indeed, the weighted average for waste generation per capita in the predominantly rural Municipality of Huejutla was reduced by almost 50 % compared to the more urbanized situation found in Juchitán.

Table 5.7 Weighted average waste per capita (kg day^{-1}) in Juchitán

Juchitán				
Area	**Total population**	**Waste sampled (kg day $^{-1}$)**	**People in sample**	**Waste per person (kg day^{-1})**
Urban	74,825	90.3	83	1.09
Rural	18,213	20.7	50	0.41
Total	93,038	110.9	133	-
			Direct Average	**0.75**
			Weighted Average	**0.96**

5.4.2. Comparison of waste composition in case study areas

The environmental conditions prevailing in the case study areas are described in Section 3.4.2 and 3.5.2. This shows there is very little in the way of seasonal variation in environmental conditions throughout the year in both regions where the case studies were located, such that, waste generation patterns are also relatively consistent with time.

In general, the proportion of food waste, combustible and non-combustible waste was highly consistent in both Huejutla and Juchitán. Specifically, food waste in Huejutla was 31.5 % and in Juchitán it was equivalent to 30 %. Combustible waste was slightly lower in Huejutla (65.9 %) compared to Juchitán (66.7 %). Non-combustible waste was also lower in Huejutla, where this fraction represented 2.6 % of the total waste generation, compared to 3.3 % in Juchitán. Garden waste was the largest combustible fraction for both regions, equivalent to 22.2 % in Huejutla and 31.1 % in Juchitán. Also, the sum of recyclable waste represented almost 15 % of the total waste generated for both case study areas.

The rate of food waste generation in Huejutla was higher in urban (32.4 %) and periurban (38.9 %) compared to rural areas (24.5 %). In Huejutla, rural households often feed food waste to house animals and livestock, reducing the amount of this waste fraction in the total waste composition. Therefore, the food waste fraction could possibly be underestimated. In Juchitán, the proportion of food waste generated was consistent in urban (29.5 %) and rural areas (31.9 %). Garden waste generation in Huejutla was largest for rural communities (28.7 %), followed by urban households (23.7 %). The lowest rate for garden waste generation was found in periurban households (12.1 %) in this Municipality. It was observed that houses located in the urban area of Huejutla often had patios or gardens, while rural households were located near farmland and green areas. This was not the case of the majority of periurban households, which were smaller and had less access to outside areas within the property. Therefore, garden waste generation was reduced in periurban households compared to urban and rural areas. In contrast with Huejutla, garden waste generation in Juchitán was larger in rural (33.5 %) compared to urban areas (20.4 %). The proportion of the total combustible waste in Huejutla was 23 % larger in rural compared to periurban areas, and 8 % larger than urban areas. The rate of combustible waste generation in Juchitán was consistent in urban (67.8 %) and rural areas (62.3 %).

5.4.3. Comparison of results with other waste characterisation analyses

Waste generation and characterisation data recorded for Huejutla Municipality was compared with the results of a study developed by the neighbouring Municipality of Atlapexco (SanJuan-Marquez and Méndez-Pacheco, 2014). The project was carried out to characterize and quantify waste for the construction of a final disposal site in the Municipality of Atlapexco, which would also serve other neighbouring municipalities (Huautla and Yahualica).

In Juchitán, the waste characterisation data was compared with the results of a project carried out by a private company with the purpose of building a waste management facility for the Municipality (Valdivieso-Rasgado, 2014). Also, the waste characterisation results for Juchitán were compared with an undergraduate thesis on solid waste management in this Municipality (Velásques-Sánchez, 2011).

5.4.3.1. Comparison of waste generation and composition in Huejutla

The waste characterisation study carried out in Atlapexco, Huautla and Yahualica (SanJuan-Marquez and Méndez-Pacheco, 2014) sampled 120 houses in each Municipality. The household waste was collected daily in each dwelling for one week in the spring of 2014. Table 5.8 presents a waste characterisation comparison between Huejutla and its neighbouring municipalities. In all the municipalities, food and garden waste were the most prevalent waste fractions. Particularly, Huautla presents the most similar results for food and combustible waste fractions compared to Huejutla. By comparison, Atlapexco and Yahualica had a lower food waste fraction and a higher proportion of garden waste generation. Collectively, the proportion of plastics generated in Huejutla (10.7 %) was similar to the fraction of plastic waste in Huautla (7.9 %), Atlapexco (11.1 %) and Yahualica (10.6 %). Sanitary waste in Huejutla was slightly higher (17.8 %) compared to its neighbouring municipalities, where this fraction was equivalent to 13.9 %, 14 % and 11.1 % in Huautla, Atlapexco and Yahualica,

respectively. Combustible waste was 7 % lower in Huautla and 16% higher in Atlapexco and Yahualica compared to Huejutla.

Table 5.8 Comparison of waste composition (% fresh weight) in Huejutla and neighbouring municipalities

Waste type	Huejutla	Huautla*	Atlapexco*	Yahualica*
Waste that can be fed to animals				
Food waste	31.5	31.8	19.9	22.4
Combustible				
Garden Waste	22.2	20.2	33.4	37.8
Wood	0.2	0.1	0.3	0.0
Cardboard and paper	5.1	6.1	7.9	7.6
High-density polyethylene (HDPE)	1.7	nm	nm	nm
Plastic bags and packaging (Low-density polyethylene, LDPE)	3.9	3.5	4.7	4.9
Polystyrene	0.5	0.3	1.4	1.1
Disposable cups, plates (Polypropylene, PP)	1.4	0.1	0.2	0.0
Polyethylene terephthalate (PET)	2.0	1.6	0.7	0.6
Hard plastic	1.2	2.4	4.1	4.0
Tetra pack	2.2	1.2	2.4	2.2
Sanitary Waste	17.8	13.9	14.0	11.1
Electrical waste, cables	0.1	nm	nm	nm
Hazardous waste	0.9	nm	nm	nm
Aluminium lined packaging / foil	0.5	0.1	0.0	0.0
Textiles	2.3	1.0	1.4	0.5
Synthetic Fibres	0.1	0.6	0.5	0.1
Rubber	0.3	0.1	0.2	0.0
Others	1.2	10.1	1.7	2.6
Residual fraction	2.6	0.0	3.6	3.4
TOTAL (combustible waste)	**65.9**	**61.4**	**76.5**	**75.9**
Non - Combustible				
Aluminium cans	0.5	0.0	0.7	0.3
Metals, metallic cans	0.9	1.0	0.4	0.4
Glass	1.2	3.4	2.1	1.1
Construction waste	0.0	2.3	0.3	0.1
TOTAL (non-combustible waste)	**2.6**	**6.7**	**3.5**	**1.9**
TOTAL	**100**	**100**	**100**	**100**

nm: not measured
*Source: (SanJuan-Marquez and Méndez-Pacheco, 2014)

Figure 5.3 shows the average waste generation per capita in Huejutla compared to its neighbouring municipalities. The directly measured average waste generation per capita (rather than the weighted average) was used in this comparison to align with the averages presented by the other studies. According to SanJuan-Marquez and Méndez-Pacheco (2014), the average waste generation per capita in the region ranges from 0.64 to 0.70 kg day^{-1}. Huejutla and Yahualica have the same per capita waste generation, which is also the lowest in the region (0.64 kg day^{-1}). Atlapexco and Huautla have the highest waste generation per capita but the difference with the other municipalities is not significant. The small difference between the average waste generation per capita in the municipalities shows that the results are consistent between each other. The average waste generation per capita Huejutla and the overall regional value was similar and equivalent to 0.64 and 0.67 kg per capita, respectively.

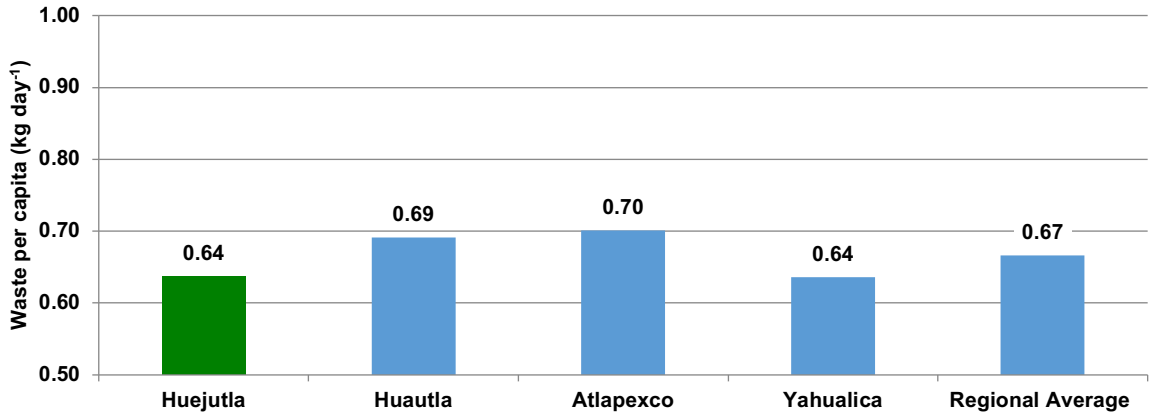


Figure 5.3 Waste per capita (kg day^{-1}) in Huejutla compared to neighbouring municipalities

5.4.3.2. Comparison of waste generation and composition in Juchitán

The waste composition in Juchitán was examined by Valdivieso-Rasgado (2014) and (Velásques-Sánchez, 2011) . In the first case, the waste characterisation was carried out in detail, and is shown in Table 5.9. For the second study, the waste characterisation was much simpler and only considered organic and inorganic waste fractions (Table 5.10).

As shown in Table 5.9, the waste composition results obtained through this research were consistent with the study carried out by Valdivieso-Rasgado (2014).

Table 5.9 Comparison of results of waste composition (% fresh weight) in Juchitán with other waste assessment study

Waste type	Juchitán (this study)	Juchitán: Valdivieso-Rasgado (2014)
Waste that can be fed to animals		
Food waste	**30.0**	**31.2**
Combustible		
Garden Waste	**31.1**	**37.6**
Wood	**0.3**	**0.3**
Cardboard and paper	**5.1**	**4.2**
High-density polyethylene (HDPE)	**2.3**	**0.9**
Plastic bags and packaging (Low-density polyethylene, LDPE)	**5.2**	**3.1**
Polystyrene	**0.4**	**0.3**
Disposable cups, plates (Polypropylene, PP)	**2.5**	**0.0**
Polyethylene terephthalate (PET)	**2.9**	**1.6**
Hard plastic	**2.2**	**3.1**
Tetra pack	**1.0**	**0.6**
Sanitary Waste	**9.3**	**6.8**
Electrical waste, cables	**0.3**	**nm**
Hazardous waste	**0.3**	**nm**
Aluminium lined packaging /foil	**0.2**	**0.5**
Textiles	**1.3**	**1.1**
Synthetic Fibres	**0.0**	**0.6**
Rubber	**0.0**	**0.1**
Others	**1.7**	**2.4**
Residual fraction	**0.5**	**0.7**
TOTAL (combustible waste)	**66.7**	**63.9**
Non - Combustible		
Aluminium cans	**0.1**	**0.1**
Metals, metallic cans	**0.8**	**0.8**
Glass	**2.4**	**2.3**
Construction waste	**0.0**	**1.8**
TOTAL (non-combustible waste)	**3.3**	**4.9**
TOTAL	**100**	**100**
nm: not measured		

The overall organic and inorganic waste fractions were calculated for comparison with the values reported by Valdivieso-Rasgado (2014) and Velásques-Sánchez (2011) and are presented in Table 5.10. This showed that the waste composition analyses reported for Juchitán were generally consistent.

Table 5.10 Comparison of results of waste composition (% fresh weight) in Juchitán with other waste assessment studies

Waste type	This research	Valdivieso-Rasgado (2014)	Velásques-Sánchez (2011)
Organic	66.5	73.4	63.4
Inorganic	33.5	26.6	36.6

Figure 5.4 presents a comparison of the waste generation per capita obtained through this research with the results obtained by Valdivieso-Rasgado (2014) and Velásques-Sánchez (2011). Both studies used direct averages for waste generation per capita. It appears that results for waste generation per capita are more consistent with the data presented by Velásques-Sánchez (2011), as the difference between the two studies is equivalent to 0.01 kg day^{-1}. According to Valdivieso-Rasgado (2014), waste generation per capita is 0.85 kg day^{-1}, which is 0.1 kg day^{-1} higher than the results obtained through this study. Nevertheless, the difference between waste generation per capita between the three studies are minor, which suggests that the results are in general consistent.

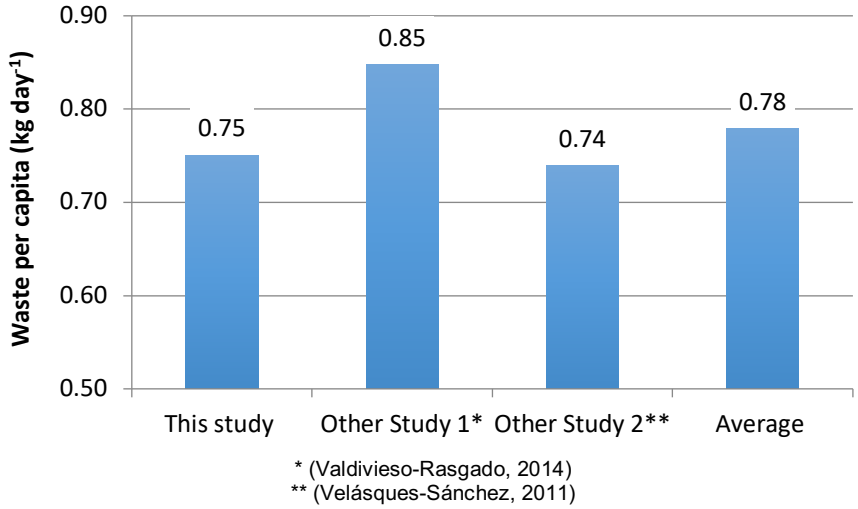


Figure 5.4 Waste per capita (kg day^{-1} fresh weight) in Juchitán compared to other waste assessment studies

6. Material Flow Analysis for case study areas

6.1. Introduction

A Material Flow Analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system. In solid waste management, MFAs are carried out to identify waste flows within the system and to the environment (Allesch and Brunner, 2017). This tool has been widely implemented to support waste management and recycling policies, as it provides a system-oriented interpretation of interlinked processes to support strategic and priority oriented decisions. This methodology facilitates the analysis of waste management systems, simplifying the process of comparison of different treatment options and their environmental effects (Moriguchi and Hashimoto, 2016).

In this chapter, information obtained from the household surveys, the waste characterisation analysis, and interviews with key stakeholders in the waste sector was used to elaborate a material flow scheme for waste generation, and the different disposal pathways operating, in the field case study areas. This provided an integrated overview of the waste mass balance in the regions, incorporating waste collection by municipal authorities and independent waste collectors, recycling rates and waste disposal by householders by alternative means (burning, burial and feeding to animals).

The aim of this chapter is to develop a waste management profile of open burning of waste in the case study areas to identify the types and quantities of MSW generated and disposed by burning by households. The specific objectives were to:

a) Determine the scale and extent of open burning of waste in the study areas in the context of the overall waste generation;
b) Quantify waste recovery for recycling and by feeding animals in households;
c) Estimate the rate of waste collection by the municipal authorities and waste collection unions;
d) Identify the amount of waste generated in urban, periurban and rural areas;
e) Quantify the amount of waste arriving at final disposal sites.
f) Integrate the information on waste pools and pathways into an overall Material Flow Analysis for each study area.

6.2. Materials and Methods

6.2.1. Sensitivity Analysis for open burning of waste

In Huejutla, the frequency of waste collections was fixed at daily and twice-weekly intervals in urban and periurban areas, respectively. The amount of waste disposed in households by open burning was estimated by assuming that the amount of waste collected at a frequency of twice per week corresponded to the waste generated over a four-day period; in other words, the quantity of waste per collection was assumed to be equivalent to the amount of waste generated by a household over the previous two day period. This assumption was informed based on householder experience. Consequently, the maximum amount of waste available to be disposed by burning corresponded to

the residual amount of waste generated per week, which was equivalent to three days of generated waste as a high estimate. A minimum amount of waste burned was also considered and in this case was assumed to be equivalent to the waste generated in one day (low estimate). Rural households were assumed to burn all the waste generated since collection services to rural areas are very infrequent (once every 1-3 months) and were only for bulky and non-compactable items including furniture and glass. Moreover, approximately 30 % of the rural population had no access to any form of waste collection service.

In Juchitán, the Municipal Authority did not provide a waste collection service to households. In this region, independent collectors operate daily in the streets of the city alerting householders by ringing a distinctive bell to bring out waste for collection when needed. The services are charged depending on the quantity of waste that is collected. Therefore, in this scheme, householders decide when to have waste collected. Results from the questionnaire (Chapter 4), showed that urban householders decide to have their waste collected 2.7 times per week on average, and rural households opted to use the waste collection service 1.6 times per week on average. Therefore, following a similar approach as applied for Huejutla for estimating the fraction of waste available for burning, it was assumed that one collection was equivalent to two days of generated waste by a household; therefore, the maximum waste available to be burned in urban areas, was equivalent to the amount of waste generated in a 1 to 2 day period, which was used to provide a low and a high estimate rate of open burning, respectively. In rural areas, the average waste collection frequency was 2 days per week and similar to Huejutla. Therefore, equivalent low and high rates of waste disposed by burning were also assumed for Juchitán, equivalent the amount of waste generated for 1 day or 3 days, respectively.

6.2.2. Assumptions and calculations for Material Flow Diagram in case study areas

Information collected from interviews with stakeholders, household questionnaires, and the waste characterisation analysis (Chapter 5) was integrated to calculate a Material Flow Diagram (MFD) to represent the different pathways for recycling and disposal of waste in each case study area. The mass flow of waste material was calculated on a fresh waste basis. The calculations and assumptions used to develop the MFA are presented in Table 6.1 and were generally similar for both case study areas. One of the main differences was that non-combustible waste was only buried in Huejutla, but burial was not practised in Juchitán as a method of waste disposal. Non-combustible waste generated in Juchitán was either sold to be recycled, collected for a fee by an independent collector, or taken by a household member to a final disposal site. Another major, and significantly more important difference between the municipalities was that burning for waste at dumpsites had ceased in Huejutla in 2013, but continued to be practised in Juchitán.

Table 6.1 Assumptions and calculations applied to estimate the waste material flow in the case study areas

Waste component	Area	Explanation of calculation	Specifics (if any)
Total waste generation	**Huejutla**	**Total Waste Generation = Waste generated in households + Commercial waste** **Waste generated in households** was calculated considering the population and the per capita waste generation (from waste characterisation analysis, Chapter 5): **Waste generated in households = (Urban population * Urban waste per capita) + (Periurban population * Periurban waste per capita) + (Rural population * Rural waste per capita)**	**Commercial waste:** Information provided by the municipal authorities (see Chapter 4). This includes waste collected in public areas. **Commercial waste = 40 t day $^{-1}$**
	Juchitán		**Commercial waste:** Information provided by waste collection unions (see Chapter 4). This includes waste collected in public areas. **Commercial waste=** 25 (SUTAJ) + 12 (Victor Yodo Union) + 3 (Flores Magón Union) + 0.6 (Isidro Morales Union) + 15 (Cecilio Villalobos Union) = **55.6 t day^{-1}**
Waste recovered at dumpsites	**Both**	Obtained through interviews with waste pickers at dumpsites.	
Waste recovered during collection	**Both**	Obtained through interviews with waste truck drivers and their assistants.	
Private recycling	**Both**	Obtained through interviews with waste recovery facilities	
Total Waste recovered	**Both**	**Total Waste Recovered = Waste recovered at dumpsites + Waste recovered during collection + Private recycling**	
Waste burned	**Huejutla**	**Waste burned = Households that burn waste * combustible waste fraction* estimated burning frequency** The proportion (%) of **households that burn waste** was obtained from the surveys (chapter 4). The **combustible waste fraction** was estimated using information from the waste characterisation analysis (chapter 5). **Sensitivity analysis:** The burning frequency was adjusted in a sensitivity analysis to test the impact on the potential amount of waste burned. This was carried out by assigning a low and high estimate for burning frequencies. For more details see section on sensitivity analysis in Section 6.2.1.	**Sensitivity analysis in urban/periurban areas:** Low estimate = 1 day per week High estimate = 3 days per week **Sensitivity analysis in rural areas:** Rural households were assumed to burn all their waste.
	Juchitán		**Sensitivity analysis in urban areas**: Low estimate = 1 day per week High estimate = 2 days per week **Sensitivity analysis in rural areas**: Low estimate = 1 day per week High estimate = 3 days per week
Waste fed to animals	**Both**	**Waste fed to animals = Households with animals fed with food waste * food waste fraction** The proportion (%) of **households with animals fed with food waste** was obtained from the questionnaires (Chapter 4). The **food waste fraction** was estimated from the waste characterisation analysis. It was assumed that all the food waste generated was fed to animals in those households that confirmed feeding food waste to animals in the household questionnaire.	
Waste buried	**Huejutla**	**Waste buried = Houses that bury waste * non-combustible waste fraction** **Houses that bury waste** were considered to be 60 % of the rural households: • 31 % of the rural population had no collection service and therefore buried all their non-combustible waste; • 29 % of rural households had a waste collection service, but also buried all their non-combustible waste because the frequency was once a month or less and general household waste was not collected (only bulky items such as tyres, bed mattresses, etc. were collected). The **Non-combustible waste fractio**n was estimated from the waste characterisation analysis.	
	Juchitán	No waste is buried in Juchitán according to surveys and interviews.	
Municipal waste collection	**Huejutla**	**Municipal waste collection = Waste generated in households – (burned waste + waste fed to animals + buried waste) + commercial waste collected**	**Municipal waste collection** according to municipal authorities is 70 t day -1
	Juchitán		**Municipal waste collection** according to waste collection unions is 123 t day-1
Final Disposal	**Both**	**Final disposal = Municipal waste collection – Total waste recovered**	
Waste burned in dumpsites	**Huejutla**	No waste is burned in dumpsites in Huejutla according to authorities.	
	Juchitán	**Waste burned in dumpsites = Final disposal * (Combustible waste fraction + food waste fraction)** Combustible waste fraction = 66.7% Food waste fraction = 30.0% Total combustible fraction = 96.7%	
Total waste burned	**Huejutla**	Same as waste burned in houses, as no waste is burned in dumpsites in Huejutla	
	Juchitán	**Total waste burned = Waste burned in dumpsites + waste burned in households**	

6.3. Results

6.3.1. Waste burned, fed to animals and buried in Huejutla

A major component of the MFA was to determine the quantities and amounts of waste that were not collected for disposal by the Municipal Authority, but were managed directly by alternative routes by householders and included waste disposed by burning and burial, and also the feeding of food waste to livestock. Table 6.2 shows the results for the amount of waste that is burned, fed to animals or buried by households in Huejutla. The sensitivity analysis for open burning of waste applied to urban and periurban areas of the Municipality considered that households burn between one or three days worth of waste per week. Rural households were assumed to burn all the waste generated, in the absence of a waste collection service. The analysis showed that the total amount of waste that was burned in the Municipality was in the range of 24.3 and 25.6 t day^{-1}. As may be expected, the majority of the waste that was disposed by burning occurred in rural areas, and this may be explained for several reasons. Firstly, 75 % of the population in the Municipality reside in rural areas and the proportion of households that burn waste is larger in rural areas; indeed 92 % of the households in rural areas that completed the questionnaire (Chapter 4) indicated that they used burning as a method of waste disposal. A third reason is that households that burn waste in rural areas tend to burn all the combustible waste generated, whereas in urban and periurban areas, households that burn waste only use this method of disposal for a fraction of the waste generated since they also have access to a frequent waste collection service. The total amount of waste fed to animals was equivalent to approximately 13 t day^{-1} and the amount disposed by burial was equivalent to 0.8 t day^{1}.

Table 6.2 Waste burned, fed to animals and buried in Huejutla

Huejutla											
		Household waste burned				Waste fed to animals			Buried waste		
Area	Population	Households that burn waste (%)	Combustible waste (% of total waste)	Sensitivity		Households that feed waste to animals (%)	Food waste fraction (% of total waste)	Waste fed to animals (kg day^{-1})	Households that bury waste (%)	Non-combustible waste fraction (% of total waste)	Waste buried (kg day^{-1})
				Low estimate [a] (kg day^{-1})	High estimate [b] (kg day^{-1})						
Urban	10,004	21.6	66.4	160	490	46.1	32.4	1,190	0	1.1	0
Periurban	30,011	36.8	58.2	930	1,900	61.8	38.9	4,970	0	2.9	0
Rural [c]	82,890	92.1	71.7	23,240	23,240	77.8	24.5	6,720	60	3.8	810
TOTAL	**122,905**	**-**	**-**	**24,330**	**25,630**	**-**	**-**	**12,890**	**-**	**-**	**810**

a) Low estimate = Houses burn 1 day generated waste per week
b) High estimate = Houses burn 3 days of generated waste per week
c) Rural areas are assumed to burn all their waste. Only rural population buries waste, as urban and periurban households have access to waste collection services. It was considered that 60 % of the rural households bury non-combustible waste (Table 6.1).

6.3.2. Integrated calculations for material flow analysis in Huejutla

Information presented in Table 6.2 was used to estimate the total rate of MSW generation in Huejutla Municipality, which is equivalent to approximately 104 t day^{-1} (Table 6.3). The results suggested that the Municipal Authority managed between 39 and 41 % of the generated household waste, and that uncollected waste was fed to animals, buried or burned. Sensitivity analysis indicated that 23 - 25 % of the total waste generated in the Municipality was burned in open fires (equivalent to

38 - 40 % of the total household waste generation), approximately 12 % (equivalent to over 30 % of the total food waste generated) was fed to animals and 1 % was buried. A small fraction, equivalent to 2 % of the total waste generated was recycled informally in Huejutla.

Table 6.3 Details of the material flow analysis estimated for Huejutla (kg day^{-1}, unless otherwise stated)

Huejutla											
Area	Population	Waste generated capita	Waste generated by households	Waste burned	Waste buried	Waste fed to animals	Household waste managed by authorities	Waste recycled	Commercial waste collected*	Municipal waste collection	TOTAL
Urban	10,004	0.80	7,970	160-490	0	1,190	6,290-6,620	2,500	40,000	64,580 - 65,870	
Periurban	30,011	0.69	20,690	930-1900	0	4,970	13,820-14,790				
Rural	82,890	0.43	35,240	23,240	810	6,720	4,460				
TOTAL	**122,905**	**-**	**63,890**	**24,330-25,630**	**810**	**12,890**	**24,570-25,870**	**2,500**	**40,000**		**103,890**
		% of Total	**61.5 %**	**23.4 - 24.7 %**	**0.8 %**	**12.4 %**	**23.7 - 24.9 %**	**2.4 %**	**38.5 %**	**62.2 - 63.4 %**	**100 %**
		% of Household Waste		**38.1 - 40.1 %**	**1.3 %**	**20.2 %**	**38.5 - 40.5 %**				
*Information reported by the authorities, includes waste generated in public spaces (streets, parks, schools and hospitals) and commercial waste.											

6.3.3. Material Flow Diagram for waste in Huejutla

The MFA for waste in Huejutla is shown in Figure 6.1. The diagram classifies waste into generated (grey), managed by the authorities (black), recovered (green) and burned or buried (orange). The daily municipal waste collection rate according was estimated to be equivalent to 64.6 - 65.9 t day^{-1}. This was consistent with the waste collection data reported by the authorities, which was equivalent to approximately 70 t day^{-1}. The rate final disposal of collected waste estimated for Huejutla was equivalent to approximately 60% of the total waste generated, at 62.1 – 63.4 t day^{-1}.

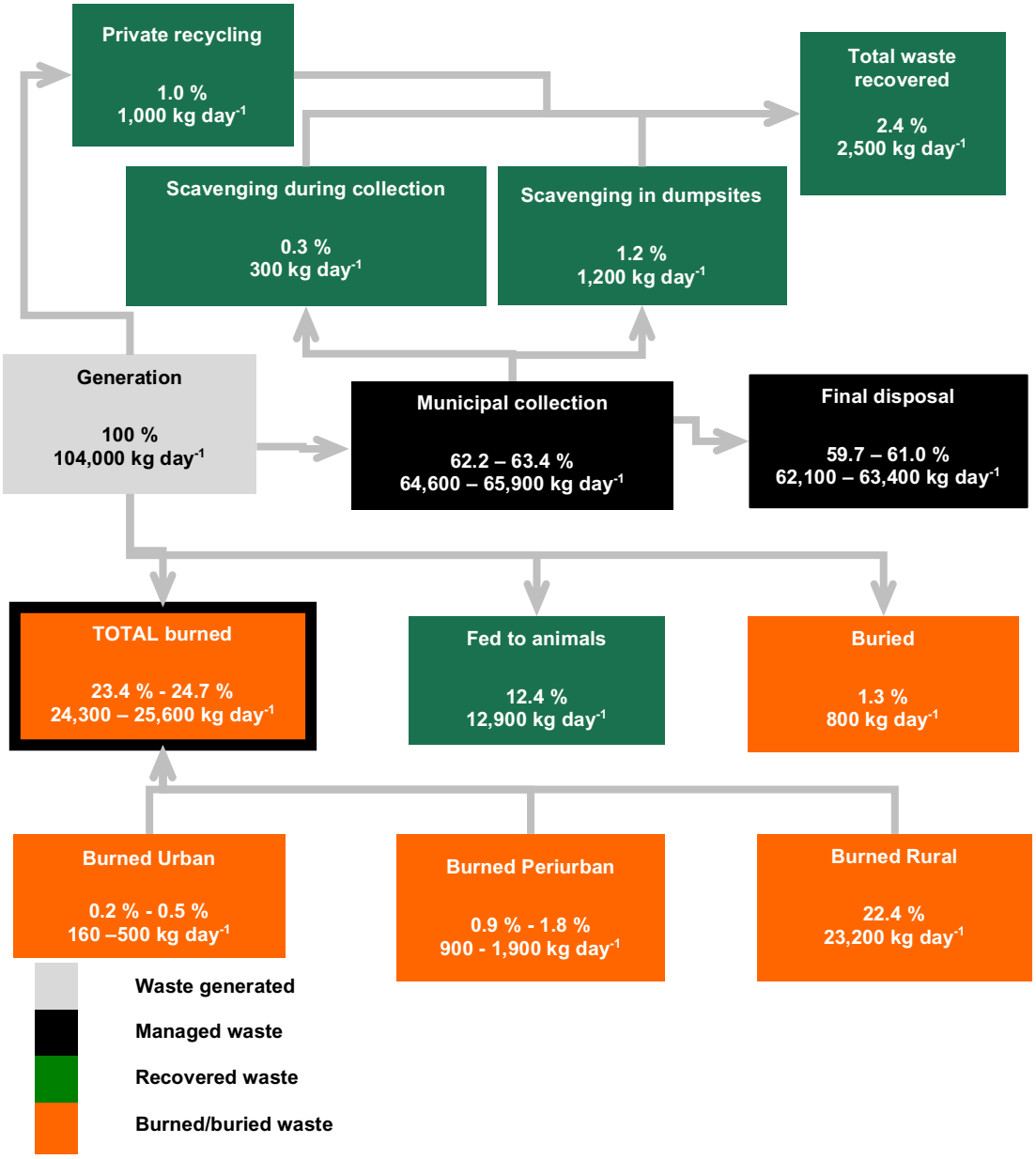


Figure 6.1 Material Flow Diagram (numerical values indicate % of total waste generated and kg day^{-1}) for waste disposal in Huejutla

6.3.4. Waste burned, fed to animals in Juchitán

In Juchitán, the sensitivity analysis applied to approximate the amount of waste burned as a method of disposal considered a low estimate where households burn the equivalent of one day of waste per week. The high estimate assumed that households burned the waste generated over a four-day period per week. Thus, between 4.5 and 9.6 t day^{-1} of waste were burned in households in Juchitán. The proportion of rural houses that burn waste was higher than in urban areas, and equivalent to 84 and 51 %, respectively, however, in contrast to Huejutla, urban households disposed of the largest proportion of the total waste generated by burning compared to rural communities. This may be explained because 80 % of the population reside within the urban zone of Juchitán Municipality and the per capita waste generation rate is more than double in urban (1.09 kg day^{-1}) compared to rural areas (0.41 kg day^{-1}). An estimated 12.5 t day^{-1} of waste is also fed to animals in Juchitán (Table 6.4).

Table 6.4 Waste burned and fed to animals in Juchitán

Juchitán								
Area	Population	Waste burned				Waste fed to animals		
		Households that burn waste (%)	Combustible waste (% of total waste)	Sensitivity		Own animals and feeds them waste (%)	Food Waste (% of total waste)	Waste fed to animals (kg day^{-1})
				Low estimate* (kg day^{-1})	High estimate** (kg day^{-1})			
Urban	74,825	51 %	67.8 %	3,970	7,930	44.5 %	29.5 %	10,690
Rural	18,213	84 %	62.3 %	560	1,680	74.0 %	31.9 %	1,770
TOTAL	**93,038**	**-**	**-**	**4,530**	**9,620**	-	-	**12,460**

Urban
Low estimate = Houses burn the equivalent to 1 day of waste generation per week
High estimate = Houses the equivalent to 4 days of waste generation per week
Rural
Low estimate = Houses burn the equivalent to 1 day of waste generation per week
High estimate = Houses the equivalent to 3 days of waste generation per week

6.3.5. Integrated calculations for material flow analysis in Juchitán

Table 6.5 integrates information from Table 6.4 to estimate the total waste generated and the fractions collected, burnt or fed to animals by households. Total waste generation in Juchitán was equivalent to 144.5 t day^{-1}. Between 75 and 81 % of the waste generated in households was collected, and the remainder was either burned or fed to animals. The sensitivity analysis showed that households in Juchitán burn between 3 and 7 % of the total waste generated in the Municipality and between 5 and 11 % of the total waste generated specifically by households. Approximately 9 % of the total waste generated was recovered by feeding to animals and almost 5 % was recycled.

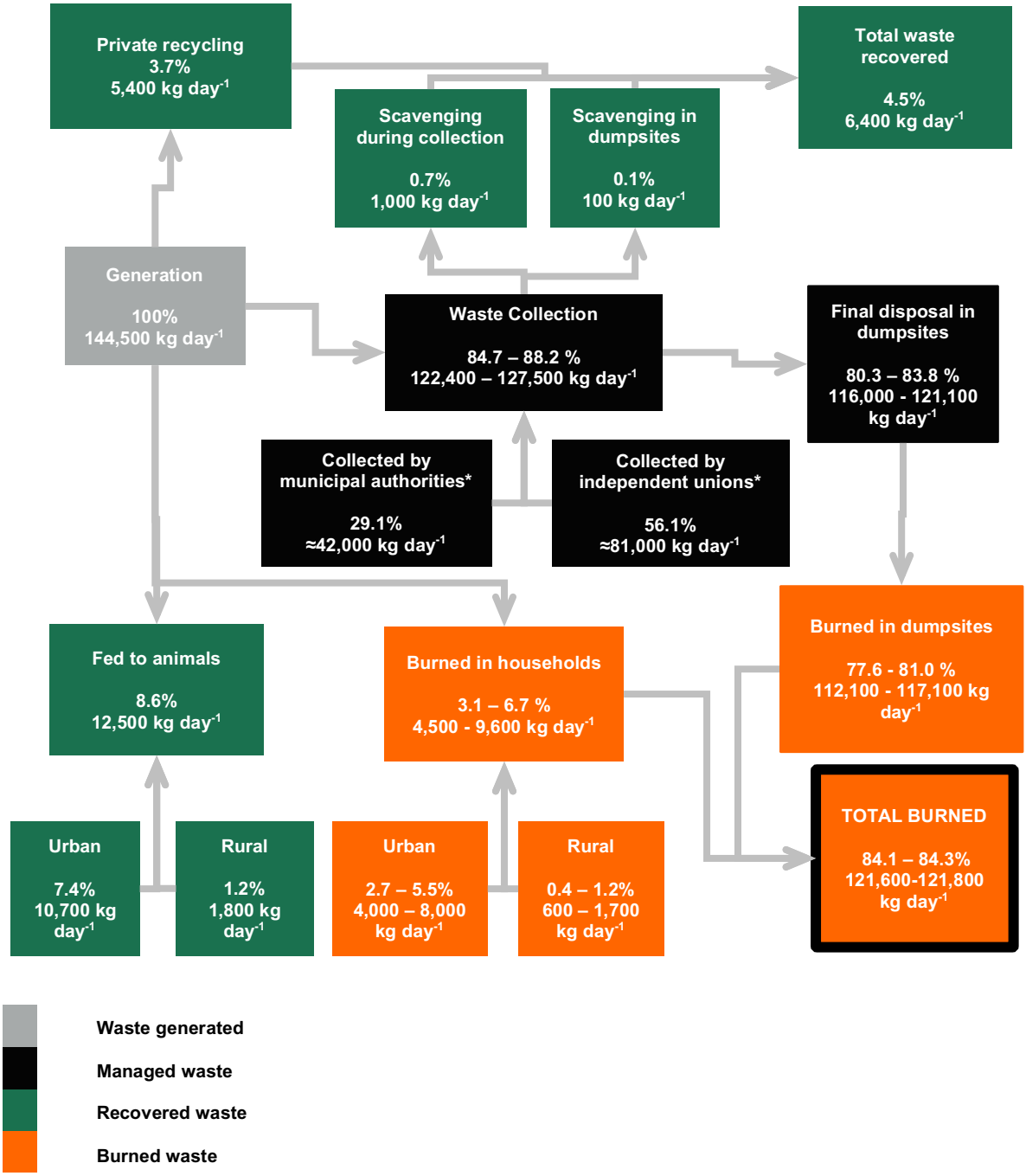
Table 6.5 Details of the material flow analysis estimated for Juchitán (kg day^{-1}, unless otherwise stated)

Waste Flow Analysis in Juchitán										
	Population	Waste per capita	Waste generated by households	Waste Burned	Waste fed to animals	Household waste collection	Waste recycled	Non household waste collected*	Total waste collected	TOTAL
Urban	18,213	1.09	81,370	3,970-7,930	10,690	62,750-66,720	6,440	55,600	122,420- 127,510	
Rural	93,038	0.41	7,530	560-1,680	1,770	4,070-5,190				
TOTAL	**111,251**	**-**	**88,900**	**4,530-9,610**	**12,460**	**66,820-71,910**	**6,440**	**55,600**		**144,500**
		% of total	**61.5%**	**3.1 - 6.7 %**	**8.6 %**	**46.2 - 49.8 %**	**4.5 %**	**38.5 %**	**84.7 - 88.2 %**	**100%**
		% of the household waste		**5.1 - 10.8 %**	**14.0 %**	**75.2 - 80.9 %**				

*Information reported by the authorities. Includes waste generated in public spaces (streets, parks, schools and hospitals) and commercial waste.

6.3.6. Material Flow Diagram for waste in Juchitán

The MFA developed for Juchitán is presented in Figure 6.2. The results indicated the total amount of collected municipal waste was equivalent to 122.4 – 127.5 t day^{-1}, representing 84.7 – 88.2 % of the total waste generated. This value was consistent with the waste collection data obtained from municipal and independent waste collection unions, which indicated 123 t day^{-1} of waste was collected. Consequently, as all of the collected waste is currently disposed at dumpsites where burning is permitted, the MFA shows that 78 - 81 % of the total waste generated was burned at dumpsites and that, overall, including waste also burned by households, 84 % of total waste generation in Juchitán is disposed by uncontrolled open burning. Indeed, the burning of waste at dumpsites to reduce volume and control pests was equivalent to 92 – 96 % of the total waste disposed by burning.



*Information provided by waste collection unions

Figure 6.2 Material Flow Diagram (numerical values indicate % of total waste generated and kg day^{-1}) for waste disposal in Juchitán

6.4. Discussion

A comparison of the MFA results obtained for the two case study areas is shown in Table 6.6. Open burning of waste is commonly practised in both case study areas considered in this investigation. However, the contribution to open burning emissions by different communities and the general waste management practices and population demography that influence this practice varied considerably between the regions. The amount of waste generated in Huejutla was approximately 104

t day^{-1}. In Juchitán, 144.5 t day^{-1} of waste were generated, and the fraction of waste disposed by burning was over 3x greater compared to Huejutla. A considerable amount of the food waste generated in Huejutla, equivalent to 12.4 % of the total waste generation, is recovered by feeding animals in both urban and rural households. However, only 2.4 % of the waste generated is recovered for recycling. The fraction of waste recovered by feeding animals in Juchitán is equivalent to 8.6 %, which is lower compared to Huejutla. Yet, the proportion of waste recovered for recycling is 2x larger in Juchitán, at 4.5 %.

Table 6.6 Comparison of MFA results in case study areas

Parameter	Huejutla	Juchitán
Urban population / rural population[(a)]	33 % / 67 %	80 % / 20 %
Waste generation (t day^{-1})	104	144.5
Waste recovered for recycling (t day^{-1}, % of total waste)	2.5 (2.4 %)	6.4 (4.5 %)
Waste fed to animals (t day^{-1}, % of total waste)	12.9 (12.4 %)	12.5 (8.6 %)
Waste collection rates (t day^{-1}), % of total waste)	64.6 - 65.9 (62.2 - 63.4 %)	122.4 - 127.5 (84.7 - 88.2 %)
Waste collection coverage in urban areas (frequency) [(b)]	Daily	100% of the population has access to waste collection at a cost. Frequency of collection is daily but the use of the service is decided by householders
Waste collection coverage in periurban areas (frequency)**	1 - 2 times per week	
Waste collection coverage in rural areas (frequency) [(b)]	80% has no service, 20 % once a month or less only for bulky materials	
Waste burned in backyards in urban areas (t day^{-1}, % of total waste)	0.2 - 0.5 (1.2 - 0.5 %)	4 - 8 (2.7 - 5.5 %)
Waste burned in backyards in periurban areas (t day^{-1}, % of total waste)	0.9 - 1.9 (0.9 - 1.8 %)	
Waste burned in backyards in rural areas (t day^{-1}, % of total waste)	23.2 (22.4 %)	0.6 - 1.7 (0.4 - 1.2 %)
Waste burned in dumpsites (t day^{-1}, % of total waste)	0	112.1 - 117.1 (77.6 – 81.0 %)
Total waste burned (t day^{-1}, % of total waste)	24.3 - 25.6 (23.4 % - 24.7 %)	121.6 - 121.8 (84.1 – 84.3 %)
a) Sections 3.5.3 and 3.6.3 b) Sections 4.3.3 and 4.3.4		

Rural and urban/periurban areas in Huejutla receive different levels of MSW collection service and this is thought to be a primary factor influencing the extent of open burning of waste by households. Rural areas, which have numerically the largest overall population compared to the urban districts have relatively poor or no collection service and therefore burn the majority of combustible waste compared to urban households. Consequently, between 91 and 95 % of the waste disposed by open burning occurred in rural communities, representing more than 22 % of the total MSW generated in

Huejutla. Nevertheless, burning was also observed in urban and periurban areas where frequent and free of charge waste collection was provided, equivalent to approximately 2 % (based on combined data for urban and periurban waste disposal by burning) of the total waste generation. This suggests that in addition to the provision of waste collection services, it is necessary to implement other control measures, incentives and education strategies to eradicate open burning of waste in the community. For example, no bins are provided for the storage of waste between collections, which might be incentivising the population to burn their waste as a more convenient means of disposal.

In Juchitán, municipal authorities do not provide waste collection services to households. However, independent unions collect waste but charge a fee for the service. The coverage of waste collection services in Juchitán is extended to 100 % of urban and rural households that choose to pay for the service. Nevertheless, in Juchitán more than 60 % of the population lives in poverty or extreme poverty conditions (Section 3.5.4), therefore some families dispose of their waste by open burning to avoid paying for waste collection services. In rural areas, where the level of marginalisation is higher, the amount of households that burn waste is increased. Specifically, 81 % of rural households dispose of their waste by open burning, while 54 % of urban dwellings use this method of waste disposal. However, because more than 80 % of the population lives in urban areas and waste generation per capita is 2x larger than in rural communities, almost 90 % of uncontrolled waste combustion in households occurred in the city.

According to the high estimate of the sensitivity analysis for household burning in Juchitán, approximately 7 % of the total waste generated was disposed by burning in backyards, which is less than a third compared to household waste burning in Huejutla. Around 80 % of the population in Juchitán lives in urban areas (Section 3.5.3), which tend to be in a better socioeconomic status compared to rural areas and could therefore be less inclined to burn waste. These results suggest that providing waste collection services is essential to reduce waste disposal by open burning in households. However, most of the waste burned in Juchitán occurs in dumpsites, equivalent to 92 - 96 % of the total waste burned. Therefore, if uncontrolled waste combustion in dumpsites would be eradicated in Juchitán, the overall contribution of open burning as a waste disposal method would be reduced compared to Huejutla, since a larger fraction of the waste generated is collected.



Figure 6.3 Smouldering waste at Municipal dumpsite in Juchitán

7. Emission factors for Black Carbon emissions from open burning of waste

7.1. Introduction

Open burning of waste by households and at dumpsites is characterised by inefficient combustion and the production of a range of atmospheric pollution emissions. Black Carbon (BC) is a major emission product from inefficient combustion processes and is a significant climate pollutant. For example, BC is estimated to have a GWP potential 1,200 – 5,100 times greater compared to CO_2 (Section 2.4.2) considering a 20-year horizon (Fuglestvedt et al., 2010; US EPA, 2012b). Consequently, BC is also a major atmospheric pollutant released during the open burning of waste (Lemieux et al., 2004; Christian et al., 2010; Wiedinmyer et al., 2014; Kodros et al., 2016; Stockwell et al., 2016). However, there is a paucity of quantitative evidence describing the extent and characteristics of BC emissions from waste burning, which are highly dependent upon the composition of the waste (Christian et al., 2010; Wiedinmyer et al., 2014).

Until now, published emission factors (EFs) for open burning of waste have been developed using a limited number of measurements and are therefore associated with high degrees of uncertainty. This is the case of the BC EF for uncontrolled waste combustion published by Christian et al. (2010) which was developed using a single measurement of open burning of waste emissions captured in each of three municipal landfills in periurban communities located north of Mexico City in April 2007. Similarly, Stockwell et al. (2016) and Jayarathne et al. (2017) published a BC EFs for open burning of waste as part of the Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE). In this case, EFs were developed using two measurements of the same type of waste sample. Until now, published reports providing BC EFs for waste combustion do not include information on the waste composition of the samples, which has a great influence on the emissions from this source.

Quantifying and characterising emissions from waste burning is necessary to understand the impact of this activity on climate change and human health. This information would assist in improving BC inventories and would provide the technical evidence needed to develop effective policies for MSW management, health provision services, and climate change mitigation. To quantify the emissions from open burning of waste, it is necessary to develop an emission factor (EF). Emission factors (EFs) are described as the mass of a pollutant emitted per unit mass of material burned (Zhang and Morawska, 2002; Lemieux et al., 2004).

One of the most effective ways to develop EFs for open burning sources is through laboratory simulations (Lemieux et al. (2004) to enable careful control of the variables that impact combustion emissions which are extremely difficult to manage in field situations Indeed, combustion conditions significantly impact BC EFs determined for the open burning of waste (Zhang and Morawska, 2002; Lemieux et al., 2004; Tissari et al., 2008). Thus, small samples of waste are combusted in controlled representative conditions and quantitative variables such as the mass of the sample, the mass of captured emissions, air flow rates, and concentrations of emitted pollutants can be carefully measured. The obtained EF is multiplied by the disposal activity level, which is usually represented as

the mass of waste burned per unit time in a specific area, to calculate emissions from open burning of waste.

One of the main methods employed to measure emissions from combustion in the field uses equipment designed to sample emission concentrations of a fire plume. This process involves several challenges, such as having to employ expensive equipment that allows measuring in close proximity to the combustion source. Also, this method measures emission concentrations, which have to be translated to total mass emissions of BC per kilogram of waste burned. In the case of open burning of waste, the concentration of the emissions in the plume is highly variable. Therefore, relating the gas mixture of the plume with the mass of waste burned would result in EFs with a high degree of uncertainty. Therefore, this research will characterise emissions from open burning sources using small amounts of the representative material in a combustion chamber in a laboratory, while simulating the conditions in the field.

The aim of this chapter is to quantify EFs for BC from the open burning of waste, using the waste composition characteristics of two case study regions and published national waste compositional data, through a controlled laboratory combustion technique. The specific objectives were to:

a) Develop a laboratory based, combustion methodology to measure BC EFs from burning waste.
b) Measure BC EFs for single waste types including: green waste, different types of plastics, textiles and paper and card.
c) Measure BC EFs for mixtures of these waste types following the waste composition in the two case study areas (Huejutla and Juchitán) and in Mexico.
d) Determine the relationship between the combustion properties of burning single materials and in combination as representative mixed waste sources
e) Quantifying appropriate constants for the general assessment of optical attenuation (ATN) measurements relative to EC for combustion emissions from waste.

7.2. Materials and methods

BC characterisation involves collecting particulate matter (PM) on filters and either (1) measuring the attenuation of light transmitted through the filter, or (2) measuring the carbon content on the filter using thermo-optical analysis (TOA) (Watson et al., 2005).

7.2.1. Waste combustion emission sampler

A laboratory combustion emission sampler was designed and constructed as shown in Figure 7.1. The structure of the equipment consisted of a conic stainless-steel hood (the diameter of the open end was 203 mm) that was fitted to an aluminium stack (internal diameter, 25.4 mm) equipped with a filter holder with a diameter suitable for 47 mm filter papers. A flowmeter was connected between the filter holder and a vacuum pump by a flexible hose. A metallic tripod was placed under the conic hood to hold porcelain crucibles containing waste samples during the experimentation process. The distance between the tripod platform and base of the hood was set at 120 mm as this provided for

efficient capture of emitted particulate matter and also facilitated sample management and observation of the combustion process.

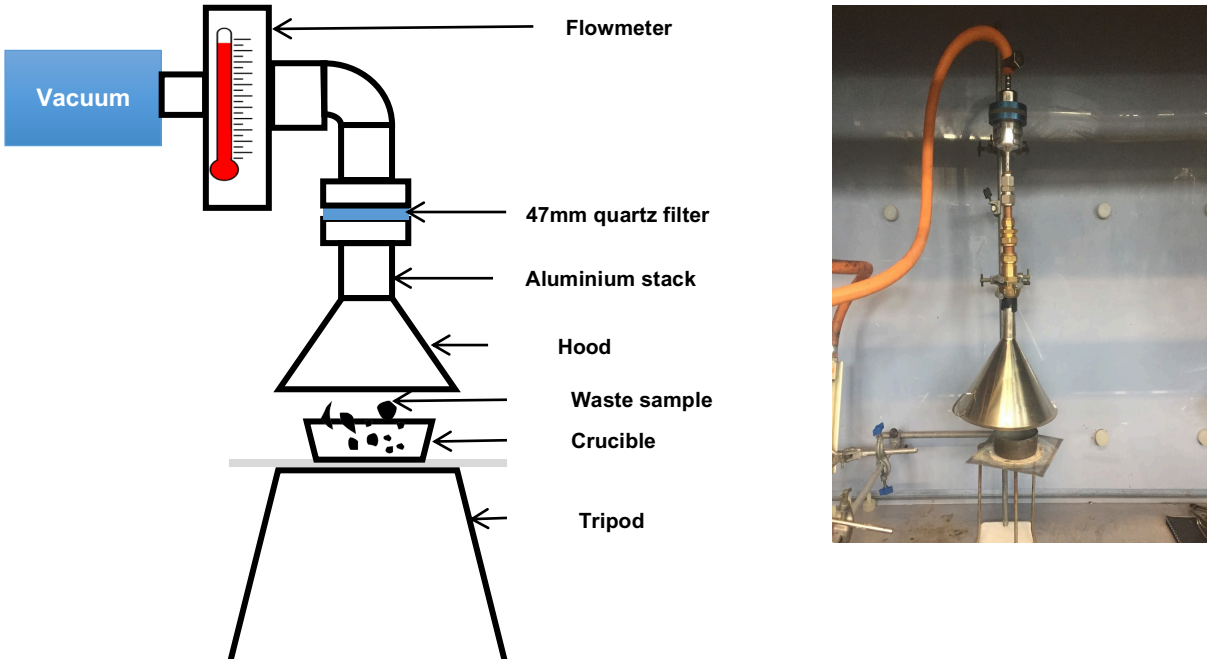


Figure 7.1 Waste combustion emission sampler

7.2.1.1. Sample ignition and emission collection procedure

Waste samples were placed in a porcelain crucible (102mm in diameter and 37mm tall) on the tripod, the vacuum pump was turned on, and the reading of the flow meter recorded. Crucibles were previously cleaned by firing them in a Gallenkamp muffle furnace (size 2) for at least 6 hours at 600ºC. The sample was set on fire with a Bunsen burner set to the full power (throat hole completely open), which was removed 10 seconds after ignition. The combustion time of the experiment was recorded with a chronometer. The resulting emissions from the combustion process were drawn through a 47 mm diameter Whatman quartz filter placed in the filter holder. The filters were weighed with a four-digit balance before and after each experiment. The total emission mass was determined by the difference of weight in the filters. The crucible and sample were also weighed on completion of the combustion test period to provide the residual mass of uncombusted material.

7.2.1.2. Preparation and storage of filters

Quartz filters are prone to adsorb volatile organic compounds because of their high active surface (Chai et al., 2012). To avoid contamination, the filters were submitted to a thermal treatment (pre-firing) before sampling, to remove volatile adsorbed carbon and reduce the OC content (Karanasiou et al., 2015). Chai et al. (2012) and Karanasiou et al. (2015) suggested using a temperature > 500ºC but <600ºC for at least 2 hours to remove organic contamination whilst avoiding physical changes in quartz filters, such as an increase in adsorption capacity. Therefore, following these

recommendations, quartz filters were pre-fired at 550ºC for 2.5 hours in a Gallenkamp muffle furnace (size 2). To avoid secondary contamination after the pre-firing treatment the filters were stored in new plastic Petri dishes and wrapped in cling film followed by aluminium foil to provide an effective atmospheric seal. The filters were only exposed to ambient air during the experimentation and measurement process to minimise exposure to potential contamination sources.

7.2.2. Preparation of waste samples

Samples were prepared by placing different types of dry waste in clean porcelain crucibles. Crucibles were pre-fired in a Gallenkamp muffle furnace (size 2) at 550ºC for 15 to 17 hours (overnight) to remove residual organic content. The types of waste tested (Table 7.1) were chosen following the main waste types identified in the case study areas (Chapter 5). Emissions were collected using samples of single waste types as well as combinations of different waste types, following the waste composition found in the case study areas. Waste emissions from combustion of waste representing the national properties in Mexico were prepared using waste composition information supplied by INECC (2012) and SEMARNAT (2013b).

The selection of the weight of the samples per type of waste was determined by the blackness of the filters after a carrying out 3 to 5 pre-tests (Table 7.1). If the filter was heavily darkened in the initial tests, the weight of the sample was reduced. This procedure was followed to avoid optical saturation of the filters. After an appropriate sample weight was determined, 10 replicate test of the same approximate sample weight were carried out. The smallest overall sample size used in the combustion analysis was established for polystyrene and was approximately 0.1 g. On the other hand, if the filters did not appear darkened during the initial experiments, the sample weight was increased to enhance the collection of particles on the filter. The largest sample size used was for PET and HDPE and was equivalent to 5 g. The samples of LDPE were smaller (3 g) because of the low density of this material. The fresh organic waste was dried in a furnace at 105ºC for 3 hours before the experimentation process to remove the moisture content, following the methodology for dry matter by oven drying by Shreve et al. (2006). The organic waste fraction was composed of garden waste (leaves and branches) to represent the organic composition of waste commonly burned in the case study areas. Food waste was not included as it is commonly used to feed animals, and does not burn easily in open fires due to its wet content.

Table 7.1 Waste sample types and sizes used in the combustion experiments

Type of waste	Sample weight (g)
National[a]	0.5
Huejutla[b]	0.5
Juchitán[b]	0.5
Paper and cardboard	3
Garden waste[c]	1
Textiles[d]	0.1
LDPE	3
HDPE	5
PET	5
Polystyrene	0.1

a) (INECC, 2012; SEMARNAT, 2013b)
b) From waste composition analysis described in Chapter 5.
c) Garden waste was composed of leaves and branches, to follow the composition of organic waste burned in case study areas.
d) Textiles were composed of 50% cotton and 50% synthetic, following the estimated composition of textile residue published by INECC (2012).

7.2.3. Preparation of mixed waste types

Mixed waste types were prepared using information gathered in the field composition analysis for the case study areas (Table 5.2 page 105, and Table 5.4 page 109) and in official sources (INECC, 2012; SEMARNAT, 2013a) for the national waste composition in Mexico (Figure 3.6 page 54, and Figure 3.7, page 55). The waste composition was simplified to include only the four main waste types in the region (garden waste, textiles, paper plus card and plastics) and is shown in Table 7.2. The composition of plastics was also simplified to consider only the four main plastic categories in the case study areas (LDPE, HDPE, polystyrene and PET).

Table 7.2 Simplified composition of mixed waste samples

Waste Fraction	National	Huejutla	Juchitán
Garden waste	25.5%	43.5%	51.8%
Textiles	16.3%	13.2%	7.0%
Paper and card	30.0%	17.3%	12.7%
Plastic 1: LDPE	10.9%	10.2%	10.6%
Plastic 2: HDPE	5.6%	4.8%	5.2%
Plastic 3: Polystyrene	6.2%	1.9%	1.8%
Plastic 4: PET	5.6%	9.0%	10.9%
TOTAL	100%	100%	100%

7.2.4. Replication of test burns

Even under controlled laboratory conditions combustion testing is potentially subjected to significant experimental variation and large numbers of replicates may be necessary to provide

statistically confident results. An exercise was therefore conducted to determine the minimum replication required to maximise the accuracy of the results for each type of waste. Two waste types were selected for this purpose: textiles and cardboard. A total of twenty replicate combustion tests was completed for each waste type and the standard deviation of randomly increasing the replications of the mean captured emission mass was calculated, based on randomly selecting sample results for each material. This exercise was repeated five times, and the overall mean stand deviation was calculated. The results of the statistical analysis showed that the mean standard deviation reached a stable value above ten replicates, as shown in Figure 7.2 and Figure 7.3. Therefore a minimum of ten replicates of combustion experiments were conducted for each waste sample type. The standard deviation was 8.2 % of the overall mean for textiles and 9.6 % for cardboard.

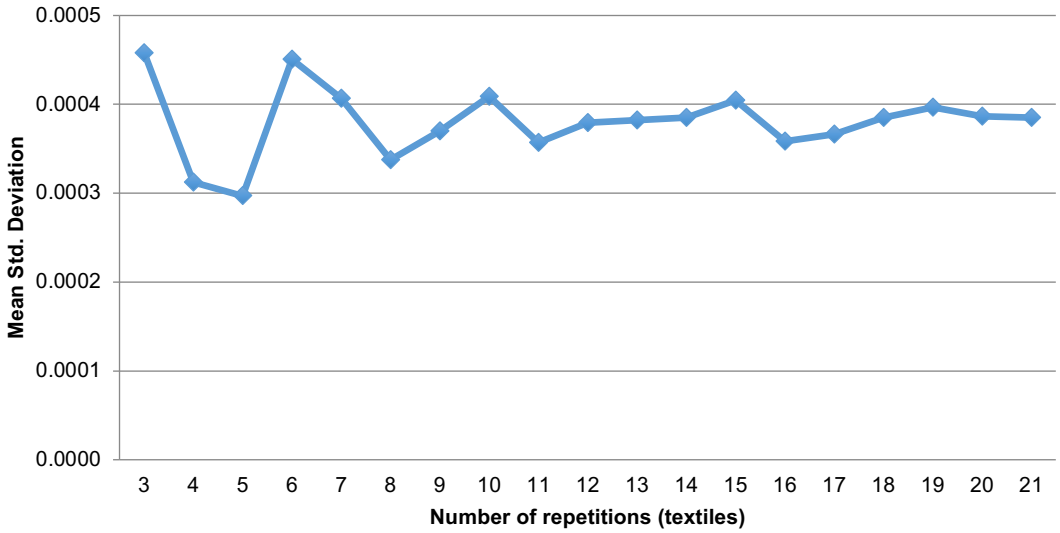


Figure 7.2 Mean Standard Deviation per number of repetitions for emissions captured (textiles)

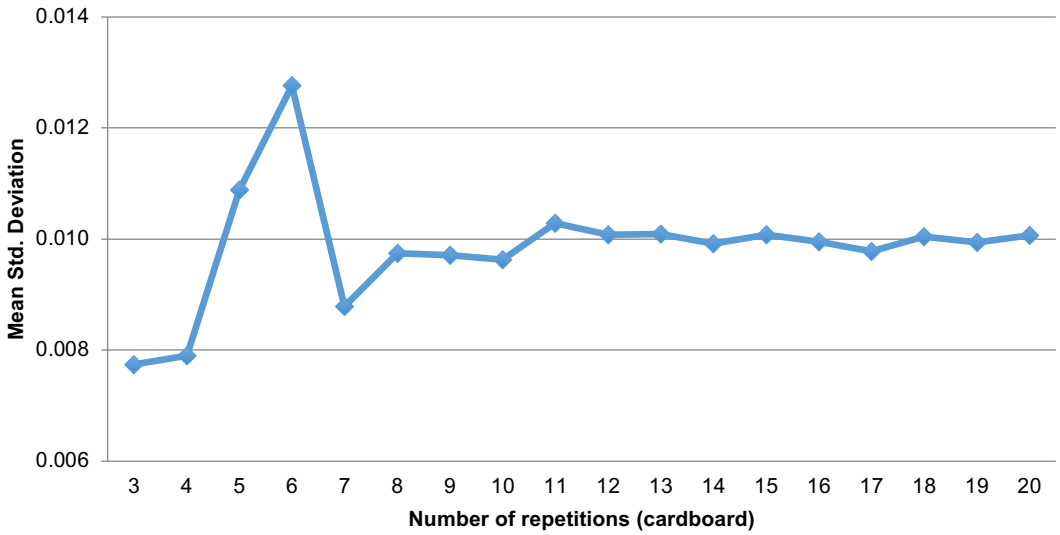


Figure 7.3 Mean Standard Deviation per number of repetitions for emissions captured (cardboard)

7.2.5. Effect of flow rate on emissions captured

The flow rate was set at 40 l min^{-1} to provide efficient emissions capture. The laboratory vacuum supply was generally stable and maintained the required flow rate, but occasionally could vary to a moderate extent (2-5 l min^{-1}). Therefore an experiment was conducted to examine the effect of flow rate on the emissions capture rate using samples of textile waste as an example. Two different flow rates were tested, including the standard condition equivalent to 40 l min^{-1} and a reduced rate of 20 l min^{-1}, although this was much smaller than the variation in flow rate observed in practice. Indeed, the flow rate decreased to a minimum of 30 l min^{-1} only very rarely The results confirmed there was no statistically significant difference (P=0.185) in the mass of emissions captured between the two flow rates tested, and the mean emission capture rates at 40 and 20 l min^{-1} were 616 and 597 x 10^{-6} g, respectively.

7.2.6. Determination of the carbon content of captured emission samples (EC/BC)

7.2.6.1. Determination of BC by Optical Analysis

Several instruments are available to determine BC based on optical properties (Section 2.5.2). A Magee Scientific Optical Transmissometer (OT-21 Magee Scientific, California, USA) was selected to complete the analysis of the exposed quartz filters because it uses a non-destructive method and can perform rapid BC determination without the need for expensive support gases or consumables. The analysis was carried out in cooperation with the Air Pollution and Public Health Laboratory, Kings College London.

The transmissometer has a tray with two filter holder slots. One of the slots measures light attenuation through the sample filter, and a simultaneous measurement is made through the reference (blank) filter placed in the rear slot. The instrument measures and compares the transmission intensity of light passing through a particle-loaded filter relative to the intensity of a blank filter to determine the attenuation (ATN) value. The transmissometer provides light absorption measurements at two wavelengths. The infrared wavelength (IR) at 880 nm is interpreted as BC and the UV wavelength at 370 nm is interpreted as a Brown Carbon (BrC), which is an indicator of aromatic organic compounds such as those found in smoke from biomass burning (Magee Scientific, 2015).

The operational manual of the OT-21 states that 1 ATN unit is equivalent to 0.06 µg cm^{-2} BC on the filter. If collected on 47 mm diameter filters at a flow rate of 16.7 L min^{-1} for 24 hours, this represents a BC concentration in air of 0.14 µg m^{-3} (Magee Scientific, 2015). According to Hansen (2005), ATN is given by the following equation:

$$ATN = 100 * \ln (I/Io) \qquad \textbf{Equation 7.1}$$

where I and Io are the respective light intensities transmitted through the loaded and blank filters. Hansen (2005) used a scaling factor of 100 for numerical convenience. Optical methods assume that ATN is proportional to the BC on the filter paper (Hansen et al., 1984; Liousse et al., 1993; Petzold et

al., 1997; Ahmed et al., 2009). Black carbon density (in μg cm^{-2}) is calculated by dividing the ATN by the mass extinction coefficient (σATN), in m^2 g^{-1}, as in the following equation (Hansen, 2005):

$$BC = ATN/\sigma ATN \qquad \textbf{Equation 7.2}$$

This coefficient, also referred to as "sigma", is not a constant, as it depends on the wavelength of the light used by the measuring instrument. The Magee Scientific Aethalometer user manual suggests a sigma of 16.6 m^2 g^{-1} for BC measurements made using the IR wavelength channel (λ) = 880 nm (Hansen, 2005). It also suggests a sigma value of 12.6-m^2 g^{-1} when calibrated against EC measured using a thermal/optical reflectance (TOR) method. Hansen (2005) also states that if EC measurements are determined using the thermal/optical transmittance (TOT) method (Section 2.5.2.4), a different sigma would be required, but did not provide a suggested value.

Several studies have stated that the rate of change in light transmission is not linear for filter samples, especially when ATN values are high, due to a saturation effect (Weingartner et al., 2003; Virkkula et al., 2007; Drinovec et al., 2015; Davy et al., 2017). When saturation occurs, assuming a linear proportionality between ATN and BC would lead to an underestimation of BC. Therefore, measurements must be compensated for this loading effect, to be able to accurately represent BC concentrations (Drinovec et al., 2015). Lack et al. (2014) summarises the three main factors that cause a non-linear response:

- **Multiple light scattering within filters**: incident light may be scattered by unloaded filter substrate (membrane or fibres) and increase the sample path. This effect varies between different types of filter substrates.
- **Filter loading**: as more particles are collected on the filter the optical sampling path is decreased leading to bias in the final calculation. This effect will vary depending on the amount of material deposited on the filter.
- **Particle scattering**: as the filter becomes loaded there is an increase in the number of light scattering particles, which leads to incident light being scattered in any direction. This phenomenon could cause higher filter reflectance and more opportunities for light to be absorbed by other particles. This variation is dependent on the aerosol type (shape, size, composition, mass).

Measurements were therefore compensated for this loading effect to accurately estimate BC concentrations using ATN values by using two different approaches to obtain the shadowing correction factor and mass extinction coefficient. A quadratic model by Virkkula et al. (2007) and used by Drinovec et al. (2015), was applied:

Equation 7.3

where *k* is the shadowing correction factor and σ_{ATN} is the mass extinction coefficient in m^2 g^{-1}.

A second calibration model (Virkkula et al., 2007) based on a logarithmic expression was also tested to derive the shadowing correction factor and the mass extinction coefficient (using the same terms as in **Equation 7.3**):

Equation 7.4

7.2.6.1.1. ATN measurements

The instructions published in the operation manual for the OT-21 were followed (Magee Scientific, 2016). At the start of each analytical session, the machine was calibrated by placing blank quartz filters in both trays of the filter holder. This machine is linked to a personal computer via software and creates .cvs files that can then be imported into Microsoft Excel. After the calibration process was completed, a blank quartz filter was placed in the rear tray of the filter holder as a blank reference filter, and the sample filter was placed in the front tray. A blank filter was used every 20 samples to ensure that there was no drift in the measurements. Whilst both UV and IR measurements are determined by the OT-21, only the IR (λ 880 nm) measurements have been considered as it is the equivalent BC component which is of interest for this project. Also, the UV values (at λ 370 nm) were too high for most of the sample filters.

7.2.6.2. Determination of EC by Thermal Optical Analysis

Combustion-generated carbonaceous aerosol is measured either optically or chemically. The optical method uses light absorption, as in the case of the OT-21, and the resulting measurements of attenuation can then be converted to BC by calibration against a quantitative chemical-thermal method. This method does not detect BC directly, and the quantity of refractory material detected (Figure 2.4) depends on the characteristics of the method. Specifically, the chemical (thermal) method determines the carbonaceous aerosol fraction of particulate matter samples, classifying it into organic carbon (OC) and elemental carbon (EC) (Cavalli et al., 2010; Karanasiou et al., 2015).

The European Committee for Standardisation (CEN) considers the thermal-optical analysis as the reference methodology to quantify EC and OC on filters. The most common protocols for this process include NIOSH-like, IMPROVE_ A and EUSAAR_2 either with transmittance or reflectance correction (Karanasiou et al., 2015). Karanasiou et al. (2015) reviewed the literature relating to these protocols and concluded that it was not possible to identify which specific thermal optical method provides the preferred approach. All of the protocols examined were comparable for total carbon (TC) concentrations. However, the various methods may provide different results for OC and EC concentration (Karanasiou et al., 2015).

In this research, a Sunset Laboratory Aerosol Analyser was used to determine the elemental and organic carbon (EC/OC) content of the emission samples. The measurements were completed by the National Physical Laboratory (NPL) in the UK, following the EUSAAR2 thermal protocol of the 16909 European Standard (European Committee for Standardisation, 2017) and using a pyrolysis correction based on transmittance. As described by Chai et al. (2012), a small circular section from the filter is placed in the analyser and heated in inert and oxidising atmospheres. At the beginning of the process,

the temperature is increased in steps up to 650ºC in a helium atmosphere. At this stage, the OC on the sample is thermally removed, oxidized, reduced, and then quantified as methane by a flame ionization detector. During this first phase, some organic compounds may pyrolyse to form 'char' that can then be mistakenly detected as elemental carbon. This pyrolytic reaction is monitored by carrying out continuous transmission measurements using a laser beam, allowing for a correction to be applied for this 'charring' process. In the second stage of the analysis, any residual char from the pyrolysed organics is oxidized, along with the original EC, in the presence of oxygen and helium. As char is removed from the filter, transmittance increases. When the transmission measurement reaches the original pre-pyrolysis value, the split between the OC and EC fractions can be determined (Cavalli et al., 2010; Chai et al., 2012).

Ten representative filters were selected from the sample bank for the mixed waste tests for both Huejutla and Juchitán (5 for each case study area) for the thermal EC analysis. They were selected to cover the full ATN range of the OT-21 transmissometer up to an ATN value of 500. The ATN properties of the selected filters are shown in Figure 7.4.

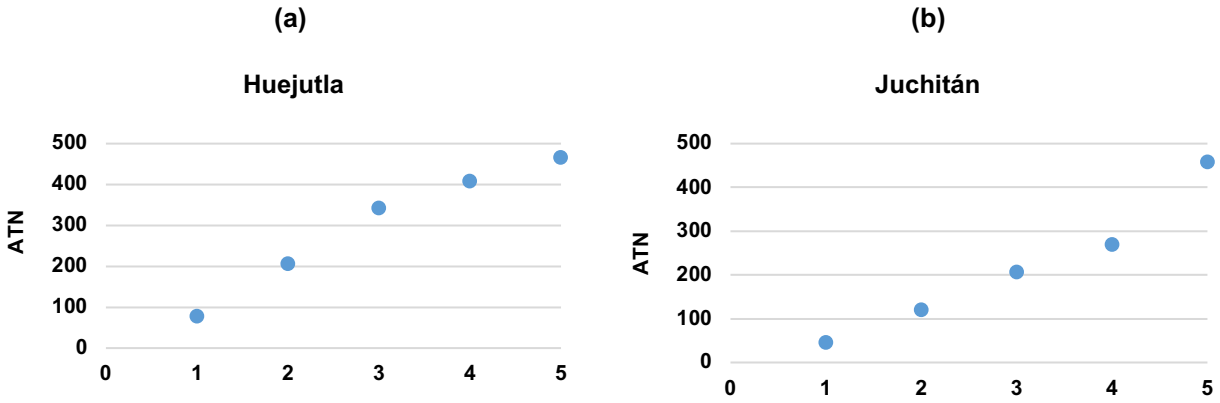


Figure 7.4 Selection of filters for EC analysis using a range of ATN measurements

7.2.7. Statistical analysis of results and data management

The relationship between EC and ATN was quantified using a quadratic expression of the general form:

Equation 7.5

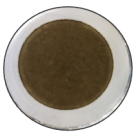
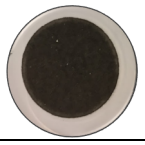
where y represents EC and x is the ATN value and a, b and c are regression coefficients.

Descriptive statistics were calculated to characterise the combustion emissions and burnt residual matter data, and include the mean, median, standard deviation, minimum and maximum values, and 95 % confidence limits. The specific data examined in this way included: sample mass before combustion, sample burned, fraction of sample burned (%), emissions captured, emissions captured/sample burned (%), total combustible mass, remaining volatile mass and ATN. These procedures were performed for the specific waste types (garden waste, paper and cardboard, textiles

and different types of plastics) and mixed waste combinations representing the composition of household waste generated in the case study areas (Huejutla and Juchitán) and also the national waste properties for Mexico.

The sample size was adjusted to minimise ATN saturation, but in some cases for plastics and mixed waste types saturation occurred and sample filters were too dark to be measured by optical methods. To avoid an underestimation of the results, the filters that were oversaturated were therefore assigned an ATN value of 500, which is the upper limit of detection of the OT-21. The number of filters that fall into this category per type of waste sample can be found in **Error! R eference source not found.** and **Error! Reference source not found.**. Representative examples showing the distinctive colour range and properties of the quartz filters after combustion and particulate collection are presented in Table 7.3. It can be observed that darker filters present higher ATN values.

Table 7.3 Range of ATN from waste combustion emissions of different materials

ATN	11.09	72.99	132.5	164.9	388.1	>500
Filter						
Waste type	HDPE	LDPE	Garden waste	PET	Huejutla	National
Sample size (g)	5	3	1	5	0.509	0.507
Sample combusted (g)	0.840	0.743	0.603	0.213	0.262	0.382

7.3. Results

7.3.1. Patterns in combustion and emission captured

Figure 7.5 shows the relationship between the amount of waste burned and the emissions captured for each experiment, by waste type. These variables were statistically tested to determine if they were normally distributed. The results showed that for both variables, skewness values were higher than 1, which is an indicator of non-normally distributed data (Bulmer, 1979). A log transformation was selected, and the skewness values of the statistical analysis showed that using this scale was appropriate as the frequency distribution of the data was normalised. Therefore, a log-log scale was chosen to visualise the mass of captured emissions data.

The sample weight for each waste type was determined depending on the resulting visual darkness of the filters after 3-5 pre-tests to facilitate optical attenuation measurement within the detection range of the OT-21 Transmissometer instrument. The largest waste samples corresponded to PET and HDPE (5g), followed by paper and cardboard and LDPE (3g). The results showed that the

emissions captured are a function of the sample size and the combustibility of the material. Consequently, as the amount of combusted material increased, in general, a similar pattern was shown in the emissions captured.

The different waste types also showed distinct patterns of combustion and particulate emissions. Thus, paper and cardboard were a highly combustible group of materials and produced large amounts of captured emissions. Other materials with similar or indeed larger sample weights did not burn as readily, such as LDPE, HDPE and PET, and in these cases, the emissions captured were reduced. Samples in the mid-size category, such as mixed waste samples (0.5g), also released intermediate amounts of particulate emissions compared to the other waste types examined. The smallest samples burned, such as polystyrene and textiles samples (0.1g for both cases), released the smallest amounts of emissions captured. Interestingly, whilst these waste types had the smallest amounts of particulate emissions, they produced darkest filters overall compared to other waste types, providing a qualitative indication of the differences in the type and nature of emitted particles between different waste types.

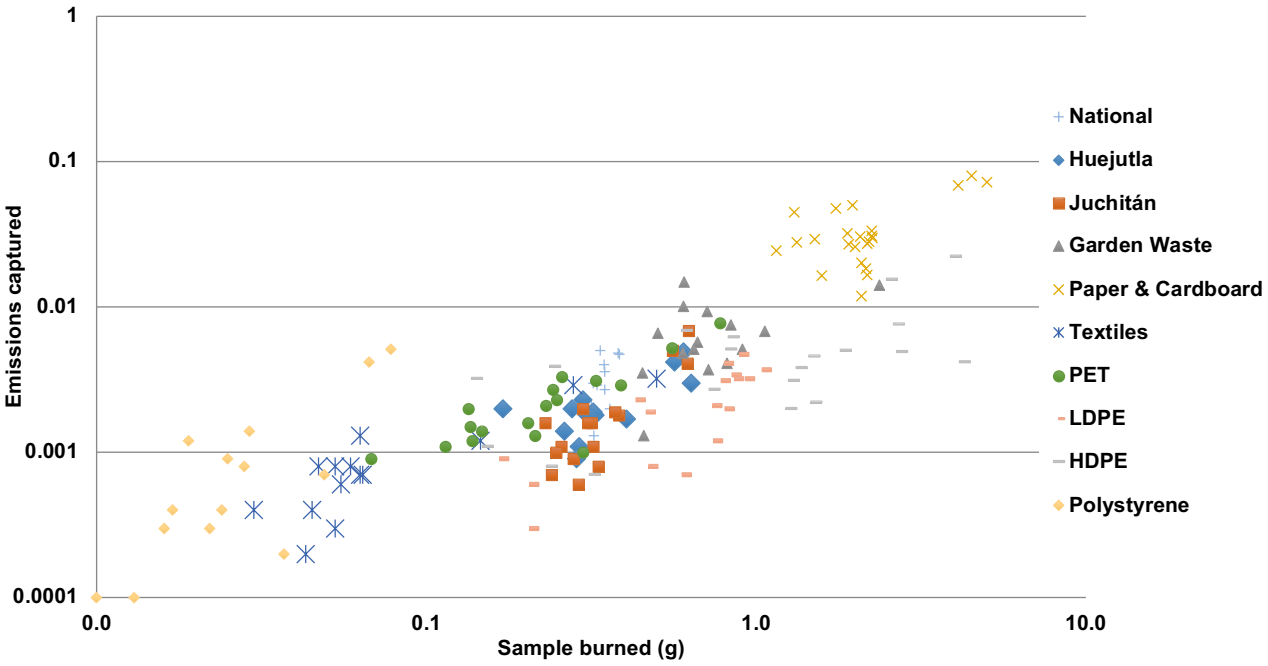


Figure 7.5 Patterns in sample combustion and emissions captured for all waste types (g)

In contrast to the quantitative mass of emissions captured, no obvious patterns were identified between combusted sample or emissions captured and ATN values (Figure 7.6 and Figure 7.7). Therefore, the relationship between the amount of waste combusted and the properties of the particulate emissions are much more complex than simple mass balance and depend strongly on the type of combusted material. For example, some of the largest samples of waste burned and emissions captured, such as paper and cardboard, produced relatively small ATN values. On the other hand, textiles and polystyrene represented examples of the smallest amounts of waste burned and emissions captured, but produced amongst the highest ATN values. Indeed, the variation in ATN observed between materials could be explained because not all the emissions captured on the filters

may be light absorbing. However, BC is a light absorbing component that is always co-emitted with a range of other pollutants and depending on the emission source, it may be a smaller or larger fraction of the total emissions released (US EPA, 2012b). For most materials, the amount of combusted sample was relatively consistent, but the ATN values were highly variable.

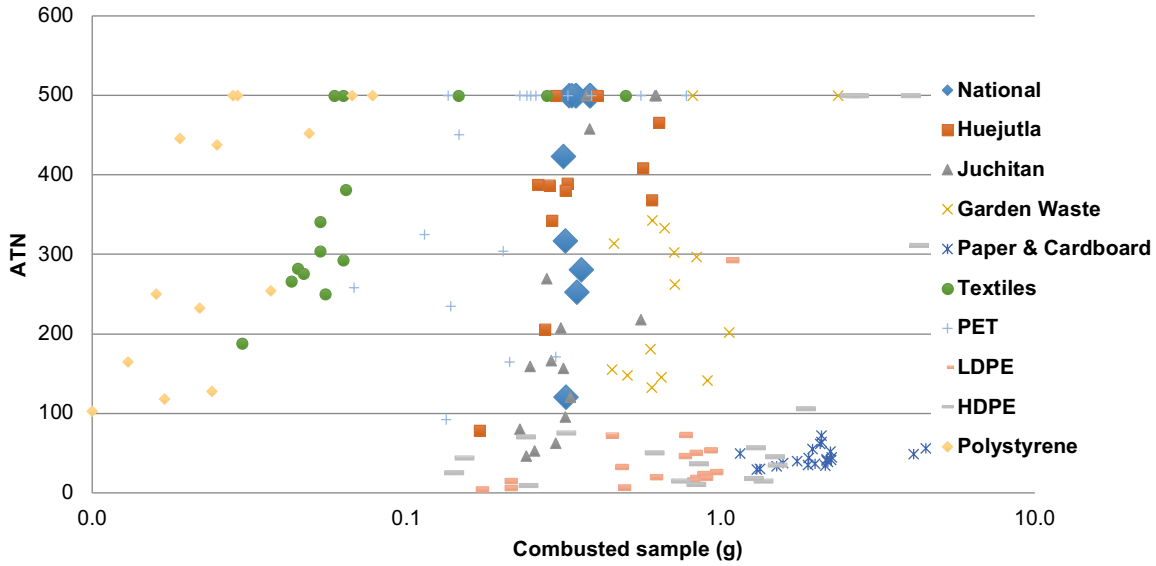


Figure 7.6) and this behaviour was particularly evident for mixed waste types (National, Huejutla and Juchitán). During the experimentation process it was observed that even though constant conditions were maintained, the combustion process varied for different samples of the same waste type. However, certain materials, such as LDPE and paper and cardboard, showed relatively consistent patterns of combusted material and ATN value.

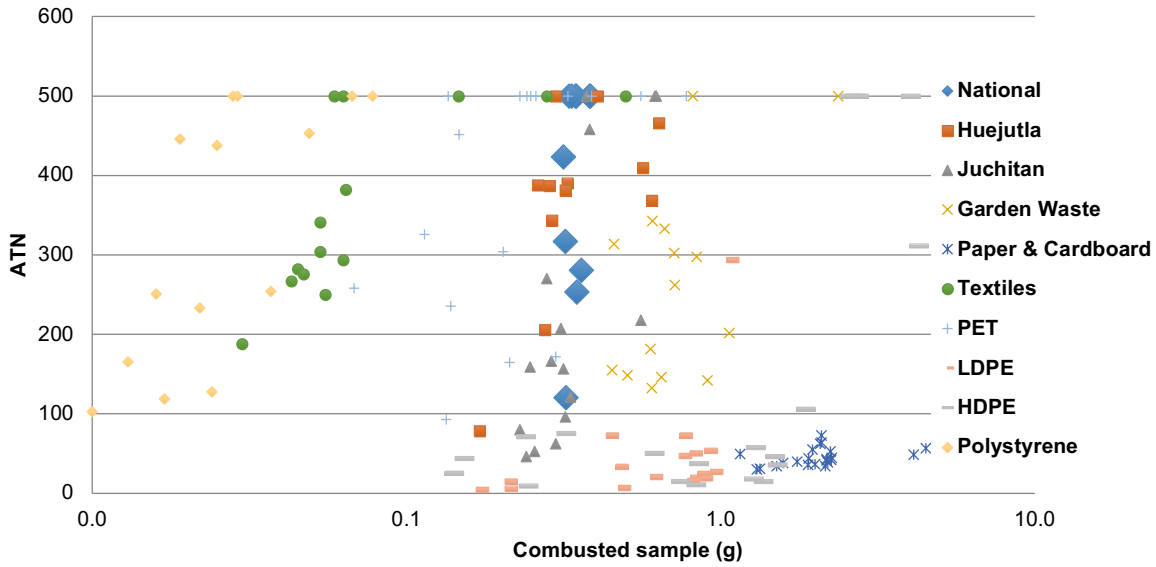


Figure 7.6 Patterns in ATN and combusted sample for all waste types

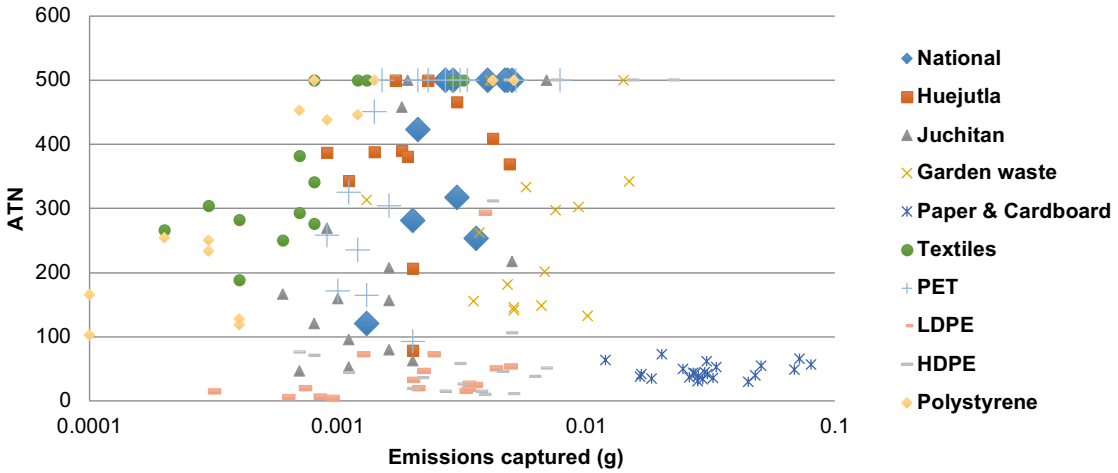


Figure 7.7 Patterns in ATN and emissions captured for all waste types

7.3.2. Descriptive statistics of waste combustion and ATN

Table 7.4 shows a summary of the statistical examination for waste combustion and ATN values for single waste and mixed waste types. The complete version of the descriptive statistics analysis for single and mixed waste can be found in APPENDIX A4 and APPENDIX A5 respectively. The characteristics of the combustion patterns for mixed samples were strongly related to the composition of the waste in each case study area. The fraction of waste burned was highest at the national level, along with the proportion of emissions captured per sample burned and the ATN values. At the national level, the waste composition contained a higher proportion of textiles and polystyrene compared to the case study areas. Specifically, national waste contained 16 % of textiles and 6 % of polystyrene (Table 7.2). In comparison, textiles are 13 % of the total waste in Huejutla and 7 % in Juchitán. Both case study areas have a similar proportion of polystyrene (2 %). Textiles and polystyrene showed high levels of combustibility and ATN compared to other waste types examined. Mixed samples based on Huejutla's waste composition showed a higher rate of emissions captured per mass of sample burned, and higher ATN values (367) compared to mixed samples based on Juchitán's waste composition (ATN = 300). This can be explained because waste composition in Huejutla (page 105) contained almost twice the amount of textiles compared to Juchitán (page 109) (13 % and 7 %, respectively) and a marginally larger proportion of polystyrene (1.9 % and 1.8 %, respectively).

For single waste types, the fraction burned was highest for paper and cardboard, and in this case, 65 % of the sample was combusted during the experiment. Garden waste and textiles also showed high levels of combustibility (57 % and 51 %, respectively). The materials with the lowest fraction burned values corresponded to polystyrene and PET, with 21 % and 10 %, respectively. The rate of emissions captured per sample burned was highest for polystyrene (3 %), followed by paper and cardboard (2 %). Conversely, LDPE and HDPE gave the lowest rate of emissions captured per mass of sample burned (0.55 % and 0.34 %, respectively). The highest mean values for ATN corresponded to PET (383), textiles (363) and polystyrene (328). LDPE and paper and cardboard presented the lowest ATN values for single waste types (46 and 62, respectively).

Table 7.4 Summary of descriptive statistics for mixed and single waste types

	Fraction burned	Emissions captured/ample burned	Total combustible mass	Remaining volatile fraction	ATN
	(%)	(%)	(%)	(%)	
National n=11 ATN>500, 6					
Mean	69	0.94	94	25	400
sd	5	0.33	159	866	135
Huejutla n=13 ATN>500, 2					
Mean	58	0.62	94	35	367
sd	10	0.33	95	40	115
Juchitán n=16 ATN>500, 3					
Mean	61	0.52	94	33	300
sd	9	0.24	94	42	166
Paper and cardboard n=23 ATN>500, 0					
Mean	65	1.6	91	24	62
sd	12	0.7	91	34	77
Garden waste n=15 ATN>500, 2					
Mean	57	0.9	94	42	264
sd	18	0.6	93	74	122
Textiles n=14 ATN>500, 5					
Mean	51	1.1	100	49	363
sd	9	0.4	100	49	114
LDPE n=17 ATN>500, 0					
Mean	24	0.3	84	60	46
sd	6	0.1	84	61	67
HDPE n=20 ATN>500, 4					
Mean	20	0.6	100	59	147
sd	28	0.5	100	90	193
PET n=17 ATN>500, 9					
Mean	10	1	100	93	383
sd	9	0.3	100	103	148
Polystyrene n=14 ATN>500, 4					
Mean	21	3	100	80	328
sd	8	2.2	100	88	162

ATN>500, n = number of filters marked as "Too Dark" by OT21; sd, standard deviation

7.3.3. Calibration relationship between ATN and elemental carbon

The ratio of transmittance (ln I_0/I = ATN/100) and EC was non-linear and was explained by a quadratic relationship, which was highly statistically significant (r^2 = 0.98, *P*<0.001) Figure 7.8). The two cases of duplication within the ATN data set provided consistent EC values providing further confidence in the calibration relationship between ATN and EC.

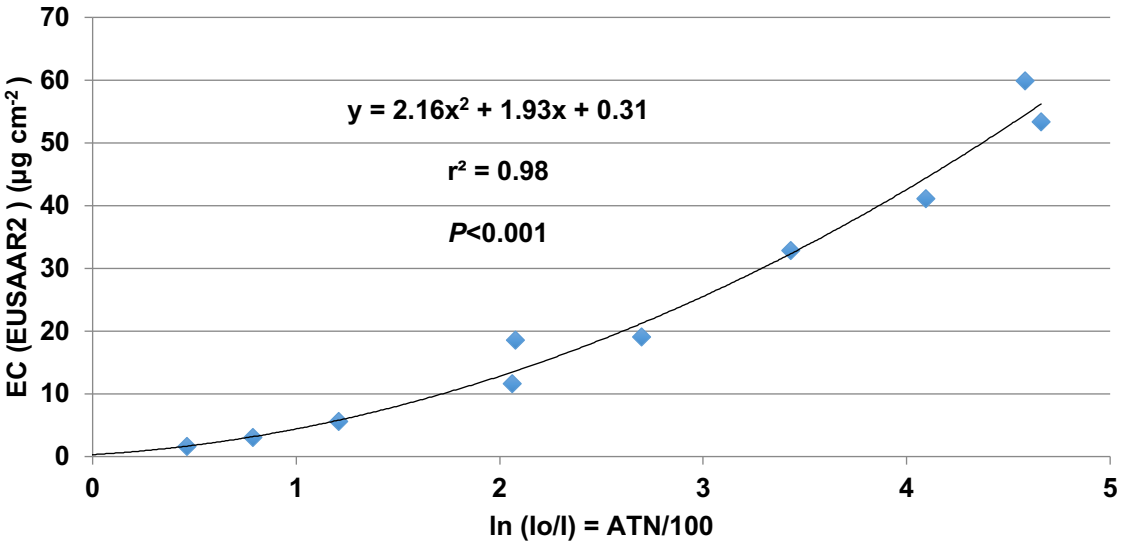


Figure 7.8 Relationship between ln (Io/I) and EC (µg cm^{-2})

As shown in Figure 7.8, the best-fit quadratic relationship between EC and ATN/100 is given by:

$$\text{EC (EUSAAR2) (µg cm}^{-2}\text{)} = 2.16(\ln(I_o/I))^2 + 1.93\,(\ln(I_o/I)) + 0.31 \qquad \textbf{Equation 7.6}$$

where EC is elemental carbon and ln (I_0/I) = ATN/100.

7.3.4. Emission factors

Elemental carbon (EC) and BC are operationally defined by the measurement method applied (Figure 2.2), although these two terms are often used interchangeably (Watson et al., 2005; Bahner et al., 2007; Ramanathan and Carmichael, 2008; Petzold et al., 2013; Greene, 2017). The thermal method strictly measures EC, but here we report the results as BC for consistency. Emission factors (Table 7.5) for BC from open burning of waste were calculated by the following procedure:

1. The amount of BC per unit area (µg cm^{-2}) was calculated using ATN/100 measurements in **Equation 7.6**.
2. The value for BC per unit area was multiplied by the exposed area of the filter (9.08 cm^2) to obtain the total amount of BC.
3. A correction was applied to account for the volatile fraction of the sample that did not burn during the combustion process. To do this, the BC per sample burned was calculated, and adjusted for the total volatile fraction.
4. Finally, the emissions per mass of waste burned were obtained in µg g^{-1}. This value was divided by 1,000 to obtain an EF in g of BC kg^{-1} of waste burned.

Table 7.5 Conversion of direct BC measurements (µg cm^{-2}) of quartz filters to EFs for waste materials (g kg^{-1}) (mean values per waste type)

Type of waste	BC (µg cm^{-2})	Total BC on filter (µg)	BC/sample burned (µg g^{-1})	BC for total volatile solids (µg g^{-1})	BC EF (g kg^{-1})
National	46	418	1,205	1,644	1.6
Huejutla	39	355	1,000	1,585	1.6
Juchitán	21	194	804	1,266	1.3
Paper and cardboard	4	33	15	21	0.02
Garden waste	24	213	276	469	0.5
Textiles	38	349	4,659	9,094	9.1
LDPE	3	23	31	108	0.1
HDPE	15	140	67	155	0.2
PET	44	397	1,784	45,723	45.7
Polystyrene	35	319	10,569	53,064	53.1

The statistical analysis of the EFs for each waste type is shown in Table 7.6. The highest EFs corresponded to polystyrene (53.1 g BC kg^{-1}), PET (45.7 g BC kg^{-1}) and textiles (9.1 g BC kg^{-1}). Thus, even the presence of small amounts of these wastes generates very large emissions of BC. The lowest EF corresponded to paper and cardboard (0.02 g BC kg^{-1}), followed by LDPE (0.1 g BC kg^{-1}). As would be expected, mixed waste containing a larger proportion of PET and polystyrene or textiles had larger EF values for EC overall compared to mixed samples with small amounts of these waste types. Thus, mixed compositions for Huejutla and National waste presented higher EFs compared to Juchitán, as these samples contained a higher proportion of textiles. However, EFs for mixed waste presented for the case study areas and for Mexico show consistent values ranging from 1.3 to 1.6 BC $kg^{-}1$.

Table 7.6 Emission factor statistics (g BC kg^{-1} of waste)

								95 % Confidence Interval of the Difference	
Type of waste	**n***	**Mean**	**Median**	**Std. Deviation**	**Range**	**Minimum**	**Maximum**	**Lower**	**Upper**
National	11	**1.64**	1.89	0.80	2.28	0.24	2.52	1.11	2.18
Huejutla	13	**1.58**	1.62	0.73	2.65	0.47	3.13	1.14	2.03
Juchitán	16	**1.27**	0.87	1.14	3.63	0.17	3.80	0.66	1.87
Paper and cardboard	23	**0.021**	0.011	0.047	0.232	0.005	0.237	0.001	0.042
Garden waste	15	**0.47**	0.30	0.31	0.97	0.16	1.13	0.30	0.64
Textiles	14	**9.09**	8.95	3.91	14.63	2.33	16.96	6.84	11.35
LDPE	17	**0.11**	0.07	0.13	0.49	0.02	0.51	0.04	0.18
HDPE	20	**0.15**	0.08	0.16	0.60	0.02	0.61	0.08	0.23
PET	17	**45.72**	11.56	58.6	189.37	2.88	192.25	15.59	75.85
Polystyrene	14	**53.06**	46.00	34.46	119.12	9.94	129.06	33.16	72.96

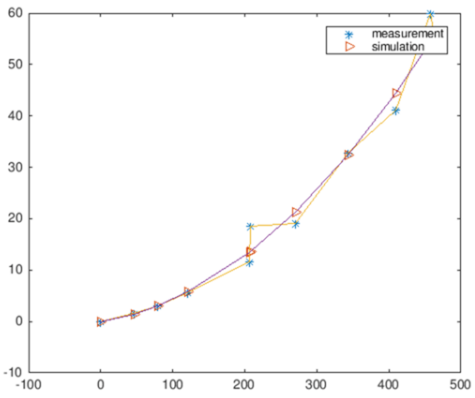
*As explained in section 7.2.4, a minimum of 10 replicates were carried out for each waste type. However, if a large number of filters appeared to be heavily darkened, more replicates were carried out to increase the number of filters within the detection range of the OT-21 Transmissometer instrument. Additionally, an increased number of replicates were carried out for certain waste fractions to determine the number of replication of test burns and the effect of flow rate in the emissions captured.

7.3.5. Conversion factor estimates for BC based on ATN measurements

Having specific mass extinction coefficients (σ_{ATN}) and shadowing correction factors (k) for this particular type of emissions (open burning of waste) and filters (quartz) is important, as they depend on multiple light scattering, filter loading and particle scattering. These factors are the cause of the non-linear response between ATN and BC, and highly depend on the filter substrate and the source of the emissions (Virkkula et al., 2007; Drinovec et al., 2015; Davy et al., 2017).

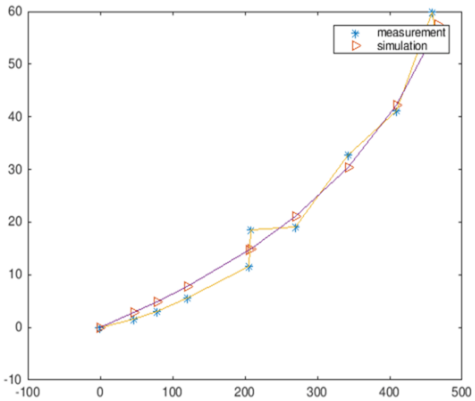
The mathematical fit of the calibration curve was carried out (using the Matlab function lsqnonlin[16]), to obtain the shadowing correction factor and mass extinction coefficient as follows:

Quadratic model
(a)



σ_{ATN} = 45.7; k = 0.0097

Logarithmic model
(b)



σ_{ATN} = 17.5; k = 0.0018

Figure 7.9 Determination of σ_{ATN} and k using (a) quadratic and (b) logarithmic models

[16] lsqnonlin function in MATLAB solves nonlinear data-fitting problems

The quadratic model in Figure 7.9 (a) gave a better fit compared to the logarithmic model (b), which overestimated the experimental data in the lower measurement range. However, the value of σ_{ATN} (45.7 m^2g^{-1}) obtained by the quadratic relationship was larger than some of the results reporting ambient BC in quartz filters. Weingartner et al. (2003) reviewed several studies on ambient BC measurements and stated that reported mass extinction coefficients range from 5 m^2g^{-1} in remote areas to 14 m^2g^{-1} at urban locations, increasing up to 20 m^2g^{-1} at near-street measuring sites. Another review (Bond and Bergstrom, 2006) reported values ranging between from 3 to 30 m^2g^{-1}. However, more recently, Davy et al. (2017) gave a value of 72 for the mass extinction coefficient and suggested that high values for quartz transmittance are likely to be related to a large transmittance ratio for quartz filters. The relatively high value for σ_{ATN} obtained here could also be explained because the measured values are not based on background ambient measurements but are determined from a direct emission source.

A simpler approach to estimate BC values from ATN measurements is applying a linear conversion factor. The recommended value suggested by the manufacturer of the OT-21 transmissometer (Magee Scientific) states that 1 ATN unit is equivalent to 0.06 µg cm^{-2} BC on the filter (Section 7.2.6.1). A linear regression analysis of the BC relative to ATN (Figure 7.10) gave a value of 0.12 µg cm^{-2} BC per unit of ATN (directly related to ATN data without adjusting by the factor of 100). This value is approximately twice than that suggested by the manufacturer and it is explained because the full ATN range of the instrument was utilised in combustion experiments performed here. Given the curvilinear pattern of the relationship between EC and ATN (Figure 7.8) and the effect of particulate interferences at high ATN values, the smaller value suggested by the manufacturer would appear to be reasonable for lower range ATN measurements.

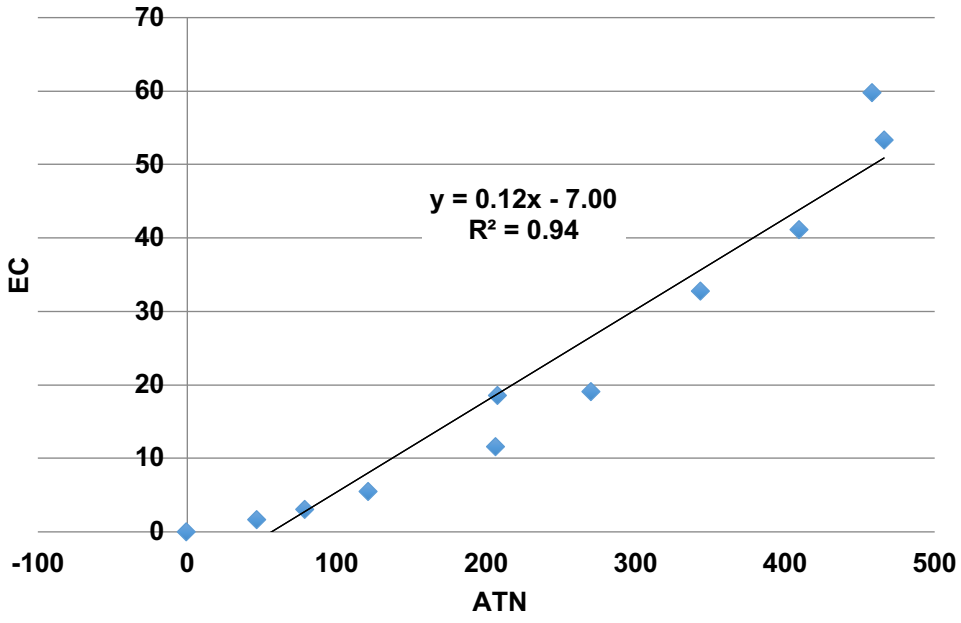


Figure 7.10 Linear relationship between ATN and EC (µg cm^{-2})

7.4. Discussion

7.4.1. Published combustion emission testing at different experimental scales

A series of publications describe biomass combustion measurements carried out in a large-scale combustion chamber (12.5 x 12.5 x 22 with a combustion capacity for up to 10kg of material) and compared to field emission measurements (Yokelson et al., 2008; McMeeking et al., 2009; Yokelson et al., 2013). Yokelson et al. (2008) reported that $PM_{2.5}$ laboratory measurements for tropical forest fires were consistent with emission measurements from the airborne campaign. McMeeking et al. (2009) characterized emissions from the open combustion of plant species through controlled laboratory burns. The results showed a consistent relationship between the laboratory experimentation and field-derived EF. McMeeking et al. (2009) highlighted the value of using controlled laboratory studies to characterise emissions from combustion sources observed in the field. Yokelson et al. (2013) published a detailed comparison of laboratory data and field measurements for prescribed fires in Missoula, and the results confirmed that laboratory based experimentation can significantly increase current knowledge on biomass combustion, especially when laboratory and field results can be combined and compared.

Downscaling the experimental measurements of combustion processes may raise questions about the representativeness of the data relative to realistic field conditions. However, the measured EF values for burning waste with the small-scale combustion emissions collection apparatus developed here were within a similar range and in some cases entirely consistent with the limited number of field measurements that have been published in the literature (see Table 7.7). This therefore suggests that the small scale testing system is both a reliable and a valid approach to estimating BC EFs for open burning of waste. Therefore, it is possible to miniaturize controlled combustion emission tests with heterogeneous materials even further and produce results that are consistent with those predicted from field analysis.

Table 7.7 Comparison between published EFs and EF values measured in controlled combustion tests reported here (g kg^{-1})

Emission factors (EF, g kg^{-1} waste)				
Number of test				
	Burn 1	**Burn 2**	**Burn 3**	**Average**
EC (Christian et al., 2010)	0.38	0.92	0.63	0.65
BC (Stockwell et al., 2016)	0.56 (wet conditions)	6.04 (dry conditions)	-	3.30
EC (Jayarathne et al., 2017)	-	-	-	2.59*
Type of mixed waste (n=repetitions)				
BC (this research)	**National (n=11)**	**Huejutla (n=13)**	**Juchitán (n=16)**	**Average**
	1.64	1.58	1.27	1.50
*Three samples were measured but only the average EF was reported.				

7.4.2. Relationship between EC and BC

Frequently the terms EC and BC synonymously refer to the most light-absorbing component of carbonaceous combustion particles, with the main distinction between them being the measurement technique applied (Petzold et al., 2013). The characterisation of EC and BC is commonly undertaken by collecting PM on filters and measuring their carbon content (EC) or the attenuation of light reflected from or transmitted through the filter (BC). Elemental carbon is measured by thermal heating and optical absorption, while BC can only be quantified through optical absorption (Watson et al., 2005; Bond et al., 2013; Petzold et al., 2013).

According to Petzold et al. (2013) in climate change and air quality research, carbonaceous aerosol is commonly addressed as BC, but is often derived from EC measurements. It is also sometimes loosely defined as soot; however, soot is the combination of particles emitted during incomplete combustion, which also include OC. The impact of BC on climate change is related to its microstructure, morphology, thermal stability, solubility, and light absorption properties. However, currently there are no measurement techniques that can quantify all of these properties simultaneously (Petzold et al., 2013).

7.4.3. Determination of BC using calculated mass extinction coefficient and shadowing correction factors

The calculated mass extinction coefficient and shadowing correction factors were used in **Equation 7.3**, together with the ATN values for all waste types to calculate BC emission factors using this alternative approach. The same steps described in Section 4.5 were followed to calculate BC EFs in g kg-1, as shown in Table 7.8. If compared to the values obtained using the regression quadratic model determined in this study (**Equation 7.6**), the numbers are extremely similar. For example, the difference between EC EFs using the regression model and BC EFs using σATN and k in **Equation 7.3** for mixed waste types was between 0.001g and 0.14g. The size of the difference in the EFs calculated using these two methods was related to the size of the EF; therefore the larger differences were presented by larger EFs (PET, Polystirene and Textiles). The results suggest that the mass extinction coefficient and the shadowing correction factor determined through this research can be used to determine BC from open burning of waste emissions captured in quartz filters by measuring ATN values, avoiding the quantitative measurement of EC, which is a complex, specialist and expensive process.

Table 7.8 BC Emission Factor using σ_{ATN} and K (mean values per waste type)

Type of waste	BC ($\mu g/cm^2$)	Total BC (μg)	BC/sample burned ($\mu g\ g^{-1}$)	BC for total volatile solids ($\mu g\ g^{-1}$)	BC EF ($g\ kg^{-1}$)	Difference *
National	46	418.8	1207	1,647	1.6	0.003
Huejutla	39	356.3	1003	1,588	1.6	0.004
Juchitán	21	194.0	805	1,194	1.2	-0.072
Paper and cardboard	3	30.9	15	20	0.02	-0.001
Garden waste	24	213.7	277	471	0.5	0.002
Textiles	39	349.7	4676	9,129	9.1	0.034
LDPE	2	21.4	26	88	0.1	-0.020
HDPE	15	138.3	63	140	0.1	-0.015
PET	44	397.9	1788	45,867	45.9	0.144
Polystyrene	35	319.2	10586	53,120	53.1	0.056
*Difference between EC EFs using the regression model and BC EFs using σATN and k in Equation 7.3.						

7.4.4. Constructed EFs

Constructed EFs for mixed waste types were calculated using EFs for single waste types. The single waste EFs were combined with data for waste composition in the case study areas to obtain constructed EFs (Table 7.9). Constructed EFs were on average, 4.7 times larger compared to those measured in the laboratory for mixed waste compositions. Nevertheless, the results suggest that it is possible to build approximate EFs for different waste compositions without conducting specific burning measurements. As a general guide, the result should be divided by 5 to obtain an approximation of a measured EF.

Table 7.9 Measured vs constructed EFs ($g\ kg^{-1}$)

Mixed Waste types	Measured EFs (g/kg)	Constructed EFs (g/kg)	EF Constructed / EF Measured	Average
National	1.64	7.45	4.53	4.7
Huejutla	1.58	6.57	4.15	
Juchitán	1.27	6.83	5.39	

At present, it is difficult to explain the difference in measured EFs for mixed waste samples compared to those constructed using EFs from single waste samples. Some of the factors that could influence these differences might be related to the amount of oxygen available in homogenous waste (as in single waste types) compared to mixed waste types. Smouldering, poorly oxygenated waste produces the highest atmospheric pollutant emissions (Solorzano-Ochoa et al., 2012). One possibility is that homogenous waste samples were more compact compared to mixed waste samples, resulting in less oxygenated combustion conditions and thus, higher EFs. However, further study would be needed to understand the interaction of materials during the combustion process of single vs. mixed waste types, as well as the influence of the particle size of the samples.

8. Quantification of BC Emissions from Open Burning of Waste

8.1. Introduction

Open burning of solid waste in backyards and at uncontrolled dumpsites is a significant source of BC, a SLCP that contributes to climate change, which also has direct detrimental impacts on human health. However, BC emissions from open burning of waste are not included in most emission inventories used to model and develop national/international climate change mitigation policies. For example, BC is not considered in the IPCC Fourth (Bogner et al., 2007) or Fifth (IPCC, 2014) Assessment Reports. Published BC EFs for open burning of waste are based on very limited field measurements and therefore have high levels of uncertainty. Large uncertainties in the available EFs and activity levels estimating the amounts of waste burned are major barriers to recognising the impact of this potentially significant emission source. Wiedinmyer et al. (2014) highlighted the need to improve the available data on open burning of waste and that attention should be given to developing EFs and providing better estimates of burning waste. Waste composition and the associated impact on the combustion characteristics have a significant effect on the nature and properties of the particulate and BC emissions from burning waste (Chapter 7). Measuring EF values for specific waste types, following the approach described in Chapter 7, and combining this information to generate overall EFs for mixed waste with different compositions may offer a practical tool to estimate EFs for different local, regional or national waste sources.

The aim of work described in the Chapter is to improve global BC emission estimates for open burning of waste (in the field case study areas, in Mexico and in different regions of the world), to calculate the carbon dioxide equivalent emissions (CO_2Eq) from this source and to compare these values in context of other, well recognized, polluting emissions from the waste sector, such as CH_4 released from landfill disposal. Specifically, the objectives of this chapter are to:

a) Estimate BC emissions from open burning of waste in the field case study areas integrating the information and measurements obtained through questionnaires (Chapter 4), waste composition analysis (Chapter 5) and controlled laboratory combustion experimentation process (Chapter 7).
b) Calculate national BC emission estimates from open burning of waste in Mexico using the activity levels obtained in Chapter 3, together with the EF data developed for Mexico based on the laboratory experimentation (Chapter 7).
c) Estimate EFs for open burning of waste for major international economic regions based EFs for single waste fractions derived through laboratory experimentation, combined with published information on waste composition for each region.
d) Calculate global BC emissions from open burning of waste using the constructed regional EFs and published data on the activity levels for open burning of waste.
e) Estimate BC emissions in the field case study areas, in Mexico and in the different regions of the world.

f) Place the BC emissions from open burning into the context of well-established CH_4 emissions from landfill disposal of waste by comparing the CO_2Eq of both emission sources.

8.2. Materials and methods

8.2.1. BC EFs for different international regions

International regional EFs for BC were calculated using EF data for specific waste streams measured in Chapter 7 (Table 7.5) and published waste composition data available for each area. For example, data are available on MSW generation and composition by region throughout the world (Hoornweg and Bhada-Tata, 2012) including: Africa Region (AFR), East Asia & Pacific (EAP), Eastern & Central Asia (ECA), South Asia (SAR), Middle East & North Africa (MENA), Latin America & the Caribbean (LCR) and countries belonging to the Organisation for Economic Co-operation and Development (OECD) (Figure 8.1). The main waste composition categories include: organic, paper and cardboard, plastics, glass, metals and others. The fraction of waste categorized under 'others' contains textiles, leather, rubber, dirt, multi-material packaging (such as tetra pack), e-waste and house appliances, and this waste stream is considered to be mostly combustible waste.

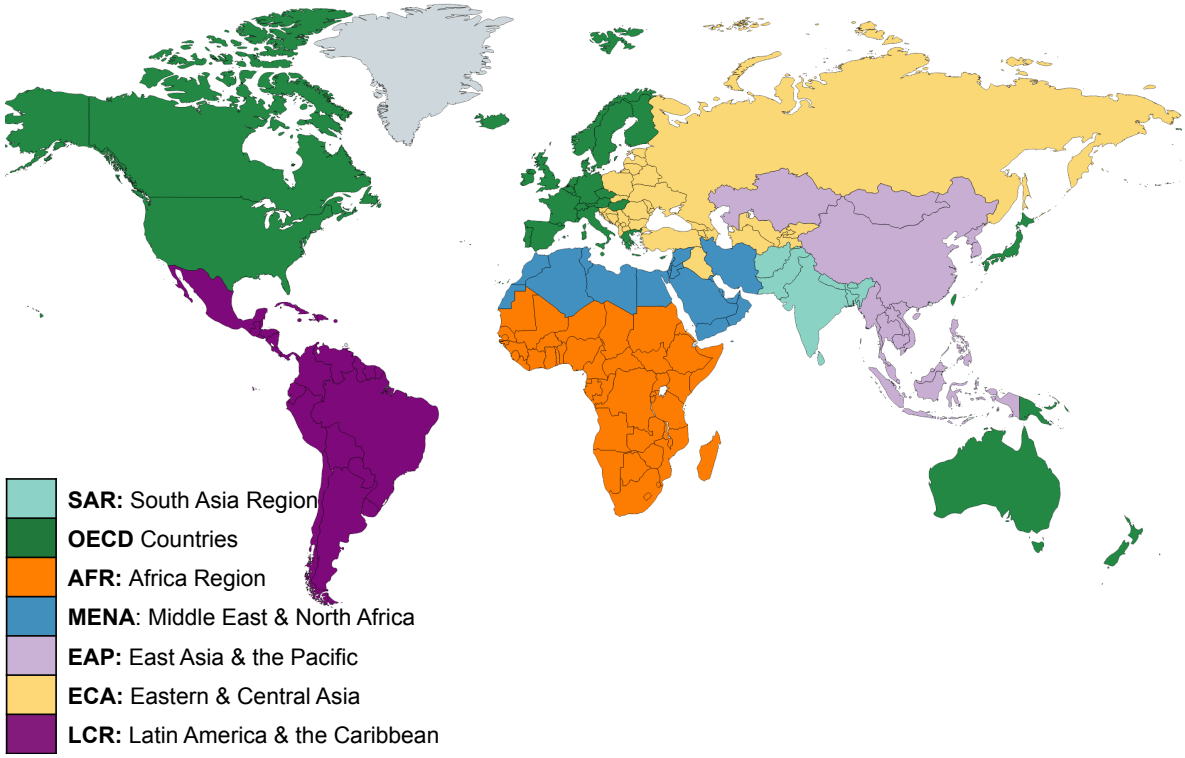


Figure 8.1 Global Economic Regions (Hoornweg and Bhada-Tata, 2012)

In Chapter 7, EFs were measured for the waste streams including: garden waste, textiles, paper and cardboard, LDPE, HDPE, polystyrene and PET. Hoornweg and Bhada-Tata (2012) do not provide details on the composition of the organic waste fraction in the global statistics and therefore additional information was sought to determine the fraction of organic waste into garden and food waste, since food waste is mainly fed to domestic animals and is not usually disposed by open burning. Furthermore, data relating to the amount of textile waste present in the regional waste

compositions was required, as this represents a significant combustible material and source of BC emissions (Section 7.3.5). Finally, information about the different plastic types in the plastic waste fractions was also investigated. Therefore, the additional data sources used to provide this further detailed waste composition information is presented in Table 8.1.

Table 8.1 Sources of detailed information on waste composition

Regions	Garden Waste fraction in 'organics'		Textile fraction in 'others'		Specific plastic fractions	
	Area	Sources	Area	Sources	Area	Sources
AFR: Africa Region	Ghana and Gaborone, Botswana	(Nagabooshnam, 2011; Miezah et al., 2015)	Gaborone, Botswana	(Nagabooshnam, 2011)	Gaborone, Botswana	(Nagabooshnam, 2011)
EAP: East Asia & Pacific	Penang, Malaysia	(UNDP, 2008)	Penang, Malaysia	(UNDP, 2008)	Bangkok, Thailand	(Areeprasert et al., 2017)
ECA: Eastern & Central Asia	St. Petersburg, Russia	(Selezneva, 2016)	St. Petersburg, Russia	(Selezneva, 2016)	St. Petersburg, Russia	(Selezneva, 2016)
SAR: South Asia Region	Lahore, Pakistan	(Kamran et al., 2015)	Lahore, Pakistan	(Kamran et al., 2015)	India	(Singh et al., 2017)
MENA: Middle East & North Africa	Israel and Jordan	(Ayalon et al., 1998), (Jordan Green Building Council, 2016) and (Abu-Salah et al., 2011)	Jordan	(Abu-Salah et al., 2011) and (Jordan Green Building Council, 2016)	Jordan	(Abu-Salah et al., 2011) and (Jordan Green Building Council, 2016)
LCR: Latin America & the Caribbean	Mexico	(SEMARNAT, 2013b) and (INECC, 2012)	Mexico	(SEMARNAT, 2013b) and (INECC, 2012)	Mexico	(SEMARNAT, 2013b) and (INECC, 2012)
OECD Countries	USA	(Subramanian, 2000) and (US EPA, 2013)	USA	(Subramanian, 2000) and (US EPA, 2013)	USA and EU	(Subramanian, 2000), (US EPA, 2013) and (European Commission: DG Environment, 2011)

In this research, emissions from open waste combustion were quantified by a thermal-optical technique that measures EC (Figure 2.4 and Section 7.2.6.2). However, the terms EC and BC are often used interchangeably (Watson et al., 2005; Ramanathan and Carmichael, 2008; Petzold et al., 2013). EC measurements were calibrated against an optical ATN method that measures BC; therefore values are reported as BC EFs for consistency. Regional BC EFs were calculated using Equation 8.1:

$$\textbf{Regional BC EFs} = [(GW_f * EF_{GW}) + (T_f * EF_T) + (PC_f * EF_{PC}) + (LDPE_f * EF_{LDPE}) + (HDPE_f * EF_{HDPE}) + (PS_f * EF_{PS}) + (PET_f * EF_{PET})] / 5 \qquad \textbf{Equation 8.1}$$

where the specific waste types included green waste (GW), textiles, (T), paper and card (PC), low and high density polyethylene (LDPE and HDPE, respectively), polystyrene (PS), and polyethylene terephthalate (PET); subscript 'f' represents the waste fraction and EF represents the emission factor for each waste type. Controlled combustion experiments reported in Chapter 7 showed there was a significant quenching effect of burning mixtures of different, representative major waste types (garden

waste, textiles, paper and cardboard, LDPE, HDPE, polystyrene and PET) compared to combusting the specific waste materials individually. Specifically, constructed EFs using EFs from single waste samples were on average 5 times larger compared to measured EFs for mixed waste samples (for further discussion see Section 7.4.4). Therefore, regional BC EFs were calculated by adjusting the measured EF values obtained for individual waste stream EFs by a factor of 0.2.

8.2.2. BC emissions from open burning of waste

Annual BC emissions for each international region and the case study areas (Chapter 3) were calculated as the product of the amount of waste burned and the corresponding EF:

$$\mathbf{BC} = W_B \times EF \qquad \textbf{Equation 8.2}$$

where W_B is the mass of waste burned and EF is the emission factor per kg of waste burned. The EF values were obtained directly for mixed waste samples representative of the household waste composition in the case study areas, Huejutla and Juchitán, from the experimental combustion results (Chapter 7) or were calculated for the different international economic regions following the procedure in Section 2.1, The total amount of waste burned (W_B) represents the sum of the total amount of domestic waste burned in backyards and the amount of waste burned at dumpsites (in the case of Huejutla, waste was only burned in households). Information on the amount of waste burned (representing the activity level) is presented in Chapter 6 for the case study regions and in Chapter 3 for Mexico as a whole. An average value of 2,200 (Table 2.3) was used as the GWP, considering a 20-year horizon, to calculate BC CO_2Eq emissions (Fuglestvedt et al., 2010; Bond et al., 2013).

8.2.3. Methane emissions from landfill disposal

The CO_2Eq value for the CH_4 emissions that would arise from the decomposition of equivalent amounts and types of waste that is currently disposed by burning was calculated for the case study areas, Mexico and the major international economic regions, to provide an overall global comparison with the CO_2Eq from BC emitted from open burning of waste. This analysis used landfill CH_4 CO_2Eq EFs for different material types (specifically, food waste, paper and cardboard and garden waste fractions) provided by the Waste Reduction Model (WARM) (US EPA, 2015). Total CH_4 CO_2Eq emissions were calculated using the following equation:

$$\mathbf{CH_4\ CO_2Eq} = (FW * EF_{FW}) + (GW * EF_{GW}) + (PC * EF_{PC}) \qquad \textbf{Equation 8.3}$$

where FW is food waste, GW is garden waste and PC is paper and cardboard. All the EFs are for CH_4 CO_2Eq emissions.

8.3. Results

8.3.1. Emissions from open burning of waste in Mexico and case study areas

The results show that the amount of BC emitted from uncontrolled burning of waste in Huejutla was in the range of 14.1 to 14.8 t y^{-1} of BC (Table 8.2), with a CO_2 equivalent (CO_2Eq) value of 30.9 – 32.6 x 10^3 t y^{-1} emissions. In Juchitán, BC emissions from open burning were more approximately four

times that observed for Huejutla since, in this case, waste is burned both in backyards and at dumpsites. Approximately 56.2 – 52.3 t y^{-1} of BC are emitted due to open burning of waste in Juchitán, equivalent to 123.7 - 123.8 x 10^3 t y^{-1} CO_2Eq.

Table 8.2 BC emissions from open burning of waste in field case study areas and Mexico

				Total BC emissions		Emissions capita^{-1}	[b] % of CO_2Eq		[c] % of total BC emissions
		Waste burned (t y^{-1})	BC Emission Factors (kg t^{-1})	BC (t y^{-1})	[a]BC (MTCO_2Eq y^{-1})	BC (MTCO_2Eq y^{-1})	Total emissions	Fuel Emissions	
Huejutla	Low Estimate	8,880	1.58	14.1	30,960	0.25	4.5%	6.6%	7.3%
	High Estimate	9,350		14.8	32,610	0.27	4.7%	7.0%	7.7%
Juchitán	Low Estimate	44,380	1.27	56.2	123,650	1.11	19.8%	29.2%	114.4[d]
	High Estimate	44,440		56.3	123,820	1.11	19.8%	29.3%	114.5[d]
Mexico	Low Estimate	3,808,050	1.64	6,261	13,774,370	0.12	2.2%	3.2%	8.0%
	High Estimate	6,524,740		10,728	23,601,130	0.21	3.8%	5.6%	13.7%

a) Average BC equivalent emissions for open biomass burning - 20 year horizon is 2200 (Fuglestvedt et al., 2010; Bond et al., 2013).
b) Total emissions per capita were 5.62 MTCO_2Eq and 3.8 MTCO_2Eq for fuel usage in 2013 (INECC and SEMARNAT, 2015).
c) Total BC emissions from (SEMARNAT, 2009)
d) Total BC emissions reported by SEMARNAT (2009) for Juchitán were smaller than the estimated BC emissions from open burning of waste calculated through this research for that Municipality.

Note: MTCO_2Eq = Metric tonnes of Carbon Dioxide Equivalent. High and low estimates in case study areas follow the sensitivity analysis for waste burned presented in Chapter 6. At the national level (Mexico), high and low estimates were calculated using different approaches for activity levels in households and dumpsites as described in Chapter 3, Section 4.5.

BC emissions from open burning of waste in the case study areas were compared to the total BC emissions inventory for Mexico (SEMARNAT, 2009). For Huejutla, open burning waste represented approximately 7 % of the total BC emissions in the municipality. However, in the case of Juchitán, the Mexican BC Inventory (SEMARNAT, 2009) suggested that the total BC emissions in the Municipality were more than 7 times smaller compared to Huejutla. However, the population size in both municipalities is similar (Huejutla = 122,905; Juchitán = 111,251 in), and Juchitán is a more urbanized compared to Huejutla. This might suggest that there is a problem with the estimation of total BC emissions for Juchitán reported in the BC inventory (SEMARNAT, 2009), and that published official statistics may be unreliable. As a result, the values reported here for open burning of waste are larger than the total BC emissions for Juchitán reported in the inventory (SEMARNAT, 2009).

The environmental emissions from burning waste in backyards were compared to other important metrics of atmospheric pollution to illustrate the relative scale and significance of the emissions from uncontrolled open fires. For example, the BC CO_2Eq linked to open burning represented approximately 5 % of the total CO_2Eq emissions and 7% of emissions related to fuel consumption in Huejutla (SEMARNAT, 2009). In Juchitán, BC emissions represent almost 20 % of the total CO_2Eq and 30 % of the fuel CO_2Eq emissions (SEMARNAT, 2009).

For Mexico, the open burning BC emissions, based on the measured EF for the representative national waste composition sample (Table 7.5) and the activity level for burning waste in the country (Section 3.3.5), was between 6.3 and 10.7 x 10^3 t y^{-1} of BC, equivalent to 13.8 – 23.6 x 10^6 t y^{-1} of CO_2Eq. According to the Mexican BC Emission Inventory (SEMARNAT, 2009), open burning of waste represents between 8 and 14 % of the total BC emissions in the country. This represents between 2 and 4 % of the total CO_2Eq emissions and between 3 and 6 % of the total national fuel CO_2Eq

emissions (Table 8.2). In Mexico, 76 – 81 % of the total BC emissions from open burning of waste originate from dumpsites (Table 3.9).

8.3.2. Black carbon emissions for different regions of the world

There are few published reports of BC EFs from uncontrolled burning of waste. The EFs for BC are highly dependent on the composition and characteristics of the burned material (Section 2.6.2, Chapter 2). The composition of waste varies greatly in different countries, therefore estimating BC EFs for different international economic regions must consider the variation in waste properties. The approach developed here was to measure BC EFs for specific, major waste fractions that could be used to formulate EFs for mixed waste streams with different representative compositions. Table 8.3 shows the waste composition for different regions of the world based on Hoornweg and Bhada-Tata (2012) with additional relevant waste fractions obtained through the data sources presented in Table 8.1. Regional BC EFs were calculated using BC EFs for single waste types and multiplied by its corresponding waste fraction (Equation 8.1). The results showed the smallest regional EF was obtained for the East Asia and the Pacific (EAP) region, equivalent to 0.76 g kg^{-1}. This may be explained because the waste composition relevant to the EAP region has a relatively small polystyrene (2.9 %) and PET (3.2 %) fractions, which have a high BC EF value, therefore, the overall BC EF for open burning of waste in the region was smaller compared to other areas. By contrast, the largest EF corresponded to South Asia Region and was equivalent to 1.33 g kg^{-1} due to the large PET (8.5 %) and polystyrene fraction (4 %) in waste from this region compared to other areas of the world and which has the largest overall BC EF compared to other waste fractions.

Table 8.3 Black carbon EFs for different major economic regions of the world

	Combustible waste fraction (%)							
Region	**Garden Waste**	**Textiles**	**Paper & card**	**Plastic 1: LDPE**	**Plastic 2: HDPE**	**Plastic 3: Polystyrene**	**Plastic 4: PET**	**Regional EF (g kg^{-1})[(b)]**
AFR: Africa Region	35.4	6.1	25.2	14.1	8.9	3.3	7.1	1.15
EAP: East Asia & the Pacific	31.9	6.7	27.4	7.2	20.8	2.9	3.2	0.76
ECA: Eastern & Central Asia	47.4	5.8	27.7	5.1	4.4	3.7	5.8	1.08
SAR: South Asia Region	35.7	4.7	27.1	10.5	9.5	4.0	8.5	1.33
MENA: Middle East & North Africa	23.1	2.6	43.6	15.2	6.5	3.7	5.3	0.96
LCR: Latin America & the Caribbean	32.8	5.3	34.6	10.6	6.0	5.4	5.4	1.20
OECD Countries	26.2	5.7	47.9	6.3	5.4	4.2	4.4	0.97
EF per waste type (g kg^{-1})[(a)]	**0.469**	**9.094**	**0.021**	**0.108**	**0.155**	**53.064**	**45.723**	**-**

Note: The main source of data used to compile the waste composition per region was Hoornweg and Bhada-Tata (2012); other data sources for garden waste, textile waste and plastic waste composition are presented in Table 8.1.
a) EFs for different waste fractions were developed by controlled laboratory combustion experiments reported in Chapter 7.
b) Refer to Equation 8.1

The EFs for international regions listed in Table 8.3 were integrated with the activity levels for open burning of waste provided by Wiedinmyer et al. (2014) to estimate total BC emissions from this source in each region of the world, shown in Table 8.4. The results showed that the region emitting the largest amounts of BC from open burning of waste is EAP, where 665 x 10^3 t y^{-1} of BC are emitted from this source. The next largest emitter of BC from this source was LCR with an emission rate of almost 50% compared to EAP, equivalent to 379 x 10^3 t y^{-1}. High income, OECD countries are

responsible for almost half of the waste generated in the world, however, they have the highest collection efficiency, equivalent to 98 % of the generated waste and open burning of waste in landfills has been eradicated (Hoornweg and Bhada-Tata, 2012); consequently, they also have the lowest BC emissions from open burning. Nevertheless, an estimated 10.1 x 10^6 t y^{-1} of waste are burned as a disposal method by households in OECD countries, releasing 10 x 10^3 t y^{-1} of BC. In total, 0.98 x 10^6 t y^{-1} of BC are released from open burning of waste around the world, equivalent to over 2,150 x 10^6 t y^{-1} of CO_2Eq. According to the World Bank (2018), the total emission of CO_2Eq in the world in 2012 was almost 51,300 x 10^6 t y^{-1}, therefore, open burning of waste represents approximately 4.2 % of total global CO_2Eq emissions. The regions with the highest percentages of BC CO_2Eq emissions from open burning of waste in relation to total CO_2 emissions were MENA (13.2 %), SAR (12.4 %) and LCR (6.7 %).

Table 8.4 also shows the percentage of emissions arising from open burning of waste in dumpsites, which may reflect the extent of waste collection services. Thus, the smallest rates of open burning waste at dumpsites occurs in the SAR, AFR and MENA regions where the majority of waste is burned in backyards by households. ECA and LCR showed the largest rates of burning waste at dumpsites, thus, potential improvements in waste collection services in these regions may actually encourage the uncontrolled burning for waste disposal at dumpsites unless there is a mandatory ban on the practice, which is in place, for example, in OECD countries.

Table 8.4 Emissions of BC and associated CO_2Eq for open burning of waste in different regions of the world

	Waste burned[a] (t y^{-1}) x 10^6	BC Emission Factors (kg t^{-1})	Emissions from dumpsite burning*	BC Emissions per year (t y^{-1}) BC x 10^3	BC (CO_2Eq)[b] x 10^6	Total CO_2 emissions [c] (t x 10^6 y^{-1})	BC (CO_2Eq) / CO_2
AFR: Africa Region	107.3	1.15	25%	124	272	4,600	5.9%
EAP: East Asia & the Pacific	396.6	0.76	32%	302	665	15,380	4.3%
ECA: Eastern & Central Asia	99.2	1.08	54%	107	235	4,762	4.9%
SAR: South Asia Region	153.8	1.33	21%	204	449	3,630	12.4%
MENA: Middle East & North Africa	61.5	0.96	43%	59	129	978	13.2%
LCR: Latin America & the Caribbean	143.7	1.20	61%	172	379	5,685	6.7%
OECD Countries	10.1	0.97	0%	10	22	16,241	0.1%
WORLD TOTAL	**972.2**	**-**	**36%**	**977**	**2,150**	**51,276**	**4.2%**

a) Amount of waste burned per region taken from Wiedinmyer et al. (2014)
b) Average global warming potential (GWP) for BC in a 20 year horizon is 2,200 (Fuglestvedt et al., 2010; Bond et al., 2013)
c) CO^2 emissions were taken from World Bank (2018)

8.3.3. Comparison of BC and CH_4 emissions

Emissions of CO_2Eq as BC from open burning were compared to those from CH_4 arising from the decomposition of equivalent amounts and types of waste following disposal, by landfill to place the impact of open burning on atmospheric pollution in context of a well-understood GHG emission source. This analysis used landfill CH_4 CO_2Eq EFs for different major and representative waste material types (specifically, food waste, paper and cardboard and yard trimming fractions) provided by the Waste Reduction Model (WARM) (US EPA, 2015). The results showed that the CO_2Eq of BC from

uncontrolled burning in backyards was approximately 14 times larger (≈2,300 t y^{-1}) compared to CH_4 potentially released from the decomposition of equivalent amounts of combustible biodegradable waste deposited at the dumpsite in Huejutla (Table 8.5). In Juchitán, the BC CO_2Eq is 3.5 times larger compared to CH_4 for disposal of similar amounts of waste taken to landfill (≈35,500 t y^{-1}). The difference in the impact of BC and CH_4 CO_2Eq emissions in Huejutla and Juchitán is explained because over 80 % of waste generated in Juchitán is disposed by open burning in dumpsites, whereas uncontrolled combustion has ceased at dumpsites in Huejutla. Food waste disposal in landfill was not included in the CO_2Eq balance for CH_4 for Huejutla because backyard burning of waste usually does not include food waste, as this waste is more difficult to combust in small fires in backyards and inhabitants of rural areas feed organic kitchen waste to animals. Therefore, waste sent to dumpsites in Huejutla potentially has a reduced amount of biodegradable waste compared to Juchitán, which is predominantly represented by an urban population. The overall CO_2Eq y^{-1} for BC from waste burning estimated for Mexico was almost 5 times larger compared to the CH_4 released by similar amounts of waste decomposing in a final disposal site.

Table 8.5 CH_4 CO_2Eq emissions for case study areas and Mexico

			EF CH_4 ($MTCO_2Eq$ Wet t^{-1})[a]				
			1.59	0.63	2.30		
	Type of household	Waste burned (t y^{-1})	Food waste (t y^{-1})[b]	Garden waste (t y^{-1})	Paper and cardboard (t y^{-1})	CH_4 $MTCO_2Eq$	BC CO_2Eq / CH_4 CO_2Eq
Huejutla	Low Estimate	8,880	Not considered	1,970	450	2,270	13.7
	High Estimate	9,350	Not considered	2,080	470	2,390	
Juchitán	Low Estimate	44,380	13,290	13,800	2,270	34,970	3.5
	High Estimate	44,440	13,820	13,820	2,270	35,820	
Mexico	Low Estimate	3,808,050	996,180	382,710	485,140	2,937,870	4.7
	High Estimate	6,524,740	1,706,870	655,740	831,250	5,033,780	

a) Emission factors for CH_4 in metric t of CO_2 equivalent per t (FW) of waste are taken from the Waste Reduction Model (WARM) (US EPA, 2015).
b) For Huejutla, no food waste was considered to be burned, as open burning only occurs in backyards (not in dumpsites) and feeding food waste to animals is commonly practised. In Juchitán and Mexico the majority of the waste is burned at dumpsites, therefore it was assumed that all the waste arriving to the dumpsite, including food waste is burned.

Methane CO_2Eq emissions for waste that is currently burned were also calculated for the different regions (Table 8.6). The results showed that CO_2Eq for BC from burning were 3.5 times larger than the equivalent amount of CH_4 generated from disposing of similar amounts of biodegradable waste in landfill. The largest impact was observed for the South Asia region (SAR), where burning waste produces over 6 times more CO_2Eq emissions than would occur if the equivalent amount of waste was disposed by landfilling. The smallest difference was found for the OECD countires, where BC CO_2Eq emissions from burning were more than double compared to landfill disposal.

Table 8.6 CH_4 CO_2Eq emissions for different regions of the world

		EF CH_4 ($MTCO_2E$ Wet t^{-1})[a]				
		1.59	0.63	2.30		
Region	**Waste burned* ($t \times 10^6$ y^{-1})**	**Food waste ($t \times 10^6$ y^{-1})[b]**	**Garden waste ($t \times 10^6$ y^{-1})**	**Paper and cardboard ($t \times 10^6$ y^{-1})**	**CH_4 $MTCO_2Eq$ ($t \times 10^6$ y^{-1})**	**BC CO_2Eq / CH_4 CO_2Eq**
AFR: Africa Region	107.3	23.1	15.1	9.7	68.3	4.0
EAP: East Asia & the Pacific	396.6	99.1	47.6	39.7	278.5	2.4
ECA: Eastern & Central Asia	99.2	9.7	27.2	13.9	64.4	3.7
SAR: South Asia Region	153.8	31.6	13.6	6.2	72.9	6.2
MENA: Middle East & North Africa	61.5	16.9	3.7	8.6	49.0	2.6
LCR: Latin America & the Caribbean	143.7	28.0	21.5	23.0	110.9	3.4
OECD Countries	10.1	0.6	1.6	3.2	9.4	2.3
AFR: Africa Region	972.2	209.0	130.3	104.2	653.3	3.5 (average)

a) Emission factors for CH_4 in metric tons of CO_2 equivalent per wet t of waste are taken from the Waste Reduction Model (WARM) (US EPA, 2015).
b) It was considered that 50% of the food waste is burned.

8.4. Discussion

Published EFs for BC from open burning of waste are extremely limited and are not related to waste composition. A comprehensive laboratory investigation of controlled combustion experiments, reported in Chapter 7, has provided EFs for mixed waste streams, representative of two case study areas in Mexico and for the national average waste composition for Mexico, and for specific, major waste components. The EF values for the representative mixed waste samples were integrated with information obtained for the waste management systems operating in these regions, gathered through questionnaires, interviews with key stakeholders in the waste sector (Chapter 4) and a waste composition analysis (Chapter 5). The results demonstrated that open burning in backyards was equivalent to approximately 5 % of the total CO_2Eq emissions and 7 % of the fuel related per capita CO_2Eq emissions in Huejutla (Table 8.2). In Juchitán, waste was burned both by households and at dumpsites, and was equivalent to almost 20 % of the total and 30 % of the fuel related per capita CO_2Eq emissions in the municipality, based on national inventories (INECC and SEMARNAT, 2015). In Mexico, emissions from open burning of waste are equivalent to 2 – 4 % of the total and 3 – 6 % of the fuel related CO_2Eq emissions per capita.

Developing specific EFs for different waste compositions is time and resource consuming. However, a practicable approach to enable the development of generic EFs for BC open burning of waste may be obtained by measuring the emissions from single waste types and using this information to estimate local BC EFs based on the waste compositional analysis, which is usually available.

Single waste BC EFs were used to develop regional EFs based on the waste composition characteristics of different areas of the world. The results demonstrated that BC emissions from open burning of waste have a significant climate impact, equivalent to over 4 % of global CO_2Eq emissions. Global BC CO_2Eq emissions from burning waste are approximately 3.5 times larger compared to CH_4

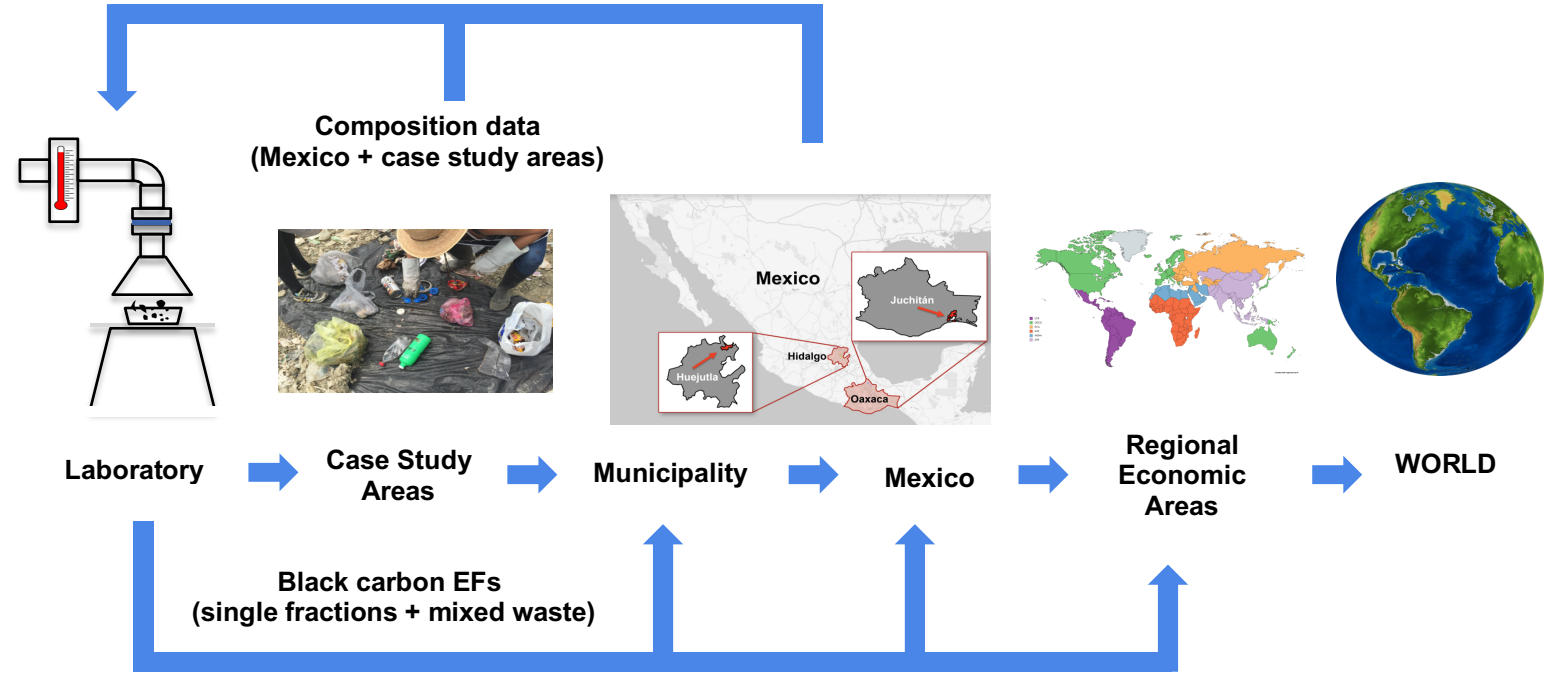
CO_2Eq emissions arising from the decomposition of equivalent amounts of combustible biodegradable waste disposed at dumpsites. The contribution of the landfill disposal of biodegradable waste to CH_4 emissions and climate change has received considerable attention and has been reduced by mandatory controls in certain developed and regulatory jurisdictions, for example, the European Landfill Directive (European Union, 1999). However, the uncontrolled burning of waste is potentially a much larger global contributor to climate change compared to the CH_4 emissions from landfill disposal of biodegradable waste.

The results presented here provide compelling evidence that action to reduce open burning of waste would have a significant and immediate impact on improving air quality and reducing climate change. Furthermore, current climate emission estimates do not consider BC generated from open burning of waste (IPCC, 2014) and therefore underestimate the overall impact of the global waste sector on climate change and particularly the major contribution made by developing countries due to the poor services and controls operating to prevent the uncontrolled burning of waste.

9. General Discussion

9.1. Overview of the research structure, strategy and key outputs

The general structure, scaling up process and main outputs of the research are summarized in Figure 9.1, which also serves as the graphical abstract of this thesis. Laboratory experiments were performed (Chapter 7) to develop BC EFs for open burning of waste using composition data in the case study areas (Chapter 5) and at the national level for Mexico (Chapter 3). Chapter 4 provided an analysis of respiratory health databases for the case study areas and an assessment of the possible link between open burning of waste and respiratory illness. Emission factors for single waste types were also determined, and these were used to calculate regional BC EFs based on the waste composition characteristics in each area (Chapter 8). Information gathered through household questionnaires and interviews with key stakeholders (Chapter 4) were combined with the waste characterisation analyisis (Chapter 5) to estimate the activity levels (amount of waste burned) by different community types (urban, periurban and rural) in Huejutla and Juchitán. One of the main outcomes of Chapter 6 was the Material Flow Analysis for the management of waste, including waste generation and the different disposal options available in the two municipalities studied. The information was combined with the EFs determined in the laboratory (Chapter 7) to estimate BC emissions from open burning of waste in the case study areas, in Mexico, in different economic regions of the world, and at a global level (Chapter 8).



• Combustion experiments (Ch7) • Calculation of single waste EFs (Ch7) • Calculation of mixed waste EFs for case study areas and Mexico (Ch7)	• Household questionnaire (Ch4) • Interviews with stakeholders (Ch4) • Waste characterisation (Ch5) • Validation of data with other studies (Ch5)	• Material Flow Analysis for Municipalities (Ch6) • Estimation of activity levels (Ch6) • Estimation of BC emissions from OBW (Ch8) • Respiratory diseases (Ch4)	• Estimation of activity levels at a national level (Ch3) • Estimation of emissions of OBW at a national level (Ch8)	• Determination of waste composition per region (Ch8) • Elaboration of EFs for regional economic areas (Ch8) • Estimation of emissions from OBW per region (Ch8)	• Estimation of emissions of OBW at a global scale (Ch8)

*OBW: Open burning of waste

Figure 9.1 Overview of the research structure and output

9.2. Waste generation per capita

Figure 9.2 presents a comparison of per capita waste generation rates estimated through fieldwork data for Huejutla and Juchitán (Chapter 5) with national published data (INECC, 2012) and average data for international regions (Hoornweg and Bhada-Tata, 2012). The rate of waste generation per capita in Mexico, equivalent to 0.85 kg day $^{-1}$, was larger compared to African countries, and smaller than all other regions of the world. The reduced waste generation rate per capita measured in Huejutla, equivalent to 0.64 kg day^{-1} reflected the predominantly rural characteristics of the Municipality, and was generally comparable to African countries, and 33 % less than the national average for Mexico. By contrast, the rate of waste generation per capita in Juchitán was higher compared to Huejutla by approximately 0.1 kg per person day^{-1}, but was nevertheless smaller overall compared to the national average value by a similar extent. Juchitán is predominantly an urban municipality, and the improved economic status, compared to predominantly rural areas, such as Huejutla, may explain the differences in waste generation per capita between the two communities investigated here. Other more developed and urbanized regions in Mexico present larger rates of waste generation per capita, therefore the average in the country is higher compared to both case study areas (Figure 3.2).

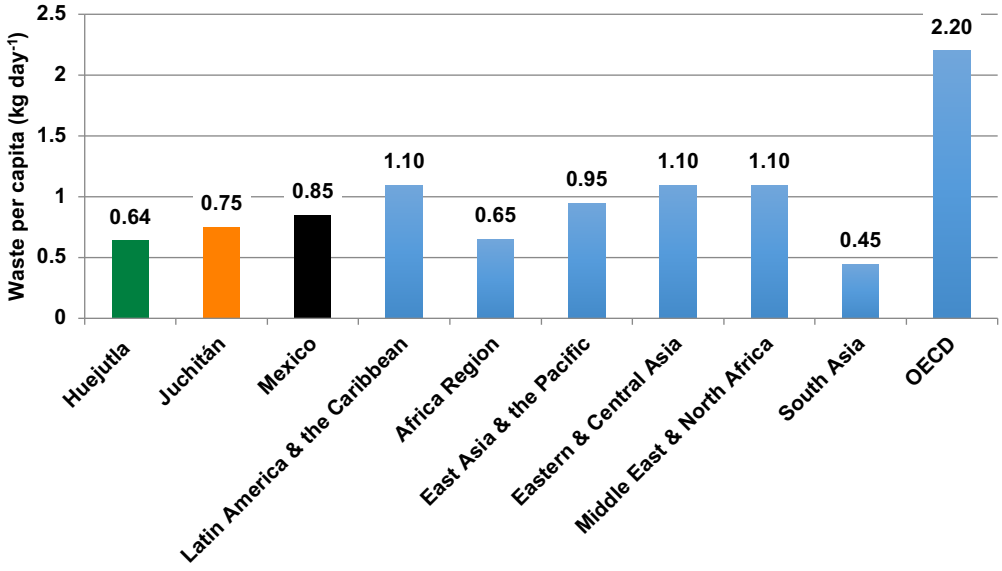


Figure 9.2 Waste generation per capita in the case study areas compared to the national average value for Mexico and other global regions of the world (Hoornweg and Bhada-Tata, 2012; INECC, 2012)

9.3. Waste composition

Emissions from uncontrolled burning of waste are highly dependent upon the composition of the combusted waste (Christian et al., 2010; Stockwell et al., 2016). A comparison of the waste composition in the case study areas (Chapter 5), in Mexico (Chapter 3) and for other regions of the world is shown in Figure 9.3, based on the data reported in Chapter 8 and by Hoornweg and Bhada-Tata (2012). The overall average organic waste fraction for Huejutla was equivalent to 54 % of the total waste FW. Compared to Juchitán, organic waste in Huejutla was 12 % smaller, but 30 % higher compared to the national average for Mexico. The proportion of organic waste found in Huejutla was equivalent to Latin America & the Caribbean and similar compared to Africa and South Asia. In Juchitán, the organic waste fraction was two thirds larger than the national average, and similar to East Asia & the Pacific and Middle East & North Africa. The average

organic waste fraction in Mexico is lower compared to other regions of the world with the exception of OECD countries. This is an expected trend, as household waste generated in low-income countries tends to contain a larger proportion of organic waste compared to higher income areas (Hoornweg and Bhada-Tata, 2012; Wilson et al., 2012). This can be attributed to the general household consumption pattern in low-income areas, where fresh fruits, vegetables and grains constitute the main food purchases in the average household. The processing of these food items generates increased fractions of organic waste in the home (Boateng et al., 2016). By comparison, households in higher income countries tend to have a lower consumption of fresh fruits and vegetables and a higher prevalence of plastic packaging materials from prepared meals (Wilson et al., 2010).

Huejutla and Juchitán generated a similar proportion of paper waste, equivalent to 5 % of the total waste FW. The paper waste fraction in the case study areas was similar to South Asia (4 %), but smaller than all the other regions of the world, including the national average in Mexico, where paper waste corresponds to 13 % of the total waste generation. However, the proportion of paper waste generated in Mexico on average is comparable to most other regions, with the exception of OECD countries, which generate an increased proportion of paper waste, equivalent to 27 % of the total waste generation.

Plastic waste generation in Huejutla (11 % of total) was similar to the national average in Mexico (12 % of total). It was also similar to the proportion of plastic waste generated on average by Latin America & the Caribbean, Africa, East Asia & the Pacific and in OECD countries. In comparison, Juchitán had the highest plastic waste generation, equivalent to 16 % of the total waste. The regions that generate the lowest plastic waste fractions are South Asia and Eastern & Central Asia.

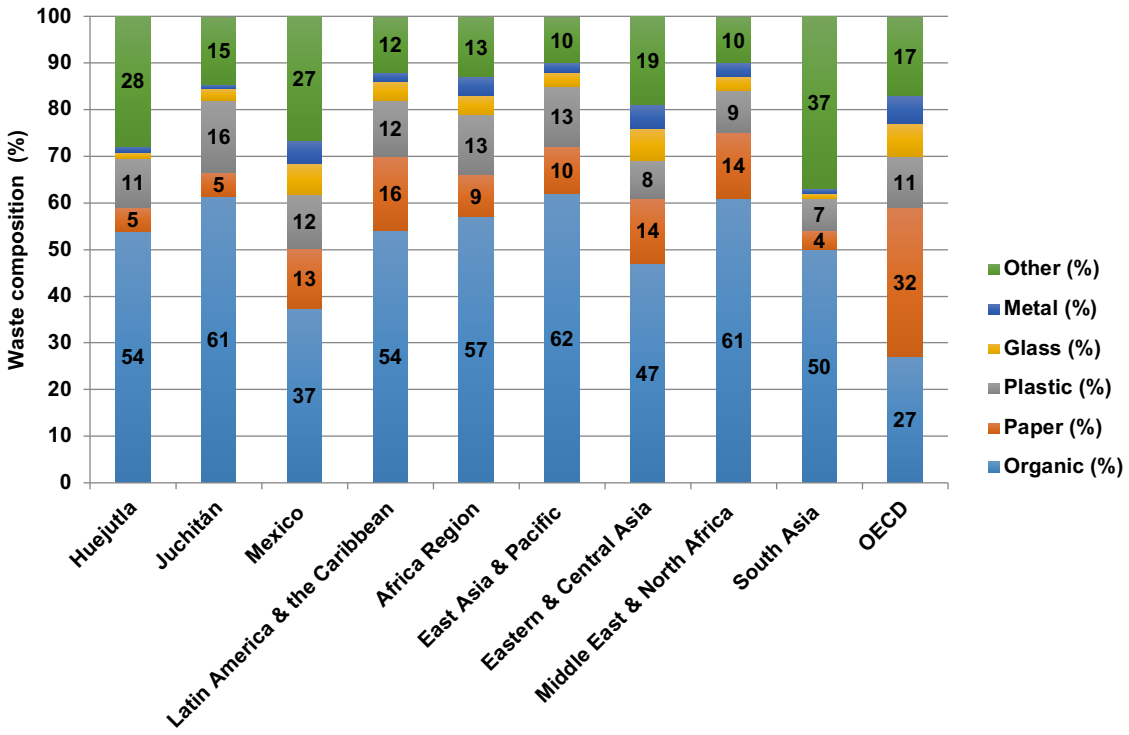


Figure 9.3 Waste composition in the case study areas compared to other global regions in the world (Hoornweg and Bhada-Tata, 2012; INECC, 2012)

9.4. Waste disposal behaviour

Table 9.1 shows the amount of total waste generated in the case study areas, in Mexico and for different regions of the world. The proportion of waste that is not collected and is burned in backyards and dumpsites is also presented. Information for Mexico and other regions was approximated by Wiedinmyer et al. (2014) using IPCC Guidelines (IPCC, 2006) to estimate the total amount of waste burned assuming a burning activity rate in each country. The methodology used total population and per capita waste generation statistics and also assumed the fraction of the population that burned waste and the proportion of waste burned relative to the total amount of waste treated (Wiedinmyer et al., 2014). South Asia, Africa and East Asia & the Pacific have the highest rates of uncollected waste in the world. Wiedinmyer et al. (2014) estimated that between 46 and 60% of the waste is disposed by open burning in the world, with the exception of OECD countries, where burning of waste only occurs in backyards and is equivalent to 1.5% of the waste generated. However, these estimates should be interpreted cautiously due to high degrees of uncertainty. Wiedinmyer et al. (2014) estimated that approximately 30 % of waste generated in Mexico was uncollected and 60 % was burned either in dumpsites or backyards. Local estimates gathered by INECC (2012), however, suggested that 12% of waste in Mexico is not collected and is considered to have an unknown final disposal destination (Chapter 3) (INECC, 2012). Hence, available published data on collection and potential burning of waste in Mexico are inconsistent.

Table 9.1 Waste generated, uncollected and burned at dumpsites and backyards in case study areas and around the world

Region	Waste Generated ($t * 10^3$ $year^{-1}$)	Waste Uncollected (% of waste generated)	Residential Waste Burned (% of waste generated)	Waste Burned at Dumps (% of waste generated)	Total Waste Burned (% of waste generated)
Huejutla	37.9	37.2	24.1	0	24.1
Juchitán	52.7	13.6	4.9	84.3	89.2
Mexico*	53,950	29.2	17.5	42.5	60.0
Latin America & the Caribbean*	246,670	38.4	23.0	35.3	58.3
Africa Region*	178,870	75.1	45.0	15.0	60.0
East Asia & Pacific*	680,270	66.3	39.8	18.5	58.3
Eastern & Central Asia*	175,370	43.4	26.0	30.6	56.5
Middle East & North Africa*	134,240	47.4	26.2	19.6	45.8
South Asia*	266,500	75.8	45.5	12.2	57.7
OECD*	696,980	11.6	1.5	0.0	1.5
*Source: Wiedinmyer et al. (2014)					

The results reported here (Figure 6.1) showed that over 37 % of the waste generated in Huejutla Municipality was not collected and that 24 % was burned in backyards, equivalent to 25 t day^{-1}. According to field data, burning of collected waste disposed at the Municipal dumpsite ended in 2013. In comparison, official government statistics (INECC and SEMARNAT, 2015) report that 0.75 t day^{-1} of waste is burned in households and 0.12 t day^{-1} in dumpsites (Table 3.10) in Huejutla. The difference in the estimated open burning of waste rates translated in an estimation for BC emissions that was over 100 times larger in this research compared to the figures published by INECC and SEMARNAT (2015) for Huejutla.

Wiedinmyer et al. (2014) estimated that approximately 29 % of the waste is not collected in Mexico. In comparison, official data published by INECC (2012) estimate that 16 % of the waste is uncollected in Mexico. The amount of uncollected waste recorded in Huejutla was 27 % higher compared to the national

average in Mexico estimated by Wiedinmyer et al. (2014), emphasising the importance of collecting local information on waste generation, collection, disposal and burning to accurately assess the impact and extent of open burning of waste. The difference between the uncollected waste and the burned fraction mainly represented waste that was either fed to animals or buried. Waste collection services in rural areas of Huejutla were generally not available. Indeed, the fraction of uncollected waste in Huejutla was comparable to Latin America & the Caribbean (38.4 %) but smaller compared to other regions of the world, with the exception of OECD countries, which have the lowest rate of uncollected waste, equivalent to approximately 12 % of the waste generated.

In Juchitán, the proportion of uncollected waste was 60 % less than Huejutla, and was equivalent to almost 14 % of the total waste generated in the Municipality. The greater coverage of waste collection in Juchitán compared to Huejutla is explained because independent commercial waste collection unions are encouraged and allowed to operate in the Municipality, which charge the householder directly for collecting and removing waste to the dumpsite. Indeed, the coverage of the waste collection in Juchitán was comparable to OECD countries and equivalent to 87 % of the waste generated in the Municipality. Nevertheless, the collected waste is ultimately burned by the independent union operators at the Municipal dumpsites, which are located within close proximity to major urban areas of the municipality. Field results showed that 84 % of the waste generated in Juchitán (equivalent to 122 t day^{-1}) was disposed by burning at Municipal controlled dumpsites (Figure 6.2). In contrast, government statistics (INECC and SEMARNAT, 2015) report that no waste is burned in dumpsites in Juchitán (Table 3.10).

A relatively small proportion of the total waste generated in Juchitán, equivalent to 5 % in average (7 t day^{-1}), was burned in backyards to avoid the payment of collection fees. This fraction is considerably smaller compared to the rate of household open burning of waste found in Huejutla, which was equivalent to 24 % of total waste generation. Therefore, the availability of waste collection services has a significant impact on the extent of uncontrolled, open burning of waste by households in developing countries. Independent commercial waste collection services could play an important role in significantly reducing the extent of open burning of waste in backyards by households. However, Juchitán is predominantly an urban municipality, therefore it is a more practical and feasible option to establish waste collection services compared to Huejutla, where the majority of the population reside in more dispersed rural communities and have a greater degree of economic marginalisation.

Nevertheless, most of the waste burned in Juchitán happens in final disposal sites, therefore waste collection services must be coupled with measures to also prevent uncontrolled burning at dumpsites. Thus, the total amount of waste burned in Juchitán was equivalent to almost 90 % of the waste generated, and this value is 50 % larger compared to the national average estimated for Mexico of 60% by Wiedinmyer et al. (2014). INECC and SEMARNAT (2015) report a considerably smaller fraction, equivalent to 0.48 t day^{-1} of waste, is disposed by burning in households in Juchitán (Table 3.10). Overall, the estimated BC emissions for open burning of waste in Juchitán in backyards and dumpsites were over 900 times larger in this research compared to those published by INECC and SEMARNAT (2015). Therefore, the results found through this investigation suggest that current official estimations for BC emissions from open burning of waste in Mexico are largely underestimated.

Accoridng to the results presented here, access to free-of-charge waste collection service significantly reduces, but does not necessarily eliminates open burning as a waste disposal method by households.

Therefore, in addition to providing regular waste collections, further support may be necessary to eradicate open burning completely, such as education programmes and providing households with a secure means of storing waste between collections. Additionally, the contribution of open burning to atmospheric pollution emissions may still be a major problem unless uncontrolled combustion is also prevented at central disposal sites.

Recycling rates estimated in this research for Huejutla and Juchitán are compared with national data for Mexico (INECC, 2012) and other international regions (Hoornweg and Bhada-Tata, 2012) in Figure 9.4, to provide representative baseline information on waste recycling practices in the selected study areas. INECC (2012) estimated that the national recycling rate in Mexico was equivalent to 9.6 %, which is lower compared to OECD countries and East Asia and Pacific regions. However, recycling rates found at the local level for small to medium sized communities in Mexico, such as Huejutla, may be considerably smaller than the national average value. Indeed, the recycling rate obtained for here Huejutla was equivalent to 2.4 % and was similar to the Latin America region and approximately 75 % lower than the national data for Mexico (INECC, 2012). In Juchitán, recycling is almost double compared to Huejutla, at 4.5 %. This is higher than in Latin America & the Caribbean, the Africa Region and Eastern and Central Asia. The regions with the highest recycling rates are East Asia & the Pacific and the OECD countries, where more than 20 % of the waste generated is recycled. The results presented here for representative medium-sized communities (Chapter 3) suggests that recycling performance is significantly lower than the average estimate for Mexico, which is probably explained by progress in areas with high population densities, such as Mexico City. Elsewhere, however, the rate of recycling waste is relatively poor overall. Nevertheless, it should be noted that recycling rates generally exclude food waste that is fed to animals, which usually has not been measured. If the fraction of waste fed to animals was included, recycling rates would rise to 15 % for Huejutla and 13 % for Juchitán.

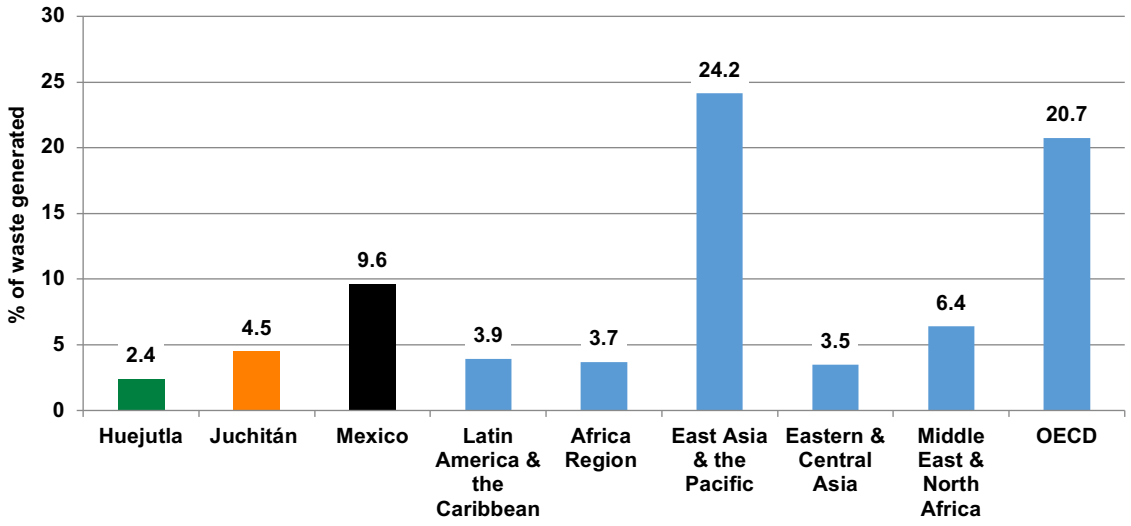


Figure 9.4 Recycling rates in case study areas, Mexico (INECC, 2012) and around the world (Hoornweg and Bhada-Tata, 2012)

As observed in Table 9.2, the figures for open burning of waste reported by INECC and SEMARNAT (2015) are very low compared to the ones obtained through the field data gathered for this research. Specifically, the estimations for BC emissions from open waste combustion in Mexico estimated through this

research were over 100 times larger compared to that published by INECC and SEMARNAT (2015). In the case of Mexico, activity levels for open burning of waste (Chapter 3) were obtained using information on household waste disposal obtained through the National Census (INEGI, 2011), waste composition reported by (SEMARNAT, 2013b), estimations of waste sent to uncontrolled dumpsites estimated by INECC (2012) and expert advice on percentages of waste burned in dumpsites in Mexico (Encarnación-Aguilar, 2015; Solorzano-Ochoa, 2015). The estimation by INECC and SEMARNAT (2015) uses data about population per state (INEGI, 2010a), percentage of households that burn waste (INEGI, 2011), per capita waste generation (INECC, 2012), quantity of uncontrolled dumpsites and the waste they receive (INECC, 2012), as well as estimations about the fraction of waste burned in houses and dumpsites according to experts in the subject. Based on this information, it is possible to observe that most of the data used by INECC and SEMARNAT (2015) and for this research come from the same sources, however, the comparison of the results shows large differences.

Table 9.2 National statistics on open burning of waste compared to this research (t y^{-1})

	INECC-SEMARNAT*				This research (using averages)			
Area	**Waste burned in houses**	**Waste burned in dumpsites**	**Total waste burned**	**BC Emissions****	**Waste burned in houses**	**Waste burned in dumpsites**	**Total waste burned**	**BC Emissions*****
Mexico	323,751	24,145	347,896	**225**	1,148,290	4,018,103	5,166,393	**23,272**
Huejutla	274	44	318	**0.21**	9,118	0	9,118	**14.4**
Juchitán	175	-	175	**0.11**	2,581	41,830	44,412	**56.2**

***Source:** INECC and SEMARNAT (2015)
** INECC and SEMARNAT (2015) used a BC EF of 0.646 published by Christian et al. (2010)
***Using emission factors from chapter 7

The official statistics (INECC and SEMARNAT, 2015) for Huejutla and Juchitán were also compared to the data reported by this research. INECC and SEMARNAT (2015), suggests that 318 t $year^{-1}$ of waste is burned in Huejutla both in backyards and dumpsites. However, the validated data collected for Huejutla reported here shows that over 9,000 t $year^{-1}$ of waste are disposed by open burning, exclusively in backyards, in the Municipality. INECC and SEMARNAT (2015) considered that open burning of waste in backyards in Juchitán accounted for 175 t $year^{-1}$ and that no waste was disposed by burning at dumpsites. However, in practice, 44,000 t $year^{-1}$ of waste are disposed by burning in Juchitán, with the majority being burned at dumpsites. Therefore, according to the results found through this research, the contribution to climate change by open burning of waste may be significantly underestimated by the official sources.

9.5. Determination of BC emissions from open burning of waste

Open burning is a highly variable process and quantitatively measuring the emissions from the combustion of highly heterogeneous waste materials represents a significant experimental and practical challenge. A small-scale laboratory based, combustion methodology to measure BC EFs from burning waste was developed using a simple waste emission sampler apparatus utilising a standard particulate impact capture approach with quartz filters, which is widely used method in atmospheric particulate research.

The experimental approach in this research employed two methods of measuring BC. The first methodology was based on optical transmission and measured light transmission through the filter, described as attenuation (ATN); this technique is simple to perform, non-destructive and requires no consumables and is inexpensive to operate and can be therefore used to determine large numbers of

samples. Due to the potential variation in optical transmission properties of the emission samples collected, which is a non-linear response, it was necessary to calibrate the ATN values by a direct analysis of the carbon composition of the PM and this was completed by thermal optical analysis (TOA), using a small number of selected quartz filters representing the full range of ATN values. Strictly, TOA measures the EC fraction of the PM, however, as EC and BC fractions are operationally defined by the measurement method applied these terms are used interchangeably (Watson et al., 2005; Petzold et al., 2013), but BC is used exclusively to describe the emissions from burning waste and was therefore adopted here.

A quadratic algorithm was applied to describe the relationship between ATN and EC, incorporating the coefficients for: (1) the specific shadowing correction factor (σ_{ATN}) and (2) the mass extinction coefficient (k), which are important in the quantitative determination of EC from ATN. The experimental results were used to quantify these coefficients, which may be generally applicable to the characterisation of BC emissions from open burning of waste by ATN. These coefficients, therefore, permit the direct determination of BC from ATN measurements without the requirement for complex and expensive TOA of waste combustion emission samples.

9.6. Emissions factors for open burning of waste

Emission factors for open burning of waste are currently based on very limited quantitative measurements and it is uncertain how representative and reliable the data are. The available published EFs are compared with a summary of the EFs developed through this research in Table 7.7. The most extensively quoted BC EF for open burning was provided by Christian et al. (2010) using single measurements of open burning of waste emissions captured at each of three different municipal landfills in periurban communities located north of Mexico City in April 2007. Measurements were taken when waste was being routinely burned at one of the landfills, but at the other two sites, representative amounts of waste were set alight specifically for the purposes of measuring the emissions released to atmosphere. However, no waste characterisation was reported. Only a brief observation was made about plastic being the most abundant material present, and that the other main waste types included paper, organic waste and textiles. Therefore, it is not possible to extrapolate the results in other areas with different waste composition. Moreover, it was practically difficult to control the burning tests, hence, the waste characteristics and burning conditions varied for each measurement. The EF was measured following a standard procedure using a commercial filter-sampling system with an internal pump and an impactor to collect PM on quartz filters (US EPA, 1999). Elemental carbon was determined by a thermal-optical transmissometer (OCEC Lab Instrument Model 5, Sunset Laboratory, Oregon US), following a similar method to the procedures adopted here (Chapter 7). The average EF obtained by Christian et al. (2010) was 0.65 g kg^{-1}, with a range of 0.38 to 0.92 g kg^{-1}. Thus, the overall average EF measured here of 1.50 g kg^{-1} for mixed waste samples (Table 7.7) was significantly larger than the value obtained by Christian et al. (2010). The difference in values may be explained because, under field conditions, it is difficult to capture all of the combustion emissions and to estimate the total amount of emissions based on single point sample collectors. Under laboratory conditions, however, it is possible to efficiently capture all the PM emitted during sample combustion. Therefore, it may be expected that the laboratory data provide higher, more rigorous, reliable quantitative values than measurements in the field, which are extremely difficult to collect and estimate.

Stockwell et al. (2016) characterized BC EFs for several combustion sources including open burning of waste as part of the Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE). The EF was

measured using a photoacoustic extinctometer (PAX; 405 and 870 nm) located in the Kathmandu Valley and in the Indo-Gangetic Plain of south Nepal during April 2015. The main aerosol optical properties analysed were used to calculate BC and brown carbon (BrC) EFs. Mixed waste combustion emissions were sampled on six occasions but aerosol properties were only determined for two of the tests. Hence, the BC EF was based on only two measurements, and therefore how representative the value is of BC emissions from burning waste in general, is questionable. The main waste material types used in the burning tests were indicated, however, the relative composition of the waste samples was not provided, again making extrapolation difficult. The EF values measured by Stockwell et al. (2016) under damp and dry conditions (representing Kathmandu and Tarai, respectively) were 0.56 and 6.04 g kg^{-1}, which, as may be expected, suggest a high variability in BC emissions, possibly related to the humidity of the waste sample. In general, smouldering conditions generate higher EFs compared to firing combustion (Christian et al., 2010; Jayarathne et al., 2017), however, samples collected in Kathmandu were damp from rainfall and therefore the fire had to be reignited with burning newspaper on several occasions (Stockwell et al., 2016). The excessive humidity of the waste could have caused the sample to burn ineffectively, thus, emissions in this case were reduced.

Jayarathne et al. (2017) used a thermal-optical transmission technique during the NAMaSTE programme to measure BC emissions from three test burns with waste and develop an EF. No waste characterisation was provided and the reported BC EF (note that the TOT method measures EC which is used synonymously to indicate BC, for a detailed discussion refer to Section 7.4.2) recorded was 2.6 g kg^{-1}.

In this research, BC EFs for individual waste streams varied significantly between different waste types. The smallest BC EF was measured for paper and cardboard waste, equivalent to 0.021 g kg^{-1}, followed by LDPE with a BC EF of 0.155 g kg^{-1}. In contrast, the largest BC EF was obtained for polystyrene, at 53.06 g kg^{-1}, followed by PET with a BC EF equivalent to 45.7 g kg^{-1}. Black carbon EFs for individual waste streams were combined in the same proportions as the composition of waste from the case study areas and, following this approach, the derived values were found to be, on average, 5 times larger compared to laboratory combustion measurements using the mixed waste fractions. Therefore, a nominal adjustment of 0.2 was applied to calculate mixed waste EFs from the single waste stream combustion test data. The reason for the difference in measured EFs for mixed waste samples compared to those derived using EFs from single waste streams is uncertain. Emission of BC increases due to poor burning conditions, for instance through oxygen limitation, which encourages an increased degree of smouldering combustion. Therefore, the increased emissions for single waste streams could be explained due to a lowering of the oxygen supply in homogenous waste samples compared to a mixture of waste materials, which may provide improved structural conditions for oxygen entry. Indeed, homogenous, single waste samples tended to have more compact properties compared to mixed waste samples, potentially reducing the oxygen availability during combustion and thus, increasing the BC EF.

Previously reported EFs for BC released to the atmosphere during the uncontrolled, open combustion of waste were based on field measurements and PM impactor sampling collected during the actual burning of waste samples in the open. Consequently, the combustion conditions and waste properties were very difficult to control, such that the extrapolation of the data to other situations and circumstances where burning conditions may differ, such as the waste composition, may not be entirely valid or representative. To overcome these limitations, an experimental protocol was developed in this research, allowing careful control

of the combustion conditions and the waste formulations tested, with sufficient levels of replication to generate reliable and statistically consistent emission measurements (Chapter 7).

However, using laboratory-scale measurements does introduce limitations and compromises. Sample sizes are very small (between 0.1 and 5 g) and therefore obtaining representative samples is difficult. Nevertheless, previous field BC EFs by Christian et al. (2010) and Stockwell et al. (2016) are within a similar range compared to the results obtained here, and those of Jayarathne et al. (2017) are also entirely consistent with our data. One of the advantages of the laboratory based BC EFs, however, is that the controlled conditions of the process allowed testing of an increased number of samples representative of different mixed waste compositions and single waste fractions. Black carbon EFs for single waste fractions can be used to determine local BC EFs based on data of the waste composition for any particular region. The experimental data applied following this approach to calculate such geographical and socioeconomic regional BC EFs are presented and discussed in Table 8.3.

9.7. Health impact of open burning of waste

The exposure to $PM_{2.5}$ emissions from uncontrolled burning of waste has been linked to heart, cerebrovascular and respiratory diseases, as well as lung cancer (Cogut, 2016; Kodros et al., 2016). Health outcomes associated with exposure to $PM_{2.5}$ are also associated with BC in most epidemiological studies (Janssen et al., 2012). Kodros et al. (2016) estimated the impact of exposure to $PM_{2.5}$ (which contains BC) from uncontrolled waste combustion could be responsible for 138,000 to 518,000 deaths per year globally. Therefore, uncontrolled waste combustion represents an important health problem. Also, the disposal of waste by open burning releases the emissions of other toxic pollutants, such as dioxins, furans, volatile organic compounds, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls (Christian et al., 2010; Wiedinmyer et al., 2014; Kodros et al., 2016), which cause reproductive and developmental problems, harm to the immune system and cause cancer (WHO, 2016).

Another reason why the uncontrolled burning of waste has potentially a high impact on health is explained due to the close proximity of the emissions and the human population, for example, household residents may be readily exposed to the emissions from the burning of waste in backyards. In developing countries, open burning of waste also occurs in dumpsites that are normally situated close to the urban areas served. Poor waste collection services directly contribute to the increased rate of open burning waste by households, and there is also a lack of awareness of the environmental and health effects of using waste combustion as a disposal method.

Health databases of two case study areas with different waste disposal behaviours were scrutinised. The results showed that, in Huejutla, where the majority of rural households (92 %) engaged in backyard burning of waste, respiratory diseases in rural areas were double compared to urban communities. This is an interesting trend because, more usually, the incidence of respiratory diseases is typically reported to be higher in urban areas due to the increased exposure to air pollution from transport (Iversen et al., 2005; O'Reilly et al., 2007; Gartner et al., 2008; Jang, 2012). In Juchitán, waste was burned both in backyards and at final disposal sites, which are located in close proximity to the urban area of the Municipality. In this case, respiratory diseases were more prevalent in the urban compared to rural areas.

Smoking is another potential cause of respiratory diseases, however, in rural areas in Mexico smoking is reduced compared to urban areas (CONADIC, 2008). Therefore, smoking is not likely to be a factor

influencing the high incidence of respiratory diseases in rural areas of Huejutla. As expected, in the case of Juchitán, household questionnaires indicated a higher incidence of smoking in urban compared to rural areas. Therefore smoking could be a factor explaining the high rates of respiratory diseases in urban areas of Juchitán. Another factor contributing to the high rates of respiratory diseases in urban areas of Juchitán includes increased air pollution from transport and industry.

In Juchitán, cooking with solid fuels was more prevalent in rural communities, in 56 % of households, whereas only 17 % of urban households used this cooking method. Therefore, the results suggested that other sources of urban air pollution were more important to respiratory health in this case compared cooking with solid fuel. In Huejutla, cooking with solid fuels was also greater in rural compared to urban areas and could therefore be a contributory factor to the observed increase in respiratory diseases in rural areas. Nevertheless, the results strongly implicate open burning of waste as a potentially important contributor to detrimental respiratory health in both case study areas.

9.8. Local and global impacts of open burning of waste on climate change

A summary of the main BC emissions estimations for open burning of waste found through this research and published data is summarized in Table 9.3. This research provided BC emission calculations for open burning of waste in two case study areas using information collected in the field and through laboratory experimentation. The results (Figure 6.1) showed that approximately 24 % of the waste in Huejutla was burned in backyards, generating BC emissions equivalent to 5 % of the total and 7 % of the fuel related per capita CO_2Eq emissions. Moreover, CO_2Eq from BC emitted by uncontrolled burning in backyards was approximately 14 times larger compared to CH_4 potentially released from the decomposition of equivalent amounts of combustible biodegradable waste deposited at the dumpsite.

Table 9.3 Summary of results for BC emission estimations in case study areas, Mexico and the World

						(% of CO_2Eq		
	Waste burned (t y^{-1})	Burned in backyards (% of total waste)	Burned in dumpsites (% of total waste)	BC emissions (t y^{-1})	BC (MTCO_2Eq y^{-1})	Total emissions	Fuel Emissions	BC CO_2Eq emissions/ CH_4 CO_2Eq
Huejutla	9,115	24.1	0	14.4	31,787	4.4 - 4.7	6.6 - 7	13.7
Juchitán	44,410	4.9	79.3	56.2	123,735	19.8	29.2 -29.3	3.5
Mexico	5,166,400	3.1	10.7	23,272	18,687,750	2.2 - 3.8	3.2 – 5.6	4.7
World	**972,200,000**	**26.1**	**14.8**	**977,274**	**2,150,002,774**	**4.2**	**-**	**3.5**
Compiled using data from Chapter 8								

In Juchitán, almost 85 % of the generated waste in the Municipality was disposed by uncontrolled burning both in households and dumpsites (Figure 6.2), but mainly (80 %) at dumpsites. Consequently, CO_2Eq emitted from open burning of waste were equivalent to 20 % of the total and 30 % of the fuel related per capita emissions in the Municipality. In Juchitán, results showed that BC CO_2Eq from open burning were 3.5 times larger than would be achieved as CH_4 CO_2Eq emitted from similar amounts of waste disposal by landfilling.

Using the EFs developed for Mexico in the laboratory and the measured activity levels for open burning of waste, it was possible to estimate the BC emissions from this source at a national level. The results showed that emissions from open burning of waste in Mexico are equivalent to 2 – 4 % of the total and 3 – 6 % of the

fuel related CO_2Eq emissions per capita. In Mexico, BC CO_2Eq y^{-1} emissions from waste burning are 4.2 times larger compared to the CH_4 CO_2Eq y^{-1} that would be released by similar amounts of waste decomposing in a final landfill disposal site.

The global impact of open burning of waste was estimated using the single waste BC EFs developed through this research (Chapter 7). Regional EFs were calculated using information on the waste composition characteristics of different areas of the world (Hoornweg and Bhada-Tata (2012). This was combined with information on the activity level of open burning by country (Wiedinmyer et al. (2014). The results demonstrate that BC emissions from open burning of waste have a significant climate impact, equivalent to 4.2 % of global CO_2Eq emissions. Global BC CO_2Eq emissions from burning waste are approximately 3.5 times larger compared to CH_4 CO_2Eq emissions arising from the decomposition of equivalent amounts of combustible biodegradable waste disposed at dumpsites.

Open burning of waste is often a neglected aspect of inadequate SWM systems in developing countries and current climate change inventories significantly underestimate the global emissions from, and impacts of, the waste management sector. Specifically, current official atmospheric emission inventories published by IPCC ignore BC emissions contributed from the uncontrolled open burning of waste and therefore significantly underestimate the global impact of the waste sector on climate change. Action to reduce open burning of waste would have a significant and immediate impact on improving air quality and reducing climate change.

10. Conclusions and further work

10.1. Open burning of waste activity level

- This research provides some of the first reported field data on the activity levels associated with open burning of waste and of the composition of waste burned in backyards using two representative communities of a developing country (Mexico), namely Huejutla de Reyes and Juchitán de Zaragoza.
- Almost 13 % of waste generated in Mexico is disposed by open burning. By contrast, official statistics reported by the Mexican Government (INECC and SEMARNAT, 2015) indicate that less than 1 % of the waste generated in Mexico is disposed by burning. Therefore, the contribution to climate change by open burning of waste may be significantly underestimated.
- In Huejtla, the Municipal Authorities ceased burining in the Municipal dumpsite and therefore claim that open burning is no longer a waste disposal practice in Huejutla. However, the validated data collected here shows that over 9,000 t $year^{-1}$ of waste are disposed by open burning (equivalent to 23-25 % of the waste generated), exclusively in backyards, in Huejutla Municipality. Official sources (INECC and SEMARNAT, 2015), suggest that 318 t $year^{-1}$ of waste is burned in Huejutla both in backyards and dumpsites, which is a significantly lower value compared to the field data collected through this research.
- In the case of Juchitán, INECC and SEMARNAT (2015) considered that open burning of waste in backyards in Juchitán accounted for 175 t $year^{-1}$ and that no waste was disposed by burning at dumpsites. However, in practice, 44,000 t $year^{-1}$ of waste are disposed by burning in Juchitán (equivalent to 84 % of the waste generated), with the majority being burned at dumpsites.

10.2. Factors influencing the open burning of waste

- In rural areas of Huejutla, waste collection services were not available and over 92 % of households indicated that they disposed of their waste by open burning. In contrast, the Local Authority provided a daily waste collection service to the urban community in the Municipality and there was a twice-weekly collection in periurban areas, which reduced the number of households that burnt waste in backyards to less than 22 % and to 37 %, respectively. Open burning of waste by urban and periurban households represented just 7% of the total waste that was disposed by burning.
- In Juchitán, independent waste collection unions provided collection services for a fee in both urban and rural areas of the Municipality. Consequently, only 3 - 7 % of the total waste generated was disposed by burning by households, compared to more than 22 % in Huejutla. Nevertheless, households in Juchitán may still rely on burning as a waste disposal method to avoid paying direct waste collection charges as, in general, the level of marginalisation in this municipality is high.
- In Juchitán, approximately 80% of the waste generated was burned by uncontrolled fires at dumpsites.

10.3. Shadowing correction factor and mass extinction coefficients

- The relationship between EC and ATN was used to quantify the shadowing correction factor and mass extinction coefficient, which may be generally applicable to the characterisation of BC emissions from open burning of waste by ATN. The specific values were: $\sigma_{ATN} = 45.7$ and $k = 0.0097$.

- A general estimate of BC from ATN for open burning of waste was also obtained using a simple linear coefficient through a linear regression analysis of TOA data, and was equivalent to 0.12 μg cm^{-2} BC per unit of ATN.
- These coefficients, therefore, permit the direct determination of BC from ATN measurements without the requirement for complex and expensive TOA of waste combustion emission samples.

10.4. Emission factors for open burning of waste

- The BC EFs measured for mixed waste samples representative of the waste composition in the case study areas were in the range 1.27 – 1.64 g kg^{-1}, and were similar to the mean BC EF reported in the scientific literature for the open burning of waste, which was equivalent to 1.98 g kg^{-1}.
- Black carbon EFs for individual waste streams varied significantly between different waste types. The smallest BC EF was measured for paper and cardboard waste, equivalent to 0.021 g kg^{-1}, followed by LDPE with a BC EF of 0.155 g kg^{-1}. In contrast, the largest BC EF was obtained for polystyrene, at 53.06 g kg^{-1}, followed by PET with a BC EF equivalent to 45.7 g kg^{-1}.
- Adjusted EF values for single waste types were used to calculate general BC EFs for different geographical-socioeconomic regions of the world based on published waste composition data for these areas. The smallest BC EF corresponded to East Asia and the Pacific (EAP), and the largest was calculated for the South Asia Region (SAR), and the BC EF values in these regions were 0.76 g kg^{-1} and 1.33 g kg^{-1}, respectively.

10.5. BC emissions from open burning of waste

- In Huejutla, BC emissions from the uncontrolled combustion of waste were between 14.1 – 14.8 t y^{-1}, and were equivalent to approximately 5 % of total atmospheric emissions as CO_2Eq and 7 % of fuel related CO_2Eq emissions in the Municipality. In Juchitán, open burning of waste released 56.2 – 56.3 t of BC y^{-1}, equivalent to 20 % of the total CO_2Eq emissions and 30 % of the fuel CO_2Eq related emissions in the Municipality.
- In Mexico, between 6.3 and 10.7 x 10^3 t y^{-1} of BC are emitted due to open burning of waste, which is equivalent to 2 - 4 % of the total CO_2Eq emissions and between 3 and 6 % of the fuel related CO_2Eq emissions.
- Globally, the regions contributing the largest overall BC emissions from open burning of waste are EAP, followed by SAR, with 665 x 10^6 and 449 x 10^6 t $year^{-1}$ of BC CO_2Eq, respectively. The results demonstrated that BC emissions from open burning of waste have a significant global climate impact, contributing an equivalent of 4.2 % of the total CO_2Eq emissions in the world.

10.6. Comparison of BC CO_2Eq emissions and CH_4 CO_2Eq emissions

- In Huejutla, BC CO_2Eq emissions released by open waste combustion could be 14 times larger compared to CH_4 CO_2Eq released by the decomposition of an equivalent amount of biodegradable waste sent to landfill.
- In Juchitán, BC CO_2Eq from open burning of waste may 3.5 times compared to CH_4 CO_2Eq arising from the decomposition of an equivalent amount of biodegradable waste sent to landfill.
- In Mexico, BC CO_2Eq from waste combustion could be 4.2 times larger than CH_4 CO_2Eq emitted by the decomposition of equivalent amounts of biodegradable waste sent to landfill.

- Globally, BC CO_2Eq emissions from burning waste may be approximately 3.5 times larger compared to CH_4 CO_2Eq emissions arising from the decomposition of equivalent amounts of combustible biodegradable waste disposed at dumpsites.

10.7. Health impact of open burning of waste

- Health databases collected in Huejutla showed that respiratory cases in rural clinics were twice those found in urban areas, which corresponds to the areas where open burning of waste is increased.
- In Juchitán, urban clinics recorded approximately double the number of cases of respiratory diseases in the Municipality in 2006 to 2015 compared to rural areas. In Juchitán most of the open burning of waste occurs in dumpsites located close to the urban areas of the municipality.
- Local health data collected from both case study areas strongly implicate the open burning of waste at dumpsites and/or in backyards as a significant contributory factor to the high numbers of respiratory diseases reported in rural areas of Huejutla and the urban area of Juchitán.

10.8. General recommendations

- Having a modernized, sustainable waste management system will probably not be achievable in the short term in the two case study areas analysed for this research. However, starting by improving waste collection and disposal services would bring immediate benefits to the environment and to the health of the population of the region.
- In Huejutla, most of the open burning of waste occurs in rural areas with no waste collection services. Therefore, to reduce BC emissions from uncontrolled waste combustion the first step should be to invest in infrastructure to improve waste collection services. Municipal Authorities could encourage private companies to provide waste collection services in rural areas, as this has been an effective way to provide waste collection in Juchitán. Authorities in Huejutla could also consider investing in education campaigns to eradicate waste burning in areas where waste collection is already in place. Other investments could include the provision of bins for a safe disposal of waste between waste collections.
- In Juchitán, waste collection services are available throughout the municipality; however, most of the waste is burned at dumpsites. Therefore, the first step in this region could be to invest in infrastructure to improve waste disposal strategies at the dumpsite with the purpose of eradicating intentional waste burning. Municipal Authorities in Juchitán could consider subsidizing waste collection services provided by waste collection unions, to decrease waste burning by householders that can not afford paying for the service. Juchitán is considered to be an area with a high level of marginalisation; therefore, households that cannot pay direct waste collection service charges currently dispose of waste by open burning in the backyard.

10.9. Further work on BC emissions from open burning of waste

- It is fundamental to generate reliable data to inform decision makers, responsible for planning and policy making, about the impact of BC emissions from open waste combustion. Specifically, information on the activity levels of open burning of waste is very limited at present. Fieldwork to accurately quantify activity levels for uncontrolled waste combustion is necessary to provide more reliable estimates of this BC emission source.

- Black carbon emissions from open burning of waste are influenced by a number of factors including: waste composition, oxygen availability (for example due to altitude and waste configuration), smouldering or firing combustion conditions, etc. Therefore, more fundamental and detailed work is necessary into the mechanisms, factors and interactions responsible for the production of BC during the combustion of different waste types and mixtures to underpin and verify the BC EF measured here for single waste fractions and mixed compositions.
- Further research should be carried out to investigate the influence of the particle size used for waste samples during combustion experiments to determine BC EFs.
- Regional BC EFs were constructed using individual waste BC EFs as a practicable approach to estimate the impacts of BC emissions from waste combustion in different geographical-socioeconomic areas. However, the uncertainty of these estimations could be further reduced by developing BC EFs using mixed waste compositions specific to other regions.
- Case control and epidemiology studies are necessary to assess the impact of BC emissions from open burning of waste on the health of the human population.
- A cost-benefit analysis is recommended to compare the cost of improving waste collection and disposal strategies relative to the provision of healthcare services to treat respiratory diseases, and the loss of economic performance and the impact on well being due to the health effects associated with the open burning of waste. This cost-benefit analysis would provide further justification to encourage federal, state and municipal authorities to address the negative impacts of open burning of waste by understanding the economic, environmental and social benefits of improved waste collection and disposal systems.
- Further fieldwork investigation should be carried out to determine the impact of seasonal variation on waste generation and composition in the case study areas. This is specially the case during municipal traditional celebrations (festivals, fairs, carnivals), which generate an increased amount of waste in the area.

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APPENDICES

APPENDIX A1. Abstract of article published in Environmental Research Journal

Uncontrolled burning of solid waste by households in Mexico is a significant contributor to climate change in the country

Absract

Uncontrolled burning of municipal solid waste (MSW) is an important source of air pollution and is wide spread in many developing countries, but only limited data quantify the extent of domestic open burning of household waste. Here, we present some of the first field data to be reported on the uncontrolled domestic burning of waste. A representative community of Mexico (Huejutla de Reyes Municipality) was investigated and household surveys, interviews with waste operators and a waste characterisation analysis were completed to assess the extent of, and factors controlling, the open burning of waste. Waste collection provision to rural communities was very limited and, consequently 92 % of households in rural areas reported that they disposed of waste by uncontrolled burning in backyards or unofficial dumps. Overall, 24 % of the total MSW generated in the Municipality was disposed by uncontrolled burning. Urban areas received twice-weekly collections and the rate of uncontrolled burning was considerably smaller compared to rural households, corresponding to approximately 2 % of total waste generation. Carbon equivalency calculations showed that burning waste in backyards represented approximately 6 % of the total and 8.5 % of fuel related CO_2Eq emissions by the municipality. Moreover, the equivalent carbon dioxide (CO_2Eq) from black carbon (BC) emitted by uncontrolled burning in backyards was fifteen times larger compared to methane (CH_4) potentially released from equivalent amounts of combustible biodegradable waste disposal at the official dumpsite. An assessment of local respiratory health data showed the incidence of disease was higher in rural than in urban areas, when the opposite trend is typically observed in the international literature; given the high rate of burning activity found in rural areas we suggest that open burning of waste could be a major reason for the apparent poorer respiratory health status of the rural population and requires further investigation. The results emphasise the importance of including BC from uncontrolled burning of waste in international emission inventories of greenhouse gases and in the assessment of the health status of local communities in developing countries where this practice is prevalent.

KEYWORDS:

Open burning of waste, black carbon emissions, air pollution, municipal solid waste, climate change, developing countries.

REFERENCE:

Reyna-Bensusan, N., Wilson, D. C. & Smith, S. R. 2018. Uncontrolled burning of solid waste by households in Mexico is a significant contributor to climate change in the country. *Environmental Research,* 163**,** 280-288.

APPENDIX A2. Abstract of article presented in the 6th International Conference on Sustainable Solid Waste Management, 13-16 June 2018, Naxos Island, Greece

The global impact of uncontrolled burning of waste

Absract

Open burning of solid waste is a significant source of air pollution emissions and a common practice in many regions of the world. Black carbon (BC) is a particularly important combustion emission pollutant having a global warming potential (GWP) up to 5000 times greater than carbon dioxide (CO_2) (Bond et al., 2013). However there are major uncertainties about the extent and impacts of the BC emissions from uncontrolled burning of waste on the environment. Specific waste BC emission factors (EFs) were measured in the laboratory to develop regional EFs based on the waste composition characteristics of different areas of the world. The results demonstrate that BC emissions from open burning of waste have a significant climate impact, contributing 4.2 % of global CO_2Eq emissions. Global BC CO_2Eq emissions from burning waste are approximately 3.5 times larger compared to methane (CH_4) CO_2Eq emissions arising from the decomposition of equivalent amounts of combustible biodegradable waste disposed at dumpsites. Action to reduce open burning of waste would have a significant and immediate benefit to improving air quality and reducing climate change.

KEYWORDS:

Open burning of waste, global estimates of black carbon emissions, air pollution, municipal solid waste and climate change.

REFERENCE:

Reyna-Bensusan, N., Wilson, D. C. & Smith, S. R. 2018. The global impact of uncontrolled burning of waste. *6th International Conference on Sustainable Solid Waste Management.* Naxos Island, Greece.

APPENDIX A3. Household Questionnaires

A3.1 Household Questionnaire for Huejutla translated to English

SOLID WASTE MANAGEMENT SURVEY HUEJUTLA 2015

HOUSEHOLDS QUESTIONAIRE

NUMBER OF QUESTIONAIRE I_____I

TOWN: _____

NEIGHBOURHOOD: _____

ZONE (see map): _____

ADDRESS (Street name, exterior number, interior number): _____

_____

MARK APPROXIMATE LOCATION OF THE HOUSE IN THE ATTACHED MAP, INDICATING THE NUMBER OF THE SURVEY

NUMBER OF VISITS OF THE INTERVIEWER	1	2	
DATE	I___I___I I___I___I DAY MONTH	I___I___I I___I___I DAY MONTH	**2015**
NAME OF THE INTERVIEWER			
STARTING TIME	I___I___:___I___I	I___I___:___I___I	
FINIDHING TIME	I___I___:___I___I	I___I___:___I___I	
RESULT*	I___I___I	I___I___I	

* Code for Results

01	Finished interview
02	Incomplete (Write down observations below)
03	Inadequate informant
04	Denied to provide information

OBSERVATIONS

_____

_____

_____

_____

THE INFORMATION THAT YOU PROVIDE IS ANONYMOUS AND WILL ONLY BE USED WITH STATISTICAL PURPOSES

	FOR EACH PERSON IN THE LIST			
	IDENTIFICATION			**AGE**
	Please, can you tell me the age and gender of each person living in this house? Don't forget to include babies and the elderly. Total number of people in household: |____|____|			Less than 1 year 00 97 or older..... 97 NR 999
	NOMBRE	**Male**	**Female**	**AGE**
01	Person 1			|____|____|
02	Person 2			|____|____|
03	Person 3			|____|____|
04				|____|____|
05				|____|____|
06				|____|____|
07				|____|____|
08				|____|____|
09				|____|____|
10				|____|____|
11				|____|____|
12				|____|____|
13				|____|____|
14				|____|____|
15				|____|____|
16				|____|____|
17				|____|____|

"Good morning (afternoon/evening). My name is _____.
As part of a collaboration project between the Imperial College in London, the National Autonomous University in Mexico and with the approval of the municipal authorities in Huejutla, I am carrying out surveys to understand different characteristics of the management of waste in the area. For this reason, we would like to ask you some questions about this topic.

THE INFORMATION THAT YOU PROVIDE IS ANONYMOUS AND WILL ONLY BE USED WITH STATISTICAL PURPOSES"

1. ¿Do you have any pets or farm animals at home?	YES.....1 NO 2	 → 6
2. ¿What type of animals?	Pets.....1 Farm animals. .....2 Both 3	 → 4
3. Type and quantity of pets **(READ ALL THE OPTIONS AND MARK THE AFFIRMATIVE ANSWERS AND SPECIFY QUANTITY)**	 a) Dogs .....|___|___| b) Cats .....|___|___| d) Others _____ .....|___|___| (Specify)	
4. Type of farm animals and quantity **(READ ALL THE OPTIONS AND MARK THE AFFIRMATIVE ANSWERS AND SPECIFY QUANTITY)**	a) Chicken .....|___|___| b) Pigs .....|___|___| c) Cows .....|___|___| d) Sheep .....|___|___| e) Others_____ .....|___|___| (Specify)	
5. Do you feed these animals with organic residues generated in the household?	YES.....1 NO 2	
6. Do you have access to a waste collection service?	 YES.....1 NO 2	
7. What type of service is it? **(LEA TODAS LAS OPCIONES HASTA OBTENER** **UNA RESPUESTA AFIRMATIVA)**	Truck.....1 Nearby waste bin .....2 Other _____.....3 (Specify) Doesn't know 8	
8. How frequently does waste gets collected?	Every day.....1 More than twice a week .....2 Twice a week .....3 Once a week .....4 Twice a month .....5 Once a month.....6 Does not know 8	
9. How much do you pay for this service	Nothing .....1 Tip.....2 Quantity per month..... 3 $|___|___|___| Doesn't know.....8	
10. Does someone independent from the municipality come to pick waste or certain materials?	YES.....1 NO .....2 Doesn't know.....8	 → 13 → 13
11. How frequently does this person come?	More than once a week.....1 Once a week .....2 Less than once a week .....3 Doesn't know 8	

12. What type of waste does he/she take?	Everything.....1 Organic.....2 Recyclables (plastic, glass, metals).....3 Other.....4 Doesn't know.....8	
13. Do you separate waste at home	YES.....1 NO.....2 Doesn't know.....8	→ 15
14. What type of waste do you separate **(READ ALL THE OPTIONS AND MARK THE AFFIRMATIVE ANSWERS AND SPECIFY QUANTITY)**	**YES NO** a) Organic 1 2 b) Glass 1 2 c) Plastic 1 2 d) Cardboard and/or paper 1 2 e) Aluminium 1 2 f) Other 1 2 e) Does not know 8	
15 Do you know if people burn waste in this neighbourhood?	YES.....1 NO.....2 Does not know.....8 NR.....9	→ 18 → 18 → 18
16. How frequently does this happen	Daily.....1 Several times a week.....2 Once a week or less.....3	
17. Where do they usually burn waste? **(READ ALL THE OPTIONS AND MARK THE AFFIRMATIVE ANSWERS AND SPECIFY QUANTITY)**	**YES NO Doesn't Know** a) In houses 1 2 8 b) In the municipal dumpsite 1 2 8 c) Illegal dumpsite/empty land 1 2 8 d) In the street 1 2 8 e) Other 1 2 8	
18. What do you do with waste if the collection service fails?	Save it until they collect it.....1 Leave it in the street.....2 Take it to the dumpsite.....3 Take it to a designated area.....4 They always come.....5 Burn it.....6 Doesn't know.....8	
19. Is waste commonly burned in this household?	YES.....1 NO.....2 Doesn't know.....8 NR.....9	→ 23 → 23 → 23
20. How frequently does this happen?	Every day.....1 Several times a week.....2 Once a week or less.....3 Doesn't know.....8	
21. Do you burn all waste or just certain materials	All of it.....1 Certain materials.....2 Doesn't know.....8	→ 23
22. If its just certain materials, which are they?	**YES NO Doesn't know**	

	a) Garden waste 1 2 8 b) Animal waste 1 2 8 c) Non recyclables 1 2 8 d) Others_____ 1 2 8 **(Specify)**	
23. Does anyone in the household smoke?	YES .....1 NO ..... 2 Does not know .....8 NR.....	
24. What is the method used for cooking in the household? **(READ ALL THE OPTIONS AND MARK ALL OF THE AFFIRMATIVE ANSWERS)**	**YES NO** a) Gas stove 1 2 b) Electric stove 1 2 c) Wood stove outside the house 1 2 d) Wood stove inside the house 1 2 e) Doesn't know 8	
25. How often do babies/kids that live in this house get respiratory diseases?	Once a year or less.....1 Two to three times a year .....2 More than 3 times per year.....3 Does not know.....8	
26. How often do the adults that live in this house get respiratory diseases?	Once a year or less.....1 Two to three times a year .....2 More than 3 times per year.....3 Does not know.....8	
27. How often do the elderly that live in this get house respiratory diseases?	Once a year or less.....1 Two to three times a year .....2 More than 3 times per year.....3 Does not know.....8	
28. Does this household have a... **(LEA TODAS LAS OPCIONES Y MARQUE TODAS LAS QUE SEAN AFIRMATIVAS)**	**YES NO** a) Fridge? 1 2 b) Washing machine? 1 2 c) Boiler? 1 2 d) Microwave oven? 1 2 e) TV? 1 2 f) Phone? 1 2 g) Cell Phone? 1 2 h) Computer? 1 2	
29. **FINALLY**, would you be willing to collaborate in a second stage of this project, where you would have to save your waste for one of our members to collect, twice a week, for two weeks?	YES .....1 NO ..... 2 At what time? _____	

A3.2 Household Questionnaire for Juchitán translated to English

SOLID WASTE MANAGEMENT SURVEY JUCHITÁN 2016

HOUSEHOLDS QUESTIONAIRE

NUMBER OF QUESTIONAIRE I_____I

TOWN: _____

NEIGHBOURHOOD: _____

ZONE (see map): _____

ADDRESS (Street name, exterior number, interior number): _____

_____

MARK APPROXIMATE LOCATION OF THE HOUSE IN THE ATTACHED MAP, INDICATING THE NUMBER OF THE SURVEY

NUMBER OF VISITS OF THE INTERVIEWER	1	2	
DATE	I___I___I I___I___I DAY MONTH	I___I___I I___I___I DAY MONTH	**2015**
NAME OF THE INTERVIEWER			
STARTING TIME	I___I___:___I___I	I___I___:___I___I	
FINIDHING TIME	I___I___:___I___I	I___I___:___I___I	
RESULT*	I___I___I	I___I___I	

* Code for Results

01 Finished interview
02 Incomplete (Write down observations below)
03 Inadequate informant
04 Denied to provide information

OBSERVATIONS

_____
_____
_____
_____

THE INFORMATION THAT YOU PROVIDE IS ANONYMOUS AND WILL ONLY BE USED WITH STATISTICAL PURPOSES

	11.1.1.1. FOR EACH PERSON IN THE LIST			
	IDENTIFICATION			**AGE**
	Please, can you tell me the age and gender of each person living in this house? Don't forget to include babies and the elderly. Total number of people in household: |____|____|			Less than 1 year 00 97 or older..... 97 NR 999
	NOMBRE	**Male**	**Female**	**AGE**
01	Person 1			|____|____|
02	Person 2			|____|____|
03	Person 3			|____|____|
04				|____|____|
05				|____|____|
06				|____|____|
07				|____|____|
08				|____|____|
09				|____|____|
10				|____|____|
11				|____|____|
12				|____|____|
13				|____|____|
14				|____|____|
15				|____|____|
16				|____|____|
17				|____|____|

"Good morning (afternoon/evening). My name is _____.
As part of a collaboration project between the Imperial College in London, the National Autonomous University in Mexico and with the approval of the municipal authorities in Huejutla, I am carrying out surveys to understand different characteristics of the management of waste in the area. For this reason, we would like to ask you some questions about this topic.

THE INFORMATION THAT YOU PROVIDE IS ANONYMOUS AND WILL ONLY BE USED WITH STATISTICAL PURPOSES"

11.1.1.2.
11.1.1.3.

11.1.1.4.
11.1.1.5.
11.1.1.6.
11.1.1.7.
11.1.1.8.

1. ¿Do you have any pets or farm animals at home?	YES .....1 NO 2	 → 6
2. ¿What type of animals?	Pets .....1 Farm animals. .....2 Both 3	 → 4
3. Type and quantity of pets **(READ ALL THE OPTIONS AND MARK THE AFFIRMATIVE ANSWERS AND SPECIFY QUANTITY)**	a) Dogs .....|___|___| b) Cats .....|___|___| d) Others _____ .....|___|___| (Specify)	
4. Type of farm animals and quantity **(READ ALL THE OPTIONS AND MARK THE AFFIRMATIVE ANSWERS AND SPECIFY QUANTITY)**	a) Chicken .....|___|___| b) Pigs .....|___|___| c) Cows .....|___|___| d) Sheep .....|___|___| e) Others_____ .....|___|___| (Specify)	
5. Do you feed these animals with organic residues generated in the household?	YES .....1 NO 2	
6. Do you have access to a waste collection service?	YES .....1 NO 2	
7. What type of service is it? **(LEA TODAS LAS OPCIONES HASTA OBTENER UNA RESPUESTA AFIRMATIVA)**	Truck.....1 Nearby waste bin .....2 Other _____.....3 (Specify) Doesn't know 8	
8. How frequently does waste gets collected?	Every day .....1 More than twice a week.....2 Twice a week .....3 Once a week .....4 Twice a month .....5 Once a month.....6 Doesn't know.....8	
9. How much do you pay for this service	Nothing .....1 Tip.....2 Quantity per month ..... 3 $|___|___|___| Doesn't know.....8	
10. Does someone independent from the municipality come to pick waste or certain materials?	YES .....1 NO .....2 Doesn't know.....8	 → 13 → 13
11. How frequently does this person come?	More than once a week .....1 Once a week .....2 Less than once a week .....3 Doesn't know 8	

12. What type of waste does he/she take?	Everything .....1 Organic .....2 Recyclables (plastic, glass, metals) .....3 Other .....4 Doesn't know 8	
13. Do you separate waste at home	YES .....1 NO ..... 2 Doesn't know 8	 → 15
14. What type of waste do you separate **(READ ALL THE OPTIONS AND MARK THE AFFIRMATIVE ANSWERS AND SPECIFY QUANTITY)**	**YES NO** a) Organic 1 2 b) Glass 1 2 c) Plastic 1 2 d) Cardboard and/or paper 1 2 e) Aluminium 1 2 f) Other 1 2 e) Doesn't know 8	
15 Do you know if people burn waste in this neighbourhood?	YES .....1 NO ..... 2 Does not know .....8 NR 4	 → 18 → 18 → 18
16. How frequently does this happen	Daily .....1 Several times a week .....2 Once a week or less 3	
17. Where do they usually burn waste? **(READ ALL THE OPTIONS AND MARK THE AFFIRMATIVE ANSWERS AND SPECIFY QUANTITY)**	**YES NO Doesn't Know** a) In houses 1 2 8 b) In the municipal dumpsite 1 2 8 c) Illegal dumpsite/empty land 1 2 8 d) In the street 1 2 8 e) Other 1 2 8	
18. What do you do with waste if the collection service fails?	Save it until they collect it .....1 Leave it in the street .....2 Take it to the dumpsite .....3 Take it to a designated area .....4 They always come .....5 Burn it .....6 Doesn't know 8	
19. Is waste commonly burned in this household?	YES .....1 NO ..... 2 Doesn't know .....8 NR 9	 → 23 → 23 → 23
20. How frequently does this happen?	Three times a week or more .....1 Two times a week .....2 Once a week or less .....3 Doesn't know 8	
21. Do you burn all waste or just certain materials	All of it .....1 Certain materials .....2 Doesn't know 8	→ 23

22. If its just certain materials, which are they?	**YES** **NO** **Doesn't know** a) Garden waste 1 2 8 b) Animal waste 1 2 8 c) Non recyclables 1 2 8 d) Others_____ 1 2 8 **(Specify)**	
23. Does anyone in the household smoke?	YES .....1 NO ..... 2 Doesn't know.....8 NR 9	
24. What is the method used for cooking in the household? **(READ ALL THE OPTIONS AND MARK ALL OF THE AFFIRMATIVE ANSWERS)**	**YES** **NO** a) Gas stove 1 2 b) Electric stove 1 2 c) Wood stove outside the house 1 2 d) Wood stove inside the house 1 2 e) Doesn't know 8	
25. How often do babies/kids that live in this house get respiratory diseases?	Once a year or less.....1 Two to three times a year .....2 More than 3 times per year.....3 Doesn't know.....8	
26. How often do the adults that live in this house get respiratory diseases?	Once a year or less.....1 Two to three times a year .....2 More than 3 times per year.....3 Doesn't know.....8	
27. How often do the elderly that live in this get house respiratory diseases?	Very rarely .....1 Two to three times a year .....2 Very frequently .....3 Doesn't know.....8	
28. Does this household have a... **(LEA TODAS LAS OPCIONES Y MARQUE TODAS LAS QUE SEAN AFIRMATIVAS)**	**YES** **NO** a) Fridge? 1 2 b) Washing machine? 1 2 c) Boiler? 1 2 d) Microwave oven? 1 2 e) TV? 1 2 f) Phone? 1 2 g) Cell Phone? 1 2 h) Computer? 1 2	
29. **FINALLY**, would you be willing to collaborate in a second stage of this project, where you would have to save your waste for one of our members to collect, twice a week, for two weeks?	YES .....1 NO ..... 2 At what time? _____	

THANK YOU FOR YOUR TIME

APPENDIX A4. Complete descriptive statistics of combustion patterns for single waste samples

		Sample Before	Sample Burned	Fraction Burned (%)	Emissions Captured	Emissions Captured/Sample Burned (%)	Total Combustible Mass	Total Combustible Mass (%)	Remaining Volatile mass	Remaining Volatile Fraction (%)	ATN
Paper and cardboard n=23 ATN>500, 0											
Mean		3.399	2.247	65	0.0345	1.6	3.076	90.5	0.830	24.4	62
Median		3.008	2.089	69	0.0294	1.4	2.720	90.4	0.730	24.3	44
Std. Deviation		1.031	0.973	12	0.0182	0.7	0.934	90.6	0.352	34.1	77
Range		3.003	3.863	45	0.0683	2.9	2.720	90.6	1.150	38.3	383
Minimum		3.002	1.152	38	0.0119	0.6	2.720	90.6	0.420	14.0	30
Maximum		6.005	5.015	84	0.0802	3.4	5.440	90.6	1.570	26.1	413
95% Confidence Limits	Lower	2.953	1.826	60	0.0266	1.3	2.672	90.5	0.678	23.0	29
	Upper	3.845	2.668	70	0.0424	1.9	3.479	90.5	0.982	25.6	96
Garden waste n=15 ATN>500, 2											
Mean		1.536	0.796	57	0.0068	0.9	1.439	93.7	0.639	41.6	264
Median		1.002	0.664	60	0.0057	0.8	0.940	93.8	0.340	33.9	263
Std. Deviation		0.918	0.465	18	0.0038	0.6	0.856	93.3	0.676	73.6	122
Range		2.009	1.910	60	0.0135	2.2	1.870	93.1	2.000	99.6	368
Minimum		1.000	0.452	24	0.0013	0.3	0.940	94.0	0.100	10.0	133
Maximum		3.009	2.362	84	0.0148	2.4	2.810	93.4	2.100	69.8	500
95% Confidence Limits	Lower	1.028	0.539	47	0.0047	0.6	0.965	93.9	0.265	25.8	196
	Upper	2.044	1.054	67	0.0089	1.2	1.913	93.6	1.014	49.6	332
Textiles n=14 ATN>500, 5											
Mean		0.209	0.107	51	0.0010	1.1	0.209	99.7	0.102	48.8	363
Median		0.101	0.057	51	0.0008	1.1	0.100	99.0	0.050	49.5	323
Std. Deviation		0.255	0.130	9	0.0009	0.4	0.255	100.0	0.125	49.2	114
Range		0.900	0.468	33	0.0030	1.6	0.900	100.0	0.460	51.1	312
Minimum		0.100	0.030	30	0.0002	0.5	0.100	100.0	0.040	40.0	188
Maximum		1.000	0.498	63	0.0032	2.1	1.000	100.0	0.500	50.0	500
95% Confidence Limits	Lower	0.062	0.032	46	0.0005	0.9	0.061	98.8	0.030	47.8	297
	Upper	0.356	0.182	56	0.0015	1.4	0.356	99.8	0.175	49.0	429
LDPE n=17 ATN>500, 0											
Mean		2.648	0.647	24	0.0022	0.3	2.232	84.3	1.584	59.8	46
Median		3.000	0.743	25	0.0021	0.4	2.530	84.3	1.720	57.3	24
Std. Deviation		0.786	0.274	6	0.0014	0.1	0.663	84.4	0.475	60.5	67
Range		2.005	0.879	20	0.0044	0.4	1.690	84.3	1.460	72.8	289
Minimum		1.001	0.167	14	0.0003	0.1	0.840	83.9	0.640	63.9	5
Maximum		3.006	1.046	35	0.0047	0.5	2.530	84.2	2.100	69.9	293
95% Confidence Limits	Lower	2.244	0.506	21	0.0015	0.3	1.892	84.3	1.340	59.7	11
	Upper	3.052	0.787	27	0.0029	0.4	2.573	84.3	1.828	59.9	81

Complete descriptive statistics of combustion patterns for single waste samples (Continued)

		Sample Before	Sample Burned	Fraction Burned (%)	Emissions Captured	Emissions Captured/Sample Burned (%)	Total Combustible Mass	Total Combustible Mass (%)	Remaining Volatile mass	Remaining Volatile Fraction (%)	ATN
HDPE n=20 ATN>500, 4											
Mean		3.577	1.467	40	0.0053	0.6	3.572	99.9	2.106	58.9	147
Median		4.998	1.287	28	0.0041	0.3	4.990	99.8	1.675	33.5	48
Std. Deviation		1.770	1.235	28	0.0052	0.5	1.769	99.9	1.596	90.2	193
Range		4.502	4.144	77	0.0217	2.2	4.500	100.0	4.000	88.8	491
Minimum		0.501	0.142	15	0.0007	0.1	0.500	99.8	0.240	47.9	9
Maximum		5.003	4.286	92	0.0224	2.3	5.000	99.9	4.240	84.7	500
95% Confidence Interval of the Difference	Lower	2.748	0.889	27	0.0029	0.3	2.744	99.8	1.359	49.5	56
	Upper	4.405	2.045	53	0.0077	0.8	4.400	99.9	2.853	64.8	237
PET n=17 ATN>500, 9											
Mean		3.944	0.263	10	0.0024	1.0	3.927	99.6	3.661	92.8	383
Median		5.001	0.230	5	0.0020	1.0	4.980	99.6	4.750	95.0	500
Std. Deviation		1.598	0.177	9	0.0018	0.3	1.591	99.6	1.648	103.1	148
Range		4.000	0.709	24	0.0069	1.2	3.980	99.5	4.170	104.3	407
Minimum		1.003	0.068	1	0.0009	0.3	1.000	99.7	0.740	73.8	93
Maximum		5.003	0.777	26	0.0078	1.5	4.980	99.5	4.910	98.1	500
95% Confidence Limits	Lower	3.122	0.172	5	0.0015	0.8	3.109	99.6	2.814	90.1	306
	Upper	4.766	0.354	15	0.0033	1.1	4.745	99.6	4.508	94.6	459
Polystyrene n=14 ATN>500, 4											
Mean		0.157	0.031	21	0.0012	3.0	0.157	100.0	0.125	79.5	328
Median		0.100	0.025	22	0.0006	2.1	0.100	100.0	0.080	80.0	346
Std. Deviation		0.122	0.020	8	0.0015	2.2	0.122	100.0	0.108	88.3	162
Range		0.400	0.068	27	0.0050	6.0	0.400	100.0	0.390	97.5	397
Minimum		0.099	0.010	10	0.0001	0.5	0.100	101.0	0.060	60.6	103
Maximum		0.499	0.078	37	0.0051	6.5	0.500	100.2	0.450	90.2	500
95% Confidence Limits	Lower	0.087	0.019	17	0.0003	1.7	0.087	99.9	0.063	72.3	234
	Upper	0.228	0.043	26	0.0020	4.2	0.228	100.0	0.187	82.2	421

ATN>500 n = number of filters marked as "Too Dark" by OT21

APPENDIX A5. Complete descriptive statistics of combustion patterns for mixed waste samples (g unless otherwise stated)

		Sample Before	Sample Burned	Fraction Burned (%)	Emissions Captured	Emissions Captured/Sample Burned (%)	Total Combustible Mass	Total Combustible Mass (%)	Remaining Volatile mass	Remaining Volatile Fraction (%)	ATN
National n=11 ATN>500, 6											
Mean		0.503	0.345	69	0.0033	0.94	0.472	94	0.125	25	400
Median		0.503	0.346	68	0.0030	0.94	0.470	93	0.130	26	500
Std. Deviation		0.003	0.024	5	0.0012	0.33	0.004	159	0.022	866	135
Range		0.008	0.069	13	0.0037	1.09	0.010	125	0.060	750	379
Minimum		0.499	0.316	63	0.0013	0.40	0.470	94	0.090	18	121
Maximum		0.507	0.385	76	0.0050	1.49	0.480	95	0.150	30	500
95% Confidence Limits	Lower	0.501	0.329	65	0.0024	0.72	0.469	94	0.111	22	309
	Upper	0.505	0.360	72	0.0041	1.16	0.475	94	0.140	28	490
Huejutla n=13 ATN>500, 2											
Mean		0.625	0.365	58	0.0022	0.62	0.587	94	0.221	35	367
Median		0.513	0.308	58	0.0019	0.58	0.480	94	0.190	37	387
Std. Deviation		0.215	0.144	10	0.0012	0.23	0.203	95	0.086	40	115
Range		0.505	0.463	46	0.0040	0.85	0.480	95	0.300	59	421
Minimum		0.502	0.171	33	0.0009	0.32	0.470	94	0.070	14	79
Maximum		1.007	0.634	79	0.0049	1.17	0.950	94	0.370	37	500
95% Confidence Limits	Lower	0.495	0.278	52	0.0015	0.48	0.464	94	0.169	34	298
	Upper	0.754	0.452	64	0.0029	0.76	0.710	94	0.273	36	437
Juchitán n=16 ATN>500, 3											
Mean		0.587	0.355	61	0.0020	0.52	0.551	94	0.195	33	300
Median		0.493	0.313	62	0.0016	0.49	0.460	93	0.175	35	244
Std. Deviation		0.205	0.130	9	0.0018	0.24	0.193	94	0.086	42	166
Range		0.516	0.395	33	0.0063	0.90	0.480	93	0.310	60	420
Minimum		0.487	0.229	46	0.0006	0.21	0.460	94	0.070	14	80
Maximum		1.003	0.624	78	0.0069	1.11	0.940	94	0.380	38	500
95% Confidence Limits	Lower	0.478	0.286	56	0.0011	0.39	0.448	94	0.149	31	211
	Upper	0.697	0.424	65	0.0030	0.65	0.654	94	0.241	35	388

ATN>500 n = number of filters marked as "Too Dark" by OT21