Waste as a Resource

Hassan El Bari
Cristina Trois *Editors*

Waste Management in Developing Countries

Springer

Waste as a Resource

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The Waste as a Resource series explores state-of-the-art knowledge and innovation in waste management strategies that are focused on approaches and technologies that ensure maximum value recovery from waste through materials recycling and energy production. The series aims to navigate the transition toward a circular economy by presenting techniques and strategies for waste minimization, effective waste diversion from landfills, and most importantly, exploring the possible pathways for the treatment of waste as a resource. The series has a global scope, with a special focus on developing countries and emerging economies, as this will assist in filling the gap in current publications that do not adequately explore valorization technologies that are appropriate for and adaptable in low-income countries or informal contexts.

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Preface

In developing countries, rapid changes in the socioeconomic context have very quickly led to the emergence of production models and consumption patterns that are not very concerned with protecting the environment. The increasing production of waste has led to the multiplication of large wild dumps everywhere around large cities. This solid waste represents an enormous loss of resources in the form of materials and energy. Furthermore, if poorly managed, they can pose many direct and indirect risks to human health and the environment. These risks can be either infectious diseases or contamination of soil, groundwater, and surface water, as well as air pollution due to greenhouse gas emissions.

The money made from recovering waste could offer these nations a significant economic opportunity according to their socioeconomic development. The rural exodus, the expansion of waste sectors, and the shift in household consumption habits are the main causes of the increase in waste. Although most cities have waste collection systems in place, their elimination exposes a management gap because most landfills are uncontrolled and have negative effects on both human health and the environment.

The purpose of this book is to bring together waste experts working in different disciplines to present some of their latest approaches in the area of solid waste management in developing countries. The main objectives of this book are to establish the state of the art of solid waste management in developing countries and outline the impact of poor solid waste management on human health and the environment. Furthermore, the aim is to determine appropriate solid waste management technologies for developing countries by focusing on the role of the informal sector and its integration with the formal economy and describing waste recovery in a circular context. The book also describes how sustainable and integrated waste management could help developing nations reduce greenhouse gas emissions.

The book contains 12 chapters covering all aspects of waste management, including legislation, governance, institutional, social, and technical aspects. It has a multidisciplinary nature. Chapter 1 covers waste generation, characteristics, and collection in developing countries. Chapters 2 and 4 present landfill disposal and leachate management in developing countries. Chapters 3 and 5 concern the relationship between waste management and climate change. Chapters 6, 7, and 8 examine the legislative-institutional, informal waste sector, and social aspects, respectively. Chapter 9 describes the urban mining and circular economy. Finally, because the organic waste fraction is typically higher in developing nations, the book includes three chapters (Chaps. 10, 11, and 12) specifically devoted to composting, biochemical conversion, and thermochemical conversion of organic waste, respectively.

The book is a useful resource and practical manual for a broad readership, including waste management professionals, policymakers, municipal authorities, industry practitioners, researchers, scientists, and master's, PhD, and undergraduate students.

We appreciate the time and work put forward by each author of this book to write their respective chapters.

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Chapter 1
Waste Generation, Characteristics, and Collection in Developing Countries

Fadoua Karouach and Hassan El Bari

1.1 Introduction

The issue of waste generation, collection, and disposal in DC started with the expansion of cities and the rise in population. In the next 35 years, the urban population of the world is expected to double to more than five billion with 90% taking place in DC (Ahmed and Ali 2004). The DC contribute about 56% of the world's total solid waste (Alam and Qiao 2019). WM consumes a significant portion of city budgets. In DC with limited resources and means, the sector faces serious problems. Despite the efforts made by the authorities and non-governmental and private organizations in the WM sector, the situation is still not fully improved.

WM refers to all operations and means implemented to limit, recycle, recover, or eliminate waste usually produced by human activity (Maamar and Kechout 2016). It means all operations of prevention, pre-collection, collection, transportation, sorting, reuse, disposal, and/or treatment, in order to minimize their effects on human health and on the environment.

The main challenge for the WM sector is adapting to this growing urbanization rate and achieving a balance between quality of service and cost-effectiveness and also to explore challenges, limitations, and constraints of existing experiences in WM at developing countries. An integrated solid wastes management system is required according to each country specification in terms of socioeconomic and technological aspects.

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Partnerships between the public and private sectors have the potential to increase the effectiveness of DC's municipal WM sector as a whole and generate new job opportunities. Because it incorporates the expertise of companies and public entities, this hybrid public-private approach is more effective.

1.2 Municipal Waste Production and Characterization

1.2.1 Waste Generation

1.2.1.1 Role of Waste Data

One of the WM keys is the availability of reliable and updated data. However, in many African cities, such data is partially or totally unavailable. Readily available data is often unreliable and not updated. Furthermore, in most cases no information is available as to where and how the data had been collected. Figure 1.1 shows the municipal waste data required for a suitable collection system design.

Knowing the reasons for errors in these data may be the first step towards improving this sector. For example, it is essential to have reliable data on waste density before starting to plan a waste collection system. Thus, it is important to focus on the selection of the best suitable WM option using the results obtained from reliable data which will be collected. The project design will be considered carefully regarding the need for the data and the required reliability of the final figures.

Figure 1.2 shows the waste data needed to be collected and analyzed including the following:

1. Data concerning the structure of area study population, the generated waste, and facilities cartography distributions.
2. Data concerning the available waste collection methods.
3. Data concerning the municipal waste composition and characteristics, using laboratory results.
4. Data concerning the waste informal sector structure using survey results.

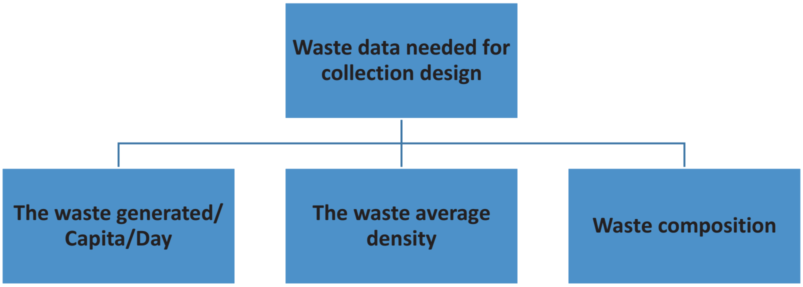

Fig. 1.1 Data on municipal waste required for a suitable collection system design

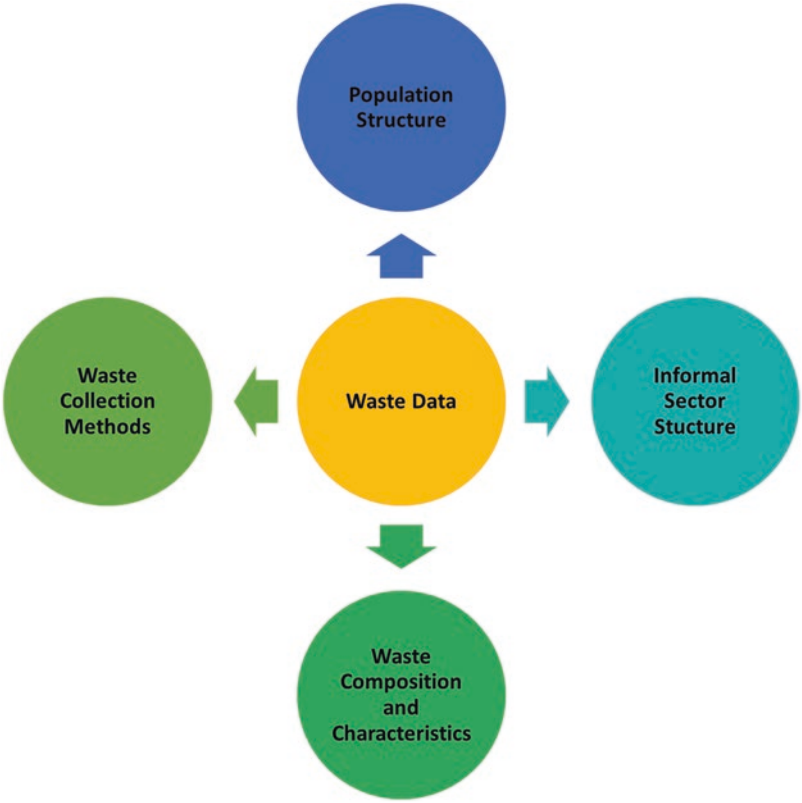

Fig. 1.2 Waste data to collect and to analysis

All these data aspects will be used to increase the efficiency of some waste indicators as shown in Fig. 1.3:

– The per capita waste generation rate
– The average waste density
– The collection rate, by optimizing the used collection method
– The recycling rate by choosing the best recycling methods.

This data will be collected. The accurate knowing of these indicators and the waste composition will be the key to design a solid waste collection system and to choose the best options of treatment and recovery.

The collected data related to the informal sector will be a significant tool for selecting the appropriate informal sector ways of integration. This suitable integration will contribute to the increasing of cited indicators. Additionally, this data will be a useful tool for planning, treating, and recovering municipal solid waste.

The availability of these data will allow a positive impact in terms of the following:

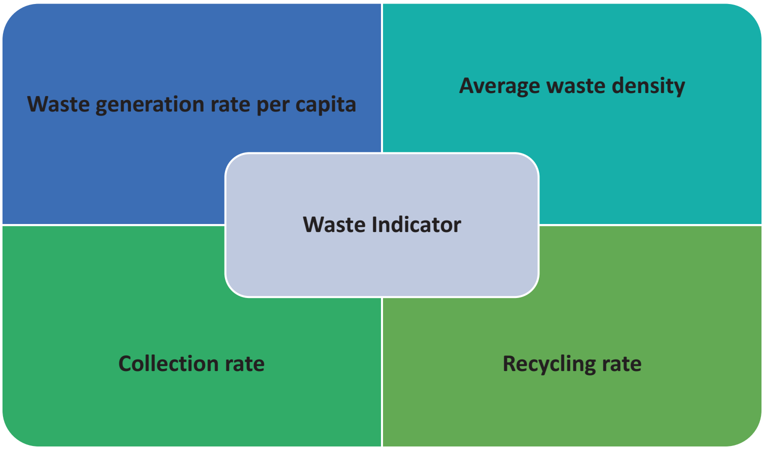

Fig. 1.3 Waste indicators obtained from reliable waste data

- *Environmental concerns:* All obtained data, needed for waste management, will be used to find an appropriate waste collection, treatment, and recovery option. The availability of collected data and knowledge management methods used by end-users can provide efficient WM in both cities. As a result, we will obtain, on the one hand, the minimization of air, water, and land pollution and, on the other hand, the climate change mitigation.
- *Economical concerns:* The organic fraction of municipal waste (OFMW) could be converted to clean and renewable energy. This energetic recovery will contribute to greenhouse gas reduction and consequently to the amount of deposed landfill decreases. The recycling rate improvement will also contribute to the creation of many new jobs.
- *Social concerns:* The informal sector workers will be more organized by integrating the formal sector suitably while increasing their incomes, which will contribute to poverty reduction.

1.2.1.2 Importance of Waste Amounts Quantification

As previously mentioned, planning, design, and implementation of waste management depend on having a well understanding of the amount of waste generated, since it allows to determine adequately the size and physical criteria of waste storage from households, industries, and institutions for efficient waste management. Additionally, accurate knowledge of waste amount avoids the possibility of under or over designing collection facilities, services, and disposal sites, leading to efficiency gains (Mbande 2003).

Waste quantities could be determined theoretically by multiplying the population by the average amount of waste produced daily per person, or depending on the number of journeys to the disposal sites multiplied by the volume of the collecting truck. Experimentally, waste generation could be estimated using a weighbridge at the waste disposal sites which is recording the load of each truck, or by counting the bags that arrive at the disposal sites.

1.2.2 Waste Characterization and Composition

For all actions involving the management of municipal solid waste (MSW), suitable infrastructure, services, and upgrades are necessary. Due to the ongoing and uncontrolled growth of city areas, this has become more and more expensive and complicated. The difficulty in providing the level of public service required in urban areas is associated to the weak financial situation (Sharholy 2008).

Additionally, the composition and volume of MSW produced serve as the foundation for planning, designing, and operating the management system. It has been shown that MSW's physical and chemical properties vary with population density; these variations reflect the impact of urbanization and development.

Direct sampling, market product analysis, and waste product analysis are the three methods that are frequently used to characterize waste. For vast geographic areas, waste product analysis and market product analysis are appropriate, although direct sampling is appropriate in the absence of site-specific data. One of the well-established methods for waste characterization that has been widely used in the literature is the international ASTM D5231-92 standard method (Al-Jarallah and Aleisa 2014).

Along with the significance of waste characterization, the importance of its composition cannot be understated. To assess the waste's potential for polluting the environment and people as well as to guide the selection of an appropriate treatment, it is crucial to understand its chemical composition. The pollutants come mainly from organic, mineral, and metallic matter. Mineral and metallic elements are generated by fractions such as glass, unclassified incombustibles, plastics, and metals. They can also come from dyes used in textiles or packaging (Aloueimine 2006).

For instance, the significant use of vegetables for diverse purposes in some countries leads to a high organic content in the MSW. Table.1.1 shows the difference in waste characteristics between some countries. We can clearly see that DC generates more organic fraction than developed countries. In addition, the waste organic fraction increases proportionally with the decrease in countries income. The amount of MSW produced is influenced by several variables, including seasons, style of living, food preferences, and commercial activity level. Data on quantity variation and generation can be used to better plan collection and disposal systems.

Due to the fact that the proportional percentage of organic waste in MSW often increases with falling socioeconomic position, rural families generate more organic waste than urban households do. A study conducted by Ozcan et al. (2016) confirmed that the organic waste component in the region with low-income level was found higher in comparison to other regions. The highest organic waste amount was found in the region with the lowest income level, while the lowest rate was found in

Table 1.1 Waste characteristics in DC (Wet weight %)

Composition (%)	Food and vegetables	Paper products	Plastics	Metals	Textile and Woods	Glass and Ceramic	Construction materials	Others	References
Morocco	60–80	7–10	4–7	1	10	1.5	–	4–7	Elhafiane (2012)
Bangladesh	74.5	9.1	3.51	1.91	0.57	0.76	1.3	8.35	Alam and Qiao (2019)
India	40–60	3–6	3–6	1–4	1–3	3–6	–	13	Sharholy (2008)
Ethiopia	67	6	8	1	–	1	–	17	Hirpe and Yeom (2021)
Comoros	50	7	5	4	3	2	6	13	Isihaka Ali et al. (2018)
Kuwait	44.4	14.2	17.7	2.8	–	5.6	–	6	Al-Jarallah and Aleisa (2014)
Malaysia	40	15	15	3	–	4	–	23	Shekdar (2009)
France	30	30	15	6	2	12	–	5	Elhafiane (2012)
Japan	26	46	9	8		7		12	Shekdar (2009)
USA	15–20	20	10	10	4	10	–	31	Abdel-Shafy and Mansour (2018)
South Africa	13	7	6	14	–	4	21	35	Nkosi et al. (2013)

the region with the highest income level. In the same line, a study performed by Suthar and Singh (2014) on household solid waste (HW) generation and composition in different family size and socioeconomic groups in India showed that food/kitchen waste was the major component of the total waste in HWs of all the socioeconomic groups of the society. However, during the conducted research to establish the relationship between waste generation and socioeconomic factors, such as income and population density, it was found that income did not influence the total amount of municipal waste generated (Ojeda-Benitez et al. 2007).

Moreover, the mix of municipal waste is significantly influenced by season. Organic waste generated in the summer is more prevalent than waste made out of cardboard fiber, bottles, wood, metal, and glass in the winter (Al-Jarallah and Aleisa 2014). The study conducted by Ozcan et al. (2016) revealed that the most significant difference in municipal solid waste between the summer and winter periods can be seen in kitchen waste. The proportion of kitchen waste in the summer period decreased according to the winter period. The evaporation of water from solid waste as a result of summer's high temperatures and increased fruit consumption is thought to be the cause of this alteration. Considering the differences in organic waste by income level and seasonal conditions, further changes related to income level were found in the winter period in comparison to the summer period.

In this context, MSW classification studies could be based on two methods: on the different income categories, the classification here divides the groups into low-, middle-, and high-income classes, and on seasonal variations (Abdel-Shafy and Mansour 2018).

1.3 Municipal Waste Transport and Collection

1.3.1 Waste Collection

The collection of waste is one of the greatest difficulties faced by public authorities. These difficulties often result in an accumulation of garbage and the creation of uncontrolled open dumps. Around the world, MSW collection is a crucial and costly public service that typically accounts for 75–80% of the MSW management budget (Huang et al. 2011).

Waste collection includes pre-collection and collection itself. The methods of collection and pre-collection are crucial, and there are few references in the literature which deal in detail with solid waste collection in low- and middle-income countries (Bruno et al. 2019). Note that many low-income cities still have poor collection (less than 50%). Furthermore, it is known that there is correlation between country income level and collection rate level.

Waste collection services may be performed by the formal sector, through either public- or private-sector operators, or by the informal sector through, for example, community-based organizations (CBOs), non-governmental organizations (NGOs), or micro- and small enterprises (MSEs). Collection services provide a primary collection to local neighborhoods on a small scale, or a secondary collection service on a large scale across the city.

Pre-collection of waste refers to all operations of its evacuation from the production to the removal by the collection service. The concept of pre-collection implies all operations that precede the collection operation. The collection is the whole of the operations which consist in the removal of waste from regrouping points to forwarding them towards a place of sorting, regrouping, recovery, treatment, or storage. It consists of the collection and the regrouping of waste for transport (Fig. 1.4). There are two collection methods: (1) door-to-door, in which the collection service ensures a regular passage for waste elimination, and (2) voluntary drop-off, in which the producer transfers waste to a collection point for its transport to a disposal or treatment site. Waste collection is a system that is relatively complex and consists of interactive, interdependent containers and vehicles (Rodrigues et al. 2016).

The choice of vehicles is one of the main problems that confront the collection service. It depends directly on local conditions:

– Type of habitation
– Quantity of waste collected
– Type of collection containers
– Distance to be covered and the nature of the areas to be served

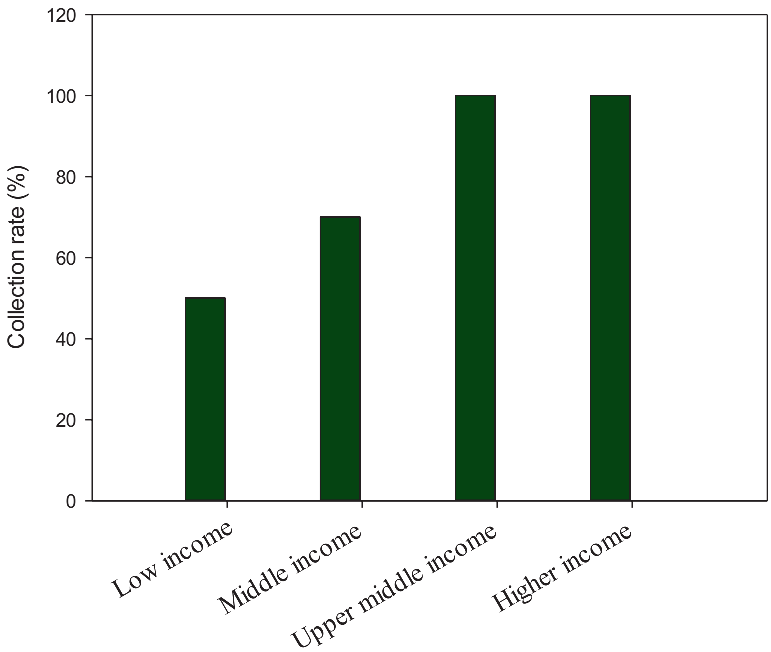

Fig. 1.4 Correlation between income level and collection rate. (Adapted from Wilson et al. 2013)

Likewise, inefficient bin collection systems, poor route planning, lack of information about collection schedules, inadequate infrastructure, bad roads, and the number of trucks used for waste collection all have an impact on collecting practices (Guerrero et al. 2013).

In some cases, it appears necessary, most often for economic reasons, to regroup the waste via transfer station before their transport towards the center of valorization or treatment.

This temporary storage can be done in waste collection centers, regrouping, and transit centers. During this storage stage, it is important to pay attention to the waste conditioning and to take different measures to limit the impact on the environment while waiting for transport and treatment.

In developing countries, waste disposal is often limited to primary collection by associations and NGOs. Secondary collection, which is often the responsibility of municipal technical services, is poorly carried out due to a lack of suitable and operational vehicles and equipment. Another point which makes the waste collection procedure more critical in developing countries is the dominance of manual handling activities which expose the workers to sanitary health threats (Bleck and Wettberg 2012) (Fig. 1.5).

Moreover, the collection system consists of different collection methods which explain how the container works with the labor and the vehicle (Rodrigues et al. 2016)

Manual collection: The worker carries, lifts, and loads waste bins or bags onto the vehicles as part of the manual collection process.

Assisted collection: It is a hybrid of mechanical and manual procedures where the lifting and emptying by the truck is the only mechanization and container displacement close to the vehicle is handled manually.

Semi-automated collection: All steps of semi-automated collection are mechanized, but a worker still needs to be outside the truck to operate the coupling and offer manual assistance during vehicle-container coupling and uncoupling.

Automated collection: During entirely automated collection, which limits workers' direct participation, a single operator within the vehicle cabin controls the interaction between the container and the truck.

Administratively, waste collection is handled in two ways: (i) direct collection, in which the local authority decides to internalize the service by assuming the cost of equipment and its renewal (bins, trucks, etc.) as well as the operation of the

Fig. 1.5 Collection system steps

service (personnel, territory), and (ii) delegated collection, in which the design, implementation, and operation of the service are carried out by outside companies, governed by the public procurement code.

The waste collection rate in African countries is very low and does not exceed 50% in many cities. To understand this problem, Loukil and Rouached (2020) conducted a study to evaluate the urban waste criticality system in African cities, through the development of a waste collection criticality index that allows us to compare waste management collection systems in municipalities, cities, or countries. The methodology employed to develop a criticality index for waste collection involves identifying key factors that impact waste management, including waste generation, inadequate collection services, and deficient urban infrastructure. The criticality index helps to highlight these crucial elements and underscores the challenges in gathering reliable data on waste management in African cities. The results of this study have shown that improving waste management is impossible without improving urban infrastructure and lowering poverty.

Moreover, according to a study conducted by Katusiimeh et al. (2012) comparing the operations and discussing the effectiveness of public and private solid waste collection in the case of Kampala, private sector clients are significantly more satisfied with the services received than their public sector counterparts. However, corruption and a lack of transparency in both the public and private sectors limit the effectiveness of solid waste collection. The issues with providing services in low income countries may be resolved by adapting private sector engagement to socioeconomic realities, intensifying efforts to encourage competition, and implementing procedures to ensure that low-income households have access to inexpensive services. This necessitates a structured public-private partnership in which the public and private sectors can cooperate together.

In another research related to the waste collection, it was reported that one of the essential phases for integrated solid waste management is source-separated collection of household-generated MSW. Unfortunately, the majority of DC does not yet successfully implement source-separated collection at the upstream of the waste management cycle (household level) (Hui et al. 2006).

1.3.2 Waste Transport

A big challenge for growing economies is the creation of an efficient and environmentally appropriate system for managing solid waste. The economics of the entire MSW system are mostly determined by the collection and transportation activities, which account between 80% and 95% of the system's overall budget (Sulemana et al. 2018). Any of these processes' poor design might lead to environmental degradation and higher operational costs. Management services will be significantly impacted by inefficient solid waste transport since it will raise operating costs and, as a result, lower profits. Municipal agencies transport MSW using their own vehicles, while in certain places they use outside contractors. Due to the labor-intensive nature of the process and the extensive usage of trucks, transportation is by far the most significant and expensive component of solid waste management. Unfortunately, many of developing countries struggle with the issue of solid waste transportation.

The difficulties of managing solid waste in more than 22 DC were revealed, and it was discovered that the high cost of waste collection and transport significantly strains local authorities' budgets (Sharholy et al. 2007). Other researchers support this assertion and believe that the lack of financing, resources, consumer resistance to paying, and inappropriate use of economic instruments all make it more difficult to provide adequate solid waste collection and disposal services (Akhtar et al. 2015). In another paper conducted by Sulemana et al. (2018), it was reported that less than 30% of the urban population has access to proper and consistent solid waste collection services, despite the fact that city authorities in most African nations spend between 20% and 50% of their revenue on solid waste management. Moreover, politicians typically prioritize other municipal tasks above solid waste management, which results in a lack of qualified and skilled workers in local government. Additionally, the poor social status conditions that waste employees are involved with discourages them from delivering their best effort. To ensure the safe collection and disposal of solid waste, competence must receive priority over preference, and there must be a significant improvement in this commitment (Alavi et al. 2009).

Poor collection schedules, inappropriate bin collection systems, inadequate infrastructure, and a lack of trucks for waste collection have all been found to have an impact on collection and transportation operations. Operations planning and vehicular routing are crucial components of solid waste collection and transportation. It has been reported according to many studies that planning should consider systematic routing using scientific methods that incorporate cost savings and environmental conservation in order to ensure effective waste collection and transportation (Henry et al. 2006; Hazra and Goel 2009).

There is no systematic or well-organized method of allocating trucks or vehicles for the collection of solid waste in the developing countries. Typically, this is based on practical experience and intuitive approaches, which produce ineffective and expensive practices with detrimental effects on the environment, public health, corporate operations, and other factors (Kanchanabhan et al. 2011).

The majority of DC lack sufficient, reliable infrastructure for transportation. The collection and transportation of solid wastes are negatively impacted by poor roads and the number of vehicles (Henry et al. 2006). Effective collection is impacted by both the character of roads and bad route planning during site physical development. The efficient routing of collection vehicles is one way to guarantee improved performance in solid waste collection (Sulemana et al. 2018). Finally, the operational staff's technical expertise or competence has an impact on WM as well. The technical aspects of the WM system are related to a lack of expertise (Aja et al. 2014). The selection of operational staff should be largely based on technical competence for optimal performance. The staff members should be up to date on current and emerging challenges and technologies (Akhtar et al. 2015).

According to a study that evaluates the effects produced by the waste management process, the plan's major potential effects are related to waste collection and transport. Reducing resource use by recycling and recovering energy through incineration partially offset these effects (Brambilla et al. 2009). The findings highlight the fact that ignoring the effects of collection and transport may lead to a serious underestimation of a waste management system's environmental effects, particularly when it comes to the depletion of fossil fuels, the emission of respiratory inorganics, and climate change. A precise optimization of waste transport is necessary to decrease the environmental impact of waste management systems. The best route planning for trucks is essential for optimizing waste transfer and transportation, which is the most expensive activity (mostly because of consumables and truck depreciation).

Another study, which plans vehicle routes for the collection of municipal solid waste in two different regions of Eastern Finland, shows that both studied levels of optimization – optimization of individual routes and optimization of routing and scheduling for the entire collection period – can result in considerable cost savings compared to the standard practice (Nuortioa et al. 2006).

In this context, Mcleod and Cherrett (2008) discuss how several waste collection options, such as cooperative collaboration between neighboring authorities, alternate weekly collection, and situating vehicle depots closer to waste disposal facilities, can reduce vehicle mileage and save time.

1.4 Municipal WM in DC

1.4.1 Case Studies

Several studies have been conducted to identify limitations and problems related to the WM sector. Most of these studies have analyzed WM systems steps including waste characterization, generation, collection, storage, transportation, treatment, and reuse.

Demographic expansion, urban evolution, and new consumption habits have made improving urban waste management in Morocco an extremely real challenge (Elhafiane 2012). Despite all of the institutional actors' efforts to enhance this sector, and despite important advancements (improved collection, landfill, and recovery rates), there are still significant issues in waste upstream and downstream management. It is necessary to adopt a new, comprehensive strategy that considers municipal solid waste (MSW) as part of the process of strengthening the waste management system.

A successful MSW management in Morocco requires promoting access to the information and its dissemination to the general public, to facilitate its participation in the democratic process and control over activities that directly affect them. The success of MSW management is a mission that must be carried out not only upstream of the management cycle but also among households and waste producers. It is a dynamic upstream/downstream interaction. From an operational point of view, we can nevertheless recognize that measures to be taken to reduce MSW at source are relatively limited (Azaitraoui and Aaziz Ouatmane 2020). Nowadays, only two main achievements initiated by the ministries in charge have been realized: the first one concerns the elimination of plastic bags and their replacement by biodegradable bags (law 77-15), and the second concerns the Ecotax on the use of plastic raw materials (Madani 2015; PNDM). Additionally, feedback from this first phase of implementation of the plastic bag ban law shows that the role of the consumer in the success of such initiatives remains very decisive and deserves special attention, as a key success factor. Another important success factors of MSW are the promotion of sorting, recycling, and recovery of waste, identification of the informal sector, and analysis opportunities for collaboration, integration of small business enterprises in waste management, and strengthening the supply of waste management in rural areas (Fig. 1.6).

In India, the composition and the quantity of MSW generated form the basis on which the management system needs to be planned, designed, and operated. In India, MSW differs greatly with regard to composition and hazardous nature. It

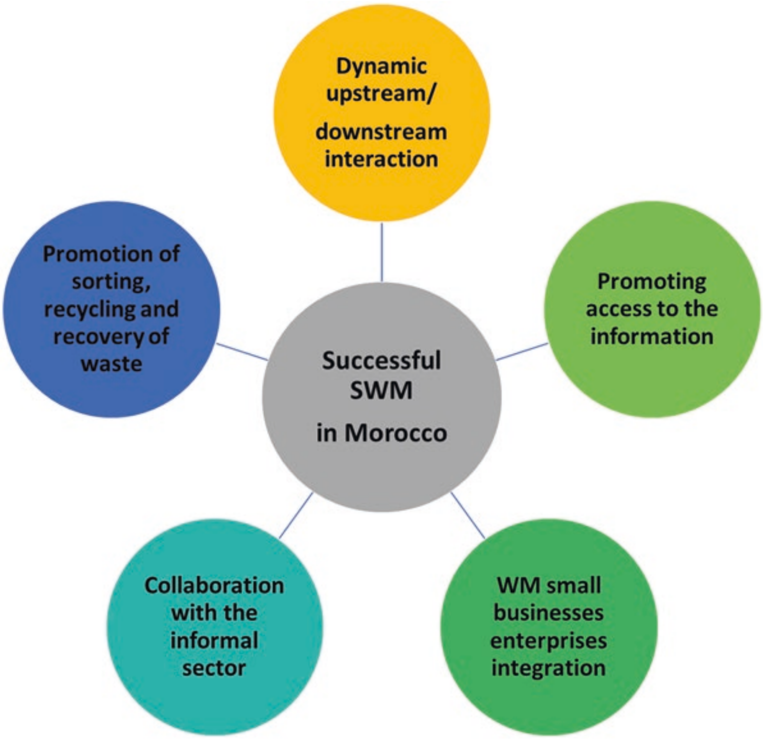

Fig. 1.6 Successful SWM factors in Morocco

generates 90 million tons of solid waste annually. Most cities in India do not use door-to-door collection. There is no practice of sorting MSW at the home level. Nevertheless, some private societies collect recyclable waste in some cities, and the segregated wastes are then mixed together in communal bins and transported to disposal sites (Central pollution control board 2015). It was reported that 75–80% of generated waste is collected and only 27% is processed at the national level (Satpal 2020).

The management of MSW is going through a critical phase, due to the unavailability of suitable facilities to treat and dispose of the larger amount of generated MSW. All aspects of the environment and human health are negatively affected by inappropriate disposal.

The management of MSW requires proper infrastructure, maintenance, and upgrade for all activities. The difficulties in providing the desired level of public service in the urban centers are often attributed to the poor financial status of the managing municipal corporations (Sharholy 2008).

In Bangladesh, studies have been conducted in six major cities, namely, Dhaka, Hittagong, Khulna, Rajshahi, Barisal, and Sylhet (Ahsan et al. 2014). It was reported in this study that authorities are responsible for overall municipal waste management, and they are facing a very complicated situation in managing the generated waste. The major portion of this waste is still unmanaged and released in open spaces, and there are no controlled landfills in the country. According to the study results, the main reasons behind this critical situation are the financial limitations, lack of effective legislation, lack of understanding factors that affect the multiples steps of WM (Bruno et al. 2019), absence of authority commitment, and sufficient updated data on municipal solid WM system (Wilson et al. 2012). An integrated approach for WM has been suggested. The main components of this approach are enhancing the communication between stockholders and integrating available and suitable techniques and technologies to achieve the objectives of an effective WM system. The strategy also involves promoting the adoption of composting units by nongovernmental organizations to produce biofertilizers, and encouraging informal entrepreneurs to establish more recycling ventures (Alam and Qiao 2019).

In South Africa, over 42 million cubic meters of general waste is generated every year. This is a result of the high amount of solid waste stream from mining, pulverized fuel, agricultural, and urban waste activities. The average amount of waste generated per person per day in South Africa is closer to the average produced in developed countries such as the UK and Singapore, 0.7, 0.73, and 0.87 kg/person/day, respectively, which cause a problematic in WM in this country (Karani and Jewasikiewitz 2007). Without a shared knowledge of capabilities and features, it is difficult to characterize and describe waste collection systems, which limits not only the evaluation of operational aspects but also the creation of unique and sustainable waste collection systems. In this context, a paper performed by Rodrigues et al. (2016) presents a taxonomy based on classifying waste collection systems considering the dichotomy of containers and vehicles. This taxonomy provides key elements concerning technologies and applications facilitating the analysis for waste managers and planners. A case study in the Greater Lisbon region of Portugal is presented in this study in order to demonstrate that the taxonomy approach is concise and uncomplicated to use (Rodrigues et al. 2016).

Modern industrial countries have achieved outstanding accomplishments in resource total utilization and solid waste management. In these countries such as Germany, Sweden, Japan, and the USA, solid waste management strategies underwent significant changes between 1960 and 2004. The start of solid waste management with reduction, using less initially and reusing more, and recycling, was one major change. Additionally, composting and incineration of organic waste have supplanted landfill disposal as the primary methods of treating solid waste.

1.4.2 Negative and Positive Impacts of WM Strategies

Waste is both a risk and a resource, but when it is disposed of without precautions, it risks degrading landscapes, polluting the environment, and exposing humans to nuisances and dangers, some of which can be very serious (Maamar and Kechout 2016).

Moreover, poor and out-of-control WM leads to the unregulated growth of slums (Bruno et al. 2019). A few landfills in DC adhere to environmental criteria that are accepted in developed countries. Gas emissions from decomposing waste are a major environmental hazard in these landfills. Waste disposal activities have the potential to pollute groundwater, which serves as a vital source of potable water, as leachate containing various toxic substances infiltrates the groundwater over time (Fadhullah et al., 2022). Furthermore, the primary cause of air pollution is the open-air combustion of waste deposits, which produces enormous amounts of smoke and unpleasant odors. Atmospheric emissions from incineration (heavy metals, VOCs, etc.), the percolation of landfill leachate, and the spreading of components or sludge contribute to the physicochemical and/or microbiological contamination of soils (ELARD 2004).

However, successful usage of the technology approaches and its adaptation to real conditions and the incorporation of unofficial refuse collectors and scavengers could have a positive impact on WM strategies. Additionally, scavengers and informal reuse collectors benefit the community in a clear economic and environmental way; hence, their work should be encouraged and developed (Zohori and Ghani 2017).

1.5 Wastes as a Source of Income

In all the cities of the world, whether in industrialized countries or in developing countries, the quantity of waste is constantly increasing. This exponential growth of waste, a corollary of galloping urbanization, and changing consumption patterns, particularly in developing countries, require a change in practices to limit landfilling and incineration. Thus, it is becoming important to recover waste. This recovery of waste, which is above all a political choice and a choice of society, is not only useful, but also desirable. It consists, in particular, giving a market value to the waste and is carried out by various means leading to savings of raw materials at the same time as it contributes in a direct way to the respect and the safeguard of the environment.

The impact on solid waste management and the choice of such management are directly related to a country's degree of development. Many developed countries use a variety of waste management techniques to create compost and other new products like renewable energy. These nations make investments in waste recycling to support agricultural activities. Decisions made by city authorities regarding the nature, volume, and quality of locally produced waste, as well as other factors, will determine the choice of solid waste management.

The classification and composition investigation play an important part in such waste management, helping to choose and prepare for the most suitable system of transportation, storage, disposal, and recovery of solid waste. Characterization is crucial, in the meantime, to identify any potential environmental effects on society and nature.

In the Northern countries and, in particular, the countries of the European Union, the recovery of the waste knows a clear improvement, even if many constraints remain to be raised. European countries have developed an approach aimed at optimizing the recovery of waste through various processes. In Sweden, recycling has been successful in recent years, with 36% of waste recycled, 14% composted, and, above all, 49% incinerated, the highest rate in the Union after Denmark (54%), far ahead of the European average (22%) (Audrey 2012).

Because nuisances are generated by conventional SWM practices, and in order to protect the environment and the health of the populations in a perspective of economic, environmental, and sustainable development, new ways of managing waste involving the concept of integrated waste management is highly recommended. The concept of integrated waste management is therefore highly recommended. An integrated SWM approach entails implementing measures such as source reduction, sorting, recycling, reuse, and regeneration (valorization) to manage waste effectively. Figure 1.7 shows integrated SWM approach model (Issihaka et al. 2015).

Recycling is the direct reintroduction of a waste product into the production cycle from which it originated, in total or partial replacement of a new raw material.

Reuse is a new use of a waste product for a purpose similar to its first use. It is, in a way, extending the life of the product before it becomes a waste. For example, the deposit of bottles is refilled after cleaning. In developing countries, this type of recovery is intensively observed in Africa.

Reemployment consists of using a waste product for a different purpose than its original use, or making another product out of a waste product than the one that gave birth to it, for example, using car tires to protect the hull of boats or trawlers.

Regeneration (Valorization) is a physical, chemical, or biological process that restores the characteristics of a waste product so that it can be used as a replace-

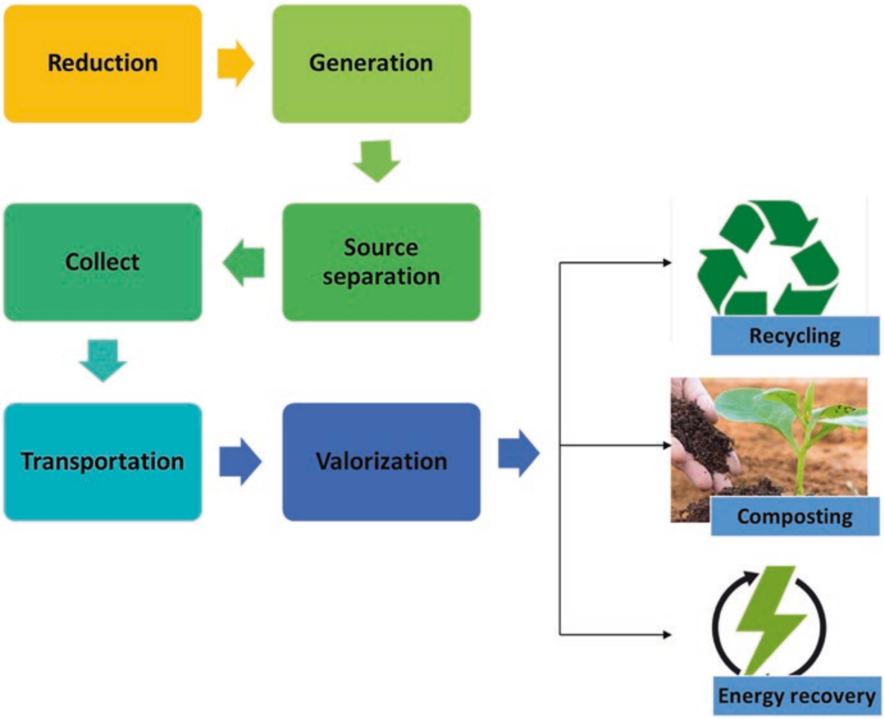

Fig. 1.7 Integrated solid waste management model

ment for a new raw material. This is the case, for example, for the regeneration of used oils or solvents, or for paper, which is both recycled and regenerated by drinking. This approach is commonly used for used oils or solvents, and for paper, which is both recycled and regenerated through pulping. Energy recovery is another waste management approach that involves extracting the calorific value of waste materials to produce electricity or heat. This method is typically achieved through incineration or methanization. Composting is another method of managing waste, particularly organic waste from agriculture, forestry, animal husbandry, food industry, and green space maintenance. Municipal solid waste (MSW) typically contains nitrogen levels between 0.5 to 0.7 and phosphorus levels between 0.5 to 0.8, with a calorific value ranging between 465 and 6978 Kj/Kg (Abdel-Shafy and Mansour 2018).

1.6 Conclusion

Obstacles in WM performance improvement include a lack of funding, a lack of political will, improper scheduling and routing, poor road network and development planning, and shoddy technological aspects. These difficulties are particularly pronounced in developing economies. Low-income countries, in particular, are primarily focused on extending waste management services to all residents and preventing illegal waste disposal. Therefore, effective waste management in these contexts requires collaboration between municipal officials and local communities to identify sustainable, context-specific solutions.

Optimal solid WM requires an optimization of the collection and transportation systems. Inadequate supply of waste collection and transport facilities negatively affects the disposal service. For example, implementation of the containers far away from waste generation points will encourage some of the bad practices such as waste dumping in open areas. Moreover, organizing the informal sector and promoting appropriate micro-enterprises are effective means to improve waste collection services. Because recycling in the informal sector already saves many cities millions of money and gives a significant portion of the urban poor a means of support, expanding on it and incorporating it into the formal system presents a big win-win opportunity.

The data collection and reporting of the overall amounts of waste produced are advisory and so irregular, resulting in this data. Studies should concentrate on data availability, adequate systems design on improving the efficiency of the vehicle routing systems through a good logistical scheduling, optimization of the routes taken by trucks, and incorporation of informatics and mathematical programming to ensure resources conservation through reduction of distance, time, traffic problems, and operational and maintenance cost.

References

H.I. Abdel-Shafy, & M.S.M. Mansour, Solid Waste Issue: Sources, Composition, Disposal, Recycling, and Valorization. Egyptian Journal of Petroleum, 27, 1275–1290. (2018) https://doi.org/10.1016/j.ejpe.2018.07.003

S.A. Ahmed, M. Ali, Partnerships for solid waste management in developing countries: Linking theories to realities. Habitat Int. **28**(2004), 467–479 (2004). https://doi.org/10.1016/S0197-3975(03)00044-4

A. Ahsan, M. Alamgir, M.M. El-Sergany, S. Shams, M.K. Rowshon, N.N. Nik Daud, Assessment of municipal solid waste management system in a developing country. Chin. J. Eng. (Hindawi Publishing Corporation) **2014**, Article ID 561935, 11 pages (2014). https://doi.org/10.1155/2014/561935

O.C. Aja, S.D. Oseghale, H.H. Al-Kayiem, Review and evaluation of municipal solid waste management practices in Malaysia. J. Solid Waste Technol. Manag. **40**(3), 216–232 (2014)

M. Akhtar, M.A. Hannan, H. Basri, E. Scavino, Solid waste generation and collection efficiencies: Issues and challenges. J. Teknol. **75**(11), 41–49 (2015)

O. Alam, X. Qiao, An in-depth review on municipal solid waste management, treatment, and disposal in Bangladesh. Sustain. Cities Soc. **52**(2020), 101775 (2019). https://doi.org/10.1016/j.scs.2019.101775

M.R. Alavi Moghadam, N. Mokhtarani, B. Mokhtarani, Municipal solid waste management in Rasht City, Iran. Waste Manag. **29**(1), 485–489 (2009)

R. Al-Jarallah, E. Aleisa, A baseline study characterizing the municipal solid waste in the State of Kuwait. Waste Manag. **34**(2014), 952–960 (2014). https://doi.org/10.1016/j.wasman.2014.02.015

S.O. Aloueimine, « méthodologie de caractérisation des déchets ménagers à Nouakchott (Mauritanie): Contribution à la gestion des déchets et outils d'aide à la décision » (2006). Thèse de l'Université de Limoges, France, pp. 35, 39, 40

G. Audrey, « A force de recycler la Suède doit importer des déchets », Paru le 22 septembre 2012 (2012). Disponible sur http://www.ecologie.blog.lemonde.fr (Consulté le 14 décembre 2016)

M. Azaitraoui, O. Aaziz, *10 Éléments clés pour réussir la gestion des déchets ménagers et assimilés au Maroc* (Heinrich Boll Stiftung, 2020)

D. Bleck, W. Wettberg, Waste collection in developing countries Tackling occupational safety and health hazards at their source. Waste Manag. **32**(2012), 2009–2017 (2012). https://doi.org/10.1016/j.wasman.2012.03.025

E.P. Brambilla, R. Raccanelli, G. Dotelli, D. Botta, P. Melià, Accounting for transportation impacts in the environmental assessment of waste management plans. Int. J. Life Cycle Assess. **14**(2009), 248–256 (2009). https://doi.org/10.1007/s11367-009-0061-0

A.D. Bruno, S.L. Felipe, C. Rodrigo, G. Gusmao, Urban solid waste management in developing countries from the sustainable supply chain management perspective: A case study of Brazil's largest slum. J. Clean. Prod. **233**(2019), 1377e1386 (2019). https://doi.org/10.1016/j.jclepro.2019.06.162

Central pollution control board, The national action plan for municipal solid waste management. In compliance with Hon'ble National Green Tribunal Order Dated 5th February 2015 in the Matter of OA No. 199 of 2014, Almitra H. Patel & Anr. vs Union of India & Ors (2015)

Earth link and advanced resources development (ELARD), (2004) Environmental impact assessment, solid waste treatment center "Jbeil-Hbaline" union of municipalities of Jbeil Caza, Lebanon

S. Elhafiane, *Gestion des déchets solides au niveau de la Commune Urbaine d'Agadir et leur impact sur le milieu naturel* (Mémoire de fin d'études, Faculté sciences et techniques de Marrakech, 2012)

W. Fadhullah, N.I.N. Imran, S.N.S. Ismail, et al., Household solid waste management practices and perceptions among residents in the East Coast of Malaysia. BMC Public Health **22**(2022), 1 (2022). https://doi.org/10.1186/s12889-021-12274-7

L.A. Guerrero, G. Maas, W. Hogland, Waste Manag. **33**(2013), 220–232 (2013). https://doi.org/10.1016/j.wasman.2012.09.008

T. Hazra, S. Goel, Solid waste management in Kolkata, India: Practices and challenges. Waste Manag. **29**(1), 470–478 (2009)

R.K. Henry, Z. Yongsheng, D. Jun, Municipal solid waste management challenges in developing countries Kenyan case study. Waste Manag. **26**(1), 92–100 (2006)

L. Hirpe, C. Yeom, Municipal solid waste management policies, practices, and challenges in Ethiopia: A systematic review. Sustainability **13**(20), 11241 (2021). https://doi.org/10.3390/su132011241

J. Huang, L. Huang, Y.J. Chen, E. Austin, C.E. Devor, F. Roegiers, Y. Hong, Differential regulation of adherens junction dynamics during apical-basal polarization. J. Cell Sci. **124**(23), 4001–4013 (2011)

Y. Hui, W. Liao, S. Fenwei, H. Gang, Urban solid waste management in Chongqing: Challenges and opportunities. Waste Manag. **26**(2006), 1052–1062 (2006). https://doi.org/10.1016/j.wasman.2005.09.005

A. Issihaka, H. El Bari, S. Belhadj, F. Karouach, Y. Joute, Y. Gradi, Contribution to the improvement of household waste management in Comoros. Int. J. Innov. Appl. Stud. **12**(4), 786–800 (2015) ISSN 2028-9324. © 2015 Innovative Space of Scientific Research Journals, http://www.ijias.issr-journals.org/

A. Issihaka, F. Karouach, N. Lahboubi, M. Bakraoui, H. El Bari, Perception and behavior analysis of comorians citizens on the solid household waste problems. Eur. Sci. J. **14**(26) ISSN 1857-7881 (Print) e – ISSN 1857-7431 (2018). https://doi.org/10.19044/esj.2018.v14n26p297

T.E. Kanchanabhan, J. Abbas Mohaideen, S. Srinivasan, V.L. Kalyana Sundaram, Optimum municipal solid waste collection using geographical information system GIS and vehicle tracking for Pallavapuram municipality. Waste Manag. Res. **29**(3), 323–339 (2011)

P. Karani, M. Jewasikiewitz Stan, Waste management and sustainable development in South Africa. Environ. Dev. Sustain. **9**, 163–185 (2007). https://doi.org/10.1007/s10668-005-9010-7

W.M. Katusiimeh, A.P.J. Mol, K. Burger, The operations and effectiveness of public and private provision of solid waste collection services in Kampala. Habitat Int. **36**(2012), 247e252 (2012). https://doi.org/10.1016/j.habitatint.2011.10.002

F. Loukil, L. Rouached, Waste collection criticality index in African cities. Waste Manag. **103**(2020), 187–197 (2020). https://doi.org/10.1016/j.wasman.2019.12.027

A.C. Maamar, A. Kechout, *Contribution à l'étude d'état de la gestion des déchets ménagers et assimilés dans la commune de Tizi-Ouzou* (Université Mouloud Mammeri de Tizi-Ouzou, 2016)

N. Madani, Droit marocain des déchets municipaux et développement durable. Law Environ. Dev. J. **11**(2), 120 (2015) disponible à http://www.lead-journal.org/content/15120.pdf

Mbande, Appropriate approach in measuring waste generation, composition and density in developing areas. J. S. Afr. Inst. Civ. Eng. **45**(3), 2–10 (2003)., paper 477

F. McLeod, T. Cherrett, Quantifying the transport impacts of domestic waste collection strategies. Waste Manag. **28**(2008), 2271–2278 (2008). https://doi.org/10.1016/j.wasman.2007.09.041

Z. Nkosi, P. Pillay, K.M. Nokes, Implementing case-based teaching strategies in a decentralised nursing management programme in South Africa. Curationis 36(1), Art. #130, 6 pages (2013). http://dx.doi.org/10.4102/curationis.v36i1.130

T. Nuortioa, J. Kyto¨jokib, H. Niskaa, O. Bra¨ysyb, Improved route planning and scheduling of waste collection and transport. Expert Syst. Appl. **30**(2006), 223–232 (2006). https://doi.org/10.1016/j.eswa.2005.07.009

S. Ojeda-Benitez, C.A.-d. Vegab, M.Y. Marquez-Montenegro, Household solid waste characterization by family socioeconomic profile as unit of analysis. Resour. Conserv. Recycl. **52**(2008), 992–999 (2007). https://doi.org/10.1016/j.resconrec.2008.03.004

H.K. Ozcan, S.Y. Guvenc, L. Guvenc, G. Demir, Municipal solid waste characterization according to different income levels: A case study. Sustainability (2016). https://doi.org/10.3390/su8101044

Programme National des Déchets Ménagers, Ministère de la transition énergétique et de développement durable – Département de développement durable, http://environnement.gov.ma/fr/dechets/117-theme/dechets#:~:text=Objectifs%20du%20PNDM%20%3A,urbains%20(100%25)%20en%202020

S. Rodrigues, G. Martinho, A. Pires, Waste collection systems. Part A: A taxonomy. J. Clean. Prod. **113**(2016), 374e387., Contents lists available at ScienceDirect Journal of Cleaner Production journal homepage: www.elsevier.com/locate/jclepro (2016). https://doi.org/10.1016/j.jclepro.2015.09.143

S. Satpal, *Solid Waste Management in Urban India: Imperatives for Improvement*, ORF Occasional Paper No. 283 (Observer Research Foundation, 2020)., https://www.orfonline.org/research/solid-waste-management-in-urban-india-imperatives-for-improvement-77129/

M. Sharholy, Municipal solid waste management in Indian cities—A review. Waste Manag. **28**, 459–467 (2008). http://dx.doi.org/10.1016/j.wasman.2007.02.008

M. Sharholy, K. Ahmad, R.C. Vaishya, R.D. Gupta, Municipal solid waste characteristics and management in Allahabad, India. Waste Manag. **27**(4), 490–496 (2007)

A.V. Shekdar, Sustainable solid waste management: An integrated approach for Asian countries. Waste Manag. **29**, 1438–1448 (2009). http://dx.doi.org/10.1016/j.wasman.2008.08.025

A. Sulemana, E.A. Donkor, E.K. Forkuo, S. Oduro-Kwarteng, Review article optimal routing of solid waste collection trucks: A review of methods. Hindawi J. Eng. **2018**, Article ID 4586376, 12 pages (2018). https://doi.org/10.1155/2018/4586376

S. Suthar, P. Singh, Household solid waste generation and composition in different family size and socio-economic groups: A case study. Sustain. Cities Soc. **14**(2015), 56–63 (2014). https://doi.org/10.1016/j.scs.2014.07.004

D.C. Wilson, L. Rodic, A. Scheinberg, C.A. Velis, G. Alabaster, Comparative analysis of solid waste management in 20 cities. Waste Manag. Res. **30**(3), 237–254 (2012)

D.C. Wilson, L. Rodic, C.A. Velis, Integrated sustainable waste management in developing countries. Proc. Inst. Civ. Eng.: Waste Resour. Manag. **166**(WR2), 52–68, Paper 1200005 (2013). https://doi.org/10.1680/warm.12.00005

M. Zohori, A. Ghani, Municipal solid waste management challenges and problems for cities in low-income and developing countries. Int. J. Sci. Eng. Appl. **6**(02) ISSN-2319-7560 (Online) (2017)

Chapter 2
Landfill Disposal in Developing Countries

Maria Cristina Lavagnolo, Valentina Grossule, and Raffaello Cossu

2.1 Waste Management Hierarchy, Circular Economy, and 3S Concept

Solid waste management (SWM) systems in developing countries (DCs) are affected by various constraints such as, mostly, the lack of technical specific knowledge, lack of awareness on environmental impacts by administrators and citizens, and shortness of economical funds. It can also happen that international collaborations and funding instead of helping with a long-term perspective may exasperate the already critical situation, implementing solutions that do not consider the local peculiarities, but just end up importing very complex solutions that fail soon or that create social inequalities. As an example, the local informal sector when existing provides a sort of virtuous service colleting and recycling valuable materials like metals, plastics, or glass, but if it is non included when a formal waste management is designed by the urban or international authorities, it will affect negatively the local economy (Environmental Justice Atlas 2020).

An inappropriate or unmanaged SWM system results in accumulation of waste that is deposited along the streets, in open dumps, or in low engineered landfills at best, often coupled with open burning of waste by the population.

Considering that it is necessary to put in place a SWM system that can effectively face and solve urgent problems, the challenge is to implement sustainable solutions to avoid further worsening of the already critical situation and, when possible, to transform the need in opportunity.

The adopted technologies should refer, as much as possible, to simple and clear solutions relying on locally available materials and on operators trained on purpose.

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In general, the designing of a proper SWM should adhere to the following principles:

- To guarantee a continuous and efficient collection and disposal service
- To consider human health and the environmental protection
- To minimize emissions and reduce the contaminating potential of waste both on a local scale (water pollution, soil, odors, etc.) and on a global scale (emissions of greenhouse gases, chlorinated gases, persistent substances, etc.)
- To minimize the waste production
- To source separate the waste and reuse the various valuable fractions
- To maximize the recovery of material and energy resources from waste
- To integrate different technologies
- To consider the environmental sustainability (i.e., progressive minimization and zeroing of environmental impacts within the period of one generation, approximately 30 years)

The above universal principles should be applied taking into consideration the specific social, economic, and geographical context. During the last decades, different models have been developed with the possibility to implement a safe and correct SWM system, starting from the *Waste Management Hierarchy* adopted by the European Union (Directive 2008/98/CE).

The *Waste Management Hierarchy* (Fig. 2.1) is based on the *3R* approach, which considers the reduction, reuse, and recycling of waste (the three pillars of any SWM system), while incineration (other type of recovery) and landfilling are included in the least preferred options to be adopted.

Many countries adopted the hierarchy of the waste management thus promoting the recycling industries and the energy recovery plants like anaerobic digestion and incineration. Despite the guidelines and the efforts, waste production is not decreased, and many municipalities are still in trouble to organize an effective SWM system. On the other hand, minimization, which should be the first action to be taken into consideration, has not been largely promoted.

The evolution of the *Waste Management Hierarchy* in Europe is the *Circular Economy* paradigm, represented in Fig. 2.2, aimed at solving two pressing global issues: the non-renewable resources exploitation and the uncontrolled waste production. The *Circular Economy* suggests to recover new resources from waste, as

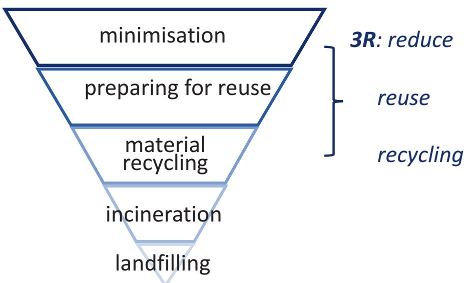

Fig. 2.1 Representation of the waste management hierarchy based on the 3R reduce, reuse, and recycle as adopted by the European Union (Directive 2008/98/CE). (Modified by Cossu et al. 2020a, b)

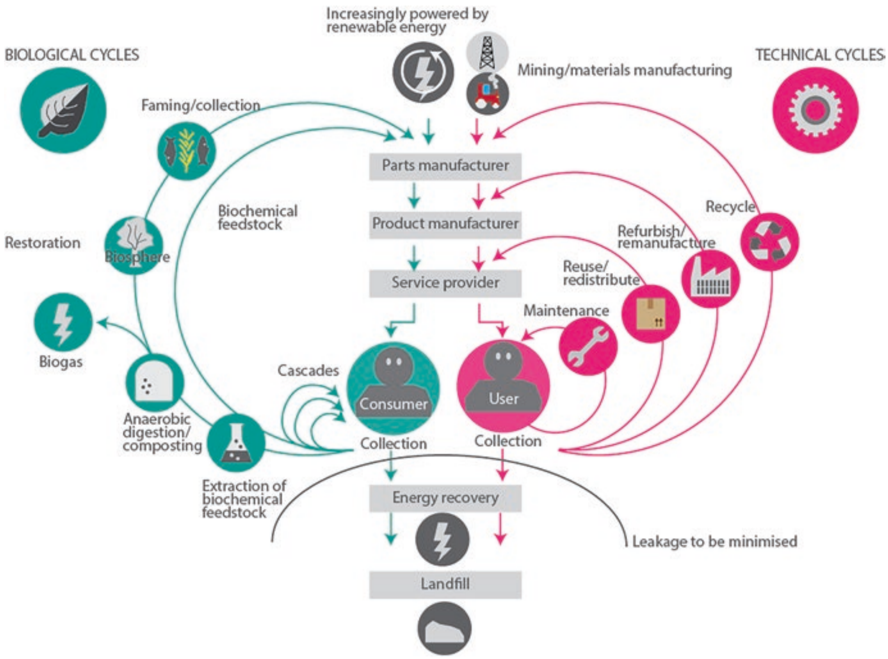

Fig. 2.2 Representation of the circular economy describing the two main cycles of materials, technical and biological. The technical cycle keeps materials in circulation as long as possible through reuse, repair, remanufacture, and recycling. In the biological cycle, biodegradable materials return back nutrients to the Earth to regenerate nature

secondary raw materials, relying on the reuse, upcycling, recycling, and eco-design. Originally, the concept was conceived as an auto-sufficient system, able to achieve the "zero waste" concept, by enhancing the entire value chain, while incineration and landfilling were not considered in the list of possible treatment technologies since all waste must re-enter in the loop. This ideological vision has suffered serious problems linked with the limits affecting the CE concept, such as the instability of the market of secondary raw materials, the impossibility to recycle all materials, and the unavoidable production of residues exiting the circle which need to be properly managed.

Both the *Waste Management Hierarchy* and the *Circular Economy* approaches need a complex well-trained organization and instruments for their implementation:

- Separate collection of waste to recover good quality of materials that means to have tracks, operators, and appropriate roads.
- Recycling technologies can be sophisticated, need funds to be designed and built, need operators, and are energy consuming.
- For specific materials and devices, proper and safe plants should be built following the basic guidelines (see above).

– In any case, the loop of non-recyclable must be closed safely and an engineered landfill must be constructed.

The requirements of a complex system may not be affordable, particularly in economically less developed countries.

A roadmap for a simpler and safe implementation of the SWM system has been recognized in the *3S* principles: *sanitization, subsistence economy*, and *sustainable landfilling* (Lavagnolo and Grossule 2018). Taking into account the hierarchy of the waste and the circular economy paradigm, the *3S* extrapolates the most urgent priorities that must be faced to solve the criticality of the solid waste management system in DCs and, at variance with the *3R* concept, is not perceived as a hierarchical structure, but rather is based equally on three pillars (Fig. 2.3):

1. *Sanitization* to improve the standards of living, achieving basic rules of hygiene in waste management. Inadequate waste disposal on the streets means direct contact between wastes and the population, therefore exposed to injury, diarrhea, respiratory disorders, and viral conditions. Furthermore, the surface and groundwater contamination, air pollution from open burning, and soil contamination from leaching can only worsen the already fragile situation.
2. *Subsistence economy* is the possibility to return waste in the economy as a resource using appropriate technologies, providing economic profits and new business opportunities, and involving the informal sector activity in a remunerated and formalized way. Waste pickers worldwide are largely informal individual workers not included in insurance schemes or social welfare; they create an opportunity for self-employment in very difficult working conditions. In the presence of an informal sector, it is critical in this context. Successful examples are the organization of informal recycler cooperatives (Gutberlet 2015).
3. *Sustainable landfilling* is the possibility to safely dispose the residues without economical or technical value, to close the loop of materials giving back to earth carbon and minerals. Open dumps do not have any barriers to prevent

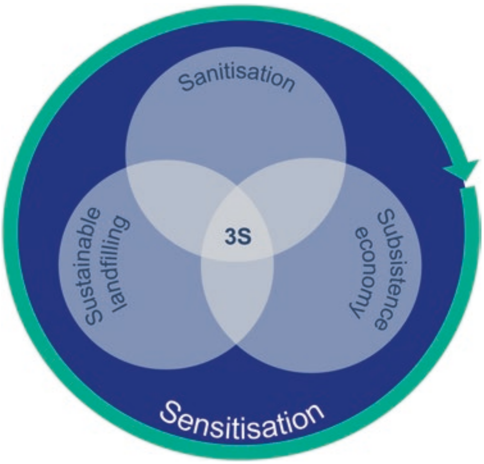

Fig. 2.3 Scheme of the 3S model to address sustainable waste management in areas with economic constraints. Sensitization embraces this special circular model highlighting the role of education. (Lavagnolo and Grossule 2018)

environmental pollution caused by leachate and biogas dispersion. Waste pickers working on the disposal site are exposed to health risks due to uncontrolled waste disposal (sharp items, infected materials, hazardous substances) and open burning releasing toxic gasses. Sustainable landfilling must be designed to avoid risks during the operation and to reduce the emission potential in the long term. In the presence of limited technical and economic situations, the following aspects should be integrated: low-cost solutions in terms of development, operation, and maintenance; simple, easily implemented technologies; and maximum utilization of natural resources and in situ materials.

Comparing the circular economy (CE), *3S* considers the same possibility of bringing materials back into the productive circle but supporting recycling for a true sustainable economy.

2.2 The Sustainable Landfilling

Historically landfilling has been the main waste treatment system, evolving in time from open dump to the sanitary landfill, gradually increasing the technological complexity and the environmental standards. Any waste deposit on the ground behaves like a normal three-phase reactor: water and air enter the reactor as individual streams or as a component of the waste mass entering the system. In the landfill reactor, biological, physical, and chemical-physical processes occur, transforming both organic and inorganic substances and producing leachate and biogas emissions, while waste represents the source of the potential residual emissions.

In recent years, the concept of sustainable landfilling has become an unavoidable principle in designing SWM systems. Cossu (2010) defined a *Sustainable Landfill* as a system that should reach an acceptable equilibrium with the environment within one generation (30–40 years). The acceptable equilibrium can be considered in terms of control of long-term emissions (gas and leachate) and compliance with Final Storage Quality (FSQ) (Cossu and Van der Sloot 2014; Laner et al. 2012). FSQ is defined as a set of values of different parameters to be achieved within the span of one generation, representing an acceptable equilibrium between the landfill and the environment. FSQ considers the quality of emissions (leachate and biogas) and deposited waste, particularly the residual concentration of organics and ammonia as most impacting factors in the long term. Just to have an idea of the FSQ values, in Table 2.1 it is reported the only existing reference for the FSQ, defined by Lombardia Region in Italy (Regione Lombardia 2014; Cossu et al. 2020a, b).

To achieve sustainability targets, a proper design and a combination of treatments (mechanical, chemical, biological, and thermal) must be implemented throughout the different life of a landfill (prior to waste deposition, in situ during operations and during the post-care phase) aimed at promoting the stabilization of the waste, thus reducing the long-term mobility of contaminants.

Table 2.1 Values of goal parameters for the definition of FSQ (Lombardia Region 2014)

Parameter		Unit	Value
Leachate	COD	mgO_2/l	1500
	BOD_5/COD	–	0.1
	$N\text{-}NH_3$	mg_N/l	50
	Cd	mg/l	0.02
	Cr; Cr VI	mg/l	2; 0.2
	Cu	mg/l	1
	Fe	mg/l	2
	Mn	mg/l	2
	Ni	mg/l	2
	Pb	mg/l	0.2
	Zn	mg/l	3
Biogas	CH_4	$Nl\ CH_4/m^2\ h$	0.5
Solids	IR_4	mg_{O2}/g_{TS}	2
	IRD	$mg_{O2}/Kg_{VS}/h$	100

2.2.1 The Bioreactor Landfill

To achieve the FSQ and thus the environmental sustainability, biological stabilization of waste is the main target, particularly in case of high percentage of putrescible fractions (emission of methane and CO_2, emission of organic contaminants and ammonia nitrogen associated to leachate, odors, risks of fires, etc.).

In landfill, the control of environmental impacts related to organics may be achieved by a series of options:

- Diversion of putrescible fraction from waste before landfilling (application of the separate collection)
- Stabilization of organics prior to landfilling (use of thermal treatment or mechanical biological treatment)
- On-site treatment to enhance biodegradation (during landfilling and/or the aftercare phase)
- A combination of the above-listed options

The term *Landfill Bioreactor* has been coined specifically to indicate a landfill in which different in situ measures are undertaken to enhance biological degradation or methane production, increase transformation of ammonia and recalcitrant organics. These measures may include leachate recirculation, introduction of water, and natural or forced aeration.

Improved control of biochemical kinetics, moisture content, and redox conditions may result in a significant shortening of the aftercare phase and, consequently, in a quicker achievement of environmentally sustainable targets.

Bioreactor landfills can have several advantages:

– Reduce environmental impacts, by improving leachate quality and controlling landfill gas (LFG) emissions.
– The aftercare time is generally shorter due to the increased stabilization rates therefore reducing aftercare costs and returning the site for different uses in a shorter timeframe.
– The leachate treatment is cheaper, since the in situ treatment enhances leachate quality.
– The landfill gas (LFG) generation in an anaerobic bioreactor is enhanced.

Bioreactor landfill can also have some disadvantages such as increased odors, physical instability of the waste mass due to the increase in moisture, higher capital and management costs for aeration, and/or leachate recirculation (Grossule et al. 2018).

Different bioreactor landfills can be designed: enhanced anaerobic, natural ventilated or forced aerated, and hybrid with alternate aerobic/anaerobic phases (Fig. 2.4).

The choice of a specific bioreactor landfill is regulated by the objectives to be pursued (i.e., energy recovery landfill gas, waste stabilization, sustainability targets, etc.) as well as by economic issues (balance between capital and operational costs and long-term savings) and the specific site conditions (e.g., waste characteristics, climate and social/economic situation, regulations).

2.2.1.1 Anaerobic Landfill

The biological process is based on maximization of the carbon gasification with the advantage to recover energy due to methane formation; therefore, it is suggested when organic contents in the waste input are particularly high. Leachate

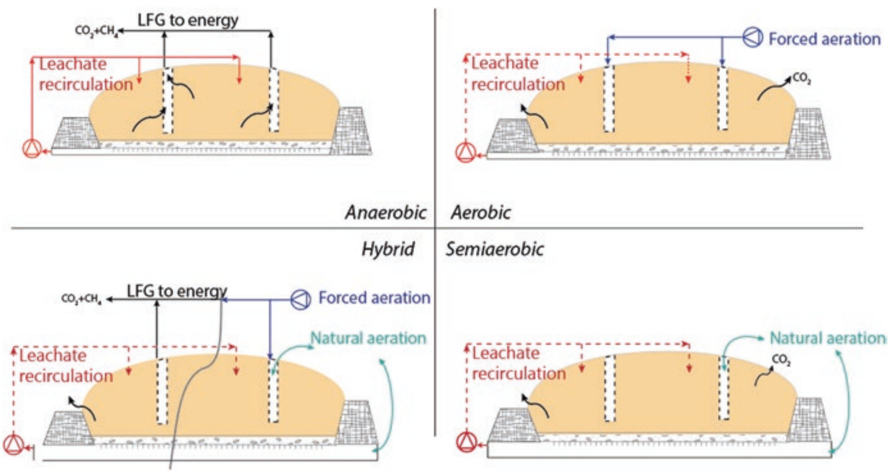

Fig. 2.4 Scheme of the different bioreactors landfill. (Modified Cossu and Grossule 2018)

recirculation is applied to enhance the biogas production and to partially pretreat the leachate itself. On the other hand, slow degradation rates and ammonia persistence put the anaerobic bioreactor far from meeting sustainability requirements, prolonging the long-term emissions, and increasing the costs associated with aftercare.

2.2.1.2 Aerated Landfill (On-Site Aeration)

Aerobic environment inside the landfill can be maintained by injecting air within the waste mass, promoting the growth of aerobic microorganisms and thus the biodegradation processes, up to 10 times faster than anaerobic ones (Grossule et al. 2018). Aeration of the waste mass prevents methane generation and thus energy recovery; on the other hand, it lowers the leachate carbon and nitrogen values resulting in financial savings for leachate treatment. Energy needs to sustain forced aeration, and difficulties of an effective air circulation inside the mass (different density, leachate lens, etc.) can lower the efficiency of the aeration. Forced aeration is mostly used for remediating old anaerobic landfill, more than a designed option for active landfill management.

2.2.1.3 Semi-aerobic Landfill (The "Fukuoka Method")

Semi-aerobic landfill systems, based on a mechanism of natural air ventilation without using highly technological solutions, promotes the presence of oxygen in the waste mass, thus accelerating waste stabilization and leachate nitrogen removal. Although semi-aerobic landfilling is characterized by a lower stabilization efficiency compared to aerobic systems, it represents a valuable solution for achieving sustainable landfilling, compromising between the technological complexity and high costs of aerobic systems, and the long-term impacts generated by anaerobic systems. The natural ventilation method is based on a simple physical principle: air flows into waste layers by means of a natural advection process generated by the difference in temperature between landfill layers and external ambient. This difference is established when the landfilled waste contains putrescible organics.

2.2.1.4 Hybrid

Hybrid bioreactors operate under a series of aerobic and anaerobic conditions, with the aim to combine the advantage of both conditions, achieving higher energy recovery and faster waste stabilization. Depending on the combination, challenge must be faced due to accumulation of ammonia in the landfill (case of aerobic-anaerobic) or high costs related to continuous air injection and leachate recirculation (Grossule et al. 2018).

2.2.2 The Barrier System

With the aim of effectively preventing or mitigating the uncontrolled emissions, it is necessary to relay to different types of barriers (not only physical), defining as a "barrier" any system designed to reduce the mass transport of contaminants from the landfill to the surrounding environment (air, water, soil). Finding the optimal combination of the barriers is a key factor for the design of sustainable landfills.

In the modern concept of sustainable landfilling, landfill can be considered as a series of different barriers that follow one another in cascade (Cossu 2018). Barriers can physically contain the emissions or can affect positively the release of contaminants through the control of the transformation process inside the body of the landfill. To better explain the landfill barriers system, in Fig. 2.5 barriers are represented by valves that can be controlled depending on their specific function. The top cover, the lining systems, the biogas, and leachate capture systems are "physical barriers" that can assure the containment (red valves) or can control the pollutants quickly draining them out towards the final treatments (yellow and green valves). On the other hand, the "reactor barriers" (in blue field) promote the biological reactions and

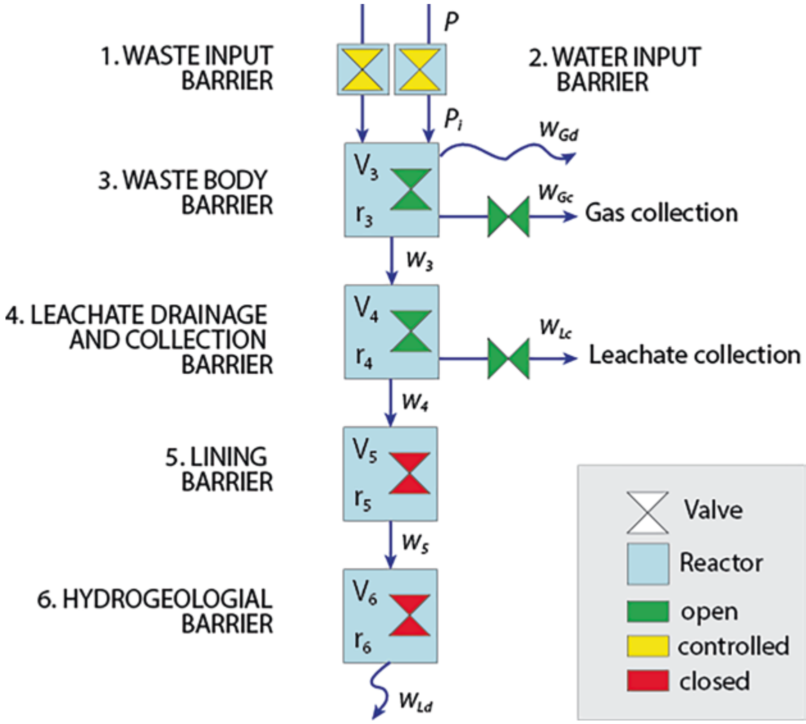

Fig. 2.5 Scheme of different barriers and contaminant (w) in a landfill system. Barriers are represented by valves that must be opened, controlled, or closed according to the specific function. (Modified from Cossu et al. 2020a, b)

carbon transformation, and depending on the landfill management, biogas or leachate production can be enhanced.

Examples of barriers are as follows:

- The waste input. Quantity and quality of organics can be controlled applying the separate collection and/or waste pretreatment prior to landfilling (e.g., washing of waste, mechanical biological treatment, waste bio-drying).
- The water input. Rain infiltration will transform in leachate and affect the landfill bioprocess is controlled by the top cover.
- The landfill processes. It controls the type of emissions and the biochemical waste transformations. Aerobic, aerated, anaerobic process or a combination of them can be used (see above bioreactor landfill).

Barriers can be both constructive (mainly physical barriers) and management tools (mainly bioreactor barriers). Depending on the type of barriers considered, the design of the sustainable landfill changes.

Following the barrier system model, a combination of possible alternatives supporting the sustainable landfilling is illustrated in Fig. 2.6. Along the solid waste management disposal chain, pretreatments of waste, in situ, and post-closure operations can be linked and proposed in series, as different possibilities to achieve a final quality of the deposit no longer harmful to the environment that we can call "geological repository":

(a) *pretreatment phase* refers to operations to be done before the deposit of the waste;
(b) in situ *treatment* must be applied during the management of the landfill on site;

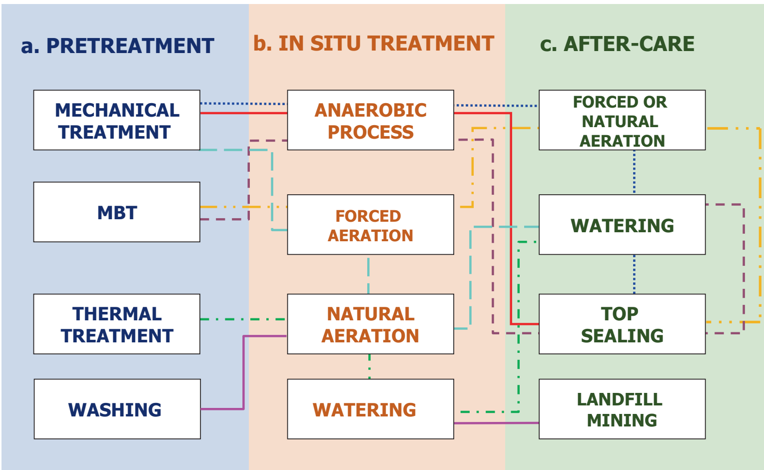

Fig. 2.6 Examples of operational alternatives to promote sustainable landfill, during the various stages of the landfill's life (*MBT* mechanical biological pretreatment). (Lavagnolo, never published)

(c) *aftercare* is the possible management of the deposit when the waste discharge is concluded.

The combination can be chosen based on the characteristics of the waste and on the local conditions.

A conventional design widely used in Europe (follow the red line in Fig. 2.6), is:

(a) solid waste undergoes mechanical treatment by shredding, sieving, and sorting of recyclables;
(b) anaerobic landfill to finalize the transformation of organics, with intense production of gas (e.g., concentrated over an indicative period of 10–15 years);
(c) top sealing as aftercare, to control the water infiltration and therefore the leachate production.

Considering the conventional European model, an improvement towards sustainable landfilling could be the application, before the final top sealing, of a forced or natural aeration in the aftercare period to promote the stabilization of the residual organics (follow the blue line in Fig. 2.6), followed by a flushing to remove out from the deposit, in a shorter range of time, the potential dissolving components preventing future leaching of pollutants.

Another example of sustainable landfilling design can be the following (orange line in Fig. 2.6):

(a) pretreatment of waste to reduce organic compounds (separate collection + biodrying);
(b) strong forced aeration during landfilling to minimize putrescibles;
(c) in the aftercare period and before the top sealing, the deposit is opened to air infiltrations as much as possible to favor natural ventilation.

2.3 Landfill Models in DCS

In most developing countries, open dumps are still the most prevalent type of disposal facility, since it entails lowest technology and operational cost requirement: the higher the compliance with environmental standards, the greater the knowledge and financial demand.

Open dumpsites are usually located in any available vacant area without a proper siting consideration and typically characterized as follows (UNEP 2005):

- No control over the amount and/or type of waste that is disposed of
- No extraction of biogas and leachate
- No soil cover
- No proper drainage
- No compaction
- Open burning to reduce the volume of waste and preserve disposal space
- Scavengers on the site

The number and seize of open dumps are increasing also due to higher waste generation rates in growing – already overpopulated – cities. Global world population is expected to grow from over 50% to 70% by 2050 with the majority of growth occurring in the poorest countries of Asia and Africa where approximately the 25% of population live in slums (UNEP 2018).

The awareness of citizens and politicians about this dangerous situation is growing also in developing countries but is still insufficient, and sustainability achievement remains a crucial challenge.

From a technical point of view, Sukholthaman and Shirahada (2015) suggest small scale, low capital cost, and energy-efficient landfills that are controlled by the local community. To ensure the sustainability of an engineered landfill in developing countries, Allen (2002) pointed out similar suggestions: low-cost solutions in terms of development, operation, and maintenance; simple easily implemented technologies, and a maximum utilization of natural resources and the properties of in situ materials. The financial sustainability of the project is strongly affected using artificial lining systems, the single most costly feature of modern landfills. The examples of engineered sanitary landfills in the larger cities in DCs have operational problems such as the cost of the daily cover (up to 50% of the operating costs), the managing of the LFG (landfill gas), and the leachate control and treatment.

Combining the *3S* concept and *the barriers system model*, considering pro and constraints of the bioreactor landfills, solutions for the design of a sustainable landfilling, specifically tailored for the developing countries, can be proposed.

Among the others, the semi-aerobic landfill seems particularly to answer to the specific needs of developing countries as it can be managed in a simple way, with low energetic demand (no biogas extraction and leachate outflow by gravity) and shorter long-term impact due to the enhanced aerobic degradation of organics.

From a structural point of view, a semi-aerobic landfill system consists of a network of horizontal pipes installed at the bottom of landfill sectors and vertical venting pipes erected at specific intersections of the horizontal pipes. The perforated horizontal pipes not only collect and quickly drain off leachate generated in the waste layers but, as part of the network of pipelines, also promote the circulation of air within the waste mass (Fig. 2.7). Despite the well-designed ventilation system, the high percentage of organics usually present in the waste in those countries may represent an issue due to the quantity of oxygen needed for the biodegradation. Natural ventilated system cannot assure in fact a perfect homogeneous distribution of air in the mass, and some methane is produced; the higher the organic percentage, the higher the possibility to have anaerobic condition.

In terms of leachate emissions, the advantages achievable with the application of the semi-aerobic landfill can be found by analyzing the graphs in Fig. 2.8 (Lavagnolo et al. 2018). The data reported refer to studies on columns (lysimeters) filled with two different types of municipal solid waste, with low (B) and high (A) contents of putrescible organic substances. Anaerobic (An) and semi-aerobic (S) situations were compared. High putrescible content represents the typical characterization of waste in DCs and anaerobic landfilling the most used controlled disposal type in those countries. In semi-aerobic conditions, for both types of waste, compared to the anaerobic conditions, there is a marked reduction in the concentration of ammonia, in volatile fatty acids (VFA), which are well representative of the putrescible

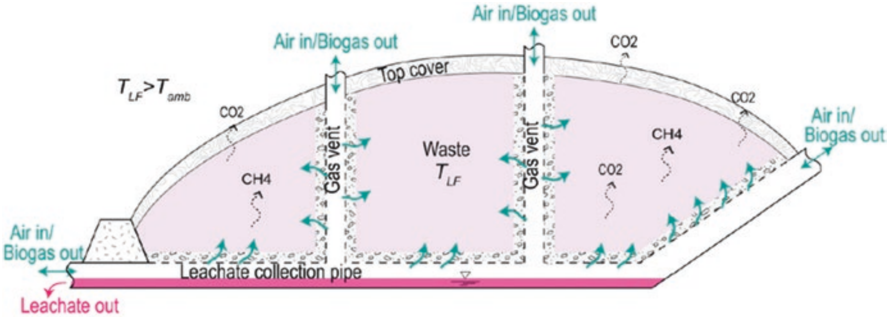

Fig. 2.7 Sketch of the semi-aerobic landfill. (Modified by Grossule et al. 2018)

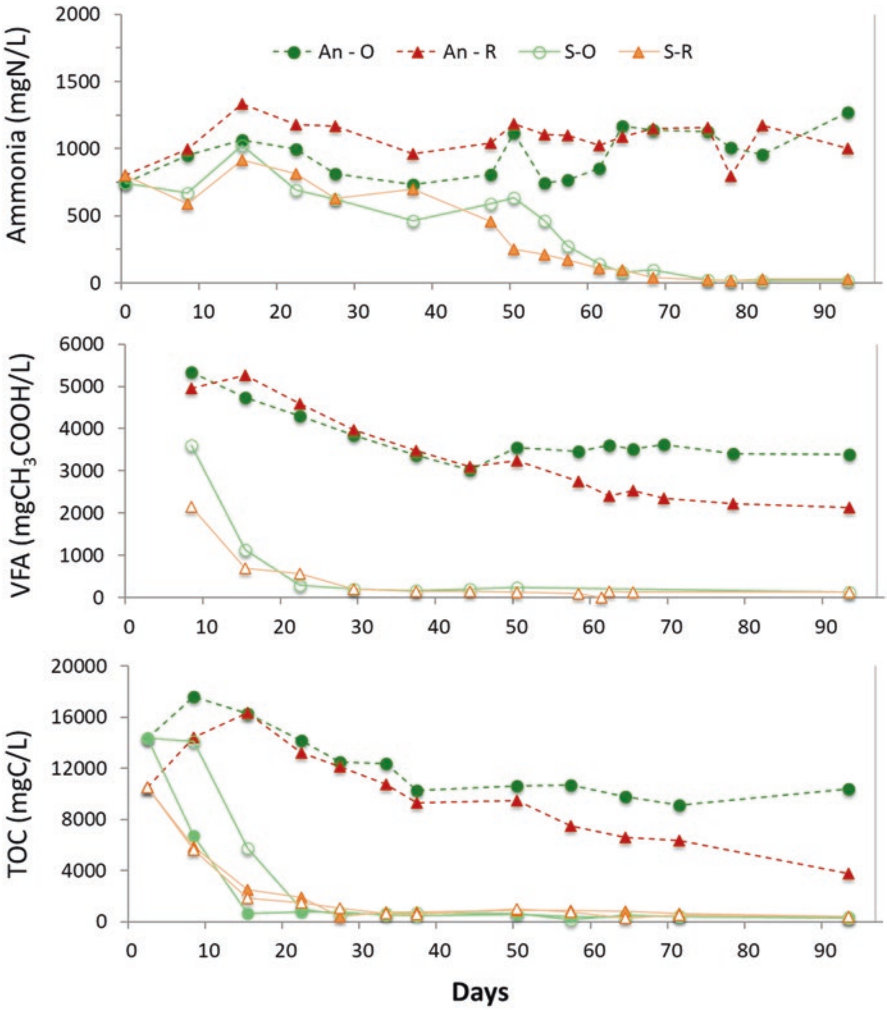

Fig. 2.8 Variation over time of some significant parameters in the leachate of anaerobic (AN) and semi-aerobic (SA) landfill (Lavagnolo et al. 2018) (*O* high organic content waste, *R* residual waste)

Table 2.2 Final storage quality requirements suggested by the Lombardy Region, Italy (D.G.R. 2461/14), and final values achieved in lysimeters at the end of the experiment

Sample	Parameter	FSQ values	AN-O	AN-R	S-O	S-R
Leachate	COD (mg/L)	1500	6800	4580	370	305
	BOD_5/COD	0.1	0.33	0.34	0.06	0.02
	Ammonia (mg/L)	50	216	181	11	6
	Cd (μg/L)	20	<10	<10	<10	<10
	Cr (μg/L)	2000	<10	102	<10	<10
	Cu (μg/L)	1000	212	225	251	234
	Fe (μg/L)	2000	3867	7667	1060	687
	Mn (μg/L)	2000	2013	2287	117	61
	Ni (μg/L)	2000	152	206	72	75
	Pb (μg/L)	200	<10	42.7	38	20
	Zn (μg/L)	3000	1070	737	702	447
Solid	RI_4 (mgO2/gTS)	2	48	38	10	5

S semi-aerobic, *AN* anaerobic, *O* high organic content waste, *R* residual waste

fraction in the waste, and in the TOC, which expresses the total concentration of organic carbon. Similar results were found in several semi-aerobic landfills (He et al. 2011; Matsufujii et al. 2018).

An innovative dual-step management of semi-aerobic landfill specifically design for tropical climate is suggested (Lavagnolo 2019), reproducing alternatively a composting phase and a flushing phase during dry and wet season, respectively. The obtained results demonstrated the effectiveness of the innovative management achieving sustainability target limits at the end of each year landfill management (Table 2.2). The innovative management requires a "horizontal growth" of the landfill, implying a need for high space requirements and resulting in high leachate production, thus linked to higher landfill management costs. However, if space is not a limiting factor, the generation of leachate is fundamental in ensuring irrigation during the dry season and enhancing both leachate evaporation and treatability, thus reducing volumes and mitigating management costs.

In conclusion, a semi-aerobic landfill operated under wet-dry climate conditions in tropical areas can be managed as a hybrid reactor, aerated throughout the dry season, and flushed in anaerobic conditions in the wet season.

2.4 Conclusions

Many different solid waste management strategies have been applied in low- and middle-income countries, but most of the time the imported solutions failed due to local technical and socioeconomic constraints. To enforce solutions adopted in the industrialized countries does not guarantee an effective and resilient solid waste management system, since both the 3R-hierarchy and the circular economy approach need time to be effectively applied and, in any case, a step-by-step implementation.

The 3S strategy not only is a roadmap for a simple and effective solution of the waste problem but also offers the possibility of organizing a system attentive to the socioeconomic needs of the local context that does not have the necessary resources to set up a sophisticated and too complex management of waste. Sustainable landfilling is a possibility to properly dispose waste otherwise abandoned in the street or in open dumps without control, and the most interesting solution for DCs seems to be the semi-aerobic landfill, with a special management in case of high content of organic waste.

References

A.R. Allen, Low-cost natural solutions to landfill management for developing nations, in *Appropriate Environmental and Solid Waste Management and Technologies for Developing Countries*, ed. by G. Kocasoy, T. Atabarut, Ý. Nuhuoðlu, (ISWA conference, Istanbul, 2002)

R. Cossu, Technical evolution of landfilling, Waste Manag. 30, 947–948 (2010)

R. Cossu, Chapter 2.1: Multibarrier principles in landfilling, in *Solid Waste Landfilling. Concepts, Processes, Technologies*, ed. by R. Cossu, R. Stegmann, (Elsevier, 2018), pp. 229–246. ISBN 978-0-12-8183366

R. Cossu, V. Grossule, Landfill bioreactors, in *Solid Waste Landfilling, Concepts, Processes, Technology*, ed. by R. Cossu, R. Stegmann, (Elsevier, 2018) ISBN: 9780128183366

R. Cossu, H. Van der Sloot, *Sustainable Landfilling* (CISA Publisher, 2014) ISBN 978-88-6265-005-2

R. Cossu, V. Grossule, M.C. Lavagnolo, *La Discarica Sostenibile* (CISA Publisher, 2020a) ISBN 9788862650182

R. Cossu, D. Sciunnach, S. Cappa, G. Gallina, V. Grossule, R. Raga, First worldwide regulation on sustainable landfilling: Guidelines of the Lombardy Region (Italy). Detritus **12**, 114–124 (2020b). https://doi.org/10.31025/2611-4135/2020.14001

Environmental Justice Atlas, The new Reppie incinerator at Koshe landfill in Addis Ababa (2020). https://ejatlas.org/conflict/the-new-reppie-incinerator-at-koshe-landfill-in-addis-ababa-ethiopia-leaves-the-wastepickers-without-livelihood. Visited 29 Oct 2022

V. Grossule, L. Morello, R. Cossu, M.C. Lavagnolo, Bioreactor landfills: Comparison and kinetics of the different systems. Detritus **3**, 100–113 (2018)

J. Gutberlet, Cooperative urban mining in Brazil: Collective practices in selective household waste collection and recycling. Waste Manag. **45**, 22–31 (2015)

P. He, N. Yang, H. Gu, H. Zhang, L. Shao, N_2O and NH_3 emissions from a bioreactor landfill operated under limited aerobic degradation conditions. J. Environ. Sci. **23**, 1011–1019 (2011)

D. Laner, M. Crest, H. Scharff, J.W.F. Morris, M.A. Barlaz, A review of approaches for the long-term management of municipal solid waste landfills. Waste Manag. **32**, 498–512 (2012)

M.C. Lavagnolo, Landfilling in developing countries, in *Solid Waste Landfilling*, ed. by R. Cossu, R. Stegmann, (Elsevier Publisher, 2019) ISBN: 978-0-12-818336-6

M.C. Lavagnolo, V. Grossule, From 3Rs to 3Ss: An appropriate strategy for developing countries. Detritus **4**, 1–3 (2018)

C. Lavagnolo, V. Grossule, R. Raga, Innovative dual-step management of semi-aerobic landfill in a tropical climate. Waste Manag. **74**, 302–311 (2018)

Y. Matsufuji, A. Tannaka, R. Cossu, Chapter 14.2: Semi-aerobic landfilling, in *Solid Waste Landfilling: Concepts, Processes, Technologies*, ed. by R. Cossu, R. Stegmann, (Elsevier Publisher, 2018), pp. 807–830. ISBN: 978-0128183366

Regione Lombardia, Linee Guida per la progettazione e gestione sostenibile delle discariche, D.g.r. 7 ottobre 2014, n.X, 2461 (2014)

P. Sukholthaman, K. Shirahada, Technological challenges for effective development towards sustainable waste management in developing countries: Case study of Bangkok, Thailand. Technol. Soc. **43**, 231–239 (2015)

UNEP, *Solid Waste Management* (UNEP, 2005) ISBN: 92-807-2676-5

UNEP, *Africa Waste Management Outlook* (United Nations Environment Programme, Nairobi, 2018) ISBN: 978-92-807-3704-2

Chapter 3
Application of the WROSE Model for Promoting Effective Decision-Making and Sustained Climate Change Stabilization in the South African Waste Sector

Cristina Trois, Yared Abera, Andrea Dell'Orto, Sameera Kissoon, and Adriana Gómez-Sanabria

3.1 Introduction

It is estimated that the waste sector in South Africa contributes with over 19 million tons of CO_{2eq} per year, or 4.1% of South Africa's total GHG emissions (DFFE 2017). In particular, the waste sector accounts for 36.5% of the total methane (CH_4) emissions in 2020. The majority of these emissions are from solid waste disposal contributing 79.2% and the remaining emissions come from wastewater. Since 2000, methane emissions from solid waste disposal have increased to 34.1%, and total GHG emissions have increased of almost 56.7% (2.7% year by year) in the past 17 years (2000–2017) (DFFE 2017). However, the waste and climate change nexus is not explicitly quantified nor addressed in current policies at national and/or local level causing a potential retarding effect on the achievement of the Nationally Determined Contributions (NDCs) and sustainability goals. At national level, GHGs from the waste sector are quantified using models and carbon emission factors developed in contexts that are not specific to South Africa (DEA 2014). There is a need to create a realistic inventory of GHG emissions from the waste sector and a comprehensive mitigation strategy for the African continent. In South Africa, the disposal of unsorted waste to landfill is still the primary waste management method across the country; however, legislative developments aim to drive integrated waste management and the circular economy, putting the disposal of waste to landfill as the least favorable waste management solution (DFFE 2018). Arguably, with almost 80% of the municipal solid waste ending up in landfill sites unsorted and untreated,

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the only reasonable "activator" of the circular economy would be an integrated waste management system, which is underpinned by an efficient separated collection at the source, followed by carefully selected and strategically localized waste treatment strategies, decentralized recycling facilities, and sustainable end-of-life disposal options. There is a need to correctly quantify the GHG emissions from the waste sector, to strengthen government's capacity in GHG monitoring and reporting, and to develop waste management strategies that, if regionally applied and correctly localized, can contribute towards the systematic reduction of GHG emissions, waste diversion, and can be a quantifiable contribution to South Africa's Nationally Determined Contributions and climate change mitigation targets (DEA 2014).

In Africa, local authorities have generally limited know-how in evaluating technology options, operate with limited resources, lack capacity and data, and function under complex institutional and social contexts which in turn increase the risk of failed inappropriate technologies and out of context installations (WMO 2018). Moreover, implementation of waste strategies is based primarily on technical and economic considerations, while environmental and socioeconomic considerations are generally subordinate to the former. In recent years, through the development of waste management legislation as well as the requirements for landfill development, local municipalities are forced to explore alternative methods of waste management (Kissoon and Trois 2022). The introduction of the waste hierarchy in South Africa as well as the National Waste Management Strategy puts the disposal of waste to landfill as an end-of-life solution (DEA 2008). This gives rise to the need for implementing alternative strategies such as recycling, recovery of biogenic waste, and the reuse of waste as a resource. However, local municipalities lack the required human capital and financial resources to implement such new systems. Up to 40% of the South African population receives little or no waste services (DEA 2008). Even though at national level there have been assessments to quantify GHG from waste, there is not a national standardized methodology specific to the South African context.

The Waste Resource Optimization Scenario Evaluation (WROSE) model/tool aims at bridging this gap as it is a waste diversion and carbon emissions reduction model that was developed by the SARChI Chair Waste and Climate Change at UKZN since 2010 (Trois and Jagath 2011) to assist municipalities and the private sector to evaluate different waste management strategies and making the best and most sustainable decision from an environmental, technical/economic, social, and institutional viewpoint.

This chapter presents the preliminary results of a study on the assessment of GHG emissions and alternative waste diversion pathways from the eight South African metropolitan municipalities using the WROSE model with the aim to develop a comprehensive waste reduction and climate change stabilization strategy for the South African waste sector. The study is intended to provide data and information to municipal waste managers about potential alternatives to landfill disposal, using their carbon footprint and potential for GHG reduction as discriminants for their choice. The chapter reports on socioeconomic drivers, waste generation, and composition data for the eight metros but details the application of the WROSE model only for the eThekwini Municipality (as representative of the other seven metros) and focuses exclusively on commercial and residential (post-consumer) municipal solid waste (MSW) as collected and disposed in urban areas in South Africa. The main aim of this project is to assess the potential annual carbon emissions reductions from optimized waste management strategies and from public sanitary engineered landfills in South Africa's eight metros and to identify feasible mitigation pathways to achieve those reductions.

The WROSE model (Kissoon and Trois 2019; Trois and Jagath 2011) was developed to assist municipal officials in the decision-making process for the implementation of appropriate waste management strategies. The model was developed in two phases: phase 1 included a scenario analysis based on environmental and economic indicators, whereas phase 2 focused on the socioeconomic and institutional aspects of the model. The WROSE model was developed in conjunction with the private sector for municipal officials looking to implement alternative waste management strategies through activating public-private partnerships. The model uses country-specific data and emission factors making it relevant to developing countries, and it covers a range of waste management technology options such as landfilling, landfilling with gas extraction and flaring, landfilling with gas recovery and electricity generation or gas upgrade, recycling, thermal treatment and incineration, anaerobic digestion, and composting. In addition, the WROSE model covers basic capital and operating cost of the waste management activities listed above. The WROSE model provides information such as GHG emission reduction potential, waste diversion rates, and landfill airspace savings realized both in terms of m^3 of airspace and in terms of the monetary value of prolonging the life of a landfill site or selling the recyclables. The model provides a detailed account of associated capital and operational costs/revenues, job creation potential and associated health risks, and the institutional framework (including possible "red tape") pertaining to the implementation of the assessed technology options. WROSE has been set up with IPCC emissions factors and follows standard methods for carbon emissions evaluation that are based on a first-order decay model (IPCC 2006). Therefore, the WROSE methodology is a reliable alternative to similar waste and carbon emission models used internationally such as WARM, WRATE, EASETECH, or GAINS (Ghinea and Gavrilescu 2010). However, since it has been developed and tested with a large number of Southern African municipalities and case studies over the past 10 years, specific emission factors have been developed and tested for a number of waste technology options for South Africa, and current research by the SARCHI Chair Waste and Climate Change is directed to test the reliability and compare these local emission factors against the results obtained using the standard approved IPCC emission factors (Friedrich and Trois 2013a, b).

3.2 Waste Management in South Africa

As a result of increased waste output brought on by fast urbanization, population growth, and economic development, South African municipalities are under pressure to provide high quality services and manage landfills (CSIR 2020). The proportion of households from which waste is removed at least once per week climbed from 58.8% in 2019 to 62.9% in 2021 (STATS-SA 2021a). According to the State of the Waste report (Department of the Environment and Energy 2018), out of the estimated 55.6 million tons of general waste produced in 2017, 0.2% was stockpiled, 34.5% was recycled or recovered, 0.1% was processed, and 65.2% was disposed in landfills. According to the State of the Waste Report Department of the Environment and Energy (2018), based on a representative sample of municipalities from each of its nine provinces, South Africa recycled 38.6% of its estimated 54.2 million tons (Mt) of general waste generated in 2017 – a sum of municipal (4.8 Mt), commercial and industrial (3.5 Mt), organic (30.5 Mt), construction and demolition (4.5 Mt), metals (4 Mt), glass (2.5 Mt), paper (2.2 Mt), plastic (1.1 Mt), tyres (0.24 Mt), and other (0.73 Mt) wastes. 38.3% of generated waste in 2017 was recovered and/or recycled, while 61.77% was landfilled or treated.

The generation of waste in South Africa is affected by numerous drivers, such as population – size, growth, and density; economy – manufacturing and industry, higher incomes, and affluence; urbanization; and globalization of the recycling market. South Africa is classified as an 'upper-middle income' country. Waste management challenges include lack of law enforcement (UNEP 2018), weak governance, low public awareness and negative attitudes, insufficient financial provision, and service backlog to address issues faced by communities (Trois and Simelane 2010).

The NWMS was developed to achieve the objectives set out in the Waste Act (SAWIC 2016). One such objective is the application of the waste hierarchy as set out by the waste act that promotes waste minimization, reuse, recycling, waste treatment, and the disposal of waste to landfill as an end-of-life method for waste management (SAWIC 2016). The National Waste Management Strategy 2020 determines three strategic pillars to improve the waste management in the country. The first pillar is waste minimization with a 5-year target of 40%, 10-year target of 55% reduction, and 15-year target of 70% reduction of waste disposed in landfills with the aim to reach in the long term "Zero waste going to Landfill." The second pillar is effective and sustainable waste services with the aim to deliver sustainable waste services to all South Africans, and the third pillar is to ensure compliance, enforcement, and awareness. South African provinces and municipalities (1) have to develop integrated waste management plans (IWMP) that integrate and optimize waste management services that support the achievement of national objectives. Figure 3.1, extracted from the South African Waste information system, presents the evolution of disposed waste tonnages in the eight metros from 2015 to 2021.

3.3 Waste Management Models and Decision-Support Tools

Waste management models are typically intended to assist decision-makers in developing integrated programs for implementing solid waste management alternatives. The majority of these decision support models are based on various methods such as cost-benefit analysis, life cycle assessment (LCA), environmental risk

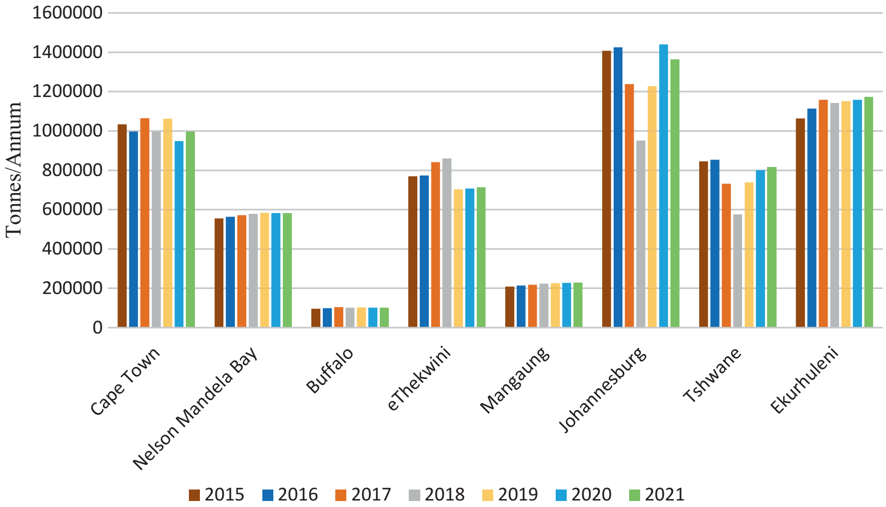

Fig. 3.1 Waste disposal data for the eight Metropolitan areas. (Source: SAWIC, 2021)

assessment, multi-criteria decision-making, and environmental impact assessment (Ghinea and Gavrilescu 2010). Several factors, including the quantity and composition of waste, socioeconomic, technological, topographical, and other variables, influence the efficiency or sustainability of waste management (Stevanović-Čarapina et al. 2019). Appropriately selecting waste processing technologies and efficient waste management strategies provide opportunities to maximize net energy production, reduce costs, increase waste diversion from landfills, reduce GHG emissions, and minimize other environmental impacts through energy and materials recovery (Levis et al. 2013).

Tables 3.1 and 3.2 compare the major features of LCA-based waste management tools most relevant to this study, including country of origin, methodological approach, database, waste stream, waste material categories, waste management process and technologies, indicators assessment, and source of references.

3.3.1 The Waste to Resource Optimization and Scenario Evaluation Model (WROSE)

The WROSE model is a zero-waste model developed in South Africa by UKZN in 2010 (Dell'Orto and Trois 2022; Kissoon 2018; Trois and Jagath 2011). The input data to the model is waste generation rate and waste composition (Table 3.2). A number of scenarios are embedded in the WROSE model, ranging from baseline (business as usual) to more complex optimized solutions (Fig. 3.2).

Table 3.1 Comparison of the waste management tools in terms of country of origin, methodological approach, database, and source of References. (Author: (Abera, 2022a))

Models	Country or region modeled	Methodological approach	Database	References
EASETECH	Denmark/ Europe	Based on the LCA and the impact categories of the LCIA methods EDIP97, EDIP2003, CML, USEtox, and IPCC 2007	Catalogues and process libraries are included in the database, such as material fraction, interface, constants and parameters, elementary exchanges, LICA (impact categories and methods such asEDIP97, EDIP2003, CML, USEtox and IPCC 2007) and material properties.	Zhao et al. (2015), Clavreul et al. (2014), Lodato et al. (2020, 2021) and Shah and Sattler (2020)
WRATE	UK/ Europe	Based on LCA in conjunction with ISO standards	Default waste stream categories, waste composition, waste property, impact assessment methods and electricity energy mix	WRATE (2014) and Shah and Sattler (2020)
GAINS	Austria/ Europe	Based on LCA	Energy database (electricity and district heat generation, energy use for primary fuel production, final energy use), activity data, control strategies, cost data and regional parameters	Amann et al. (2011) and IIASA (2021)
WARM	USA	Based on the LCA and the impact categories of the LCIA method (IPCC 2006)	Material properties, energy units, labor hours, wages, taxes and GHG emission factors	U.S.EPA (2016) and Shah and Sattler (2020)
WROSE	South Africa/ Africa	Based on life cycle assessment and multi-criteria decision analysis (MCA) methods	Emission factors, economic data, social and institutional data for South Africa	Kissoon (2018), Friedrich and Trois (2013a, b) and Trois and Jagath (2011)

Author: Abera (2022)

3.4 Methodology

3.4.1 Data Collection and Analysis: Waste Statistics and Socioeconomic Drivers

This study comprised of four different components in assessing potential zero waste strategies: a waste stream analysis to determine the waste composition and generation rates, a carbon emission/reduction assessment, a landfill airspace, and a waste

Table 3.2 Comparison of relevant waste management tools in terms of waste streams, waste fractions, and indicators (Author: (Abera, 2022a))

Models	Waste streams	Waste fractions	Waste management process and technologies	Indicators assessment
EASETECH	Municipal solid waste	Vegetable food waste, animal food waste, magazines, newsprints, advertisements, book, phone books, office paper, other clean paper, paper and carton containers, other clean cardboard, milk cartons (carton/plastics), juice cartons (carton/plastic/aluminum),kitchen towels, glass, plastic, metals and residuals	Source separation, collection, transportation, material recovery facility (MRF), anaerobic digester, incineration, composting, LFG flaring, LFG to electricity and also included life cycle cost	Global warming, stratospheric ozone depletion, human toxicity, cancer effects, human toxicity, non-cancer effects, particulate matter/respiratory inorganics, ionizing radiation, human health, photochemical ozone formation, human health, acidification, eutrophication terrestrial, eutrophication freshwater, eutrophication marine, eco-toxicity freshwater, resource depletion, mineral, fossil depletion, fossils and renewables
WRATE	MSW, household, bulky households commercial office waste, civic amenity, litter, street sweeping, co-collected trade waste, building waste and highways waste	Paper and card, plastic film, dense plastics, textiles, absorbent hygiene products, wood, combustibles, non-combustibles, glass, kitchen and garden waste, ferrous metal, non-ferrous metal, material <10 mm, electrical/electronic equipment and household hazardous waste	Collection and transportation, intermediate facilities, recycling, pyrolysis, anaerobic digestion, composting, gasification, incineration, autoclave, landfilling, landfill with flaring, landfill gas with electricity generation and also allows the user to define the new process and technologies	Climate change, acidification, eutrophication, freshwater eco-toxicity, human toxicity and abiotic resource depletion

(continued)

Table 3.2 (continued)

Models	Waste streams	Waste fractions	Waste management process and technologies	Indicators assessment
GAINS	Municipal solid waste (MSW) and industrial solid waste (INW)	Food, plastic, paper, glass, metal, wood, textile, and other waste, the industries included are food industry, pulp and paper, rubber and plastics, textiles, wood, and other manufacturing industries	Open burned, scattered and/or disposed to watercourses, unmanaged solid waste disposal site – low humidity – <5 m deep, unmanaged solid waste disposal site – high humidity – >5 m deep, compacted landfill, covered landfill, landfill gas recovery and flaring, landfill gas recovery and used, incineration (poor air quality controls), anaerobic digestion, composting and recycling	Fine particulates and ground-level ozone, risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated levels of ozone, as well as long-term radiative forcing. Also the model calculate PM, SO_2, NOx, VOC, NH_3, CO_2, CH_4, N_2O, HFCs, PFCs and SF6
WARM	MSW, construction and demolition waste and electronic waste	Aluminum cans, mixed paper, aluminum ingot, food waste, asphalt waste, mixed plastics, mixed recyclables, newspaper, branches, glass, office paper, PET, carpe, grass, phonebooks, HDPE, electronic waste, copper wire, LDPE, poultry, corrugated cardboard, leaves, PP, LLDPE, PS, dairy products, magazines, PVC, medium density fibreboard, steel cans, mixed electronics, textbooks, drywall, mixed metals, tires, mixed MSW, construction and demolition waste, mixed organics, wood flooring, mixed paper (general) and yard trimmings	Waste collection and transportation, source reduction, recycling, anaerobic digestion, incineration, composting, landfilling, landfilling with gas recovery (electricity generation and flaring), energy impact, and economic impact	Global warming potential, energy impact, economic impact (wage and taxes) and labor hours

WROSE	MSW and source separated streams (including industrial solid waste (INW); C&D waste; organic/biogenic waste etc.)	Newspaper, general mixed paper, scrap boxes and cardboard (K4), low density polyethylene (LDPE), high density polyethylene (HDPE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), glass, steel cans/tin, aluminum cans, biogenic food waste, garden refuse green, garden refuse wood, other	Landfilling, landfill flaring, landfill gas recovery and electricity generation, recycling, anaerobic digestion and composting	Global warming potential/CO_2eq Landfill-space savings Waste diversion rate Energy consumption Operating cost Capital cost/revenues Job creation Direct and indirect health risks Public involvement Environmental legislation License requirements Energy legislation Financial and administrative regulation

Author: Abera (2022)

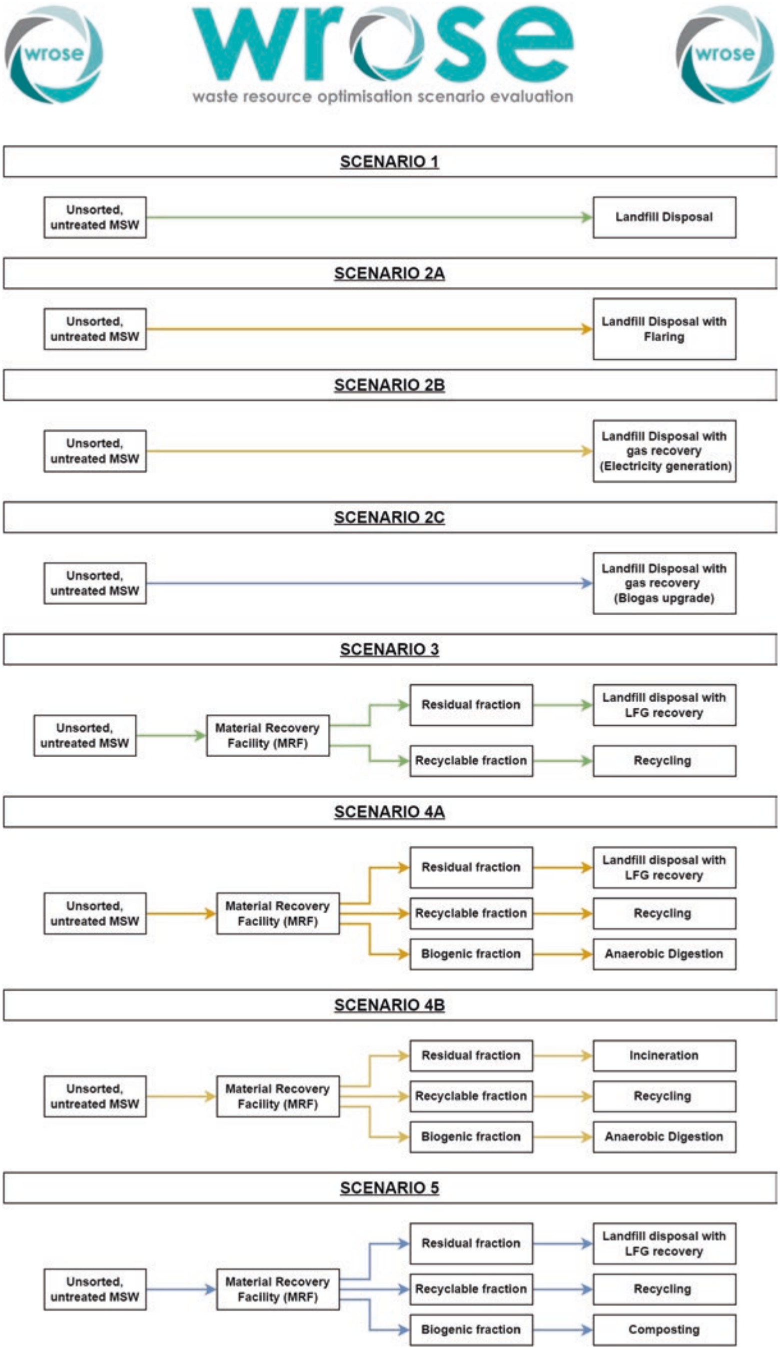

Fig. 3.2 WROSE scenarios schematic. (Dell'Orto and Trois 2022; Trois and Jagath 2011)

diversion rate assessment. Firstly, integrated waste management plans (IWMPs) were analyzed for each of the eight metros. Various datasets have been collected to estimate waste generation and disposal in South Africa's metropolitan municipalities. Reviewing the metro and province's integrated waste management plans (IWMP) and Integrated Development Plans (IDP), the South African waste information system, and different waste reports and published articles for South Africa was the initial step in the waste data collection process. Several data were collected, including population, population growth, income level, GDP, amount of garbage deposited into landfills, waste composition, waste collection rate, and the geographic location of landfill sites. The data analysis highlighted inconsistencies in the way waste categories are determined across the eight metros. To standardize the data forecasting for the study, specific waste streams were selected based on available literature as follows: mixed MSW, food waste, garden refuse, mixed paper, glass, mixed metals, LDPE, HDPE, PET, and others. Gaps in the available waste data and inconsistencies on how waste data is collected and reported in the IWMPs compounded with outdated waste characterizations for certain municipalities made it difficult to predict current waste generation trends.

3.4.2 Waste Generation

The total amount of waste generated by South African metropolitan municipalities is not precisely reported for all municipalities. Hence, quantity of waste disposed, collection rate, population, and income level have been utilized to estimate the waste generation. Equation 3.1 calculates the total waste generation for the municipalities for which waste disposal and diversion data is available:

$$W_G = \frac{\left(W_{DL} + W_D\right)}{W_C} \tag{3.1}$$

Where:

W_G is the waste generation (tons/year)
W_{DL} is the waste quantity disposed to landfills (tons/year)
W_D is the waste quantity diverted from landfills (tons/year)
W_C is the waste collection rate (%)

Equation 3.2 calculates the total amount of waste generated in municipalities where waste disposal and diversion rates are unavailable.

$$W_G = \sum\left(W_{gX} * P_X * 365 * 10^3,\ \text{for}\, X = 1,2,3\ldots N\right) \tag{3.2}$$

Where:

W_G is the total waste generation (tons/year)
W_{gX} is the waste generation per capita (Kg/day)
P_X is the population for each income level categories
X is the income level type

Due to the lack of information regarding the waste diversion rate, it is presumed that all collected waste is sent to landfills. Equation 3.3 calculates the total waste disposal quantity.

$$W_{DI} = W_G * C_R \tag{3.3}$$

Where:

W_{DI} is the total Waste disposal quantity (Tonnes/Year)
W_G is the Total waste generation (Tonnes/Year)
C_R is the Waste collection rate (percentage)

3.4.3 Carbon Emissions/Reduction Assessment

Using the waste fractions calculated above, the carbon emissions production or reduction potentials were calculated in $MTCO_2eq$ using emission factors from the IPCC (2006) as quoted in U.S.EPA (2016). The tier 1 approach was adopted, as this is the methodology for countries where national data and statistics are not available. The emissions factor for the biological treatment of biogenic MSW as listed by the guidelines is 1 g CH_4/kg of wet waste. Nitrous oxide emissions are assumed to be negligible, and an assumed 95% of methane is recovered for energy generation. GHG impacts are considered from the point at which the waste is discarded by the waste generator, to the point at which it is disposed, treated, or recycled into new products (U.S.EPA 2016). The emissions factors for the anaerobic digestion of biogenic MSW were developed using the same streamlined LCA approach as per the IPCC (2006) as detailed in Trois and Jagath (2011).

The equation below was used to determine the methane emissions or emission reduction potential in $MTCO_2eq$ for all municipalities:

$$\text{Waste quantity in tons} \times \text{emission factor} = \text{MTCO2eq} \tag{3.4}$$

The emissions produced/reduced were calculated for a 50-year period for each of the defined scenarios selected, using the appropriate emission factors.

3.4.4 Landfill Space Saving and Waste Diversion Rate

The estimation of landfill space savings from waste diversion is largely an empirical calculation, as the unique conditions and operational activities on site, specifically compaction of waste into landfill cells, influence the actual airspace saved. Actual landfill space savings (LSS) depend on the degree of compaction employed and the efficiency to which it is conducted.

$$\text{LSS} = \frac{tw}{C_{\text{ave}}} \tag{3.5}$$

where LSS = total landfill space savings, *tw* = total waste in tons, Cave = average compacted of MSW. The value for the compacted density of MSW was assumed to be 1200 kg/m^3 (1.2 tons/m^3).

The waste diversion rate refers to the total quantity of waste that is diverted from the landfill.

$$\text{WDR} = \frac{\text{total quatity of waste diverted}\left(\text{tons}\right)}{\text{total quantity ofwaste entering waste stream}\left(\text{tons}\right)} \tag{3.6}$$

3.5 Case Study: South African Metropolitan Municipalities

There are eight metropolitan areas in South Africa as detailed in Fig. 3.3 (Abera, 2022b). This chapter presents a closer look at the eThekwini Municipality as one of the most populous municipalities in the country.

The total national population in 2020 is estimated around 60 million (Statistics South Africa 2021). 57% of the population is concentrated in three provinces, of which 26% of the population resides in Gauteng, 19% in KwaZulu-Natal, and 12% in Western Cape. The remaining 43% is distributed in the rest of the provinces, having Northern Cape the lowest population (2% of the total national). National urbanization rate is estimated at 67% (UNDESA 2019). Gauteng is the most urbanized province (99%), followed by Western Cape (87%). KwaZulu Natal, North West, and Free State have an urbanization rate of 60% (Kamalie 2017). Limpopo is the less urbanized province with 20% of the population living in urban areas. Future estimates suggest that urbanization in South Africa will reach 79.8% by 2050 (UNDESA 2019). At a metropolitan level, Johannesburg is the most populated metro with 5,874,882 people, followed by Cape Town and eThekwini (Stats-SA 2021). Figures 3.4 and 3.5 show the MSW generation and composition in the metropolitan areas, respectively.

Figure 3.4 illustrates that MSW generation in the metropolitan areas is expected to grow to 9671 kt by 2050, which is 42% higher than the current amount. The

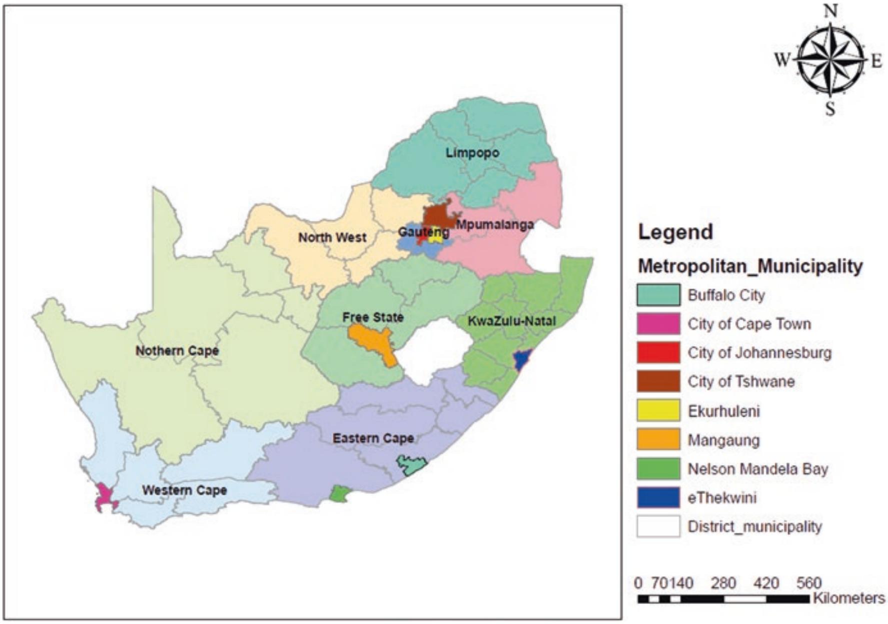

Fig. 3.3 Map of South Africa provinces and metropolitan municipalities. (Abera, 2022b)

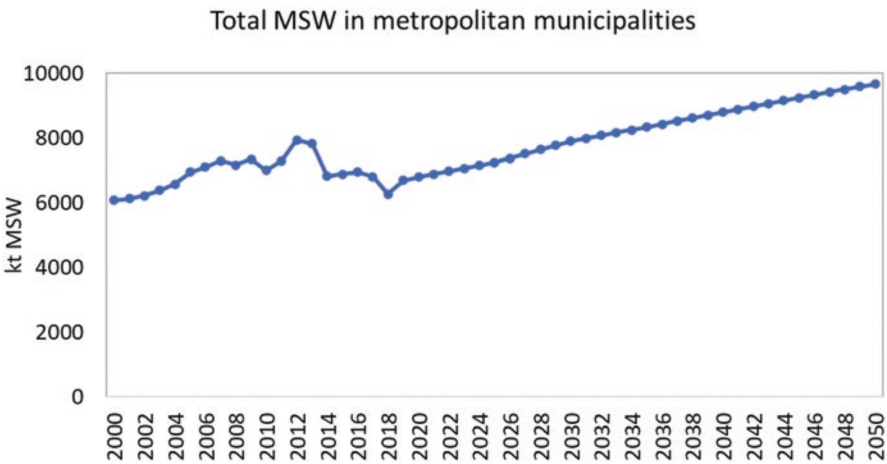

Fig. 3.4 Total MSW generation in metropolitan areas. (Source: IIASA 2022)

estimates in Fig. 3.5 suggest that the average estimated MSW composition of the metropolitan municipalities in 2020 is 42% food, 14% plastic, 13% paper, 6% glass, 3% metal, and 22% other waste (including textile, wood, diapers, some e-waste, among others). By 2050, shares are expected to be the same; however, as total MSW is increasing over time, it is likely that food waste will increase by 39% and other fractions between 42% and 45% compared to current levels.

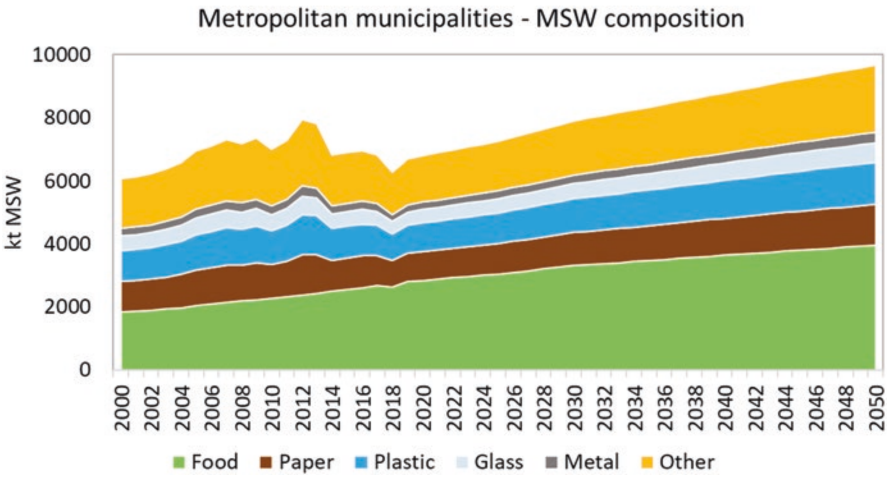

Fig. 3.5 MSW composition metropolitan areas. (Source: IIASA 2022)

3.5.1 Focus on the eThekwini Municipality – KwaZulu-Natal Province

The eThekwini municipality is located on the KwaZulu-Natal Province's southern, eastern coastline, with an approximate area of 2297 km^2. eThekwini has an approximate population of 3,158,000 million, consisting of 45% rural, 30% peri-urban, and 25% urban areas. eThekwini Municipality currently has two active general waste (MSW) landfill sites (i.e., Illovu and Buffelsdraai landfill sites) as well as two closed facilities (Bisasar Rd. and Marianhill landfills) that accept construction and demolition waste and garden refuse. The Buffelsdraai Landfill was commissioned in 2006. It has an estimated lifespan of 60 years. The landfill is surrounded by sugarcane farms and low-income housing (eThekwini 2016). The landfill covers 100 hectares of land and has a total capacity of 45 m^3. The Illovu landfill site is located south of Durban. The landfill is surrounded by sugarcane plantations and has an estimated lifespan of approximately 18 years. The landfill covers around 52 hectares of land.

In addition to the seven transfer stations within the municipality, there are a further fourteen garden waste transfer stations (DSW 2016). The transfer sites are open for public use, and some of the sites double as drop off centers for other recycling material (DSW 2016). The municipality also has two additional garden refuse landfill sites, Wyebank and Shallcross (DSW 2016). According to the Cleansing and Solid Waste Unit (CSW), the garden landfill site Wyebank reached capacity in 2016.

In the eThekwini Municipality, collection of waste is done by either DSW (Durban Solid Waste) or CBCs (Community Based Contractors) for collection of household waste at low-income and high-density settlements. The integrated waste management plan of the eThekwini Municipality (eThekwini 2016) shows that DSW provides households with a once per week waste collection service. Waste is collected from households, commercial areas, and industrial areas. Household

Table 3.3 Features of major sanitary landfill facilities in the eThekwini Municipality

Features	Bisasar Rd	Mariannhill	Buffelsdraai	Illovu
Status	Closed (2015)	Closed (2019)	Open	Open
Years to closure	0	0	50+	50+
Type of waste accepted	Since 2015 accepts only garden refuse, sand, C&D waste	Since 2019 accepts only garden refuse, sand, and C&D waste	MSW Garden refuse C&D waste	MSW Garden refuse C&D waste
Type of facility/ baseline scenario	Sanitary landfill with gas recovery and LFGTE facility for the generation of electricity (6 MW)	Sanitary landfill with gas recovery and LFGTE facility for the generation of electricity (1 MW)	Sanitary landfill with gas recovery and flaring	Sanitary landfill with gas recovery and flaring
Average received waste (t/day)	1000	300	2135	770
Area (m^2) for landfilling	0	0	25,020	0
Design airspace availability (m^3)	25,000,000	4,400,000	43,026,691	9,660,000
Approximate remaining airspace availability (m^3)	330,000	102,500	40,185,392	8,786,615
Remaining landfill years	0.9	0.9	52	31.7
Remaining design life (year)	1	1	52	32
Rehabilitated areas (m^2)	360,000	193,000	232,350	8500

waste is collected in DSW supplied black plastic bags, placed on kerbs on the required collection day. The use of orange and clear plastic bags is adopted for certain recyclable waste. In commercial and industrial areas, waste is collected either by CSW or by private waste collection companies. Table 3.3 presents the main facilities present in the eThekwini Municipalities and indicate the baseline scenarios adopted in the WROSE simulations.

The eThekwini metropolitan municipality shows an increasing trend of MSW per capita throughout the study period. MSW per capita is assessed at 196 kt/cap/year (0.54 kg/cap/day) in 2000, showing an increase of 12% in 2020 compared to 2000. By 2050, per capita MSW rate is expected to be 239 kg/cap/year (0.65 kg/cap/day) (Fig. 3.6). In Fig. 3.6, it can be observed that MSW per capita grew relatively faster than GDP per capita between 2006 and 2018. Projections show that after 2025, GDP per capita is expected to grow at faster pace compared to MSW per capita.

Figure 3.7 presents the total MSW generation in eThekwini. The total MSW generation in 2000 is assessed at 593 kt per year. In 2020, it is estimated that the MSW generation reached 873 kt which represents an increase of 46% compared to

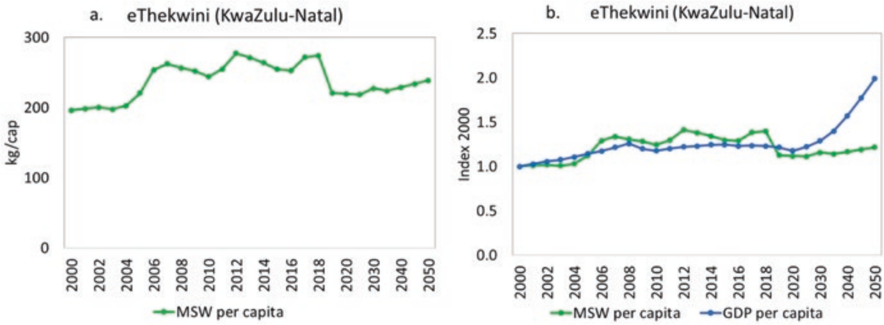

Fig. 3.6 (**a**) MSW per capita and (**b**) MSW per capita and GDP capita index 2000. (Source: IIASA 2022)

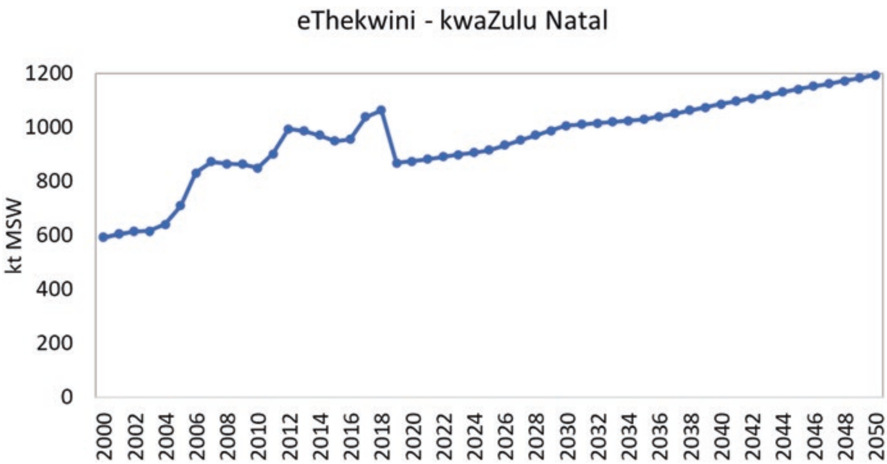

Fig. 3.7 Total MSW generation eThekwini. (Source: IIASA 2022)

2000. By 2050, it is estimated that MSW quantities will rise up to around 1193 kt. The annual growth rate between 2020 and 2050 is assessed at 1.05%.

Figure 3.8 shows the MSW composition in the eThekwini metropolitan area.

Figure 3.8 shows that food waste is the biggest fraction of the MSW stream, with 57% back to 2000 and estimated to be around 53% towards 2050 or 637 kt per year. Paper, plastic, and other mixed waste made up 34% of the MSW in 2000 and 36% in 2020. By 2050, it is estimated that these fractions will make up 37% of the total MSW generated, of which 10% is plastic, paper 14%, and mixed waste 13%. Figure 3.9 presents the total waste entering eThekwini landfills since 2001.

Figure 3.9 shows that prior to the commissioning of the Lovu landfill site and the Buffelsdraai landfill, that majority of the waste went to the Bisasar Road landfill site. When Bisasar reached the final stages of capacity, the amount of waste per annum reduced.

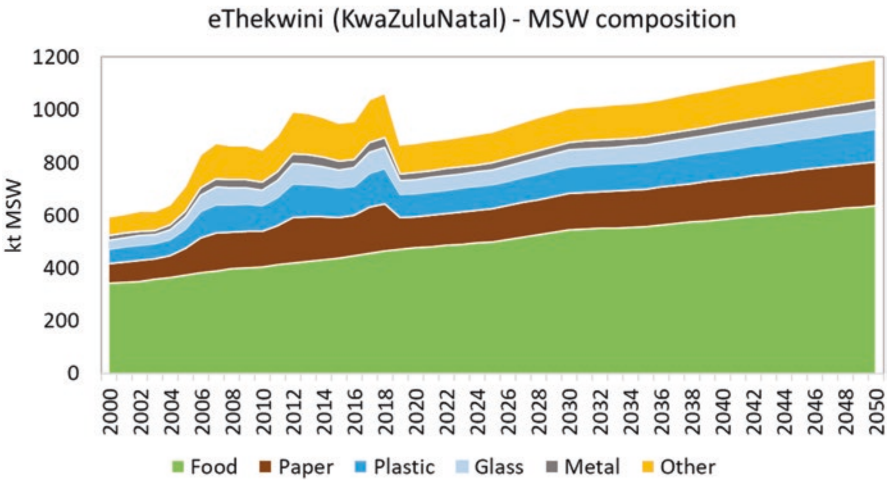

Fig. 3.8 MSW composition in eThekwini. (Source: IIASA 2022)

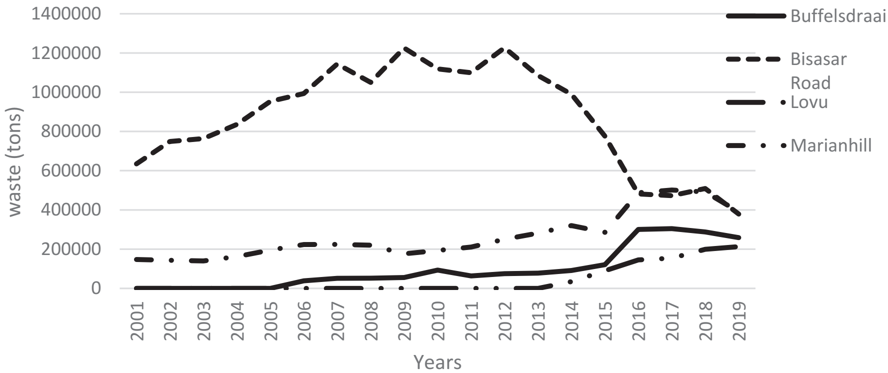

Fig. 3.9 Total waste entering eThekwini landfills in the past 19 years. (UKZN 2022)

3.6 Results and Discussions

From Fig. 3.2, the scenarios chosen for the eThekwini Municipality simulations in WROSE are as follows:

– Scenario 2B (BAU – baseline)
– Scenario 4B – Anaerobic digestion
– Scenario 5 – Aerobic composting

The simulation was run for Buffelsdraai and Lovu only, due to the other existing landfills having reached maximum capacity. The analysis was run using a projection until 2081, for both landfill sites. Although the Lovu landfill site has a lower life expectancy than the Buffelsdraai landfill site, the projection until 2081 is justified as

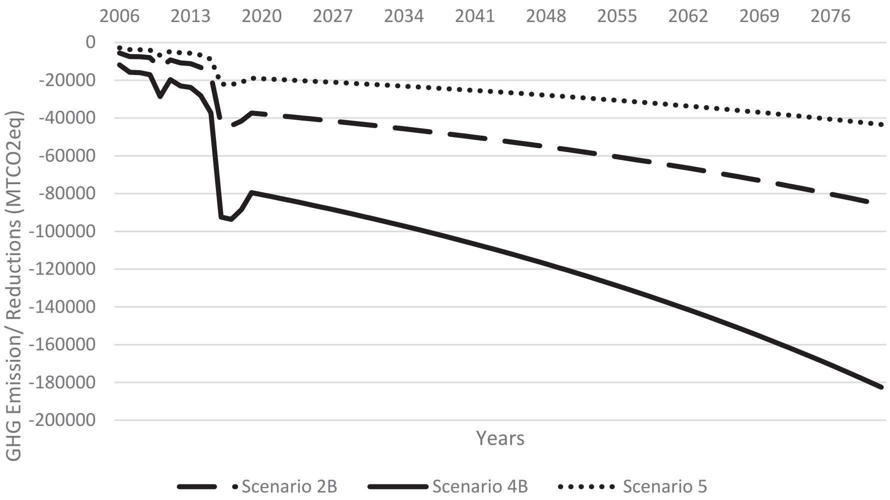

Fig. 3.10 GHG emissions reductions for the Buffelsdraai landfill

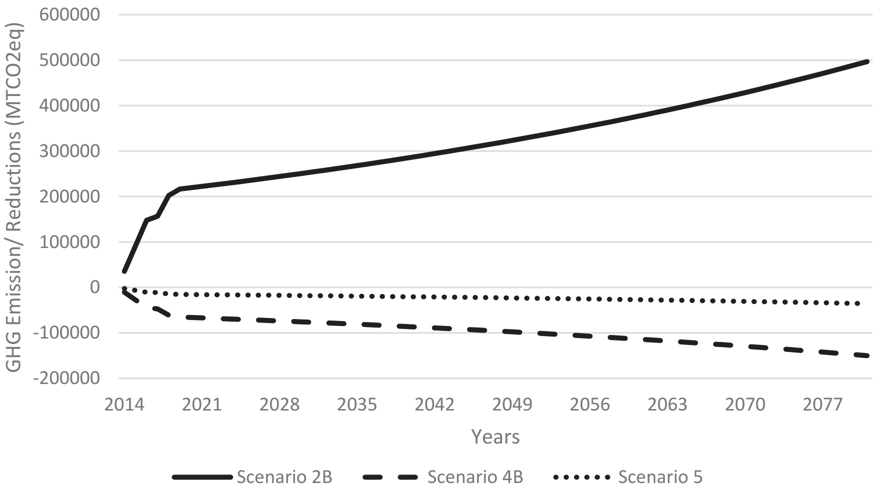

Fig. 3.11 GHG emissions reductions for Illovu landfill

adopting a sustainable waste management strategy will help divert waste and preserve the life expectancy. The carbon emissions/reductions for each landfill and their respective scenarios are shown and discussed below.

Figures 3.10 and 3.11 display the estimated future GHG reductions for each of the scenarios selected.

From Figs. 3.10 and 3.11, it is evident that scenario 5 (landfill gas recovery, recycling, and composting) is the least favorable waste management strategy as it

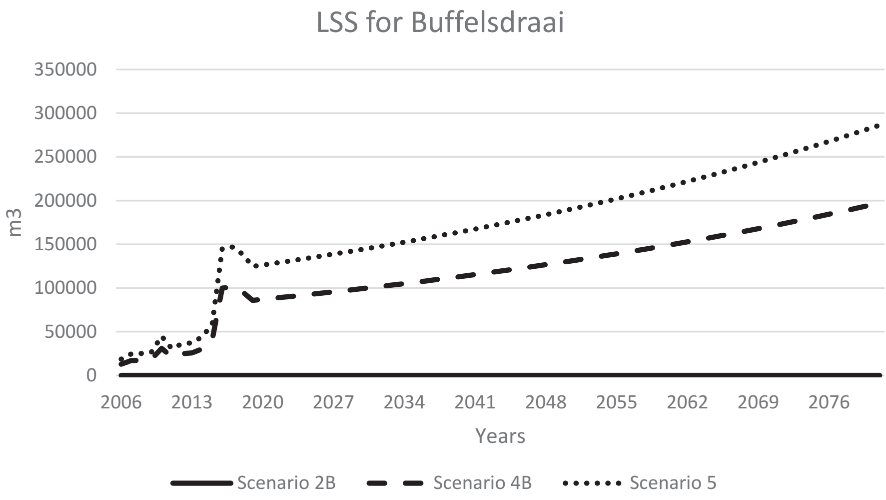

Fig. 3.12 Landfill Airspace Savings (LSS) for the Buffelsdraai Landfill

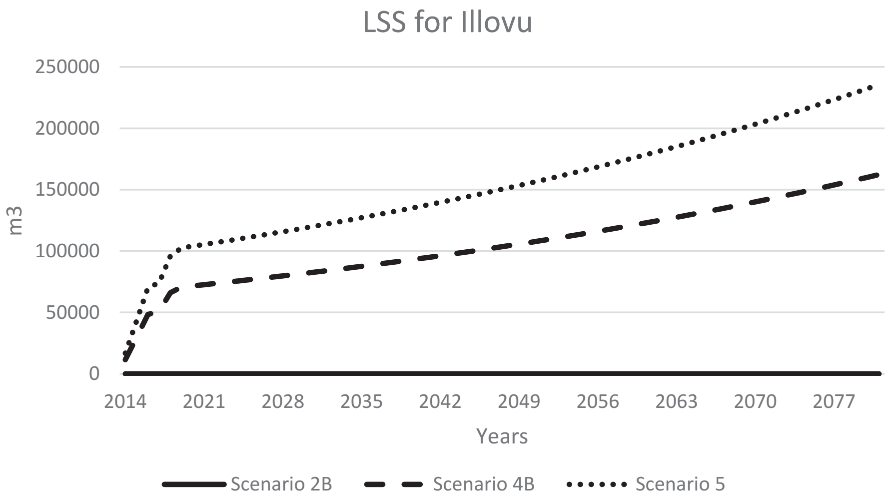

Fig. 3.13 LSS for the Illovu landfill

reduces the least amount of carbon emissions, while scenario 4B (landfill gas recovery, recycling, and anaerobic digestion) produces the most favorable results as it reduces the most amount of carbon emissions.

The landfill space savings are summarized below for the respective landfills and scenarios in Figs. 3.12 and 3.13.

From Fig. 3.12, scenario 2B offers no landfill space savings as no waste is diverted. Scenario 5 offers the highest LSS over the projection period due to waste

Table 3.4 Waste diversion rates

	Scenario 2B	Scenario 4B	Scenario 5
Buffelsdraai landfill	0	39.85%	57.85%
Lovu landfill	NA	39.85%	57.85%

Table 3.5 Waste diversion rates for food waste, biogenic waste, and garden refuse streams only

	Scenario 2B	Scenario 4B	Scenario 5
Buffelsdraai landfill	0	28.22	46.22
Lovu landfill	NA	28.22	46.22

streams like garden refuse and biogenic food waste being diverted. On average, scenario 5 saves up to 45% more landfill space than scenario 4B. This makes scenario 5 the most viable option in terms of promoting longevity to landfills. Figure 3.13 presents the projected landfill airspace savings for the Illovu landfill.

From Fig. 3.13, it is evident that scenario 5 is again the preferred scenario as it produces the most landfill airspace saved during the projection. The waste diversion rates (%) are summarized in Tables 3.4 and 3.5 for both landfills.

Both landfills have the same diversion rates for scenarios 4B and 5 as the same waste composition ratio was used for the simulations. From Tables 3.4 and 3.5, it is evident that scenario 5 offers the highest diversion rate as it diverts recyclables, biogenic food waste, as well as garden refuse.

3.7 Conclusions and Recommendations

The aims of this study were to find the most appropriate waste management scenario, which can be adopted by South African municipalities to reduce future GHG emissions while achieving a high waste diversion rate as well as determine how to optimize the conversion of biogenic food waste to a resource and thus improving environmental sustainability. The GHG emission/reduction results, simulated by the WROSE model, showed that scenario 4B (land fill gas recovery with electricity generation, recycling, and anaerobic digestion) was the most appropriate scenario as it provided the greatest GHG emission reductions for both landfills. The landfill space savings simulated by the WROSE model showed that scenario 5 (landfill gas recovery with electricity generation, recycling, and composting) offered the highest landfill space savings as well as the best diversion rates. Scenario 5 offered the highest waste diversion rates and landfill space savings. The main limitations of the study are related to the absence of a standardize outlining and reporting of MSW and the lack of available and reliable data. This limitation combined with the lack of available and reliable data sources forces the adoption of approaches to construct MSW datasets at metropolitan municipality level that somehow reflect past and current MSW generation and composition. As projections build on current MSW information, the assumptions will increase the uncertainty of the resulting future estimates. It is also important to note that the backcast and projections of waste generation and composition are just indicative as they build on only GDP per capita and do not consider any cultural traditions or latest technological developments that can influence the composition of MSW in the future.

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References

Y. Abera, *Map of South Africa provinces and metropolitan municipalities [Map]. 1:100,000. WGS 1984. Created using ArcGIS software* (2022a)

Y. Abera, *Integration of the Four Levels of Sustainability in the Framework of WROSE Model Focus on South African Municipalities (Unpublished doctoral dissertation)*. PhD, University of KwaZulu-Natal, Durban, South Africa (2022b)

M. Amann, I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj, Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environmental Modelling & Software, **26**, 1489–1501 (2011)

R. Couth, C. Trois, Carbon emissions reduction strategies in Africa from improved waste management: A review. Waste Manag. **30**, 2336–2346 (2010)

R. Couth, C. Trois, Waste management activities and carbon emissions in Africa. Waste Manag. (Elsevier Ltd) **31**(1), 131–137 (2011)

J. Clavreul, H. Baumeister, T.H. Christensen, A. Damgaard, An environmental assessment system for environmental technologies. Environmental Modelling & Software, **60**, 18–30 (2014)

CSIR, *Annual Report 2020/21* (CSIR, 2020)

DEA, Republic of South Africa, National Environmental Management: Waste Act [Online] (2008). Available https://www.dffe.gov.za/sites/default/files/legislations/nema_amendment_act59_0.pdf. Accessed 18 Nov 2022

A. Dell'orto, C. Trois, Considerations on bio-hydrogen production from organic waste in south African municipalities: A review. S. Afr. J. Sci. **118**, 1–8 (2022)

DEA, South Africa's Greenhouse Gas (GHG) Mitigation Potential Analysis. Pretoria, Department of Environmental Affairs (2014)

Department of the Environment And Energy, National Waste Report 2018 [Online] (2018). Available https://www.dcceew.gov.au/sites/default/files/documents/national-waste-report-2018.pdf. Accessed 18 Nov 2022

DFFE, The 7th National GHG Inventory Report, Department of Forestry, Fisheries and the Environment South Africa (DFFE, 2017)

DFFE, *Department of Environmental Affairs Annual Report 2018/19* (DFFE 2018)

DSW, DSW annual report (2016)

Ethekwini, eThekwini Municipality Integrated Waste Management Plan 2016–2021 (2016)

E. Friedrich, C. Trois, GHG emission factors developed for the collection, transport and landfilling of municipal waste in South African municipalities. Waste Manag. **33**, 1013–1026 (2013a)

E. Friedrich, C. Trois, GHG emission factors developed for the recycling and composting of municipal waste in South African municipalities. Waste Manag. **33**, 2520–2531 (2013b)

C. Ghinea, M. Gavrilescu, Decision support models for solid waste management – An overview. Environ. Eng. Manag. J. (EEMJ) **9**, 869 (2010)

IIASA, GAINS user guide tutorial for advance users. https://gains.iiasa.ac.at/gains/download/GAINS-tutorial.pdf, in: (IIASA), I. I. F. A. S. (ed.). Laxenburg, Austria (2021)

IIASA, South Africa: Assessment of Emissions Reduction Potential from Organic Municipal Solid Waste and Possible Mitigation Pathways (Unpublished report). Task 1 and 2 Inception Report International Institute for Applied Systems Analysis, Laxenburg, Austria (2022)

IPCC, Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories Volume 5 Waste [Online] (2006). Available https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html. Accessed 18 Nov 2022

Y. Kamalie, *Spatial Distribution of the Population in South Africa: A Statistical Approach* (University of the Western Cape, 2017)

S. Kissoon, *The Advancement of the Waste Resource Optimization and Scenario Evaluation Model: The Inclusion of Socio Economic and Institutional Indicators* (Master of Science in Civil Engineering, University of Kwa-Zulu Natal, 2018)

S. Kissoon, C. Trois, Application of WROSE the model to municipal integrated waste management plans: Focus on socio-economic and institutional indicators, in *Sardinia 2019, 17th International Waste Management and Landfill Symposium*, (Sardinia, Italy, 2019)

S. Kissoon, C. Trois, Plastic waste management for landfill space savings and GHG emission reduction in the garden route district municipality, in *Wastecon 2022*, (2022)

K. Komen, N. Mrembu, M. van Niekerk, The role of socio-economic factors, seasonality and geographic differences on household waste generation and composition in the City of Tshwane, in *Proceedings of the 23rd WasteCon Conference*, (Johannesburg South Africa, 2016), pp. 17–21

J.W. Levis, M.A. Barlaz, J.F. Decarolis, S.R. Ranjithan, A generalized multistage optimization modeling framework for life cycle assessment-based integrated solid waste management. Environ. Model. Softw., 51–65 (2013). https://doi.org/10.1016/J.ENVSOFT.2013.08.007

C. Lodato, D. Tonini, A. Damgaard, T. Fruergaard Astrup, A process-oriented life-cycle assessment (LCA) model for environmental and resource-related technologies (EASETECH). Int. J. Life Cycle Assess. 25, 73–88 (2020)

C. Lodato, B. Zarrin, A. Damgaard, H. Baumeister, T.F. Astrup, Process-oriented life cycle assessment modelling in EASETECH. Waste Manag. 127, 168–178 (2021)

K.V. Shah, M.L. Sattler, Development of solid waste management decision making life cycle assessment tool for growing economies: A state-of-the-art (2020, October)

SAWIC, Waste Policy and Regulations, . In: DEPARTMENT OF ENVIRONMENT, F. A. F., SOUTH AFRICAN WASTE INFORMATION CENTRE (SAWIC) (ed.). (2016)

SAWIC, 2021. South African Waste INformation Centre. www.sawic.environment.gov.za

STATS-SA, Department of Statistics Republic of South Africa. General Household Survey, 2021 [Online]. Available: https://www.statssa.gov.za/?p=15482 [Accessed November 18 2022] (2021a).

Statistics South Africa, Statistics South Africa, Republic of South Africa. POP302-mid-year population estimates (2021). Retrieved 2022

H. Stevanović-Čarapina, J. Stepanov, D. Prokić, Model for evaluating municipal waste management system applying the LCA: Part I: Review of LCA software. Recycling Sustain. Dev. **12**, 43–51 (2019)

C. Trois, R. Jagath, Sustained carbon emissions reductions through zero waste strategies for South African municipalities, in *Waste Management*, (INTECH Publications, 2011) ISBN 978-953-307-179-4

C. Trois, O.T. Simelane, Implementing separate waste collection and mechanical biological waste treatment in South Africa: A comparison with Austria and England. Waste Manag. **30**, 1457–1463 (2010)

U.S. EPA, *Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)* (U.S. EPA, 2016), p. 129

UNDESA, *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. [Online]. [Accessed] (2019)

UNEP, *South African Municipal Waste Management Systems: Challenges and Solutions* [Online]. United Nations Environment Programme. Available: https://wedocs.unep.org/bitstream/handle/20.500.11822/33287/SAM.pdf?sequence=1&isAllowed=y [Accessed June 2022 2022] (2018).

UKZN, South Africa: Assessment of Emissions Reduction Potential from Organic Municipal Solid Waste and Possible Mitigation Pathways (Unpublished report). Task 1 and 2 Inception Report University of kwaZulu-Natal, Durban South Africa (2022)

WMO, 2018 Annual Report World Meteorological Organization (WMO) for the Twenty-first Century (2018)

Wrate, Waste and Resources Assessment Tool for the Environment user manual V3. **3**, 264 (2014)

Y. Zhao, W. Lu, A. Damgaard, Y. Zhang, H. Wang, Assessment of co-composting of sludge and woodchips in the perspective of environmental impacts (EASETECH). *Waste Management*, **42**, 55–60 (2015)

Chapter 4
Efficiency of Leachate Treatment Costs in Latin America

Mario A. Gandini

4.1 Introduction

In Latin American countries, municipal waste management (MSW) strategies are strongly oriented toward final disposal in terms of landfilling. Other SWM important alternatives which could be implemented such as waste treatment, material, or energy recovery are still lacking or have been implemented on a small scale, only. What is more, in the last two decades, important efforts have been made within the region in order to shift final disposal practices from open dumps to engineered landfills. In countries like Colombia and Brazil, the proportion of population whose solid waste is disposed of in landfills has significantly increased (Manzi et al. 2020).

This shift from open dumps to engineered landfills could be regarded as a step in the right direction in terms of reducing the potential environmental impacts associated to the generation of MSW. In fact, the final disposal of MSW can be regarded as a critical step in solid waste management, since it is in this phase that the most significant environmental impacts can be originated, especially those involving long-term effects on sensible environments. All the steps which precede final disposal, such as source separation, recollection, transport, treatment, materials, and energy recovery, have direct effects on this final and definitive, in sustainable terms, stage. In other words, whatever is done in the previous steps affects the potential environmental impacts that can be brought about by MSW final disposal (Wiszniowski et al. 2006).

In Latin America landfilling is by far the most commonly used technological solution for the final disposal of MSW. Huge efforts have been made in several countries in order to shift from open dump practices to engineered landfills, and yet the implementation of treatment and mass and energy recovery from waste are

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incipient. As mentioned above this fact implies that, given that MSW reaches landfills without any kind of previous treatment or recovery, the associated environmental impact potential is certainly high. Most of this environmental impact potential, including long-term concerns, is related to leachate production and treatment. Leachate treatment becomes then a key issue in the solid waste management strategies in the Latin American context. Failing to fulfil the environmental leachate treatment demands would mean that the shift from open dumps to sanitary landfills has only translated the problem from a diffuse pollution issue to an end-of-tube one. What is more, it has to be highlighted that the long-term environmental impacts of a landfill without proper leachate treatment could be higher than those associated to leachate produced in open dumps (Cossu and Stegmann 2019). As a consequence, in Latin America, one of the main concerns in MSW management is leachate treatment, and, particularly, leachate treatment costs (Gupta and Singh 2007). The increment in MSW service tariff which can derive from implementing leachate treatment is on the top of the agenda of MSW management companies, environmental authorities and regulators, and state entities. The point is how to meet environmental standards in terms of leachate discharges (treatments effluents) quality while attending the requisite of efficient costs.

Leachate treatment cost efficiency depends on treatment objectives. How environmental authorities in Latin American countries set environmental standards, and in this case, leachate treatment objectives remains an open issue. Generally environmental standards or permissible discharges limits are taken from other continents without taking into account the regional and local specificities. In this sense, a fundamental aspect which very often is not considered for setting leachate treatment objectives by environmental authorities is the pollution assimilative capacity of water-receiving bodies. This can obviously lead to inefficient leachate treatment cost. On the one hand, it could be the case that the defined treatment objectives do not recognize the pollution assimilative capacity of receiving water body, and in consequence the contaminant removal requirements are overstated leading to cost inefficiency. On the other hand, it could be also the case that the leachate treatment objectives arbitrarily defined are lax and do not recognize the scarce or inexistent pollution assimilative capacity of the receiving water body, and even reaching the effluent quality that the objectives imposed the environmental impact cannot be avoided, leading again to inefficient costs.

This work looks at the efficiency of leachate treatment costs in Latin America aiming at providing a conceptual framework to understand the concept of cost efficiency applied to leachate treatment and at showing some study cases in which some leachate treatment expediencies in Latin America are assessed from a cost efficiency approach. The efficiency of leachate treatment costs depends on, firstly, the achievement of the proposed treatment objectives and, secondly, on the minimum total cost of achieving those. Thus, efficient leachate treatment costs will be those associated to the technologies which allow fulfilling the treatment objectives at minimum investment capital and operational expenses. It is then proposed that regulators state bodies should recognize efficient costs in the MSW tariff structure.

4.2 Environmental Impacts Associated to a Shift from Open Dumps to Landfills

Whatever is done in the MSW management has an effect on the potential environmental impacts associated to the final disposal. Final disposal of MSW can be regarded as a critical step in solid waste management, since it is in this phase that the most significant environmental impacts can be originated, especially those involving long-term effects on sensible environments. All the steps which precede final disposal, such as source separation, recollection, transport, treatment, and mass and energy recovery, have direct effects on this final and definitive, in sustainable terms, stage. In other words, whatever is done in the previous steps affects the potential environmental impacts that can be brought about by landfilling.

In most Latin American cities, landfilling is the only technological option of MSW management. It means that no treatment or any kind of recovery is implemented before waste is disposed of. MSW in Latin America is characterized by a very strong organic matter fraction. Biowaste, as it is often named, represents more than 60% of the total MSW produced in an urban area. Since biowaste is by far the biggest MSW fraction that is landfilled, the generation of biogas and leachate is an important issue in terms of originating environmental impacts. While biogas may generate greenhouse gas emissions (CO_2 and CH_4) and eventual health risks (COVs), leachate can impact water resources (groundwater, superficial water bodies) and soils (Kjelsen et al. 2002). Leachate composition in the case when biowaste is the main fraction of the waste mass disposed of is strongly marked by high organic matter and ammoniacal nitrogen concentrations.

The switch from open dumps to landfills that is currently taking place in Latin America is certainly an improvement in MSW practices. However, it represents a challenge, in terms of dealing with leachate treatment and discharges, for both solid waste services operators and environmental authorities. For solid waste services operators, it means that the technical and economic requirements must be met, while environmental authorities have to be capable of setting appropriate leachate treatment standards and controlling the operation of the whole landfill.

The magnitude and spatial scale of environmental impacts associated to landfilling depend mainly on the composition of leachate, which is highly variable. It depends on the following factors: (i) weather conditions in the area of the landfill location (precipitation, temperature, evaporation); (ii) landfill type and operation characteristics; (iii) physical, chemical, and microbiological characteristics of confined waste; and (iv) age of confined waste. The latter factor plays a key role in the temporal variability of leachate, which in turn constitutes one of the most important challenges for treatment. The different substances present in leachate can be classified into four groups: (i) dissolved organic matter, (ii) inorganic macro-components and heavy metals, and (iv) xenobiotic organic compounds (Kjelsen et al. 2002). Each of the groups of substances mentioned can cause specific environmental impacts, with different extensions in space and time, whether for deficiencies in the landfill barriers or in leachate treatment. When the latter situation occurs, environmental impacts take place when leachate comes into contact with the ground or with a surface water source, altering some or some quality characteristics of these environmental matrices. These environmental impacts may even constitute a health risk concern in the event that a receiver (a population or community) is exposed to the substances mentioned (Watts and Teel 2005).

The environmental impacts associated to the presence of dissolved organic matter (measured as BOD and COD) refer to effects on water sources exposed to organic loads. The most notorious environmental impact is the decreased of dissolved oxygen due to the aerobic biological oxidation of the biodegradable fraction (Kjelsen et al. 2002). High values of BOD, such as those that occur during the acid phase of operation of a landfill leachate, indicate that this is likely to cause an impact on a superficial water source. In contrast, when the ration BOD/COD approaches zero, typical condition of mature leachate (methanogenic phase) that is for small values of BOD, the leachate potential to cause this impact is dramatically reduced.

Among inorganic macro-components, undoubtedly the greatest health and environmental importance is nitrogen. Given the anaerobic conditions occurring within a landfill, the predominant form of nitrogen corresponds to ammonia nitrogen ($N\text{-}NH_4^+$), and no changes occur in the concentrations reported between the acid phase and methanogenic phase. This means that in the methanogenic phase and even in the landfill after-care period, concentrations of ammonia nitrogen do not decrease, which makes this substance the main concern given its huge potential impact on water sources (Yusof et al. 2010). The environmental impacts that may cause ammonia nitrogen are related to the consumption of dissolved oxygen (oxidation of ammonia nitrogen by nitrification), with toxicity and eutrophication (the latter also caused by other species of nitrogen).

The presence of heavy metals in leachate has always received great interest because of the danger that they might represent in terms of public health. However, in general the concentrations of heavy metals in leachate reported in the literature are low (Ehrig and Robinson 2011). During the acid phase, due to the lower values of pH which increase the solubility of the metals, the highest concentrations of these substances are found, while in the methanogenic phase, neutral pH favoring the phenomena of adsorption and precipitation within landfill, an as a consequence, low concentrations of heavy metals in mature leachate are found.

Xenobiotic organic compounds correspond to aromatic hydrocarbons, halogenated hydrocarbons, phenols, aliphatic chlorinated compounds, pesticides, and others. Many of these compounds are considered a priority due to the negative effects they can have on aquatic ecosystems due to their potential toxicity. However, young leachate concentrations for these compounds reported in the literature are generally low. In the long run, it is expected that concentrations of xenobiotic organic compounds are reduced as a result of biological degradation processes (Kjelsen et al. 2002).

Leachate treatment is then a key issue from an environmental perspective for Latin America MSW practices. Failing to meet the challenge in which leachate treatment arises, given the shift from open dumps to sanitary landfills in Latin America, would mean that there has only been a change from diffuse pollution problems to an end-of-tube one that could even have more environmental consequences in the long term.

4.3 Leachate Treatment Objectives and Associate Costs

The costs of treating leachate are directly associated to the treatment objectives or effluent standards that have to be met. While the rationale for setting leachate effluent standards is to protect the receiving water body from harmful contaminant concentrations, the setting of leachate treatment objectives greatly varies from country to country. To make an example in the Latin American context, it cannot be the same, in environmental and economic terms, to discharge the effluent of a leachate treatment plant into the Amazon River than in the Magdalena River. Leachate effluent standards must recognize the difference.

Thus, the variables that determine the leachate treatment costs are, firstly, the quantity and quality of leachate produced and, secondly, the treatment objectives set to meet effluent standards by the respective environmental authority. Depending on the contaminants to be treated, the costs will be related to investment and operational conditions of specific technologies:

- Organic matter susceptible to biological oxidation: predominates in young leachate. For treatment biological oxidation technologies are required, either aerobic- or anaerobic-based.
- Refractory organic matter: predominates in mature leachate. Biological treatments are not effective for treatment, and therefore advanced methods such as chemical oxidation, adsorption, and membrane filtration are required.
- Ammoniacal nitrogen: present throughout the landfill operation, and in each of its phases, it requires alternating aerobic and anaerobic environments for the oxidation of ammonia nitrogen (nitrification) and subsequent reduction of nitrates into molecular nitrogen (denitrification). In the case that the biological treatment is not sufficient to reach the effluent quality standards, membrane filtration technologies or the so-called air stripping maybe be required.
- Heavy metals: in general are expected in low concentrations. Physical-chemical treatment is suitable.

In Table 4.1 it is shown the expected leachate treatment efficiency of some technologies, taking into account the age of leachate. Regarding leachate treatment objectives in terms of discharge effluent quality, there are big differences between countries as it is shown in Table 4.2.

Table 4.1 Some technologies for leachate treatment

Technology	Treatment efficiency		
	Leachate age		
	Young	Medium	Mature
Leachate transfer			
Combination with DWW	Good	Aceptable	Deficient
Recirculation	Good	Aceptable	Deficient
Ponds	Good	Aceptable	Deficient
Biological treatment			
Aerobic processes	Good	Aceptable	Deficient
Anaerobic processes	Good	Aceptable	Deficient
Physical-chemical treatment			
Coagulation/Floculation	Deficient	Aceptable	Aceptable
Chemical precipitation	Deficient	Aceptable	Deficient
Adsorption	Deficient	Aceptable	Good
Chemical oxidation	Deficient	Aceptable	Aceptable
Air stripping	Aceptable	Aceptable	Aceptable
Membrane filtration			
Ultrafiltration	Deficient	Deficient	Deficient
Nanofiltration	Good	Good	Good
Inverse osmosis	Good	Good	Good

Table adapted from: Renou et al. 2008, landfill leachate treatment, review and opportunity

Table 4.2 Permissible effluent limits for treated leachate discharges in some countries

	Country				
Parametro (mg/L)	USA	Germany	France	Hong Kong	South Korea
COT	NA	200	120	200	50
BOD	220	20	30	800	NA
NH3-N	10	NA	NA	5	50
Total N	NA	70	30	100	150
Total P	NA	3	NA	25	NA
Cd (II)	0,01	0,1	NA	0,1	NA
Cr(III)	NA	0,5	NA	0,1	NA
Cr(VI)	0,05	0,1	NA	NA	NA
Ni(II)	0,013	1	NA	0,6	NA
Pb(II)	0,03	0,5	NA	NA	NA
Cu(II)	0,07	0,5	NA	1	NA
Zn(II)	0,3	2	NA	0,6	NA
ag(I)	0,05	NA	NA	0,6	NA

Table adapted from Kurniawan et al. 2006, physicochemical treatments for removal of recalcitrant contaminants from landfill leachate

4.4 Cost Efficiency in Leachate Treatment

It has been pointed out that according to the environmental impacts, which leachate may bring about in accordance with its composition, treatment objectives have to be set in terms of the required quality of the effluent. Ideally, these treatment objectives should be compliant with the local characteristics of the specific situation. Among the local characteristics, the receiving water body plays an essential role. Thus, the treatment objectives must guarantee that the waster uses of the receiving water body, which have previously been established by territorial and environmental planning policies, are not threatened by the discharge of the treatment system effluent.

In order to set leachate treatment objectives in line with an analytic procedure, it is then necessary to carry out environmental studies which take into account permanent monitoring of the quality of the receiving water body and, above all, simulation of transport and fate of contaminants present in leachate. From these studies it is possible to estimate the assimilative capacity of the water-receiving body, bearing in mind the water quality demanded for other uses of the source. Once the assimilative capacity of the receiving water body is estimated for the different contaminants present in leachate, the objectives of leachate treatment can in consequence be set, as well as how they have to be adjusted in time, in accordance with the expected changes in leachate production, both in quantity and quality.

The mentioned analytical procedure is, however, hardly implemented in Latin American countries, given the lack of environmental information regarding water bodies and basins and the costs of the environmental studies involving simulation of transport and fate of contaminants. It is unfortunately the case that leachate treatment objectives are very often arbitrarily set, following maybe some international effluent discharge guidelines. This situation can easily lead to strong inefficiencies in the costs of leachate treatment.

The efficiency of leachate treatment is related to, on the one hand, meeting the treatment objectives in terms of effluent discharge quality and, on the other hand, the minimum cost criterion associated to the implementation of technologies capable of reaching the corresponding contaminant removal. It can therefore be argued that efficient leachate treatment costs will be those incurred while the treatment system reaches the effluents discharge quality at minimum cost. National regulatory tariff policies should thus be oriented toward the achievement of efficient leachate treatment costs.

In this context, two situations may lead to cost inefficiency in leachate treatment. Firstly, when the treatment objectives are arbitrarily set without taking into consideration the assimilative capacity of the receiving water body, it could happen that the contaminant removal entailed to the treatment system is extremely high. This first situation may occur when the contaminant of interest is organic matter and the receiving water body is a large-flow river. Secondly, when the arbitrarily set treatment objectives are so lax and do not recognize the low (or even inexistent) assimilative capacity of the receiving water body. This means that even in the case that the effluent discharge quality is met by leachate treatment, serious environmental damage can be brought about upon the water source. This second situation may take place when ammoniacal nitrogen is discharged into a small-flow river.

This argument is illustrated in Fig. 4.1, where pollution units are related with unitary costs of treating pollution. While pollution units associated to a specific contaminant of interest present in leachate are shown on the abscissa (e.g., kg of BOD or N-NH_3), the cost of treating one unit of that pollution is shown in the ordinate axis. For analysis the initial point corresponds to the total number of pollutant units (UCi), where there has not been any treatment. The negative slope of the straight line implies that as leachate is treated, the cost of treating a new unit of pollution increases. This feature is evident in the costs of so-called tertiary treatment or polishing. Now, assuming that it has been possible to quantify the assimilative capacity of the water source and that it corresponds to UC *, one can state that the efficient costs for the treatment of leachate are those corresponding to treat from UCi until UC *. The costs associated with any treatment to a different level to UC * are by definition inefficient: firstly, at the left of UC *, inefficiency arises because leachate is being treated at extremely high contaminant removal rates, ignoring the assimilative capacity of the receiving source (UCm), and, otherwise, at the right of UC *, inefficiency occurs because the level of treatment is insufficient and therefore is causing a negative impact on the water quality of the receiving source (UCn).

Treatment costs can finally be expressed as a function of the kilograms or tons of the interest contaminant to be removed from leachate (Fig. 4.2). Although it is generally not easy to access to related information with real initial investment and operation and maintenance costs of leachate treatment systems, if this difficulty could be overcome, it would be useful to construct curves such as those presented in the figure below (Fig. 4.2), where the unit costs of removing a contaminant of concern for different treatment trains are presented. The curves show (for sake of simplicity straight lines are drawn) for a specific situation the unit costs of treatment, i.e.,

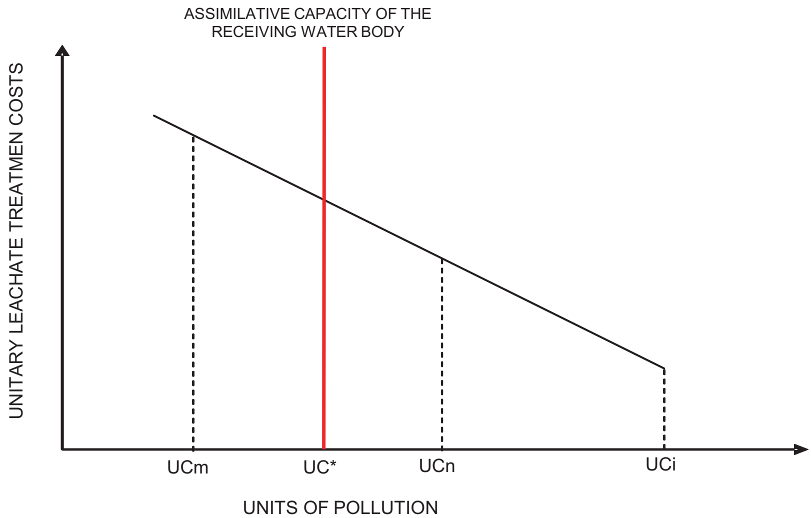

Fig. 4.1 Unitary costs of leachate treatment

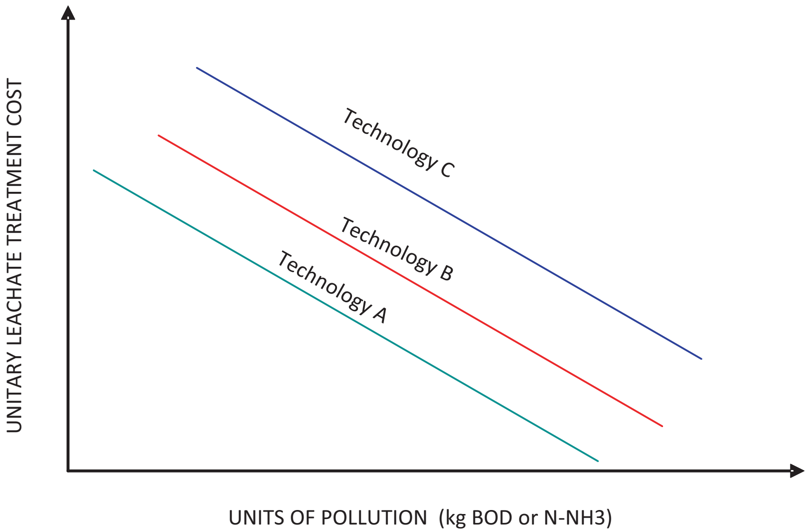

Fig. 4.2 Unitary costs of different leachate treatment technologies

the cost associated to the removal of 1 kilogram of BOD, NH_3 (or any pollutant) for different leachate treatment trains (Technology A, B or C).

To determine the total leachate treatment cost for a particular situation, once established the type of load in question (organic load or nitrogen load, for example) it is appropriate to include in the analysis the treatment objectives, in accordance with the assimilative capacity of the receiving water body, as illustrated in Fig. 4.3. UCi corresponds to zero time, or starting point, where there is no leachate treatment, while UC * units correspond to meeting the treatment goals established by the environmental authority. The total cost is found by calculating the area under the curve.

4.5 Technology Selection to Achieve Cost-Efficient Leachate Treatment Costs

At the moment there is a very wide range of technologies that can meet the most demanding objectives of leachate treatment, and it will be the responsibility of operators to select those technological alternatives to achieve the pollutants removal efficiencies required by environmental authorities at reasonable costs. It is emphasized at this point the importance of requiring MSW service operators to conduct rigorous and judicious selection of technology for leachate treatment processes. Any technology chosen for leachate treatment should fulfil the following conditions:

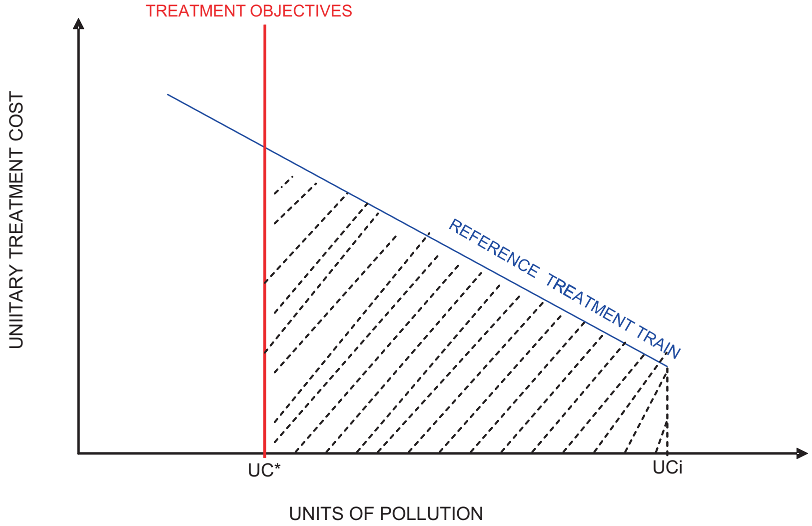

Fig. 4.3 Total leachate treatment cost

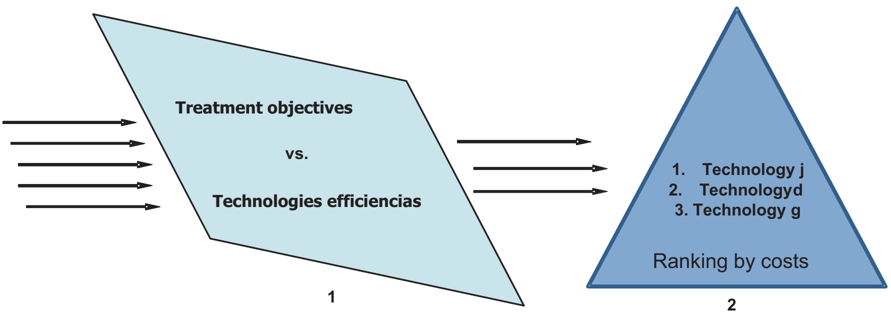

Fig. 4.4 Simplified model for leachate treatment technology selection

- Meeting the leachate treatment objectives.
- The costs of the technology (investment and operational costs) should be equal to or lower than other technological options which also allow achieving the objectives of treatment.

With the above purpose, it is suggested to encourage the implementation of a simplified model for selecting treatment technology such as that presented in the figure below. Technological options (treatment trains) are represented by arrows, while the selection criteria correspond to triangles or rectangles, as it is shown in Fig. 4.4. The selection criteria are the filters through which the various technological options can access or not. The passage of a technological option through a criterion depends on whether it satisfies or not certain predetermined criteria. The purpose is to carry out a selection process by which the chosen technological option guarantees the achievement of cost efficiency. In this simplified model of technology, selection criteria are recognized as follows:

- Criterion 1A. Treatment objectives: are defined in terms of what the ultimate destination or use of effluent treatment. Specifically they will be oriented removal of specific contaminants such as organic matter and ammonia nitrogen.
- Criterion 1B. Treatment efficiencies to ensure the goals of treatment: refers to the efficiency of each technology to remove pollutants of concern that are subject to the goals of treatment options. At this point the area available for the treatment plant plays a key role when evaluating extensive technologies compared with intensive technologies.
- Criterion 2 Ranking for costs: those technologies that pass through Criterion 1 are ranked according to the total treatment costs (including investment, operation, and maintenance).

4.6 Cases of Study

In the Latin America context, there are a few cases when the process of leachate treatment technology selection has not been carried out following the exposed criteria. This situation has led to inefficiencies in leachate treatment cost, putting at risk both MSW management and environmental sustainability. Three examples are mentioned in dealing with these cost inefficiencies.

- Study case 1: A landfill for a city of 250,000 inhabitants in Colombia. It was found efficient costs for the build leachate treatment plant. Further expansion or additional treatment units to increase contaminant removal will fall into inefficient costs. There is no correspondence between the treatment requirements in the environmental license required to permit the effluent discharge on the river and the selected and designed technological option. That is, the chosen treatment train allows the removal of biodegradable organic matter above 95%, exceeding the 85% set by the environmental license.

In terms of cost-effectiveness improving from 85% to 95% removal efficiency of BOD5 represents a significant increase of the costs not reflected in environmental benefits in terms of water quality in the receiving source. In other words, increasing the removal of organic matter does not lead to any benefit at the water source, while significantly increasing treatment costs.

- Study case 2: A landfill for a city of 550.000 inhabitants in Colombia. It was found inefficient costs associated to some treatment units such as active carbon adsorption unit and disinfection (coloration) unit. The leachate treatment plant built and operating in the landfill comfortably ensures compliance with treatment goals. The theoretical efficiency of the treatment train is above 90% efficiency of organic matter and suspended solids.

In the documentation submitted by company which operates the landfill, there is no justification for building such a robust plant. That is, there is no analysis indicating the environmental benefits of achieving greater than 95% removal of the organic load, as observed in the last monitoring conducted in the influent and effluent of the treatment plant. Thus, in the absence of an analysis of the environmental benefits of achieving such as high contaminant removal efficiencies, it can be concluded that the incurred additional costs are not efficient.

- Study case 3: A landfill for a city of 2.500.000 inhabitants in Colombia. It was found inefficient costs due to excessive treatment objectives in particular ammoniacal nitrogen removal requirements. The quality objectives imposed by the regional environmental authority for the effluent treatment plant of the leachate treatment plant are supremely demanding. It would be interesting to know the studies on which this provision was adopted.

The technology selection process presented by the landfill operator rightly led to an appropriate treatment train. In other words, it is considered that the methodology presented by the company for technology selection adequately responds to the particularities of this case.

4.7 Conclusions

In Latin America, landfilling is the most implemented solid waste practice. In terms of MSW, important progress has been made within the region in order to pass from open dump practices to engineered landfills, making still emphasis in final disposal only. The main environmental concern, in this concern, is the potential environmental impacts that leachate, if not properly treated, may arise in both superficial and groundwater resources. It can then be stated that leachate treatment is key issue for the sustainability of MSW systems in Latin America. Failing to fulfil the environmental leachate treatment demands would mean that the shift from open dumps to sanitary landfills has only translated the problem from a diffuse pollution issue to an end-of-tube one.

The cost of leachate treatment is obviously a main matter for landfill operators in the region. It should be guaranteed by both landfill operators and environmental authorities that the technologies chosen for leachate treatment are cost-efficient. Leachate treatment cost efficiency is associated to achieve the treatment objectives, which must be set according to local environmental conditions, at a minimum cost. To attain efficient leachate treatment costs, the most important barrier that Latin American countries have to overcome is that leachate treatment objectives are arbitrarily set. It is required to establish the treatment leachate objectives following an analytical procedure.

Once leachate treatments are analytically established for every single case, which is the responsibility of the environmental authorities, technology selection for leachate treatment has to be carefully undertaken. Special attention has to be paid to expensive technologies which do not contribute to a significant improvement of the water quality of the receiving body, as well as the so-called low-cost technological options which may not achieve the effluent quality imposed by the treatment objectives.

If for a specific case, the procedures here outlined are followed, and as a consequence, the leachate treatment costs are efficient, and regulators state bodies should recognize these costs in the MSW tariff structure.

References

R. Cossu, R. Stegmann, *Solid Waste Landfilling* (E&FN SPON, Padova, 2019)

H.J. Ehrig, H. Robinson, Landfilling: Leachate treatment, in *Solid Waste Technology & Management*, ed. by T. Christensen, (Wiley, Chichester, 2011)

S.K. Gupta, G. Singh, Assessment of the efficiency and economic viability of various methods of treatment of sanitary landfill Leachate. Environm. Monitor. Assess. **135**, 107–117 (2007)

P. Kjeldsen, M. A. Barlaz, A. P. Rooker, A. Baun, A. Ledin, T.H. Christensen, Present and long-term composition of MSW landfill leachate: a review. Crit. Rev. Environ. Sci. Technol. **32**(4), 297–336 (2002)

T.A. Kurniawan, W.H. Lo, G.Y.S. Chan, Physico-chemical treatments for removal of recalcitrant contaminants from landfill leachate. J. Hazard. Mater. **B129**, 80–100 (2006). leachate, Waste Management 30 (2010) 100–109

T.V. Manzi, L.I. Rendón Muñoz, M. Herrera Rodas, M.A. Gandini Ayerbe, L.F. Marmolejo Rebellón, Estado de la valorización de biorresiduos de origen residencial en grandes centros urbanos. Rev. Int. Contam. Ambient. **36**(3), 755–774 (2020)

S. Renou, J.G. Givaudan, S. Poulain, F. Dirassouyan, P. Moulin, Lanfill leachate treatment: Review and opportunity. J. Hazard. Mater. **150**(2008), 468–493 (2008)

R.J. Watts, A.L. Teel, Groundwater and air contamination: Risk, toxicity, exposure assessment, policy and regulation, in *Environmental Geochemistry*, ed. by B. Sherwood, vol. 9, (Treatise on Geochemistry, 2005), pp. 1–16

J. Wiszniowski, D. Robert, J. Surmacz-Gorka, K. Miksch, J.V. Weber, Landfill, Leachate treatment methods: A review. Environ. Chem. Lett. **4**, 51–61 (2006)

N. Yusof, M.A. Hassan, L.Y. Phang, M. Tabatabaei, M.R. Othman, M. Mori, M. Wakisaka, K. Sakai, Y. Shirai, Nitrification of ammonium-rich sanitary Leachate. Waste Manag. **30**(2010), 100–109 (2010)

Chapter 5
Optimized Organic Waste Management Strategies for Sustained Carbon Emissions Reduction and Climate Change Stabilization in the Garden Route District of South Africa

Sameera Kissoon and Cristina Trois

5.1 Introduction

Within South Africa, 80% of municipal solid waste is disposed of into landfill, the disposal of organic waste to landfill contributes approximately 4.3% towards the country's total GHG emissions (Oelofse 2014). Waste management in South Africa is an emerging sector with increasing emphasis placed on the development and application of integrated waste management strategies through the waste hierarchy via the National Environmental Management: Waste Act – NEM:WA (DEA 2009) and the National Waste Management Strategy – NWMS (DEA 2011). The South African Department of Forestry, Fisheries, and Environment (DFFE) conducted a Mitigation Potential Analysis (MPA) in 2014 which focused on GHG mitigation options in various economic sectors (DEA 2014). The focus of this study aligns with the MPA conducted by the DFFE through the assessment of mitigation pathways in the waste sector (DEA 2014). The aim of which is to develop scenario appropriate waste management strategies. The technologies assessed and strategies identified in this study contributes to the diversion of waste from landfill for the reduction of methane emissions and subsequently the production of new products. This will ultimately activate better waste to resource management and contribute to the circular economy. The circular economy is one potential driver of sustainable development; this can be achieved through the shift of the flow of materials from a linear flow or disposal to landfill to a circular flow through the identification of alternative uses to extract materials through the pipeline prior to the disposal of materials to landfill (Korhonen et al., 2017). The drive towards a circular economy is steered by the collective efforts both governmentally and in the private sector.

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This is through the transition from integrated and industry waste management planning mechanisms to the introduction and implementation of extended producer responsibility (EPR) mechanisms such as the draft EPR regulations of the NEM:WA gazetted in 2020 (DEA 2009). This addresses the issue of the producers' responsibility in a post-consumer phase of a products life cycle.

Over the last two decades, the Western Cape, one of the largest provinces in South Africa, has focused its efforts on establishing itself as the "green hub" of Africa. The Western Cape houses 1 metropolitan municipality (City of Cape Town), 5 districts, and 24 local municipalities. Amongst these municipalities is the Garden Route District Municipality (GRDM). The GRDM, with its seven local municipalities, faces a pressing issue of limited landfill airspace. Furthermore, the Western Cape Provincial Government has issued a ban, which stipulates zero organics to landfill by 2027 with a halfway target of 50% reduction of organics to landfill by 2022. Therefore, all municipalities within the Western Cape are mandated to find alternative waste management solutions for food and organic waste fractions (DEA & DP 2022). Within South Africa, waste management policies and legislations are gearing towards a low carbon economy. The Western Cape is among those transitioning towards a decarbonized economy.

The development and application of integrated waste management systems and ERP regulations aim to assist municipalities and the private sector in reducing the volume of waste disposed of into landfill facilities. For the purpose of this study, this is achieved through the advancement of the "Waste to Resource" economy using methane emissions as an indicator for the development of integrated waste management plans, thus reducing waste disposal to landfill. This serves as a driver in the development of a climate change stabilization wedge for the activation of the circular economy.

The climate change stabilization wedge is a concept introduced by Pacala and Sacolow in 2004. In recent years, the growing belief that methane emissions can be stabilized through the introduction of integrated waste management mechanisms has gained traction with various studies conducted globally. This is due to the complexity of waste management systems that differ from geography, policy, capital, and operational costs among others (Bahor and Van Brunt 2009). A stabilization wedge (or triangle) is the triangle formed by the comparative analysis of the 50-year trajectory of methane emissions from the disposal of waste to landfill as business as usual and those reduced from another more optimized scenario. Stabilization is achieved by flattening the trajectory through the introduction of interventions.

The aim of this study is to create a climate change stabilization wedge/strategy for the GRDM by determining the effect on methane emissions, over a 50-year period and the potential to replace the BAU scenario with more optimized scenarios that maximize diversion of organic waste from landfills. In this study, a multi-criteria methodology is utilized through the integration of the WROSE model into the mitigation potential strategy for South Africa and identify scenarios to achieve the highest mitigation potential. The WROSE model (Trois and Jagath 2011) is utilized to create a climate change stabilization wedge (triangle) for each scenario. The climate change stabilization wedge/triangle forecasts, over a 50-year period, the volume of methane emissions (estimated in metric tons of CO_2eq) that would be offset if landfilling were to be progressively replaced by alternative, more optimized, scenarios for food waste and garden refuse streams. Methane emissions for the WROSE scenarios evaluated are calculated using emission factors and methodology derived by the 2006 IPCC guidelines (IPCC 2006).

5.2 Study Area

The GRDM, formerly known as the Eden District Municipality, was selected as the study area. The GRDM is the third largest district in the Western Cape covering 23,331 km^2 in surface area (Gibb 2020). The total population of the GRDM is at 635,600 as per the 2020 integrated waste management plan (Gibb 2020). The GRDM conducted an in-depth waste stream analysis in 2019 to determine the household solid waste stream profile across the district which was communicated in the Engineering third Generation IWMP (Gibb 2020). The outcome of which determined that recyclables including hard and soft plastic, paper, cardboard, metal, and glass accounted for 40.3% of the total waste fraction. The total organic waste fraction accounted for 35.6% which included both food waste and garden refuse. The remaining 24.1% included textiles, nappies, e waste, hazardous waste, and other. Figure 5.1 depicts the waste generation percentages per fraction which is the basis for all of the analysis conducted. As seen in Fig. 5.1, the food waste fraction is the

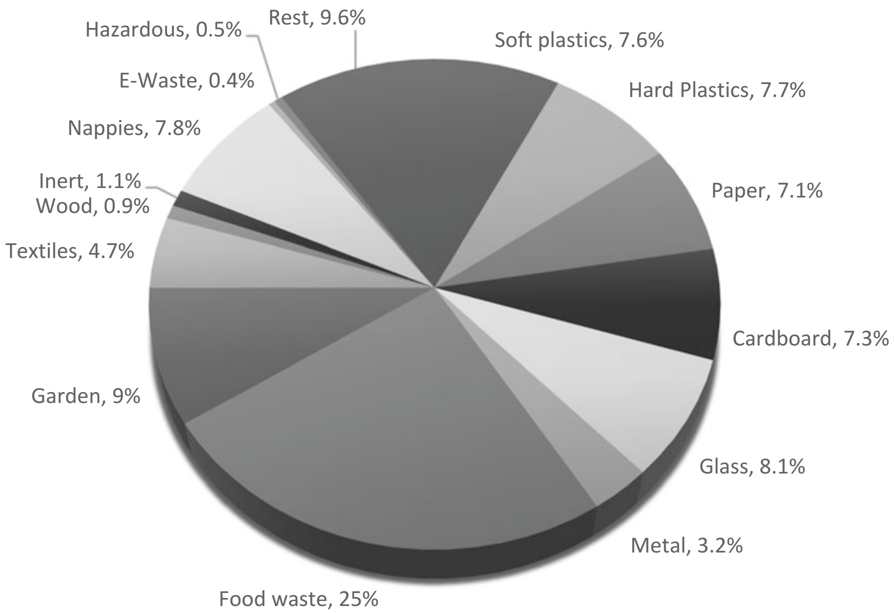

Fig. 5.1 Average domestic waste profile in the Garden Route District Municipality. (Gibb 2020)

largest fraction disposed of into landfill. Garden refuse is a second organic waste fraction that is taken into account for the purpose of this study, and therefore, a combined organic waste fraction of 35.6% is considered for the study.

The Oudtshoorn, Kannaland, and Hessequa local municipalities house their own local landfill facilities and will continue to utilize these sites for the disposal of their general MSW, whereas Mossel Bay, Bitou, Knysna, and George Municipalities currently have no operational landfill facilities accepting general MSW.

All of the MSW collected is disposed of into the PetroSA sanitary landfill facility within Mossel Bay Local Municipality. The PetroSA site faces the pressure of limited landfill airspace and reduced life span of the facility. The GRDM is currently in the process of developing a new regional landfill facility due to the closure of the preexisting facility which has now reached its maximum capacity in order to accommodate the waste volumes generated by the four municipalities. The GRDM has undergone a public private partnership (PPP) process for the construction, development, and operation of a new regional landfill facility which will service four of the seven local municipalities in the district (Gibb 2020). The facility will include a material recovery facility (MRF), a composting facility, and a construction and demolition waste recycling facility (Gibb 2020). The GRDM along with four local municipalities have undertaken a pilot home composting program in efforts to manage the organic waste fractions to meet the requirements of the Western Cape Provincial Government (Gibb 2020).

5.3 Methodology

The methodological approach used in this study employs a combination of steps to achieve a climate change stabilization wedge. Due to a lack of reliable, available data, specific boundary conditions needed to be assigned in order to achieve the aim of the study are as follows:

1. Historical Integrated Waste Management Plan (IWMP) and Integrated Development Plan (IDP) data was extracted and utilized for the forecasting of total population and waste generation figures.
2. Population growth was established at 2% per annum based on the projections conducted by the Department of Social Development in the Garden Route District Municipality in line with the district.
3. Average waste characterization percentages were extracted from the third-generation IWMP for determining waste fractions in tons.

The first step in this study was the waste characterization conducted by the GRDM. The data collected during the waste stream analysis fed directly into step two, the scenario identification. The second step in the process is the waste strategy scenarios identification and selection. This was achieved through the use of the WROSE model (Trois and Jagath 2011).

The Waste Resource Optimization and Scenario Evaluation (WROSE) model is a methodology developed by the University of KwaZulu-Natal to aid municipalities in the decision-making process as a zero waste and GHG emissions reduction model (Trois and Jagath 2011). The WROSE model is used to assist municipalities in aligning with national legislative requirements and achieving sustained waste and emissions reduction through the evaluation of integrated waste management scenarios upon all levels of sustainability (environmental, economic, social, and institutional).

A number of scenarios are embedded in the WROSE model, ranging from baseline (business as usual) to more complex optimized solutions (Fig. 5.2). For this study, five scenarios were considered:

1. The disposal of unsorted, untreated MSW to landfill (BAU).
2. The disposal of unsorted, untreated MSW to landfill with landfill gas recovery and electricity generation (BAU+).
3. Unsorted and untreated MSW undergo a mechanical pretreatment with recovery of recyclable fraction through a Material Recovery Facility (MRF).
4. Unsorted and untreated MSW undergo a mechanical pretreatment with recovery of recyclable fraction through a Material Recovery Facility (MRF), with anaerobic digestion of biogenic food waste.
5. Unsorted and untreated MSW undergo a mechanical pretreatment with recovery of recyclable fraction through a Material Recovery Facility (MRF), with composting of biogenic food waste (Trois and Jagath 2011).

Figure 5.3 outlines the scenarios of the WROSE model graphically. The WROSE model uses waste tonnages of each waste fraction generated as input data; the outputs of the model are methane emissions productions or reductions. The outputs of the model are not limited to methane emissions but rather expand to a range of indicators such as landfill airspace savings (LSS), economic indicators, job creation potential, health risks associated with the jobs created, and institutional indicators.

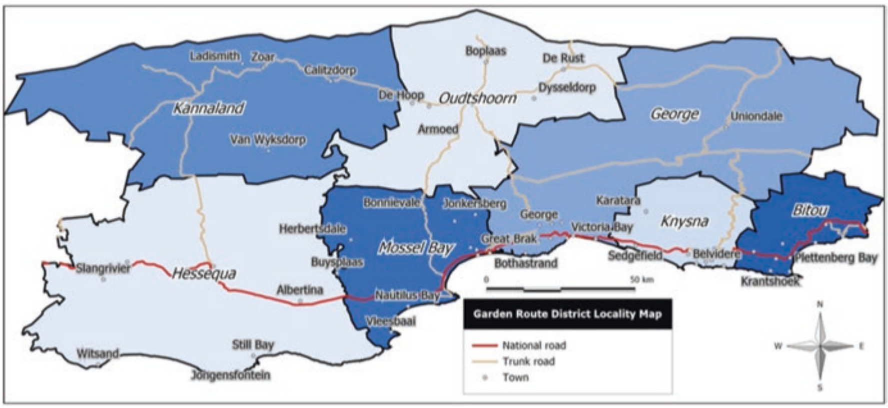

Fig. 5.2 Garden Route District Municipality, South Africa. (Source: https://municipalities.co.za/map/145/garden-route-district-municipality)

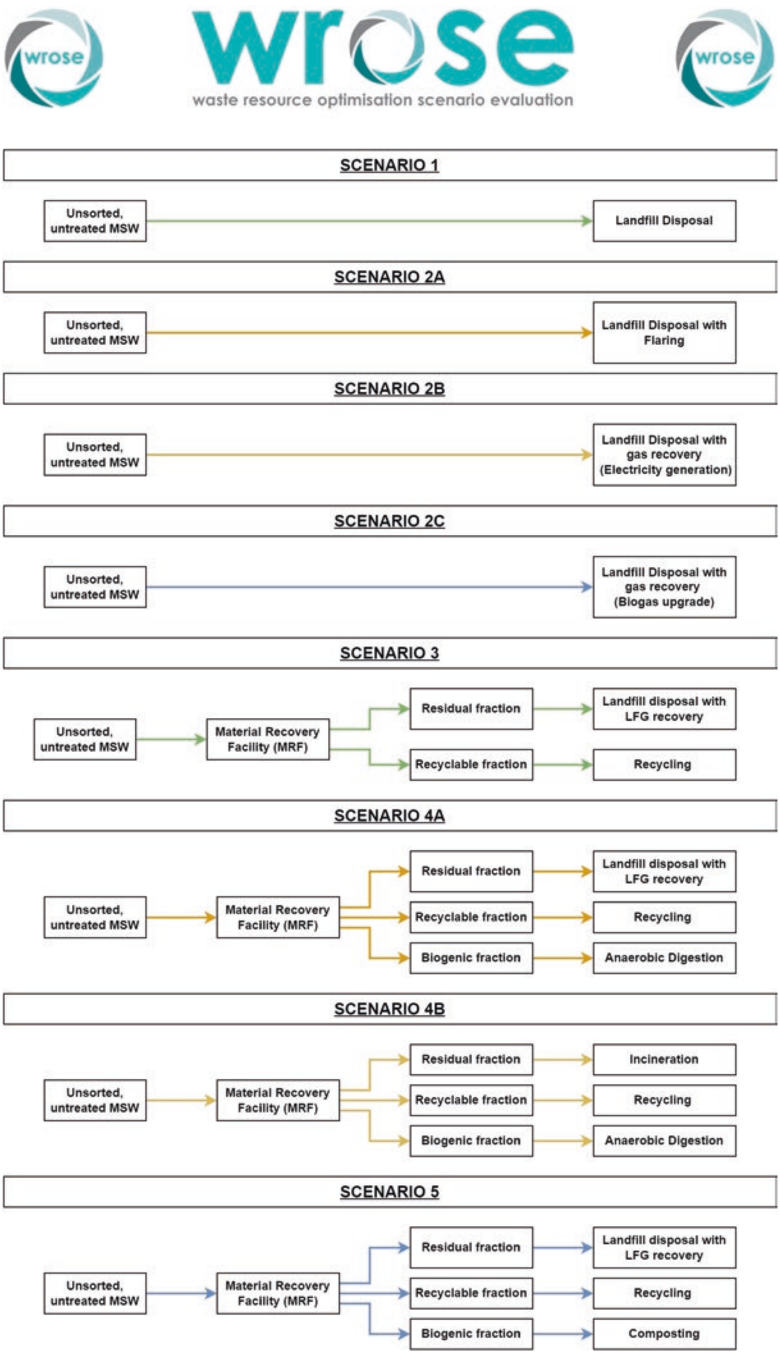

Fig. 5.3 WROSE scenarios schematic. (Trois and Jagath 2011; Dell'Orto and Trois 2022)

For the purpose of this study, the WROSE model was utilized for the selection of the scenarios that were assessed. Due to organic waste management forming the core focus area of the study, the scenarios identified as most applicable to this study are as follows:

1. SCENARIO 1 – The disposal of unsorted, untreated MSW to landfill (BAU).
2. SCENARIO 4 – Unsorted and untreated MSW undergo a mechanical pretreatment with recovery of recyclable fraction through a Material Recovery Facility (MRF), with anaerobic digestion of biogenic food waste.
3. SCENARIO 5 – Unsorted and untreated MSW undergo a mechanical pretreatment with recovery of recyclable fraction through a Material Recovery Facility (MRF), with composting of biogenic food waste.

Historical census population data was extracted from the first-, second-, and third-generation IWMP documents of the GRDM, previously called the Eden District Municipality, to determine the population growth rate annually and to conduct forward projections (Gibb 2020). From Eq. 5.1, a population growth rate of $r = 2\%$ per year was identified as per the increase in population figures extracted from Table 5.1 for the years 2013 to 2018.

The growth rate was determined using Eq. 5.1 that represents the estimated total annual population:

$$Pn = Po \times (1 + r)n \tag{5.1}$$

Where:

Pn = Estimated final population per year
Po = Initial population
r = Growth rate (%)
n = Number of years

Using the 2% identified population growth rate based on the annual total population increase as per Table 5.1, estimated projections for the total population per annum were calculated for the next 50 years.

A waste tonnage growth rate of 2%, in line with the population growth rate, was estimated from Table 5.1 and used for 50-year projections of the estimated final waste tonnage per annum, using Eq. 5.2.

Table 5.1 Historical population and waste tonnages figures

Year	Total population	Waste tonnages per year
2013	535,341	213,526
2014	548,316	218,710
2015	561,669	224,043
2016	575,414	229,530
2017	589,563	235,175
2018	601,354	239,879

Gibb (2020)

$$Wn = Wo \times (1 + r)n \tag{5.2}$$

Where:

Wn = Estimated final waste tonnage per year
Wo = Initial waste tonnage
r = Growth rate (%)
n = Number of years

From the third-generation IWMP developed by the GRDM in 2020, the total organic fraction in the MSW stream sent to landfill equated to 35.6% of the total domestic waste profile (Fig. 5.1). This percentage was used to simulate the projections of organic waste tonnage over the next 50-year period. It is to note that this percentage of organic waste was kept constant in the simulations conducted despite the population growth, based on the assumption that no interventions will be put in place by the municipality to divert this specific waste stream during the next 50 years. A conservative approach was also used assuming that the percentage of organic waste (a range between 30% and 40%) will remain constant in line with national trends (DFFE 2018).

The total organic waste fraction per year were calculated using Eq. 5.3:

$$\text{Total waste generated}\left(\text{tons per year}\right) \times 35.6\% = \text{Total organic waste fraction}\left(\text{tons per year}\right) \tag{5.3}$$

Using the waste fractions calculated above, the carbon emissions production or reduction potentials were calculated in $MTCO_2eq$ using emission factors from the IPCC (2006) as quoted in USEPA (2016) (Table 5.2).

The equation below was used to determine the methane emissions or emission reduction potential in $MTCO_2eq$:

$$\text{Waste quantity in tons} \times \text{Emission factor} = \text{MTCO}_2\text{eq} \tag{5.4}$$

The emissions produced/reduced were calculated for a 50-year period for each of the defined scenarios selected, using the appropriate emission factors. Taking into consideration that the total volume of organic waste may not be viable for scenario 4 due to contaminants in the organic waste stream or factors such as the presence of substances not suitable for AD, assumptions were made for determining viability of organic waste for use in AD. Simulations were conducted at 5% intervals up to 40% assuming that due to contamination only a portion of the organic food waste

Table 5.2 Table of emission factors

Waste fraction	Landfill disposal emission factors	Anaerobic digestion emission factors	Anaerobic composting emission factors
Biogenic food waste	1.54	−0.04	−0.15
Garden refuse: Green	−0.16	–	−0.12
Garden refuse: Wood	−0.26	–	−0.12

IPCC (2006), USEPA (2016)

component is viable for use in an AD facility. The results for which are discussed in the further section.

5.4 Results and Discussion

Figure 5.4 depicts the historical projection of food waste and garden refuse from 2013 to 2020 along with a projection of food and garden refuse volume increases at a rate of 2% per annum over the next 50 years. It is evident from the graph that the food waste volume increases from 22211.7 tons per year in 2020 by almost three-fold in the projected time frame to 59784.7 tons by the year 2050. This stresses the need for the urgent implementation of alternative waste management strategies for the management of organic waste fractions to comply with the landfill bans imposed.

The estimated tonnage of food waste combined with the IPCC emission factors were used to determine a baseline scenario of the volume of methane emissions for scenario 1: The disposal of unsorted, untreated MSW to landfill or BAU as seen in Fig. 5.4. This refers to the total volume of methane emitted through the disposal of unsorted, untreated MSW to landfill in the GRDM over the next 50 years. Figure 5.4 highlights "the risk of inaction" by continuing with scenario 1. The net zero emissions seen in Fig. 5.5, for the disposal of garden refuse to landfill, is the result of a significantly lower emission factor of 0.16 (IPCC 2006) as well as lower amounts with respect to the higher quantities of organic food waste and their associated higher emission factor of 1.54 (IPCC 2006).

Scenarios 1, 4, and 5 of the WROSE model were selected as they are most applicable to the management of the organic fraction municipal solid waste (OFMSW).

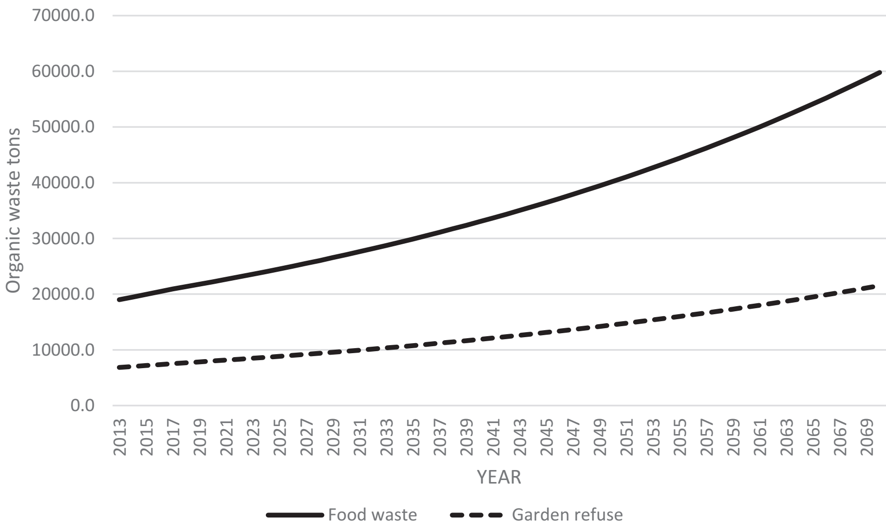

Fig. 5.4 Projection of food waste and garden refuse tonnages in the Garden Route District Municipality from 2013 to 2070

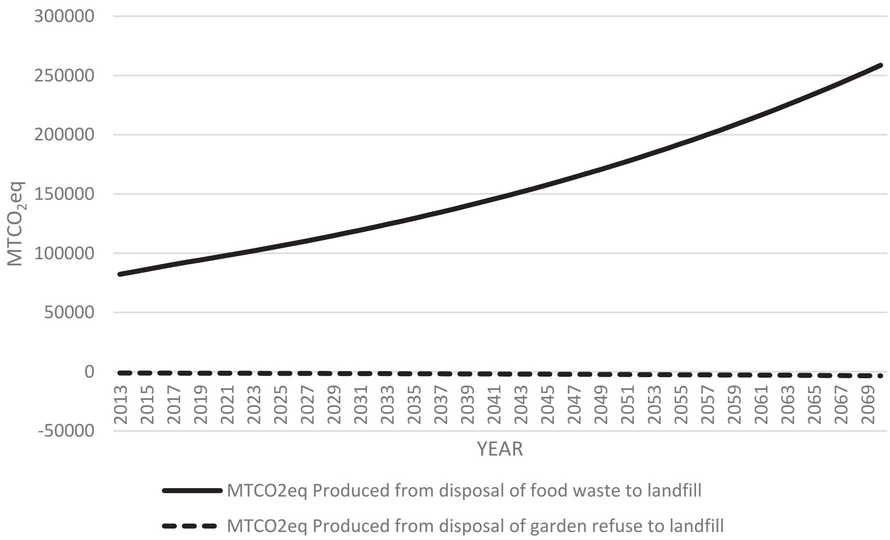

Fig. 5.5 50-year projections of $MTCO_2eq$ emissions for the disposal of food waste and garden refuse to landfill (BAU)

The variances in results will determine which of the scenarios/interventions will be most relevant for the stabilization of GHG emissions for the next 50 years. Subsequently to the development of the GHG emissions stabilization wedge, the potential viability of the organic food waste fraction for anaerobic digestion was assessed as per discussion in the section above.

Based on Figs. 5.4 and 5.5, as waste generation rates increase by more than triple in the next 50 years, so do the GHG emissions from the organic waste fractions. Figures 5.5 and 5.6 depict the outcome of the comparison of the selected scenario:

For scenario 1, the model depicts the steady increase of GHG emissions for both organic waste and garden refuse. This rate of GHG emissions is unsustainable for long-term climate contributions due to the global warming potential of CH_4 being 25 times more harmful than that of CO_2 according to the USEPA (2021).

For scenario 4, the introduction of AD facilities for the treatment of all organic food waste at 100% viability for digestion is shown to reduce the GHG emission levels to a stable state, i.e., no upward trajectory over the next 50 years.

Should no interventions be put in place over the next 50 years, the impact of waste disposal to landfill grows exponentially. This is a direct result of the global warming potential of methane emissions from the decomposition of organic waste in landfill facilities. Figure 5.6 depicts the potential for the reduction of methane emissions from 258619.33 $MTCO_2eq$ by the 2070 through the disposal of food waste to landfill to −2391.39 $MTCO_2eq$ through the channeling of food waste to an AD facility.

For scenario 5, two simulations were conducted, the first being the potential GHG emission reduction composting as a treatment method for biogenic food waste fractions is shown to reduce GHG emissions to a stable level for the next 50 years, similar to that of AD as seen Fig. 5.7.

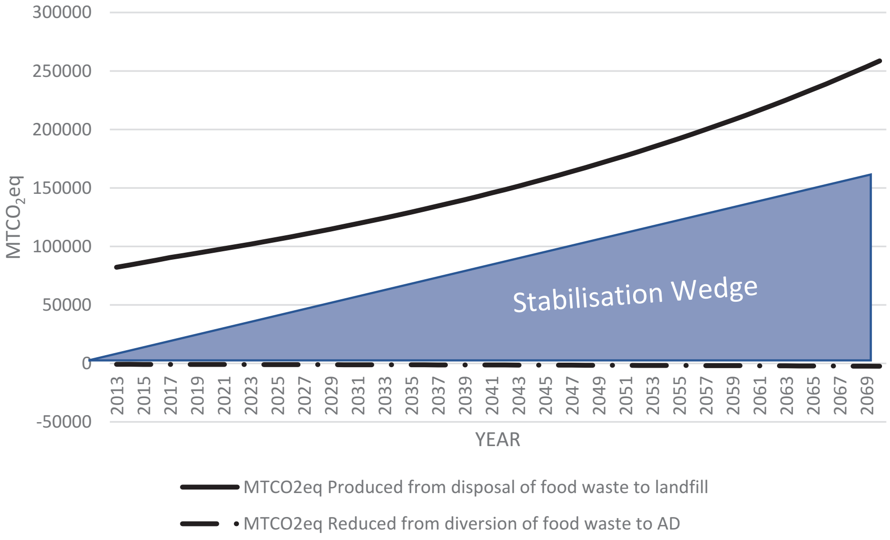

Fig. 5.6 Climate change stabilization wedge for 50-year projections: Comparison between food waste to landfill (BAU) versus food waste to anaerobic digestion (AD)

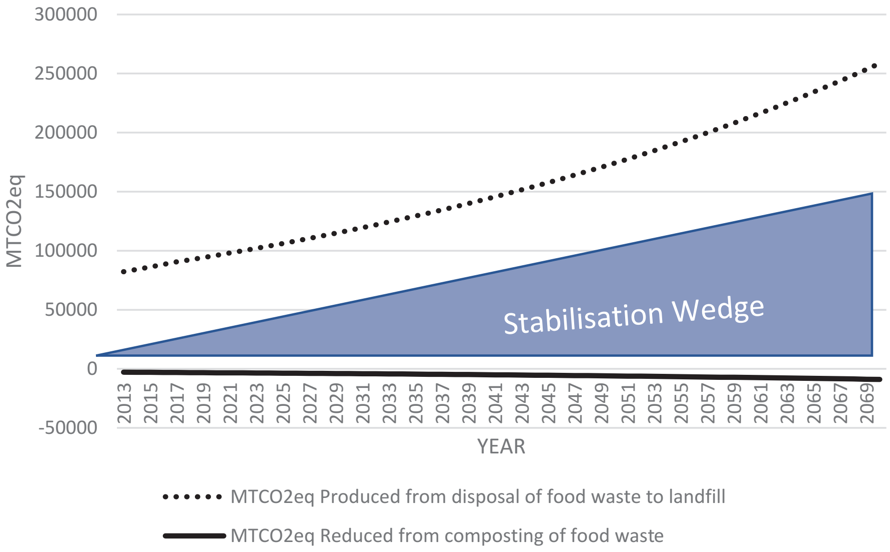

Fig. 5.7 Climate change stabilization wedge for 50-year projections: Comparison between food waste to landfill (BAU) versus food waste to composting

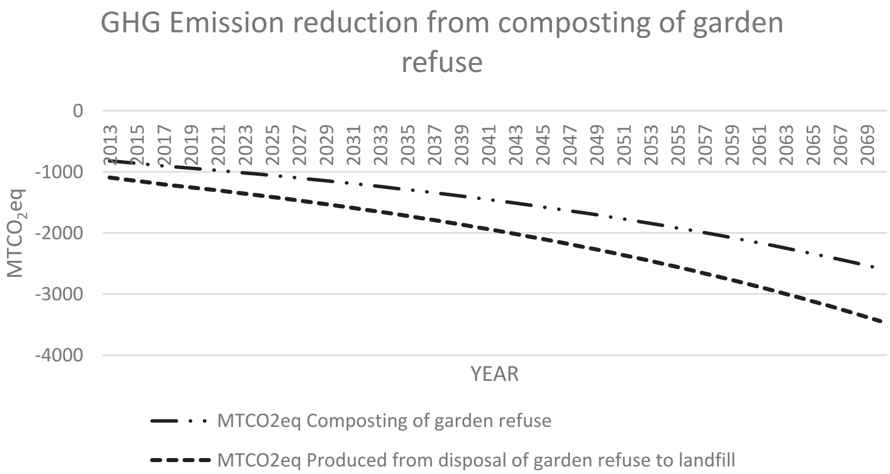

Fig. 5.8 Comparison between 50-year projections of GHG emissions for food waste to landfill (BAU) versus food waste to composting

The second simulation for scenario 5, composting as a treatment method for garden refuse fractions, is shown to reduce GHG emissions to a stable level for the next 50 years, lower than that of AD as evidenced in Fig. 5.8.

The implementation of an AD facility in the Garden Route at maximum capacity reduces the GHG emissions to a stable level, i.e., no upward trajectory; however, of the total waste volume generated, organic food waste accounts for 25%. Of the 25% of the total organic food waste generated, consideration is given to the potentiality that not all of the organic food waste within the 25% generated is viable for use in an AD facility. Therefore, Fig. 5.9 assesses the potential viability of organic waste from the total organic food waste fraction generated (25% of the total waste volume) at 10%, 20%, 30%, and 40% viability. As evidenced from Fig. 5.9, the larger the volume of viable organic waste for an AD facility, the greater GHG emission reductions that can be achieved.

5.5 Conclusions and Recommendations for Future Research

This study aligns with the efforts of DFFE through the use of the multi-criteria WROSE methodology to strengthen and enhance the mitigation potential analysis within the waste sector. Thus, activating optimized waste to resource management which allows for practical implementation of waste diversion from landfill and GHG emission reduction strategies in the waste sector. This is achieved by integrating the WROSE methodology into the mitigation strategy by technology and scenario assessments in terms of mitigation potential. The assessment of GHG

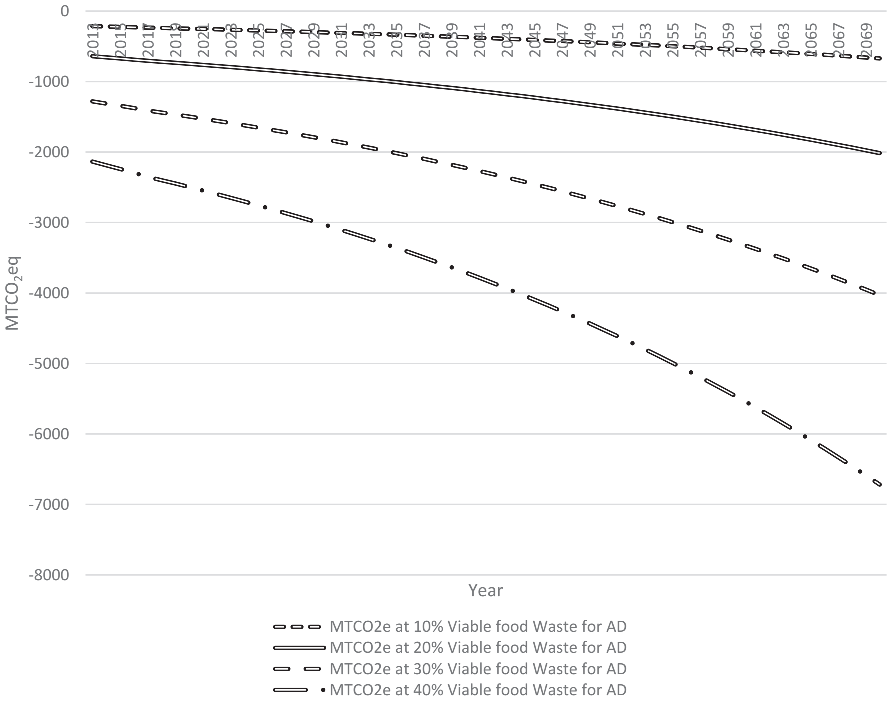

Fig. 5.9 Projected carbon emissions reductions for various percentages of viable food waste fractions for AD

emissions through the scenario BAU over a 50-year period for the Garden Route District Municipality has depicted a CO_2eq yield from 96,000 MTCO_2eq in 2020 to almost triple in 50 years of >250,000 MTCO_2eq by the year 2070. The assessment of mitigation strategies qualifies as a stabilization wedge by lowering the trajectory of emissions to a stable emission volume over the next 50 years. The scenarios which are most applicable for achieving these stabilization rates for organic waste fractions are scenario 4 and 5 of the WROSE model. This will aid the Garden Route District Municipality in achieving part of the mandate for the diversion of all organics from entering landfills by the Western Cape Government and activating aspects of the circular economy. The development of the climate change stabilization wedge is one of the very first for a South African Municipality in the waste sector. Such a study can contribute towards future IWMP developments and municipal waste management planning within the Garden Route District Municipality.

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References

B. Bahor, M. Van Brunt, J. Stovall, K. Blue, Integrated waste management as a climate change stabilization wedge. Waste Manag. Res. **27**(9), 839–849 (2009). https://doi.org/10.1177/0734242X09350485

Dell'Orto A, Trois C. Considerations on bio-hydrogen production from organic waste in South African municipalities: A review. S Afr J Sci. 2022; 118(Special issue: Waste as a Resource), Art. #12652. https://doi.org/10.17159/sajs.2022/12652

Department of Environmental Affairs, *South Africa State of Waste. A Report on the State of the Environment. Final draft report* (Department of Environmental Affairs, Pretoria, 2018), p. 112

Department of Environmental Affairs (DEA), *South African Government, National Environmental Management: Waste Act 59 of 2008* (Government Gazzette, Cape Town, 2009) Available from: https://www.gov.za/sites/default/files/gcis_document/201409/32000278.pdf

Department of Environmental Affairs (DEA) (2011). South African Government, National Waste Management Strategy. Available from: https://www.dffe.gov.za/sites/default/files/docs/nationalwaste_management_strategy.pdf

Department of Environmental Affairs (DEA) (2014). South African Government, South Africa's greenhouse gas mitigation potential analysis. 2014. Pretoria. Available at: https://www.environment.gov.za/sites/default/files/docs/mitigationreport.pdf

Department of Environmental Affairs and Development Planning (DEA & DP), *Western Cape Government. Reducing Waste in Western Cape Landfills* (Cape Town, 2022) Available from: https://www.westerncape.gov.za/eadp/files/atoms/files/Green%20Ambassador_Special%20Edition%202021_Organic%20Waste_0.pdf

Gibb Engineering and Architecture, *Garden Route District Municipality Integrated Waste Management Plan 3rd Generation* (Garden Route District: Garden Route District Municipality, 2020), p. 231. Available at: https://www.gardenroute.gov.za/wp-content/uploads/2021/05/GRDM-3rd-Generation-Integrated-Waste-Management-Plan-2020-2025.pdf

IPCC, in *2006 IPCC Guidelines for National Greenhouse Gas Inventories – Prepared by the National Greenhouse Gas Inventories Programme*, ed. by H.S. Eggleston, K. Miwa, N. Srivastava, K. Tanabe, (IGES, Japan, 2006)

J. Korhonen, A. Honkasalo, J. Seppälä, *Circular economy: The concept and its limitations, ecological economics* (Elsevier, 2017), pp. 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041

S.H. Oelofse, C. Mouton, The impacts of regulation on business on the waste sector: Evidence from the Western Cape, in *Proceedings of the 20th WasteCon Conference*, (Somerset West, Cape Town, 2014), pp. 48–54

C. Trois, R. Jagath, Sustained carbon emissions reductions through zero waste strategies for South African municipalities, in *Integrated waste management – Volume II*, ed. by S. Kumar, (IntechOpen, London, 2011. Available from: https://www.intechopen.com/chapters/18498). https://doi.org/10.5772/17216

U.S. Environmental Protection Agency (USEPA), *Documentation for green house gad emission and energy factors used in the Waste Reduction Model (WARM)* (ICF International, 2016) Available from: https://archive.epa.gov/epawaste/conserve/tools/warm/pdfs/WARM_Documentation.pdf

United States Environmental Protection Agency USEPA (2021). Overview of Greenhouse Gases. Available from: https://www.epa.gov/ghgemissions/overview-greenhouse-gases#main

Chapter 6
Waste Management Institutional and Legislation Aspects in Developing Countries

Françoise Bonnet, Nabila Lahboubi, Sanae Habchi, and Hassan El Bari

6.1 Introduction

Worldwide, municipal waste management (MWM) is considered as a public service like others (transport, water, and electricity distribution) that requires a set of rules to be respected and good governance between the different stakeholders involved. In most countries, this service is provided by local authorities as one of their municipal competences; those competences are usually regulated by a national legal framework.

National governments create laws and regulations in industrialized nations that set objectives, benchmarks, and operational and environmental requirements. Solid waste management (SWM) strategies that are effective and efficient help to resilient city governance and planning (Muheirwe et al. 2022).

In developing countries, SWM is most of the time characterized by a lack of regulation as well as bad governance. Where legislation exists, it is usually weakly enforced. In addition to that, the informal sector is an important player in the system which renders law enforcement and governance more difficult. In many other developing nations, there are still alleged *governance* issues that explain low SWM management efficiency (Batista et al. 2021).

Waste management in MENA countries represents a major challenge for the years to come under the combined effect of strong urban growth and economic development. In most of them, governments are aware of the importance of the

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problem and are making numerous efforts to put in place an effective legislative framework. However, notwithstanding those efforts, the adoption of regulations is still uncomplete and only one side of the coin. Its enforcement is the other side, even more problematic as it requires a well-established governance allowing for efficient monitoring and control.

Recycling in developing nations is greatly aided by the informal sector because materials like glass, plastic, paper, and metal have generated markets. To support these efforts, appropriate actions should be taken, such as raising public awareness, passing specific legislation and regulations, and putting in place sustainable waste management infrastructures (Ferronato and Torretta 2019).

The SWM is a complex subject with political, institutional, environmental, and social, economic components. Due to a primary financial limitation, it can be challenging for local governments in developing nations to construct sustainable municipal SWM that meets the needs of the general public (Yoshida 2016). With the help of a political framework and policy, environmentally responsible waste management can be promoted, and landfilling and incineration's negative environmental effects can be avoided.

While it is relatively easy to promulgate regulations, their implementation has proven to be a challenge, not only in poorer nations but also globally. The lack of adequate infrastructure, roadmaps, or programs in place to support the required compliance levels, as well as the social and technical gaps that must be addressed, are the main causes of the enforcement of regulations' widespread failures in Africa, in particular (Godfrey et al. 2019; Nyathi and Togo 2020).

In this chapter, special attention will be paid to the case of MENA (Middle East and North Africa) countries in terms of the governance and legislative aspects of waste management.

6.2 Basic Regulation and Governance Needed Towards an Integrated Sustainable Waste Management (ISWM)

It is well known that developing a waste management system is not an easy task and requires several essential elements.

Beside a set of appropriate set of rules, other important elements have to be taken into consideration:

– The infrastructure.
– The parties involved, including local, regional, and national governments, waste producers/generators, producers (those who release goods onto the market that end up as waste, including manufacturers, brand owners, importers, and others in the supply chain), service providers (whether public or private sector, formal or informal, large, or small), civil society, and non-governmental organizations (NGOs), potential fund donors (international agencies).
– The governance.
– The financing.

All the above considerations should always underpin the rules and policy instruments in a coherent way. A new set of indicators, for example, was created based on a study of the data available in the 66 Mexican municipalities and can be used to evaluate various facets of the governance of the municipal solid waste management (MSWM) system in scenarios where the system is still being implemented (Turcott Cervantes et al. 2021).

6.2.1 Key Legal Principle

It is important to note that rules and regulations are needed to improve waste management. (Trinh et al. 2021). Laws and regulations define basic concepts, set out all "guiding principles" on which the strategy is based, allocate competences and responsibilities, set norms and standards requested for facilities and operations, and of course provide with sanctions in cases of noncompliance.

In most MENA countries, waste legislation incorporates several basic principles like the life-cycle method and the waste hierarchy, the preventative concept, and the concept and producer extended obligation. It is as well foreseen competences and responsibilities among the different stakeholders.

A nation's waste acts set environmental policy and law, notably the general framework of environmental law. The nation's waste act should include a number of new guiding ideas to the nation's environmental legislation, such as the polluter-pays concept, producer obligation, the precautionary concept, and the life-cycle concept to waste management (Department of Environmental Affairs, Republic of South Africa 2018).

Figure 6.1 shows the principal key legal for integrated sustainable waste management.

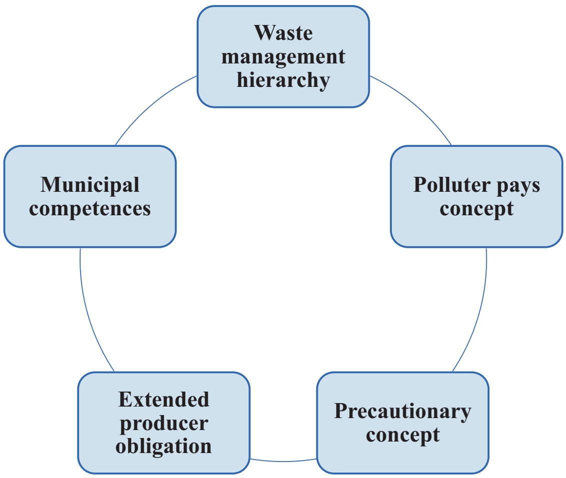

Fig. 6.1 Key legal principle

6.2.1.1 The Waste Management Hierarchy

The waste hierarchy is a significant notion that often underpins all waste management legislation (Lansik scale). This rule can be summarized in the Fig. 6.2.

According to Fig. 6.2, the idea is to render end-of-life treatments (landfilling and incineration) less attractive than recycling or reuse. This shall be enforced through legal and economic instruments. A strong legal instrument is the ban on landfilling certain types of waste or the imposition of a maximum quantity sent to landfill.

A framework that was developed through research for MSW integration and sustainability outlines the most recent challenges and crucial success factors (CSFs) needed to achieve S-ISWM in developing nations (Batista et al. 2021). The authors showed how, despite several obstacles, the use of CSFs might enable waste to be converted into renewable energy, ensuring the existence of future generations by offering them workable solutions to decrease waste's volume and weight as well as the predominance of open dumps and landfills.

Mandatory recycling targets by waste stream are another "common recipe" helping to apply the waste hierarchy in an effective way.

6.2.1.2 The Polluter Pays Principle

According to this waste-related principle, the producer of the wastes should be responsible for paying for its collection and treatment. Most of the time, the application of this principle consists in applying a flat rate that is supposed to represent the cost of collection and treatment of an "average" quantity of waste produced per household. In several developed countries, this principle tends to be applied as close

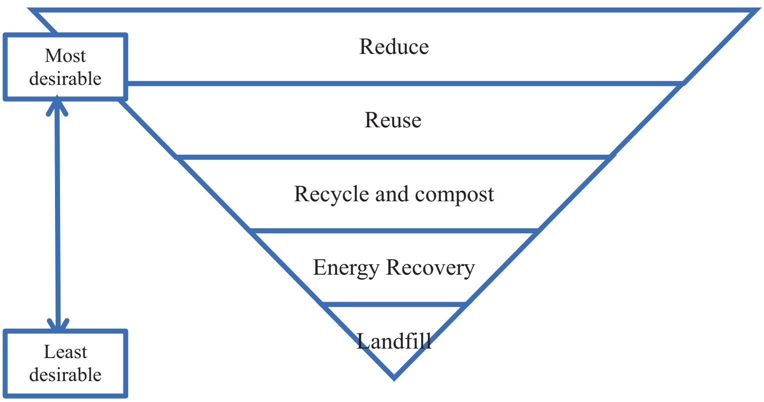

Fig. 6.2 The waste hierarchy

as possible to the "polluter" through taxation systems that vary according to the quantity of waste collected, the so-called 'PAY AS YOU THROW" system. While in most developing nations, this is far from being the case.

In fact, it can be said that even if this principle exists on paper (which is the case in MENA countries), its application is far from being effective, at least in terms of waste treatment cost coverage. Municipal waste collection and treatment is a public service financed by the national budget and partly by local taxes that usually have nothing to do with waste management.

6.2.1.3 The Extended Producer Responsibility Principle

The environmental policy concept known as "extended producer responsibility (EPR)" is based on the premise that manufacturing and consumption decisions should take whole product life-cycle costs into account (Compagnoni 2022).

In reality, EPR suggests that manufacturers take on the burden of gathering or returning used items as well as sorting and treating them for future recycling. Such a duty could also be just organizational or pecuniary. The policy first appeared in a few European Member States towards the end of the 1980s, specifically for packaging waste. The main reason for setting up such an instrument was to find new sources of funding for municipalities that were faced with a continuous increase in the cost of collecting and treating municipal waste.

The purpose of EPR is to internalize environmental externalities and to give producers a motivation to consider environmental factors throughout the life of their products, from the design stage to the end of their useful lives.

EPR is an important element in the Waste Hierarchy Principle's application. EPR, along with other important economic tools, can promote behavior change among all parties involved in the product value chain, including producers, retailers, consumers and citizens, local government agencies, waste management companies, both public and private, recyclers, and social economy players. The EPR system targets consumers of things that produce waste at the end of their useful lives, whereas waste taxes shift the burden of waste treatment on families and citizens.

EPR principle is more and more implemented in developed countries. On the other hand, in developing nations, this principle is only very marginally applied, mainly as a pilot project involving the private sector (large agri-food companies) and waste pickers. In MENA countries, it is a work in progress. Most of them are working on the implementation of such a system which still requires adaptation of their legislation (Fig. 6.3).

Both Japan and South Korea have created their own e-waste regulations in this regard, with Japan being the first to implement the EPR system (Rajesh et al. 2022).

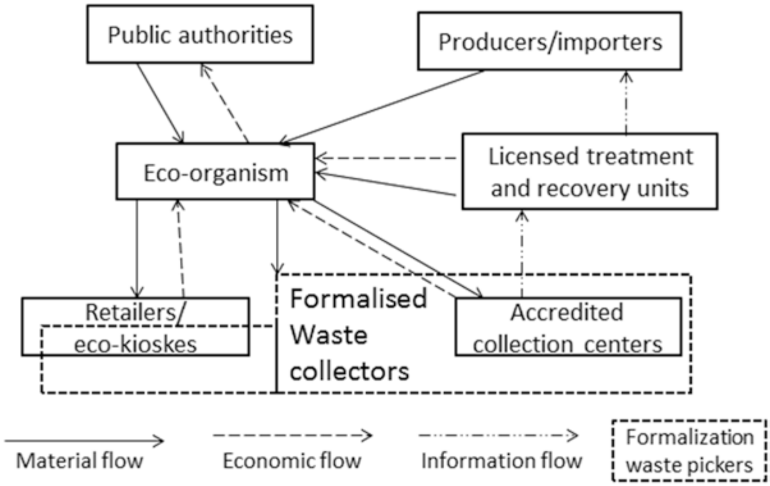

Fig. 6.3 Flow sheet of responsibilities of public authorities and producers

6.2.1.4 The Municipal Competences

Municipalities most frequently handle waste management in a decentralized fashion. The design of SWM systems typically takes into account regional factors, including the availability of funding, regional standards, the physical structure of settlements, and the ability of residents to pay for services.

Where it is possible and convenient, several municipalities can manage solid waste services together through an intermunicipal body. In nations of the European Union like France, Italy, and Belgium, intermunicipal cooperation is frequent and results in economies of scale, cost reductions through fewer investments and a wider range of finance sources, decreased personnel demands, and the sharing of technical knowledge. When operational goals and guidelines are the same across entities, as in the case of EU member states with similar policy and legal frameworks, intermunicipal coordination is most effective.

Often waste management services are provided through public-private partnerships. Under the correct circumstances, private operators can improve waste management systems' efficiency and financial stability. The private sector is frequently enlisted to assist public agencies in enhancing operations and reducing the prevalent issue of unequal access to collections across economic cohorts. This is the case in most MENA countries where municipalities delegate their competences to delegated companies through public procurements and fixed-term management contracts.

Two major categories of expenses are typically incurred by municipalities that provide waste management services: (1) capital expenditures, which are frequently connected to infrastructure investments, and (2) operational expenditures, which are connected to service provision and equipment maintenance.

Planning for these two different categories of expenses is usually different. It may occur that planning for the first category of expenditures is made at national level, especially for large infrastructure investment in order to avoid overcapacities and because the expense of building and maintaining facilities could affect the city's final disposal decisions.

It can be said that most of the MENA countries are still suffering from a lack of autonomy, capacity, and financial means at local level where waste management is supposed to occur. A true and efficient administrative decentralization is still needed.

The municipality of Mexico, which has a local MSWM legal framework and financial control, might be cited as an example of intermediate waste management advancement in the region (differentiated budget and full costs provided). The formulation and execution of local waste management legislation and regulations, as well as the appropriate functioning of other components of the relevant service, were found to have a high correlation (Turcott Cervantes et al. 2021).

6.2.2 Economic Instruments

Through market-based incentives and disincentives, economic instruments serve to influence stakeholders' attitudes and practices in the direction of strategic goals. Pay-as-you-throw (PAYT) charging systems for residual (mixed) waste, for instance, will encourage people to separate their waste; taxes on landfilling or incineration will deter people from choosing these methods; and EPR will hold producers and importers responsible for the goods they place on the local market.

So far, none of the MENA countries has a set of economic instruments to make their waste management policies efficient and effective.

The requirement for the environmental manager to utilize legal and financial law regulations to inform society, as well as apply legal penalties in cases of noncompliance, motivates the Legal Aspects pillar (Batista et al. 2021).

6.2.3 Social Instruments

Social tools rely on contact, communication, and raising of awareness between the public, other stakeholders, and government organizations. Information alone will not be enough to alter people's beliefs and behavior. At least as vital are inspiring others, interacting with communities, and setting an example. Social tools rely on contact, communication, and raising of awareness between the public, other stakeholders, and government organizations. At least as vital are inspiring others, interacting with communities, and setting an example.

Much work remains to be done in this area in all MENA countries. The population is still very little aware of the waste issue. The same is true for many local elected officials who do not yet understand the importance of waste management (and selective collection) as a public policy, nor the economic potential that sustainable waste management could bring.

6.2.4 Governance

Governance is, broadly speaking, a concept representing the way in which a field of activity (waste management for what concerns us) is governed. Governance does not necessarily refer to a single decision-making entity, but rather to a system of decision-making entities that directs a certain field of activity. Governance is thus a concept based on the systemic approach. It corresponds to the institutional structure that is in place; the institutions' abilities to create and, in particular, implement laws; and their ability to work together and with other players in all factors (mainly the private sector and the citizens).

Typically, SWM is the responsibility of several ministries within both the national and municipal governments. Enforcement of solid waste laws and rules might also be the duty of central bodies.

To establish uniformity and prevent overlaps or gaps in responsibilities between several levels of government, coordination is necessary. A more general, equally significant governance issue has to do with how the government and its institutions interact with other system stakeholders.

6.3 Gaps in Developing Nations: Lack of Data

Programs for managing solid waste must not only have legal backing, but also be contextualized and co-produced in order to achieve smart and clean cities. In developing nations, different obstacles are shown in the application of the waste management, such as lack of data in different sectors. Figure 6.4 shows the source data activities.

6.3.1 Lack of Municipal Autonomy

A study examines the primary consequences of waste improper handling in emerging countries, with a focus on environmental pollution and socioeconomic difficulties. Inadequate economic resources and legal framework are the main causes of the lack of effective healthcare waste management systems and disposal facilities in Dhaka (Ferronato and Torretta 2019).

A research investigates the discussion of sub-Saharan Africa's SWM laws and policies, based on a literature review (Muheirwe et al. 2022). The authors indicated that awareness of communities is necessary to ensure adherence and promote

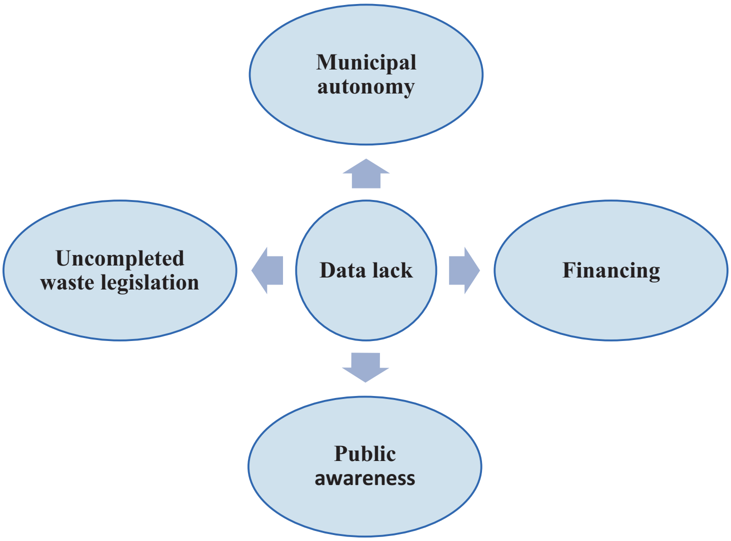

Fig. 6.4 Source of data lack activities

involvement. Activism should be used, according to the authors, to pressure the government to dedicate more resources to the implementation of policy-related initiatives.

6.3.2 Lack of Financing

The lack of advances in financing and management approaches to reach profitable results targets is driving the public-private partnership (PPP) pillar. As a result, the PPP administrative concession contract and its characteristics have the potential to outperform traditional contract models, offering as a viable choice for long-term projects (Batista et al. 2021).

6.3.3 Uncompleted Waste Legislation

A study discusses the challenges of policy implementation in Vietnam's MWM system (Trinh et al. 2021). The authors declare that the goal of that study is to identify the limitations, constraints, and challenges of policy implementation in Vietnam's MWM system so that the circumstances, strengths, and weaknesses of the system may be better understood. It then moves on to correct solutions for increasing implementation efficiency.

6.3.4 Lack of Public Awareness: Need to Educate People

In order to understand policies, the sensitization of urban residents is necessary for efficient policy implementation. In 2000, regulations governing the collection of MSW were enacted. Solid waste separation cannot be accomplished solely by workers. It is also a shared obligation with consumers (Rajesh et al. 2022).

6.4 Tentative of Tailored Solutions at Short-Mid Term

6.4.1 E-Waste Management in DC

Electronic waste (e-waste) includes a variety of electronic parts, especially cables, plastics, metals, and non-metals. These wastes are produced from high demands of electronic devices such as computers, mobiles, refrigerators, and other electronic equipment.

6.4.1.1 Waste Impacts on Human Health and Environment: India and China Example

E-waste is a kind of indirect trash and unfathomable pollution that pollutes natural resources such as air, soil, and water, causing harm to humans, animals, and the ecosystem. Long-term e-waste accumulation and contamination may have a negative impact on the resources of the environment. The two countries with the highest levels of electronic device consumption worldwide are also responsible for an increase in electrical and electronic waste equipment (Rajesh et al. 2022).

6.4.1.2 E-Waste in DC Disposed in Landfill: E-Waste Export Banned Recently

E-waste is primarily disposed of in landfills and incinerators, as well as exported from industrialized nations to developing nations like Pakistan, China, India, and Malaysia (Rajesh et al. 2022). Most nations have banned the export of e-waste in recent years, and they have enacted separate legislation for proper e-waste disposal.

6.4.1.3 E-Waste Legislation in India

In India, a paper examines the concerns surrounding the development of future electrical and electronic trash (WEEE) management regulations (Pathaka and Srivastava 2017). The authors begin by highlighting the global (WEEE) management concerns and how other nations/regions handling them (e.g., the European Union, Japan, South Korea, and Taiwan) are dealing with them. The report then discusses the current state of WEEE generation and disposal in India, environmental and public health effects.

The development of India's legal system has also been examined in order to arrive at the country's recently enacted e-waste legislation of 2016, as well as the success and potential of WEEE management within the Indian context (Pathaka and Srivastava 2017).

6.4.2 Plastic Waste Management in DC

At an unprecedented rate, single-use plastic is pouring into the environment, including the marine ecosystem, making waste plastic a particularly problematic material (Godfrey 2019). Countries all over the world are taking action to lessen these effects. Some of these actions include the elimination of single-use plastics; the substitution of petroleum-based plastics with bio-friendly alternatives such as paper, glass, or biodegradable plastics; and the improvement of waste collection systems to guarantee that all garbage is appropriately gathered, processed, or disposed of safely. Due to the planned and unforeseen implications of these "solutions" however, business, the government, or civil society frequently oppose them, leading many to wonder what would be the best way to stop the leaking.

Plastic pollution of the environment is mostly a problem of human conduct. Each of these three "solutions" while important contributes in a different way, in our opinion, stop plastic from leaking into the environment. Instead, the answer is probably going to involve a combination of all three factors.

If recycling certain products at the end of their useful lives is unlikely to ever be economically viable, the solution for a developing country is likely to involve a combination of (i) better waste collection, (ii) product replacement with bio-beneficial alternatives, and, if still necessary, (iii) regulatory intervention to force the change (Godfrey 2019).

6.5 Proposed Solution for Improvement of Waste Management Legislation

Strong governance is required to build sufficient capacity in the financial, institutional, technological, and infrastructural sectors to encourage garbage management that is environmentally responsible. How infractions and criminal behavior are handled (such as indiscriminate dumping) by law enforcement officers are the principle actions to promote sustainable waste management.

By assessing and improving their policy framework, governments can encourage sustainable waste management techniques. In this context, we will outline on three examples of best practices. Figure 6.5 shows the three examples of policy framework for best sustainable waste management.

A policy framework should include all laws governing waste, including those pertaining to recycling, dumping, transportation, etc. This strategy guarantees coherent legislation and enables the detection and correction of flaws and contradictions.

The procedures for coordination between all parties should be outlined in policy frameworks. An ineffective waste infrastructure network might result from a lack of vertical coordination within governmental entities (i.e., creating and implementing solutions simultaneously).

The creation of waste management plans should be incorporated into policy frameworks as a mandate. These strategies must include measurable goals, doable finance and implementation tactics, and methods to track and monitor success.

To encourage efficient waste management, the government can alter the law and create new guidelines. These guidelines are outlined as follows:

- Tougher penalties for illegal dumping to make sure offenders are punished severely for potentially damaging human health and the environment and to prevent repeat offenders.
- The adoption of legislation requiring separation at source regulations to promote waste reuse, recycling, and recovery.
- The implementation of laws that guarantee the disposal of hazardous waste in a way that is environmentally sustainable and safe.
- Implementing laws and formulating guidelines that establish licensing requirements for municipal landfills and waste management facilities.

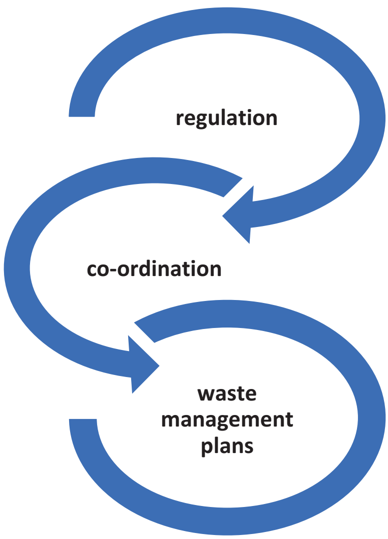

Fig. 6.5 The examples of policy framework for best sustainable waste management

- Service requirements for separating, compacting, and storing will be outlined in municipal bylaws. To guarantee that trash is handled properly and dumped in a way that is not damaging to the environment.
- Implementing new resources, a new set of policy concepts, and legislation that mandates local governments recycle or compost a percentage of their trash will enable municipalities to recycle as much waste as possible.

6.6 Waste Management Legislative Aspect: Study Case of Morocco

In order to reform the waste management sector, Morocco has taken a number of strategic measures, including strengthening the legal framework, implementing SWM programs, supporting the National Household Solid Waste Program (PNDM), creating a national master strategy for management of hazardous waste, and reforming local taxation.

Morocco recently implemented a pro-active management strategy for environmental preservation and long-term growth. Many programs and advances, such as those connected to expert collection services, cleaning, and disposal of domestic garbage, have emerged since the foundation of a government department in 1992 that is in charge of the environment (Ministry of the Environment Morocco 2008).

6.6.1 Management of Solid Waste in Morocco

The majority of MENA countries' solid waste management is characterized by a lack of planning, poor disposal, and insufficient collection services, unsuitable technologies for the regional conditions and technical needs, and insufficient finance. As a result, waste management generally consists only of collection, transportation, and disposal (Hemidat et al. 2022).

Municipal solid waste (MSW) is typically poorly managed and poorly controlled in developing nations. Due to the environmental issues connected to this issue, several nations adopted national regulations to specify the kinds of garbage that should be reused, recycled, and treated in order to implement the best solutions. Alternative plans were investigated and analyzed in this study with the goal of improving MSWM in Morocco.

Morocco is still dealing with waste management issues. There have been several initiatives to raise the standard of waste management (collection, sorting, disposal, etc.). Through the development of an integrated strategy to accomplish the goals, it has attempted to lessen the level of waste management hazards (Ouigmane et al. 2018), using two methods:

- Methodology aspect (typology and features of trash, collecting methods appropriate for urban settings, creation of landfill and recovery facilities, etc.)
- Socioeconomics aspect (including populations that benefit directly or indirectly from garbage recovery and recycling, the development of new industries, etc.)

Increased economic activity and population growth in Morocco are closely related to rising consumption, which results in rising solid waste output. According to recent surveys, Morocco produced more than 6.8 million tons/year MSW and 1.6 million tons/year of industrial waste (El Bari 2016).

Figure 6.6 resumes the different problems of waste management in developing nations; we can cite the inadequate waste separation, insufficient separation, lack financing, and also having trouble applying the law.

6.6.2 Moroccan Legislation on Waste Disposal

The MSWM calls for an understanding of the institutional and regulatory frameworks that govern this sector. The primary issue with the MSW management sector in Morocco is reflected in the institutional and legal framework, specifically the inadequate legal and regulatory framework and the lack of adequate solid sanitation resources accessible to the responsible local authorities. Morocco has undertaken a

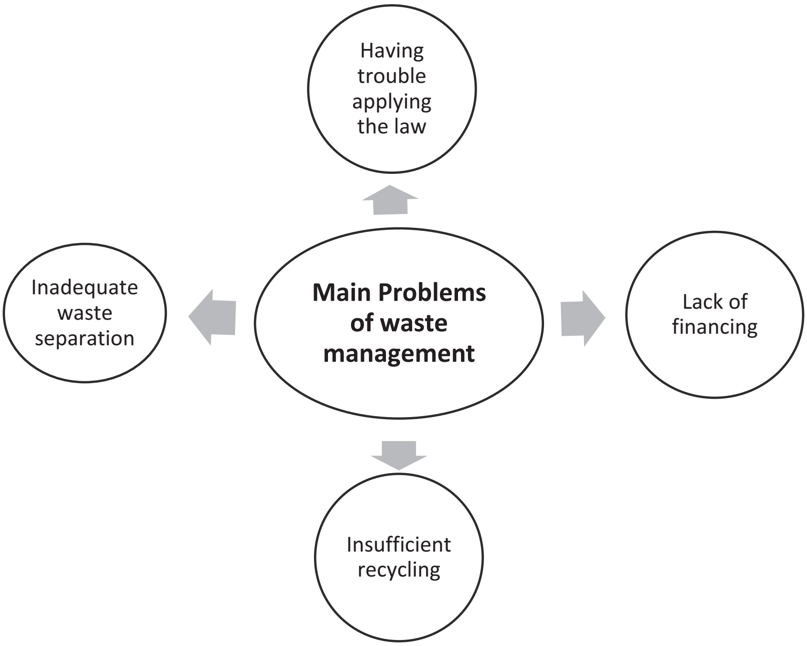

Fig. 6.6 The principal problems of waste mismanagement developing nations

number of initiatives despite these issues, introducing Law 28-00 on waste management in 2006 and the national strategy for household trash management (Hasib et al. 2020).

6.6.2.1 Regulation of Waste Management and Disposal Under Law No. 28-00

Due to the fact that Morocco has a large number of environmental protection texts, the nation has started, since the turn of the century, to accumulate a new arsenal of texts, laws, and regulations intended, on the one hand, to preserve the environment and, on the other hand, to follow and dedicate its commitments. Table 6.1 presents the main subjects of the law on waste (El Bari 2016).

Waste management is governed by Law 28-00, which addresses the entire chain, including collection, disposal, and treatment. This law divides waste into four categories: household, industrial, medical, and hazardous. This law covers significant topics, most notably the section on the control of trash import and export. Therefore, exporters are required to have both a written agreement from the authorities of the nation where the waste will be dumped or treated and prior authorization from the supervisory administration (EL BARI 2016).

The Law 28-00 regulation is intended to preserve human health and also the air, soil, ecosystems, sites, and landscapes as well as the environment as a whole from the negative consequences of garbage. This is its goal:

- The decrease of trash production and prevention of its harmfulness.
- The collection, handling, storage, treatment, and disposal of waste with consideration for the environment.
- The process of recovering waste by reuse, recycling, or any other procedure designed to produce useable materials or energy from waste.
- Making plans for municipal, regional, and national garbage management and disposal.
- Providing the public with information on the detrimental consequences of waste on public health, the environment, and actions to mitigate those effects.
- The creation of a system to police and punish crimes committed in this area.

Table 6.1 The main directives of the law on waste adopted

Law	Subject
No. 11-03	Protection and enhancement of the environment
No. 10-95	Water
No. 12-03	Environmental impact studies
No. 13-03	Fight against air pollution
No. 28-00	Waste management and disposal

6.6.2.2 The Decrees of Law 28-00

By creating technical specifications for the avoidance, collection, conversion, handling, and disposal of waste, Law No. 28-00 on Waste Management (2006), along with its decrees and implementation orders, was the first significant step in the sectoral legislative action.

The Moroccan government considers proper management of household and similar garbage to be a national priority, which is why it passed the Waste Management and Elimination Law (Law 28-00) in 2006 and started the National Municipal Solid Waste Program (PNDM), a three-phase, 15-year program, in 2008 (Ministry of the Environment Morocco 2008).

Because of private sector's involvement, especially in larger cities, significant progress has been made in modernizing garbage collection and final disposal services. In contrast, because of their limited financial resources and rising levels of waste, small- and medium-sized cities and rural areas have seen relatively little improvement. On the other hand, issues related to a lack of land for disposal sites in metropolitan municipalities have come to be recognized as significant hurdles to their effective waste management. Reducing the amount disposed of is vital because there are not many lands accessible for disposal locations.

The Moroccan government has come to feel that it is essential to find an appropriate waste treatment system that is adapted to the local technical and economic requirements for diverse areas in Morocco. Figure 6.7 summarizes the main decrees of Law 28-00 and their description.

Prior to 2008, Morocco's collected waste was disposed of at local landfills. They are typically in county regions that are arbitrarily chosen for being close to the city without doing any environmental impact studies. There are thought to be 300

Fig. 6.7 The main decrees of Moroccan waste Law 28-00

landfills in total (Ministry of the Environment Morocco 2008). These websites have a number of issues:

- Ample space.
- There is no security and there is no taxiway.
- Heterogeneity of waste (household, medical, industrial, etc.).
- Many of the site's informal workers live in extremely precarious circumstances (no regulations, waste, disease risks, etc.).
- Outdoor garbage burning releases foul odors (for neighbors: villages, cities, dressers, etc.).
- Fragmented plastic packaging.

The best management of solid waste – which includes municipal wastes, plastics waste, e-waste, industrial and hazardous wastes, biomedical wastes, and construction and demolition wastes – wastewater and sludge, agricultural waste, end-of-life vehicle wastes, and renewable energy and electricity are all included in the national strategy and remain the main initiatives that receive attention (Dahchour et al. 2021).

A significant amount of diverse chemical wastes are produced as a result of the exponential growth in the usage of chemicals in scientific research. These chemical wastes can potentially pollute land, water, and air and have negative impacts on human health. In light of this, it is unquestionably necessary to manage and handle these products in compliance with national and international legislation (Housni et al. 2022).

6.7 Conclusion

Political, institutional, environmental, social, and economic factors all play a role in the complexity of the SWM. In addition, in developing nations, different obstacles are shown in the application of waste management, such as a lack of reliable and updated waste data. Although it is easy to create regulations, both industrialized and developing countries suffer from the enforcement of them. Indeed, in developing nations, the enforcement of waste-related laws faces several obstacles due to a lack of adequate technical infrastructure and the absence of effective regional waste management programs. In many developing nations, the legislative and regulatory framework for waste management is inadequate, scattered, and incomplete.

In developing countries, it can be said that even if the polluter pay principle exists on paper, its application is far from being effective, at least in terms of waste treatment cost coverage. Municipal waste collection and treatment is a public service funded in part by municipal taxes that typically have nothing to do with waste management and partially by the national budget. The EPR concept is increasingly being used in developed countries, but it is only slightly used in developing countries.

Developing countries need effective policy support and adequate governance to achieve waste management and recovery in an integrated and sustainable manner. The life-cycle approach, the preventative concept, the polluter pays concept, producer obligation, and enforcement of rules requiring local authorities to recycle their waste and separate it at source are some of the fundamental principles that should be incorporated into a nation's waste law.

In order to understand policies, the awareness of the urban community is necessary for efficient policy implementation. Strong governance is required to build sufficient capacity in the financial, institutional, technological, and infrastructural sectors to encourage garbage management that is environmentally responsible. The adoption of legislation requiring separation at source regulations to promote waste reuse, recycling, and recovery. The implementation of laws that guarantee the disposal of hazardous waste in a way that is environmentally sustainable and safe. These two actions could encourage efficient waste management.

References

M. Batista et al., A framework for sustainable and integrated MSW management: Barriers and critical factors to developing countries. J. Clean. Prod. **312**, 127516 (2021)

M. Compagnoni, Is extended producer responsibility living up to expectations? A systematic literature review focusing on electronic waste. J. Clean. Prod. **367**, 133101 (2022). https://doi.org/10.1016/j.jclepro.2022.133101

A. Dahchour, S. El Hajjaji, D. Dhiba, S.K. Ghosh, Circular economy in Morocco: Status and perspectives. Circ. Econ. Recent Trends Glob. Perspect. **29–67** (2021). https://doi.org/10.1007/978-981-16-0913-8_2

Department of Environmental Affairs, Republic of South Africa, Guidelines on separation of waste at source. In: Affairs, D. E. (ed.), (2018)

H. El Bari, Gestion et Valorisation des Déchets Solides Ménagers, Published by Fondation Allemande Konrad Adenauer-Stiftung (2016)

N. Ferronato, V. Torretta, Waste mismanagement in developing countries: A review of global issues. Int. J. Environ. Res. Public Health **16**, 1060 (2019)

L. Godfrey, Waste plastic, the challenge facing developing countries – Ban it, change it, collect it? Recycling **4**(1), 3 (2019). https://doi.org/10.3390/recycling4010003

L. Godfrey, M. Ahmed, S. Oelofse, O. Osibanjo, U. Henning Richter, A. Yonli, Solid waste management in Africa: Governance failure or development opportunity? in *Regional Development in Africa*, ed. by N. Edomah, (Intechopen, 2019). https://doi.org/10.5772/intechopen.86974

A. Hasib, A. Ouigmane, O. Boudouch, et al., Sustainable solid waste management in Morocco: Co-incineration of RDF as an alternative fuel in cement kilns, in *Strategies of Sustainable Solid Waste Management*, ed. by H.M. Saleh, (IntechOpen, 2020). https://doi.org/10.5772/intechopen.93936

S. Hemidat, O. Achouri, L. El Fels, et al., Solid waste management in the context of a circular economy in the MENA region. Sustainability **14**, 480 (2022). https://doi.org/10.3390/su14010480

H. Housni, K. Bendahhou, M. Tahiri, N. Tahiri Jouti, Compliance assessment of scientific research laboratories with legal requirements regarding the integrated management of chemicals and hazardous waste. Chem. Afr., 1–23 (2022). https://doi.org/10.1007/s42250-022-00386-5

Ministry of the Environment Morocco, Programme National des Déchets Ménagers (PNDM), Maroc, 2008

F. Muheirwe, W. Kombe, J.M. Kihila, The paradox of solid waste management: A regulatory discourse from Sub-Saharan Africa. Habitat Int. **119**, 102491 (2022). https://doi.org/10.1016/j.habitatint.2021.102491

B. Nyathi, A. Togo, Overview of legal and policy framework approaches for plastic bag waste management in African Countries. J. Environ. Public Health **1**, 8 (2020). https://doi.org/10.1155/2020/8892773

A. Ouigmane, O. Boudouch, A. Hasib, M. Berkani, Management of municipal solid waste in Morocco: The size effect in the distribution of combustible components and evaluation of the fuel fractions, in *Handbook of Environmental Materials Management*, ed. by C. Hussain, (Springer, Cham, 2018). https://doi.org/10.1007/978-3-319-58538-3_82-1

P. Pathaka, R.R. Srivastava, Ojasvic, Assessment of legislation and practices for the sustainable management of waste electrical and electronic equipment in India. Renew. Sust. Energ. Rev. **78**, 220–232 (2017)

R. Rajesh, D. Kanakadhurga, N. Prabaharan, Electronic waste: A critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. Environmental Challenges **7**, 100507 (2022). https://doi.org/10.1016/j.envc.2022.100507

L.T.K. Trinh, A.H. Hu, S.T. Pham Phu, Situation, challenges, and solutions of policy implementation on municipal waste management in Vietnam toward sustainability. Sustainability **13**, 3517 (2021). https://doi.org/10.3390/su13063517

D.E. Turcott Cervantes et al., Assessment of some governance aspects in waste management systems: A case study in Mexican municipalities. J. Clean. Prod. **278**, 123–320 (2021). https://doi.org/10.1016/j.jclepro.2020.123320

Yoshida, M., Political economy of municipal solid waste Management in urban areas of developing countries and framework of capacity development support. In Fifth international conference on advances in Applied Science and Environmental Technology – ASET 2016, pp. 17–22 (2016). https://doi.org/10.15224/978-1-63248-106-1-34

Chapter 7
The Waste Informal Sector Impact in Mena Region

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7.1 Introduction

Improving urban waste management in the MENA Region is increasingly a real challenge imposed by significant population growth, real urban evolution, and the emergence of new consumption patterns. Despite all the efforts made by institutional actors to improve this sector, and despite considerable progress (improvement in collection, landfill and recovery rates), the general observation is that serious problems persist both upstream and downstream of the waste management cycle.

Stakeholders are faced with a service that is increasingly costly and a source of tensions and pressures that are difficult to identify. Decision-making and the completion of tenders have also become a delicate exercise, given the rapid evolution of the national legal arsenal and the slow implementation of the application texts, and the challenge of finding technical solutions adapted to the specificities of each city.

In the majority of MENA cities, waste pickers are informal actors operating on the margins of the waste value chain and play an important role in the circular economy system. These informal waste pickers have always been pushed to the

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margins, edges, and interstices of large cities and the "holes" of metropolises (Florin 2016).

Informal recyclers play a fundamental role in the urban solid waste management system. Their activity valorizes recyclables produced by households, businesses, and industries. Although it could allow the recovery of a more or less important portion of household and similar waste, the organization of this activity is currently limited to a few cooperatives of sorters at the level of the new controlled landfills, while it is still informal, unstructured, and not very profitable at the level of the cities.

In this context characterized by the complexity of the field and the multitude of stakeholders, there is a growing consensus on the need for a new integrated approach capable of capturing all aspects likely to improve the waste management system, particularly municipal solid waste. Analyzing the weak links of the current model, questioning the roles of all potential actors, should define new rules and rethink the roles required to continuously and efficiently improve the current situation.

The research methodology is based on interviews conducted in Morocco, Algeria, and Tunisia. It also relies on the review of existing literature and documentation on the subject in the MENA Region, observation of recovery, reclamation, and recycling activities.

7.2 The Informal Sector in the MENA Region's Urban Waste Management System

7.2.1 Waste Management Policies

Worldwide, urban waste management is considered as a public service, like water distribution or energy delivery. In most countries, this service is provided by local authorities as one of their municipal competences; those competences are usually being regulated by a national legal framework. As a general rule, waste management policy consists in putting in place the infrastructures (collection system, sanitary landfills and/or energy recovery plants, sorting and recycling facilities); setting up a separate collection system as well as waste transport, underpinned by a strong set of legislations; and establishing a sustainable cost recovery system based on the "polluter pays" principle, as well as respecting the waste hierarchy. This should be done in an integrated way (integrated sustainable waste management), meaning that:

- All physical elements (infrastructure) of the system, from waste generation through storage, collection, transport, transfer, recycling, recovery, treatment, and disposal, are considered.
- All stakeholders are involved, including municipalities, regional and national governments, waste generators/service users (including industry, business, institutions and households), producers (those who put products on the market which

become waste at the end of their life, including manufacturers, brand owners, importers and others in the supply chain), service providers (whether public or private sector, formal or informal, large or small), civil society and non-governmental organizations (NGOs) (which play a variety of roles, including facilitating the participation of other parties), international agencies, etc.
- All strategic aspects, including the political, health, institutional, social, economic, financial, environmental, and technical facets, are taken into account.

Waste management in developing countries is not conducted in such an integrated way and is most of the time characterized by not only an absence of waste collection (or at least an absence of separate collection) and disposal schemes but also an absence of adequate treatment facilities, – leading to improperly managed dumping sites – as well as by weakly enforced environmental and municipal solid waste legislation, when existing.

Solid waste management (SWM) is one of the most important environmental challenges that countries in the MENA region face. Indeed, "the rapid growth of the population, a booming economy, rapid urbanization, and high standards of living in the community have significantly accelerated the rate of solid waste generation" (Hemidat et al. 2022).

The MENA region countries suffer from an insufficiently regulated context, a lack of long-term planning, an over centralization of authority at national level, and a lack of cost recovery mechanism at national and local level. Notwithstanding, some countries do have a waste management strategy and legislations; however, most of them still do not have appropriate long-term vision, legislations, and strategies. Moreover, in countries where waste management laws and strategies exist, their enforcement, the other side of the coin, remains problematic.

In addition to that, when implementing waste management strategies, priority is given to the sanitation of existing dumping sites. Collection schemes, when existing, are mingled ones. So far, there is no systemic separate collection in any of the MENA countries.

It can be said that while sanitation of dumpsites and building of adequate infrastructures are increasing year after year, separate collection still does not exist in a systematic way. Separate collection schemes exist only as pilot projects, which end when donor funding expires.

Separate collection is usually considered as a financial issue for municipalities, since it leads to an important increase of the municipal budget, due to the lack of an adequate cost recovery system. Furthermore, since separate collection is handled by informal waste pickers, introducing separate collection schemes is concerning for local decision-makers who do not want to provoke a social crisis, as waste pickers could get less revenues in case a formal system would be put in place.

There exist multiple reasons for that situation: on the one hand, an inadequate governance of local authorities and, on the other hand, an absence of efficient fiscal and financial system allowing the concrete implementation of the waste strategy.

7.2.2 Collection System Context

– What should be collected and how should it be collected?

When talking about urban waste (or municipal waste), we intend to cover household waste and assimilated ones, made of an important organic fraction and a packaging/dry fraction (paper, cardboard, glass, metal, and plastic). The collection we deal with here is the dry fraction. Nevertheless, we must bear in mind that organic waste can be collected as (animal) feed in very poor areas.

In the MENA region, most of the time, municipal wastes are collected under the responsibility of the municipality, with some exceptions or less efficient systems in remote areas. It is well established that the selective collecting of household waste is largely carried out by the informal sector. "Recyclables" are collected by waste pickers (informal collectors), straight from household waste, with the result that much of this waste escapes the quantity of household waste collected by the municipalities and their delegates.

Waste pickers operate in two different modes.

- Part of them collect separately in the dumpsites, with or without adequate tools, in precarious conditions, regardless of hygiene and security. They usually collect the recyclables in landfill, generally located on the outskirts of urban centers, after the trucks in charge of collecting mixed household waste have taken the (unsorted) waste to the landfill. Only a few controlled landfills now have operational sorting lines where waste pickers are "employed" to carry out the sorting operations under better conditions. There are three sorting lines of this kind that are operational in Morocco: in Rabat, Meknes, and Marrakech.
- Others roam around the city's neighborhoods and rummage through the garbage (household and similar waste bins and industrial waste bins) to sort and recover all recyclable waste, especially PET bottles, metals, paper, and cardboard. The waste that is collected in the city is generally less dirty and soiled than the waste collected in landfills, since it is collected further upstream and can therefore constitute a better-quality recyclable material.

The means of collection and recovery vary according to age, location, and habitat: it can be realized on foot, bicycle, small or large carts, carts with donkeys, and three-wheelers.

The working conditions are harsh both from a sanitary and technical point of view. Their activity is not recognized and therefore informal.

– How is waste collection financed?

In developed countries, financial means rely on the application of the "polluter pays" principle applied as closest as possible to the producer of waste (the citizen, local taxes, and/or the consumer, extended producer responsibility (EPR) systems).

In those countries (mainly EU, North America, Canada), EPR systems/schemes have been implemented for many years and allow for a sustainable management of waste (by sustainable management, we mean a management where waste is considered as a resource and is put back into a circular process, essentially thanks to selective collection and recycling activities adapted to the existing material flows).

Similarly, waste-related taxation is now applied at the local level and becomes an economic incentive for households that produce less waste (pay as you through system) or sort more. On the contrary, in developing countries, collection (and waste management) is most of the time financed by the general budget of the municipality. This budget is made of local taxes (tourism…) – without any connection either with the waste management service or with the quantity of waste produced – and subsidies from the national government. The cost of basic municipal waste management operations (collection and transport to the landfill) occupies a considerable portion of city budget in developing nations. It is therefore unthinkable for local authorities to implement a separate collection system without additional funding.

To address this budget deficit, several MENA countries have begun to think about developing an EPR system. Besides the usual problem of lack of legislation and appropriate facilities, they are then faced with the problem of the informal sector. This informal sector can only be part of the solution, but it needs formalization (in order to avoid unsound practices) and professionalization.

7.2.3 The Relationship Between the Informal and Formal Sector

Once collected, the recovered waste is usually sold by the waste pickers to various kinds of intermediaries and wholesalers. The size of the wholesalers depends on their premises: those located in the cities (generally in poor areas) have small premises (garages) and those located in the periphery have larger premises (sometimes up to 1000 m^2). They usually store, sort, and/or wash recyclable waste purchased from waste pickers or smaller intermediaries. Then, they sell it to wholesale shredders. At that stage of the process starts the "formal" sector. Some "shredders" are still informal, but others are patented recycling companies with storage facilities. After shredding, the material is resold to manufacturers.

Due to their poor conditions of work, lack of means (no storage place, no trucks, etc.), and lack of consideration, the first level of the chain (waste pickers) is exploited and poorly paid. The people working on the next level are slightly better regarded and so on, depending mainly on the quantity they can offer in once.

Without any doubt, the informal sector contributes significantly to the recycling rates of many cities in the MENA region (Hemidat et al. 2022). Thus, reducing the volume of waste sent to landfills, and environmental pollution, while creating local added value through the recycling market and informal employment opportunities.

However, despite these benefits, the informal sector is also associated with negative social and economic conditions, such as poverty, bad working conditions, exploitation, discrimination, child labor, social rejection, and lack of education.

Working as a waste picker is associated with low status and considered undesirable. There is a general disrespect for the work, thus producing low working ethics of workers and poor quality of their work.

In light of this situation, policy- and decision-makers are well aware of the contribution of the informal sector and consider the waste pickers as relevant stakeholders in their waste management systems. Nevertheless, they still have difficulties understanding how to formalize them, while improving their working conditions and socioeconomic situation, without threatening dozens of jobs provided by such a system. For sure, the right recipe depends on the socioeconomic and cultural context, which varies from one country/region to another.

Based on an international benchmark of proven initiatives, the main forms of support for the organization of the waste recovery business can be listed as follows:

- Creating a cooperative or association of waste pickers managed by an office.
- Encouraging wholesalers to establish a formal framework with micro-associations of waste pickers.
- Tripartite agreement: wholesalers/recyclers/municipality and service provider company.
- Developing a micro-credits system: For the purchase of materials and equipment or loans.
- Creating dedicated sorting centers (like the three ones in Morocco).
- Creating a municipal/intermunicipal development company.
- The recovery of recyclable waste sector has its own organization, rules, actors, and dynamics, specific to each territory. The solution must be tailored to these criteria or will not be a solution.

7.3 Waste Management: A Multitude of Actors

Approaches to the management of essential urban services in the MENA region have undergone profound changes in recent years. These changes are linked to public service reforms that have involved a wide variety of decentralization, liberalization, privatization, democratization, and participatory processes (Jaglin and Zerah 2012). In the case of urban waste, these changes are part of the modernization of the management of the service that has interested low- and middle-income countries in the last two decades and that has often referred to Western models based on centralized and technical approaches to waste collection and treatment, developed at the scale of the urban perimeter (Spaargaren et al. 2005). However, in MENA countries, modernization in MSW management is taking place with a multitude of actors, represented mainly by individuals or micro-enterprises, often belonging to the informal sector, already filling the waste collection, recovery, and recycling niches.

In local and national contexts of political, legislative, and administrative reforms of waste management systems, there is a reconfiguration of the relationships, roles and places of the different actors dealing with waste, as well as the emergence of new actors in a sector that seems, all in all, increasingly lucrative. This growing profitability of waste is explained by the rise in raw material prices, leading to a renewed interest in secondary raw materials.

On an international scale, the increasingly precise organization of the materials chains, whether for recovery, processing, or export, raises the question of the international circulation of waste, whether formal or informal, official, or clandestine. The new international waste players deserve our attention. Finally, the global environmental context, the need to reduce waste, and the problems of its reuse, recycling, and treatment have become priorities that impact local and national policies, all the more so as waste production is constantly increasing.

7.3.1 Increasingly Privatized Solid Waste Management

Solid waste management is a particularly significant challenge for developing countries, where resources are limited but urbanization is increasing. Municipalities operate within a limited framework: rigid laws, large numbers of employees due to the manual tasks involved in cleaning and collection services, and consequently the influence of unions on the overall organization.

Municipalities delegate waste management tasks in order to reduce costs, particularly wage costs: unlike employees of private companies, municipal employees are members of unions and their wages are high. Services can be delegated to private companies (public-private partnerships) or to NGOs.

According to Dorvil (2007), one argument in favor of public-private partnerships is that a private contractor is better able to control costs, respond to client needs, and adopt new technologies and better management practices.

In this section, we consider the case of three MENA countries: Morocco, Algeria, and Tunisia.

7.3.2 Laws Governing the Collection and Disposal of Waste in Morocco

Law n°28-00 on waste management and disposal (B.O. n° 5480 of December 7, 2006) is the first law in Morocco dedicated to the waste sector. It provides for the elaboration of three waste management master plans, at three different territorial levels, for three distinct types of waste: a national master plan for the management of hazardous waste; a regional master plan for the management of non-hazardous industrial, medical, and pharmaceutical waste and ultimate, agricultural, and inert waste; and a prefectural or provincial master plan for the management of household and similar waste. In the framework of the law n°12-90 on urban planning, the Urban Development Master Plan notes: “the places to be used as deposits for household waste must be submitted to the communal councils concerned prior to their approval." In January 2007, the National Household Waste Program (PNDM), developed by the Secretary of State for Water and the Environment and the Ministry of the Interior, was allocated $4.3 billion over a 5-year period for the implementation of a national solid waste program. This program is a clear signal from the state to local authorities, who must now implement integrated projects to reduce untreated waste and increase recycling rates. The recent law n°54-05 relating to the delegated management of public services has strengthened the legal arsenal of public procurement, particularly for the delegated management of the solid waste sector.

Article 12 of law n°28-00 provides that the prefectural or provincial master plan for the management of household and similar waste is drawn up on the initiative and under the responsibility of the governor of the prefecture or province concerned, in consultation with a consultative commission made up of representatives of the councils of the communes and their groupings representatives of the prefectural or provincial council, representatives of the administration, representatives of professional bodies concerned with the production and disposal of such waste, and representatives of neighborhood associations and environmental protection associations operating in the prefecture or province concerned. The master plan takes into account the needs and potential of neighboring areas outside the territory of its application, as well as the possibilities of inter-prefectural or inter-provincial cooperation in this field. The plan is subject to a public inquiry. It is approved by order of the wali or the governor after the opinion of the prefectural or provincial council (B.O. N°5480 OF DECEMBER 7, 2006). The territory of each prefecture or province must be covered by a prefectural or provincial master plan for the management of household and similar waste as of the year 2011. It is drawn up for a period of 10 years. This plan determines, in particular, the objectives to be reached in terms of collection and elimination rates for household and similar waste; the appropriate sites for the establishment of elimination and storage facilities for this waste, taking into account the orientations of urban planning documents; a 5-year and 10-year forecast inventory of the quantities of waste to be collected and eliminated according to their origin their nature and type; an investment program for the same duration including the evaluation of the costs of realization of the controlled landfills and the installations of treatment, recovery, storage, or elimination of these wastes, as well as the rehabilitation of the noncontrolled landfills, the financial and human means necessary, the measures to be taken as regards information, sensitizing, and council.

The Communal Charter of 30/09/1976 entrusts local authorities with the responsibility of managing household waste (solid waste). Article 30 of the communal Dahir n°17-583 relating to the communal organization establishes that "the communal council regulates by deliberation the affairs of the commune and, to this end, decides on the measures to be taken to ensure the full economic, social and cultural development of the local community." By law n°28-00, the communes or their groupings are required to establish a communal or inter-communal plan for the management of household and similar waste, which defines the operations of pre-collection, collection, transport, dumping, elimination, treatment, and recovery and, if necessary, sorting of this waste. Article 17 of the same law establishes that the communal or inter-communal plan must take into account the orientations of the prefectural or provincial master plan for the management of household and similar waste. It defines, in particular, the zones where the communes or their groupings are required to ensure the collection, transport, elimination, or recovery of household and similar waste; the routes, frequency, and timetables for the collection of this waste; the methods of waste collection; the frequency of cleaning operations by zone; and the zones where the transport and dumping of this waste are the responsibility of its generators. This plan is established for a period of 5 years and approved by order of the governor of the prefecture or province concerned. The municipalities or their groupings decide on the management methods of the public service of household and similar waste, by direct management, autonomous management, concession, or any other form of direct management or delegated management. When the management of this service is delegated, the operator is subject to the provisions of the law and its application texts. In addition, the municipality must organize awareness-raising activities to involve the citizen in the actions that the community undertakes to improve waste management (use of appropriate containers, ensuring the cleanliness of public roads, making efforts to sort waste upstream, etc.) and information sessions for the public on respect for the environment, the various types of waste, their disposal, etc. Regarding the collection and disposal of waste Role of the municipalities, Article 16 of Law No. 28-00 on the management and disposal of waste establishes that the communal public service of management of household waste and similar includes the collection, transport, disposal, treatment, recovery and, where appropriate, sorting of such waste. This service also includes the cleaning of roads, squares, and public places as well as the transport and elimination of cleaning waste, under the same conditions as household waste management.

7.3.3 Informal Waste Actors in Morocco

Informal recyclable material collectors are fundamental actors in the urban solid waste management system in most developing countries. Their activity valorizes recyclable materials rejected by households, businesses, and industries and is carried out in a context of low involvement of public authorities in source separation actions. This context is also marked by the saturation of landfills, illegal deposits, low collection rates, the increase in the quantity of household waste, and negative effects on the environment and public health. Although it allows for the recovery of a more or less important portion of these recyclables, the informal recycling activity is, most of the time, neither recognized nor supported by the authorities (Azaitraoui 2007).

The sector is relatively structured (the chain is complete, from the recovery of waste from garbage cans to the recycling industry) and the actors in the informal sector are numerous. We can identify (Soudi and Chrifi 2008) as follows:

Landfill collectors: They wait for the arrival and emptying of dump trucks to sort the waste and recover the maximum amount of recyclable products.

Itinerant waste pickers: They work mostly at night or at least before the municipal service truck arrives. They drive through the city in a cart and collect recyclable waste from the garbage cans.

The garbage collectors: To improve their income, they sort the recyclable waste in the collection truck in order to sell it to wholesale intermediaries. However, this activity is not allowed in private waste management companies.

Intermediary washer/sorters: Usually located in working-class neighborhoods, they store, sort, and/or wash recyclable waste purchased from reclaimers or smaller intermediaries. They then resell it to wholesale shredders. They are therefore simply traders in the material.

Wholesaler-shredders: They are mainly located in Casablanca. They collect the plastic recyclable waste from the reclaimers and then grind them before reselling them to the industrialists.

The recycling industries: There are an estimated 9500 mikhali (recyclers) in Morocco, who operate at landfill sites or in cities, with an average income of no more than 35–60 DH (3–5.50 €) per day. The incomes of intermediaries and wholesalers would be much higher than those of reclaimers, as their intermediation margin would reach 50%. At this level of the sector, the beginning of industrialization can be observed: crushing, processing, and organized transport. The reclaimers are sometimes subsidized by an intermediary (salary advances, purchase of carts, loans, etc.). Similarly, there are certain special relationships between recovery companies and wholesalers (establishment of specifications, exclusive supply in the case of the paper-cardboard and glass sectors, etc.). Recovery companies are mainly located in Casablanca; paper and cardboard are directed to Kenitra.

7.3.4 Laws Governing the Collection and Disposal of Waste in Algeria

We had to wait for the establishment of the Ministry of Territorial Planning and Environment in 2000, so that we can for the first time in Algeria feel a certain strategy, whether in waste management or in the environment in general.

The texts of application in the field of the household and assimilated waste in Algeria are the following ones: Law N°90-08 on the communal code; Law N°01-19 of 12/12/2001 on the management, control, and elimination of waste; Law N°03-10 of 19/07/2003 on the protection of the environment within the framework of sustainable development; Executive decree n° 02-175 of 20/05/2002 on the creation of the National Agency of Waste; Executive decree n° 02-372 of 11/11/2002 relating to packaging waste; Executive decree n° 04-199 of 19/07/2004 fixing the methods of creation, organization, functioning, and financing of the public system of treatment and recovery of packaging waste "ECO-JEM"; Executive decree N° 04-210 of 28/07/2004 defining the methods of determination of the technical characteristics of the packagings intended to contain directly food products or objects intended to be handled by the children; Executive decree N° 04-410 of 14/12/2004 fixing the general rules of installation and exploitation of the installations of treatment of waste and the conditions of admission of these waste at the level of these installations; Executive decree 07-205 of 30/06/2007 fixing the modalities and procedures of elaboration, publication, and revision of the communal plan of management of the household and assimilated waste; Inter-ministerial decree of 06/04/2004 fixing the technical characteristics of the plastic bags intended to contain directly food products (MATET – PNUD). The law n°01-19 of 27 Ramadhan 1422 corresponding to December 12, 2001 relating to the management, the control, and the elimination of waste aims at fixing the methods of management, control, and treatment of waste, on the basis of the following principles: (1) the prevention and reduction of the production and harmfulness of waste at the source; (2) the organization of the sorting, collection, transport, and treatment of waste; (3) the recovery of waste through its reuse, recycling, and any other action aimed at obtaining reusable materials or energy from this waste; (4) the environmentally sound treatment of waste; and (5) the information and awareness of citizens on the risks presented by waste and its impact on health and the environment, as well as the measures taken to prevent, reduce, or compensate for these risks (Journal Officiel de la Republique Algrienne, 2001). This legislative effort was then consolidated by a regulatory and institutional system that resulted in the implementation of communal waste management plans; the introduction of ecological taxation; the creation of the National Waste Agency (AND); the establishment of a national system for the recovery and recycling of packaging waste to promote the emergence of a national waste market and encourage the development of activities in the field of waste sorting, recycling, and recovery; and the implementation of an ambitious national program of integrated municipal waste management.

A PNAE-DD, a National Action Plan for the Environment and Sustainable Development, was drawn up in 2002 with timetables for reflection and implementation. He notes: "as regards urban waste, it must be noted that, with the exception of the Algiers landfill for which precautionary measures have been taken, no global approach has been undertaken to date". The budgets allocated are most often used to acquire collection equipment while the issues of site selection, facility management, operator training or public awareness are not addressed. The non-rational and insufficient management of solid waste results in the pollution of water tables, the appearance of gas fumes, the proliferation of mosquitoes and rodents, impacts on public health due to the incineration of waste in landfills, economic losses (non-recycled materials, lack of composting, loss of land, etc.) and aesthetic losses (degradation of the environment, loss of income, etc.) and aesthetic losses (landscape degradation) (MATET 2002). The option chosen for the treatment and elimination of waste is the creation of technical landfill centers (CET). At the same time, a national household waste management program, PROGDEM, was launched to provide municipalities with waste management master plans. The three actions implemented within the framework of PROGDEM are the elaboration of master plans of household waste management, the realization of technical landfills and the acquisition of material means, and the closure and rehabilitation of illegal dumps. This program consists, in particular, of reorganizing the municipal administration in charge of waste management, strengthening the collection and transport capacities of the municipal services in charge of waste management, opening up the public urban waste management service to private investment and concessions, implementing a training and technical assistance program for local authorities, and setting up appropriate collection equipment (MATET undated).

In accordance with Article 107 of Law No. 90-08 of 7 April 1990 on the commune code (Title III: Responsibilities of the commune; Chapter VI: Hygiene, sanitation, and environment), the commune is responsible for maintaining public hygiene and sanitation, particularly with regard to the evacuation and treatment of wastewater and solid urban waste (Journal Officiel de la Republique Algrienne, 1990). According to the provisions of Law 01-19 relating to the management, control, and elimination of waste (Article 32), "the management of household and similar waste is the responsibility of the commune in accordance with the legislation governing local authorities" (Journal Officiel de la Republique Algrienne, 2001).

7.3.5 Institutions Responsible for Waste Collection and Disposal

Role of the Municipalities The Law n°01-19 of 27 Ramadhan 1422 corresponding to December 12, 2001, relating to the management, control, and disposal of waste endows the municipalities with the responsibilities to elaborate and implement the municipal waste management plans as planning and management instruments. These plans must be consistent with the wilaya development plan and approved by the wali. Their role is also to continuously improve the conditions of waste collection and disposal by regulating the conditions under which waste is presented for collection. They also set the standards and conditions for the collection and disposal of waste, rationalizing the collection routes. In particular, they establish specifications specifying the obligations of the companies responsible for waste collection and disposal, by providing users with sealed containers. In addition, the utilities designated in Section 32 include the following:

- The setting up of a system for sorting household and similar waste with a view to its recovery
- The organization of the separate collection, transport, and appropriate treatment of special waste generated in small quantities by households
- The setting up of a permanent information and awareness system for inhabitants on the harmful effects of waste on public health and/or the environment and on the measures intended to prevent the said effects

- The implementation of incentives for the development and promotion of sorting systems for household and similar waste (Journal Officiel de la Republique Algrienne 2001).

Role of the Wilaya The Wilaya's environmental department assists the municipality through, for example, the implementation of the communal waste management master plan.

Delegation of Urban Waste Management Services The participation of the private sector in waste management is practically absent in Algeria. Therefore, the authorities have decided to promote incentives to stimulate the participation of this sector (creation of micro-enterprises) in activities related to waste management. Under the form of contracts or concessions, the activities of collection, operation of landfills, recycling, sorting, and composting can be subcontracted. The National Environment and Pollution Fund (FEDEP), the National Waste Agency (AND), and the National Agencies for Supporting Youth Employment (ANSEJ) and Investment Development (ANDI) are called upon to assist in the support and implementation of viable projects. In Séààètif, the APC (Assemblée Populaire Communale) decided to delegate the collection of household waste in six suburban areas on January 1, 2009 (peripheral cities such as Aïn-Trick, Cheïkh Laïfa and Abid Ali), to six micro-companies created in this framework. This "experiment," the first of its kind in Algeria, was motivated by the growth of the city and the need for greater resources to manage the collection. These micro-enterprises were created by young university students with the support of ANSEJ, which provides a facilitating framework since they benefit from a tax exemption for the first 5 years and support for the management of the company. These micro-enterprises obey a set of specifications drawn up initially by the ANSEJ management, then later with the environmental management; an agreement is signed between the municipality and each micro-enterprise, which must have a 12-ton capacity tipper and hire 10 workers. These companies currently manage only the collection but also have the possibility to invest in sorting and are about to start working at the site of CET to extract recyclable materials, through contracts with the APC (Azaitraoui and Moretto 2012).

7.3.5.1 Informal Waste Actors in Algeria

Following the implementation of technical landfills in Algeria, a measure responding to an emergency in the field of waste management has been put in place within the national program of municipal solid waste management. However, recycling/recovery is still underdeveloped in the country. In this context, selective collection and waste sorting projects are about to be launched by the Ministry of Land Management and Environment (MATE). Informal recovery activities, which are rather developed in the country, should be taken into account in the context mentioned above; informal but spatially and economically organized, the recovery sector includes informal reclaimers from the landfill and the city, intermediaries, and wholesalers. The informal reclaimers do not really have a name; the French semantic of chiffonnier is the one most often used in the press. The term zabaleen, which is sometimes used to refer to reclaimers, actually refers to those who produce the waste and is, therefore, quite apart from its pejorative aspect, not appropriate to refer to reclaimers.

7.3.5.2 Laws Governing the Collection and Disposal of Waste in Tunisia

In the field of waste management, Tunisia has a strategic reflection at the central level, the local level being strongly supervised by the State via ANGed (National Agency of Waste Management), agency in charge of planning and adopting the strategies at the national level.

The organic law of the communes and the law n° 96-1996 relating to waste and the control of their management and elimination constitute the two basic regulatory texts governing the solid waste sector in Tunisia. At the national level, the laws governing the collection and disposal of waste are the following: the framework law 92-122 of December 29, 1992, creating the fund of depollution whose object is the financing of the projects of appropriate management of the solid waste; the law n°96-41 of June 10, 1996, relating to waste and the control of their elimination; the law 97-11 of February 3, 1997, carrying promulgation of the code of the local taxation; the law 2001-14 of January 30, 2001, fixing the methods of collection, transport, storage, and treatment of the non-dangerous waste; the law 2003-80 of December 29, 2003, creating the "Fonds de Propreté de l'Environnement et de l'Esthétique des Villes" (Cleanliness Fund for the Environment and the Aesthetics of Cities); and the decree 2005-2317 of August 22, 2005, creating ANGed and entrusting it with the mission of waste management at the national level by the elaboration and implementation of plans, programs, and national projects related to the management of waste. The National Solid Waste Management Program (PRONAGDES) was the strategic framework for waste management for the period 1995–2006. The new strategic framework, renamed PROGIDD (Programme National de Gestion Intégrée et Durable des Déchets), will cover the period 2007–2016 (SWEEP-NET/AMRA Consulting, 2010). Its two main overall objectives are to improve environmental protection through the implementation of integrated and sustainable waste management and to promote the quality of life of citizens. To achieve these objectives, the national strategy will be based on two basic principles: prevention, by reducing the source and environmental damage caused by waste, and the participatory approach, by involving the various stakeholders in the different stages of waste management, from design and planning to implementation. The overall objectives are detailed in four specific objectives which are the reduction of waste quantities; the treatment, recycling, and recovery of waste; the improvement of the legal and financial institutional framework of waste; and the improvement of communication, consultation, awareness, and data control in this sector (Ferchichi, 2010).

At the local level. The organic law of the communes 95-68 published in 1995 entrusts the communes with the responsibility of household waste management at the local level.

7.3.6 Institutions Responsible for Waste Collection and Disposal

The Ministry of the Environment and Sustainable Development develops the country's general policy on the environment and land use planning and proposes a regulatory framework in this area; it supervises the budgeting of plans, programs, and actions undertaken by the implementing body, ANGed. It supervises the National Agency for Environmental Protection.

Implementation of the national policy. ANGed, created in 2005, is a public company under the supervision of the Ministry of the Environment, which is in charge of national waste management programs. It promotes the partnership between all the stakeholders and, in particular, between the local authorities, the industrialists, and the private sector. It helps and assists municipalities and industrialists in the field of sustainable waste management and prepares and implements awareness programs on waste management, in collaboration with environmental associations, in particular. It promotes systems and programs for the collection, recycling, and recovery of waste.

7.3.7 The Eco-Lef Plastic Sector

The state strategy foresees the setting up of technical disposal centers, essentially reserved for the burial of final waste, which implies that the state has set up in parallel mechanisms and tools for the recovery and recycling of materials contained in household waste: Eco-Lef is a public system of recovery and valorization of used packaging which was set up in 2001. Currently, almost all the industrial packers of water, soft drinks, juices, and milk derivatives adhere to the Eco-Lef system. A network of Eco-Lef points for the collection and transfer of packaging waste has been set up, particularly in large cities. The Eco-Lef point constitutes a primary reception center for packaging waste, by paid contribution, with a view to its recovery. This system can be a source of income for individual collectors. The main objectives of this project are to stimulate the packaging waste recovery market by giving this waste a market value, the "take-back price," and to involve local actors (municipalities, associations, waste collectors, etc.) more closely. Between 350 and 370 micro-enterprises have been created in Tunisia under this program, offering nearly 20,000 jobs for executives with a minimum of 4 years of higher education. Thus, the Eco-lef, a scheme mixing social, economic, and environmental aspects, is a mechanism that works well, with rates of 90–95% of plastic recovery and interesting consequences on the social level. The waste management channels that have been set up for recoverable waste are packaging, used oil and filters, accumulators, and batteries; other channels are being set up for used tires, paper, and cardboard (Azaitraoui and Moretto 2015).

7.3.8 Informal Waste Actors in Tunisia

Informal recovery is "semi-formalized" through the Eco-lef system, which accepts products only from approved establishments, but continues to have the population of informal collectors as its main base. The informal sector is therefore in the process of being formalized and is less prevalent than it was a few years ago; the means to achieve full inclusion of the informal sector remain to be implemented. Mostly men, the scavenging activity concerns a minority of women, who tend to work in the city, and children, for whom scavenging is a seasonal activity corresponding to the school vacations. The earnings from salvage work are between 3 and 12 dinars (1.50 and 6 €) per day, which compared to the daily salary of a municipal worker (5 dinars, or 2.50 €) remains reasonable; however, many salvagers are heads of families with many dependents. The work of recuperation remains physically and morally very difficult. The vast majority of reclaimers have a previous professional activity related to another field (handicrafts, construction, etc.), but reclaiming is a primary source of income. Although they have very little contact with other waste management actors, apart from wholesalers, reclaimers in the city are often in contact with residents who sort their materials and give them to them; this is an element that should be taken into account in a source separation program.

7.4 The Integration of Informal Waste Sector

The lack of urban solid waste management (SWM) policies that incorporate the informal waste sector (IWS) reinforces developing countries' negative perceptions about informal recycling. (Sembiring and Nitivattananon 2010). The majority of pickers continue to labor alone, often in hazardous conditions, putting their health at danger and leaving them subject to the recycling industry's exploitation (Silva de Souza and Mancini 2017). Poor and marginalized social groups engage in informal waste recycling as a means of generating cash and, in some cases, daily survival. The IWS is common in developing world cities. This is a disadvantaged population's adaptive response to scarcity. Informal recyclers frequently constitute distinct social groupings or belong to minorities, such as Egypt's Zabbaleen in Egypt (Wilson et al. 2006). Many countries have tried to integrate informal collection, but success stories are rare. Most integration courses have focused entirely on public policy and the legal collection system, leaving the private sector out of the picture (Xue et al. 2019).

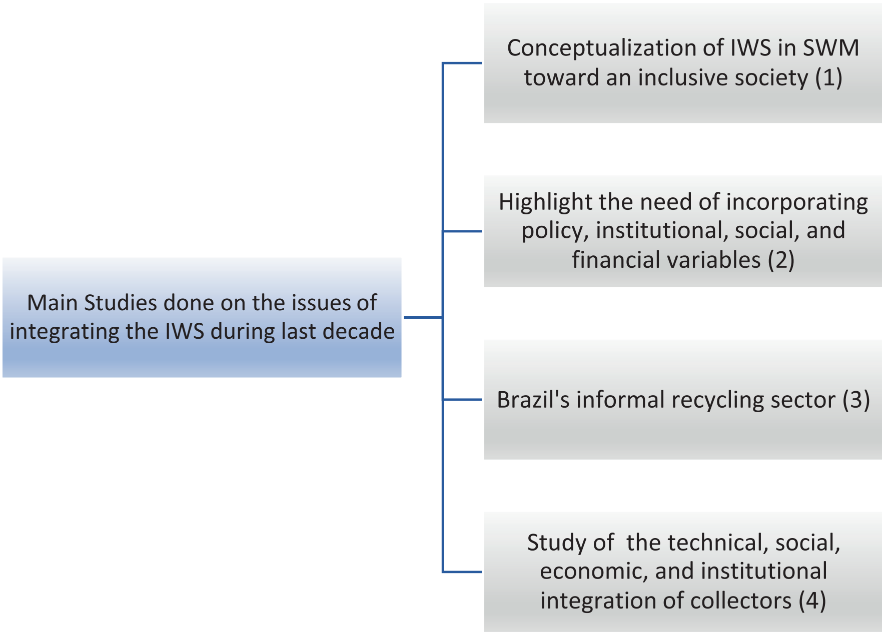

Fig. 7.1 Main studies on IWS integration during the last decade. (1) Sembiring and Nitivattananon (2010), (2) Aparcana (2017), (3) Silva de Souza and Mancini (2017) and (4) GIZ (2018a, b)

Several studies have been done on the issues of integrating the informal waste sector in developing countries, as shown in Fig. 7.1 (Sembiring and Nitivattananon 2010; Aparcana 2017; Silva de Souza and Mancini 2017; GIZ 2018a, b). In this context, authors proposed a contribution to a conceptualization of the informal sector's integration in SWM toward an inclusive society by emphasizing the problem that decision-makers face when integrating this informal sector (Sembiring and Nitivattananon 2010).

In other study, the authors highlight the need of incorporating policy, institutional, social, and financial variables to increase the likelihood of a successful formalization process (Aparcana, 2017). While Silva de Souza and Mancini (2017) examine Brazil's informal recycling sector (IRS), focusing on the ongoing integration process by providing the history and context of this integration, as well as its economic, social, and environmental benefits and current obstacles.

Furthermore, other authors have deeply studied the technical, social, economic, and institutional integration of collectors in order to have a better knowledge of the difficulties in finding solutions. They try to answer the question: What sorts of collaborations and initiatives could help to enhance informal collectors' incorporation into service and value chains? (GIZ 2018a, b).

7.4.1 Role and Benefits of IWS Integration

Considering the waste management in circular economy context, the informal sector plays a critical role, and finding sustainable ways to integrate it into the value chain is critical (Diaco et al. 2020).

However, it will be difficult to persuade municipal officials and politicians to change their traditional strategies of repression, neglect, or cooperation with the informal recycling sector in favor of the integration with the formal SWM system. The recognition of the economic, social, and environmental benefits of informal recycling by individuals in positions of authority is a critical first step (Wilson et al. 2006)

Indeed, the numerous measures taken to develop appropriate IWS integration methods focused on improving waste workers' working conditions and livelihood outcomes. In the first place, alleviate both their vulnerability and improve their access to livelihoods through increased income (Paul et al. 2012).

In addition, integration of the informal sector has resulted in social, economic, and environmental benefits, such as increased income, poverty reduction, and resource preservation. In this context, continuing the integration process will benefit both the pickers and the municipality, as landfill costs will be reduced (Silva de Souza and Mancini 2017). In fact, increased waste collection and recycling activities, if done correctly, can boost the economic position of informal waste workers, and a focus on capacity building and training can guarantee that these employees benefit from the circular economy shift as well (Diaco et al. 2020).

The main roles and benefits of integrating the informal waste sector are illustrated in Fig. 7.2. Collaboration and integration of collectors into municipal waste can lead to new commercial opportunities, as well as new environmental services such as separate recyclables collection and environmentally suitable development (GIZ 2018a, b).

As a consequence, finding an informal collector integration solution is critical for ensuring the waste management sustainability (Xue et al. 2019). The IWS formalization will restore the dignity of informal waste pickers by providing stable job and social coverage and highlighting the beneficial impact and critical significance of their work in improving social, economic, and environmental outcomes (Diaco et al. 2020).

7.4.2 Barriers Affecting the Formalization of IWS

According to the author, the integration and ascension of the IWS remains a serious issue, as well as a gap in most developing nations' waste management legislation (Paul et al. 2012).

The goal of research into the barriers to integration is to provide different methods to analyzing formalization initiatives, with the objective of finding not only the

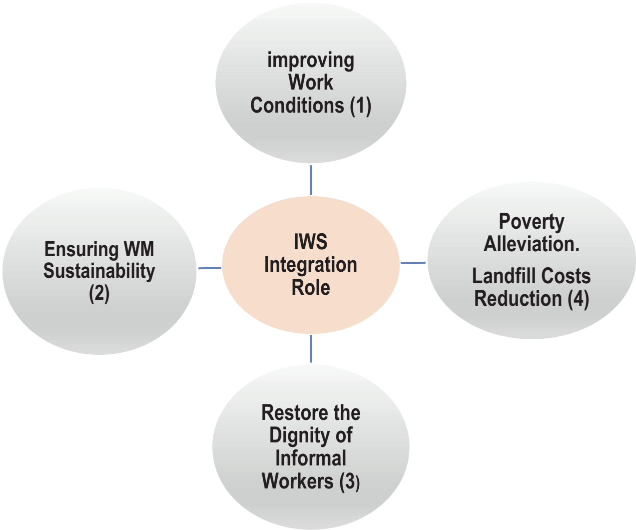

Fig. 7.2 Role and benefits of IWS formalization. (1) Paul et al. (2012), (2) Xue et al. (2019), (3) Diaco et al. (2020) and (4) Silva de Souza and Mancini (2017)

normal barriers but also the enabling elements that contribute to successful and long-term formalization activities. (Aparcana 2017)

The organizational problems of the cooperatives, the characteristics of the recycling market, the dependence on the public sector, and the low participation of the community are the main obstacles to the integration of SRIs in Brazil (Silva de Souza and Mancini 2017).

Some integration solutions have been viewed only through the perspective of poverty alleviation, taking into account collectors' economic survival strategies but ignoring the collection business model's long-term viability. The majority of informal sector integration attempts were affected by policy/legal and institutional obstacles, according to 20 cases of informal sector integration from ten low- and middle-income countries (Aparcana 2017) (Fig. 7.3).

7.4.3 Towards a Success of IWS Integration

The effectiveness of the process of integrating the IWS with formal waste management operations depends on a shift in public perception. It is critical for the citizens to know the link between recycling and better waste management (Ali 1997; Masood and Barlow 2013).

Collaborating with the informal sector to help them organize and add value to their recycled materials before selling them on is one step toward integration, since it allows them to climb up the hierarchy and extract higher value from recovered resources (Wilson et al. 2006).

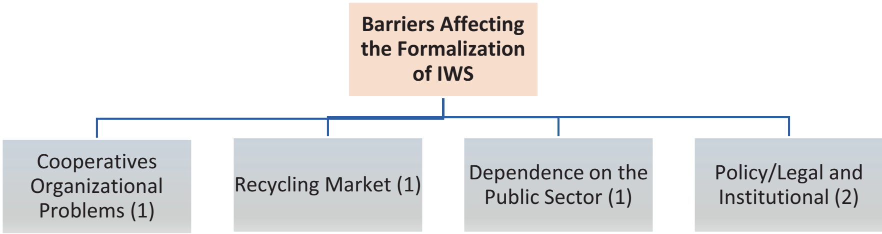

Fig. 7.3 The main barriers affecting the IWS integration. (1) Silva de Souza and Mancini (2017) and (2) Aparcana (2017)

In recent study, the authors suggest three assessment criteria for formalization initiatives:

(i) social mobilization and acceptance (social element);
(ii) stakeholder, legal, and institutional arrangements comprising roles, responsibilities, and management functions (policy and institutional element); and
(iii) financial and operational aspects (Zurbrügg et al. 2012). Integration with private companies or the public sector may need the use of an intermediary.

It is susceptible to political changes and would be more secure if incorporated in law and/or contracts, allowing it to function as a structural integration tool (GIZ 2018a, b).

In this context, it's important to conduct a complete waste characterization study in order to identify material potentials and establish new recycling programs that could provide more livelihood. opportunities for the IWS. The present material recovery system, as well as prospective new markets, should be clarified as part of this. It is crucial to conduct a stakeholder role analysis to identify potential supporters as well as the forces that stand in the way of improving the IWS integration process during the planning phase (Paul et al. 2012).

Velis et al. (2012) established the "InterRa" assessment tool, which is based on a typology for categorizing potential interventions to encourage the integration of informal recycling systems into a city's SWM system. The authors look at three main intervention areas (the SWM system, the materials and value chain, and society as a whole), all of which are supported by organizational and empowerment dimensions. According to the authors, a balanced development of all four intervention areas would boost the likelihood of formalization success. Furthermore, they claim that informal waste-recyclers' organization and empowerment is a critical aspect in enabling MSWM systems to evolve into more fully integrated systems (Velis et al. 2012; Aparcana 2017). The "InteRa" tool examines a collection of initiatives to integrate the informal sector into four categories: materials and value chain, social aspects, organization and empowerment, and solid waste management system (Silva de Souza and Mancini 2017). The "InteRa" tool has shown to be a very effective tool for analyzing integration efforts in a specific city and comparing the results to other examples (Silva de Souza and Mancini 2017).

7.4.4 IWS Formalization Countries Experiences

Many obstacles remain in integrating informal recycling with formal MSWM systems. One could argue that, despite 20 years of efforts to ameliorate the living and working conditions of Cairo's 60,000 Zabbaleen, government attitudes remain antagonistic. After years of deliberation over how to improve waste management services in the city, the authorities opted to privatize the whole MSWM system in 2002, awarding four contracts to international businesses to begin in January 2003 (Iskandar 2003; Wilson et al. 2006). It may be argued that a more cooperative approach, incorporating the Zabbaleen and NGOs working with them in the planning process before to privatization, would have been preferable to attempting to achieve an agreement after the contracts were let (Wilson et al. 2006).

As shown in Fig. 7.4, in developing countries we can find several approaches and tools for IWS integration. In the Philippines, the relevant local government selects and trains a devoted project management team, which later organizes and oversees the IWS integration process. Preparation and execution of pilot programs involves waste pickers for increased material recovery. Such programs should include a series of seminars or workshops where waste pickers can learn about and appreciate the municipal SWM enhancement program's efforts and transparency (Paul et al. 2012). The National Framework for the IWS in Solid Waste Management aims to integrate the IWS. The Philippines' National Framework for the Informal Sector in Solid Waste Management strives to integrate the informal sector by providing an enabling policy environment, skills and livelihood development, jobs, and secure social services (Aparcana 2017).

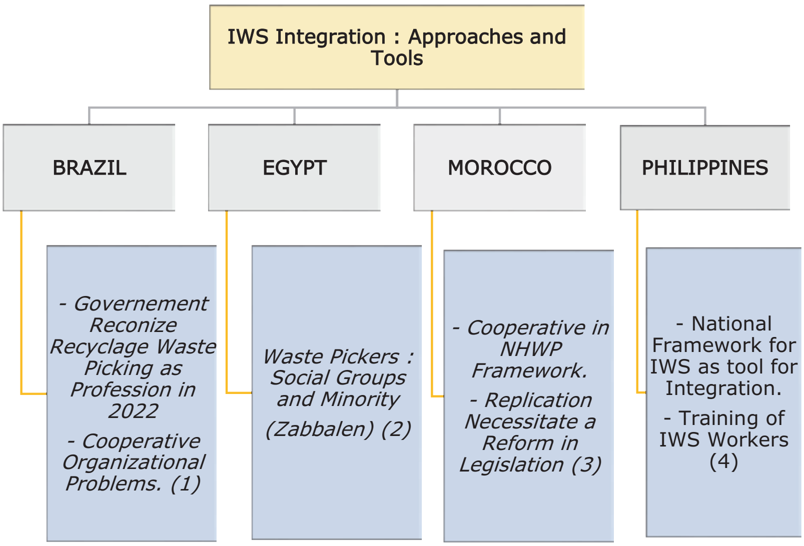

Fig. 7.4 Approaches and tools for IWS integration: some countries cases. (1) Silva de Souza and Mancini (2017), (2) Wilson et al. (2006), (3) Diaco et al. (2020) and (4) Aparcana (2017)

In Brazil, throughout the 2000s, social consciousness grew as a result of the formation of numerous social movements and increasing attention from the public sector. The Brazilian Work Ministry recognized recyclable materials picking as a profession for the first time in 2002, signaling the start of the integration process of Brazil's informal recycling sector. By federal mandate in 2006, recyclable materials created in all public buildings have to be delivered to picker cooperatives to assist generate cash (Silva de Souza and Mancini 2017).

In Morocco, the sorting center at the Oum Azza landfill (Rabat) proved to be a success as part of the National Household Waste Plan (NHWP). For a variety of reasons, replicating this approach in other kingdom cities makes sense. The replication will necessitate a reform in legislation that:

(i) Supports the structuration of those employees by developing a simple registration mechanism for those informal rag pickers in dedicated cooperatives, associations, or directly at recycling factories
(ii) Assists cooperatives and associations in training and equipping registered rag pickers with at least basic equipment to ensure their safety and efficiency. As recommendations for household waste sector, integrating informal waste pickers in local waste sorting and collection operations by putting up a simple registration mechanism for them in dedicated cooperatives or recycling plants (Diaco et al. 2020)

References

S. M. Ali, Integration of the official and private informal practices in solid waste management, PhD Thesis, Water, Engineering and Development Centre, Loughborough University (1997)

S. Aparcana, Approaches to formalization of the informal waste sector into municipal solid waste management systems in low- and middle-income countries: Review of barriers and success factors. Waste Manag. **61**, 593–607 (2017)

M. Azaitraoui, La gestion des déchets urbains au Maroc: Limites de la gestion intégrée et niveaux de la gouvernance locale. Cas de la ville de Meknès. Thèse de doctorat en géographie. Université Cà Foscari de Venise et Université Mohamed V de Rabat (2007)

M. Azaitraoui, L. Moretto (sous la dir.), Regard croisé sur le système de gestion des déchets urbains au Maghreb : le cas de Beni Mellal au Maroc, Sétif en Algérie et Sfax en Tunisie, rapport de recherche CIUDAD, Coopération en matière de Développement Urbain et de Dialogue, (2012)

M. Azaitraoui, L. Moretto, La valorisation des déchets urbains à Sfax (Tunisie): entre réformes politiques et récupération informelle, dans Sociétés Urbaines et Déchets : éclairages internationaux, Presses Universitaires François Rabelais, Tours, France, (2015)

M. Diaco, M. Alami Merrouni, S. Bougarrani, Circular economy in the Africa-EU cooperation – Country report for Morocco. Country report under EC contract ENV.F.2./ETU/2018/004 project: "Circular economy in Africa-Eu cooperation", Trinomics B.V., ACEN, Adelphi Consult GmbH and Cambridge Econometrics Ltd. (2020)

L. Dorvil, Private sector participation in integrated sustainable solid waste management in low- and middle income countries, PhD Thesis, University of St. Gallen (2007)

M. Ferchichi, Green business et croissance verte : quelle nouvelle croissance verte dans les pays en développement ? [En ligne]. FFEM, Conférence du 6 avril (2010). Disponible sur http://www.ffem.fr/jahia/webdav/site/ffem/shared/ELEMENTS_COMMUNS/U_ADMIFFEM/Evenements/M.Ferchichi.pdf

B. Florin, « Rien ne se perd ! ». Récupérer les déchets au Caire, à Casablanca et à Istanbul, in « Réparer le monde », Techniques & Culture. Éditions de l'EHESS (2016)
GIZ, Accompagnement de la ville de Tetouan pour la mise en place d'un projet de tri sélectif des déchets à la source, 2018a
GIZ, Inclusion of informal collectors into the evolving waste management Systemin Serbia, A roadmap for integration. GIZ, 2018b
S. Hemidat, O. Achouri, L. El Fels, S. Elagroudy, M. Hafidi, B. Chaouki, M. Mostafa Ahmed, I. Hodgkinson, J. Guo, Solid waste management in the context of a circular economy in the MENA region. Sustain Rev. **14** (2022)
L. K. Iskandar, Integrating local community-based waste management into international contracting. In Proceedings of solid waste collection that benefits the urban poor, 9–14 March, Dar Es Salaam, Tanzania. Switzerland. The SKAT foundation [CD-ROM], (2003). http:// www.skat-foundation.org/
S. Jaglin, M.-H. Zerah, Eau des Villes: Repenser des services en mutation. Introduction. Revue Tiers Monde **203**(juillet–septembre), 7–22 (2012)
M. Masood, C.Y. Barlow, Framework for integration of informal waste management sector with the formal sector in Pakistan. Waste Manag. Res. **31**, 93 (2013)
Ministere De L'amenagement Du Territoire, De L'environnement Et Du Tourisme (MATET). Le PROGDEM [En ligne]. Non daté. Disponible sur https://www.mate.gov.dz/doc/le_progdem.doc
Ministere De L'amenagement Du Territoire, De L'environnement Et Du Tourisme (MATET). Plan National d'Actions pour l'Environnement et le Développement Durable (PNAE-DD) [En ligne]. République Algérienne Démocratique et Populaire, janvier (2002). Disponible sur http://www.ambalgott.com/download/algerie-paned.pdf
J.G. Paul, J. Arce-Jaque, N. Ravena, S.P. Villamor, Integration of the informal sector into municipal solid waste management in The Philippines – What does it need? Waste Manag. **32**, 2018–2028 (2012)
E. Sembiring, V. Nitivattananon, Sustainable solid waste management toward an inclusive society : Integration of the informal sector. Resour. Conserv. Recycl. **54**(2010), 802–809 (2010)
N.L. Silva de Souza, S.D. Mancini, Integration of informal recycling sector in Brazil and the case of Sorocaba City. Waste Manag. Res. **35**(7), 721–729 (2017)
B. Soudi, H. Chrifi, « Gidd: Quelles options de gestion des déchets solides municipaux adaptées au contexte marocain ? », Séminaire technique consacré à la gestion intégrée et durable des déchets, produits et ressources, 16 juin 2008 – Rabat, Maroc, (2008). http://www.acrplus.org/upload/documents/webpage/document447.pdf
G. Spaargaren, P. Oosterveer, J. van Buuren, A. P. J. Mol, Mixed modernities: Towards viable urban environmental infrastructure development in East Africa. Position paper, environmental policy department. Wageningen University and Research Centre, The Netherlands (2005)
C.A. Velis et al., Analytical framework and tool ('InteRa') for integrating the informal recycling sector in waste and resource management systems in developing countries. Waste Manage. Res. **30**(9), 43–66 (2012)
D.C. Wilson, C. Velis, C. Cheeseman, Role of informal sector recycling in waste management in developing countries. Habitat Int. **30** (2006)
Y. Xue, Z. Wen, H. Bressers, N. Ai, Can intelligent collection integrate informal sector for urban resource recycling in China ? J. Clean. Prod. **208**, 307–315 (2019)
C. Zurbrügg et al., Determinants of sustainability in solid waste management – The Gianyar waste recovery project in Indonesia. Waste Manag. **32**(11), 2126–2133 (2012)

Chapter 8
Max-Neef's Fundamental Human Needs as Social Indicators for Sustainability: Examples of Waste Management in South Africa

Catherina Schenck, Charlotte Nell, Derick Blaauw, and Lizette Grobler

8.1 Introduction

The debates on both circular economy (CE) and Sustainable Development Goals (SDGs), as approaches to addressing broader sustainability challenges, are gaining momentum. The CE is framed as a transformative model with economic, environmental and social benefits, while the United Nations (UN) created the SDGs in an attempt ultimately to guarantee social, economic and environmental well-being (Fig. 8.1).

According to Clube and Tennant, the current interpretations of CE, as well as sustainability, fall short in delivering clarity on the social dimension or indicators of sustainability (Dempsey et al. 2011; Kissoon 2018; Clube and Tennant 2020).

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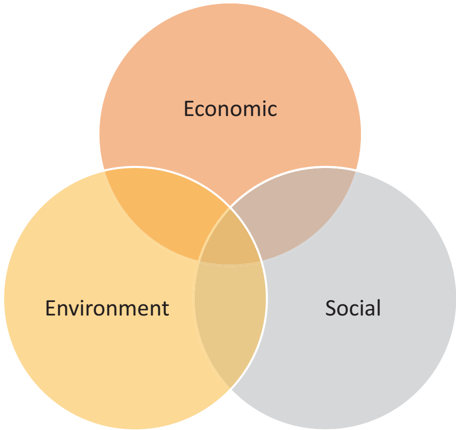

Fig. 8.1 The three dimensions of sustainability. (Source: Author's construct)

Already in 1991, Max-Neef, the Chilean 'barefoot economist', as he called himself, stated that in the traditional paradigm of sustainability, we have indicators that pertain to the social dimension of such sustainability. One example would be the gross national product (GNP), which is a gauge of society's quantitative economic growth. He then argued that we need indicators for the qualitative growth of society.

> What should that be? Let us answer the question thus: The best development process will be that which allows the greatest improvement in people's quality of life. The next question is: What determines people's quality of life? Quality of life depends on the possibilities people have to adequately satisfy their fundamental human needs. A third question therefore arises: What are those fundamental needs and/or who decides what they are? (Max-Neef 1991: 16)

This chapter aims to describe Max-Neef's identified generic, universal and finite fundamental human needs (FHNs) as social indicators for sustainability in the context of waste and waste management in a developing country, such as South Africa.

The chapter will start with the description of social dimensions/indicators of sustainability, followed by a description of Max-Neef's Human Scale Development (HSD) framework. We then illustrate the nine FHNs as social indicators for human well-being in the context of waste management in lower-income areas in South Africa.

We see the chapter as an introductory and working document to guide thinking with regard to social indicators for sustainability using Max-Neef's HSD and taxonomy of FHNs.

Let us first take a look at what literature puts forward as social dimensions/indicators of sustainability.

8.2 The Social Indicators of Sustainability

Current research on the social indicators of sustainability refers to aspects, such as human interactions, organisations, relationships, culture, as well as the physical, environmental, emotional and intellectual facets of society. How people live, work, play, connect with one another, co-operate to meet their needs and generally survive as members of society is the aspect identified by Torjman (2000). For Torjman, the social dimension of sustainability and social development should result in poverty reduction, social investment (e.g. improved education, health and social cohesion) and the building of safe, caring and cohesive communities. Talan et al. (2020) highlight aspects such as equity, diversity, quality of life, as well as social cohesion, empowerment, participation, sense of place, integrity, influence, competence, diversity, networking, equal access, education and health and safety to describe the social features of sustainability. Similar to Max-Neef, Dempsey et al. (2011) summarised the social dimension of sustainability as pertaining to the *quality of life* and the *well-being* of the person, the society, the environment and the economy and identified social dimensions as social interactions and networks, participation, stability, pride and sense of place and safety and security.

8.3 Max-Neef and Human Scale Development

Max-Neef (1991) developed an alternative framework to what he refers to as neoclassical models for development. He introduced the HSD framework to assist researchers and development practitioners to think more broadly than economic growth as the core indicator for development and that the human/social dimension had to be included to achieve sustainability. The HSD framework is a holistic system of interrelated fundamental human needs (FHNs), which are few and finite. The nine FHNs are identified as *subsistence*, *protection*, *affection*, *participation*, *understanding*, *idleness*, *creation*, *identity and freedom*. These are considered universally applicable FHNs and independent of culture and context. For Max-Neef, poverty exists if any of the FHNs are not met, and the well-being of the person and society is compromised (Nel et al. 2021). The holistic FHN taxonomy provides a lens through which to view the currently neglected social component of sustainability and circular economy (Schenck et al. 2017).

The HSD framework provides both the FHN taxonomy (the theory) and the participation guideline. This guideline can be used to facilitate a participatory process to identify a community's FHNs and plan how each identified FHN can be satisfied or fulfilled (Gimelli et al. 2019).

For Max-Neef (1991), HSD is a people-centred approach with the goal of increasing the self-reliance and well-being of the person. Self-reliance should be the key outcome of the HSD process. The social indicators of sustainability and the SDGs ultimately have the same goal: to ensure human well-being, which is achieved through fulfilled FHNs and being self-reliant. Spiering and del Valle Barrera (2021) explain that HSD provides a set of guidelines for co-producing three types of knowledge needed to achieve sustainability transformations: systems knowledge (what is), target knowledge (what should be) and transformation knowledge (how to get from where we are to where we should be). The most important principle on which the HSD framework is built is that people should be protagonists with regard to their future and at the centre of the development process.

It is important to note that Max-Neef diverted from Maslow's hierarchy of needs. Max-Neef believed that all nine needs are equally important and that there is no specific order in which they should be fulfilled.

8.3.1 On Needs and Satisfiers

It is Max-Neef's distinction between *needs* and *satisfiers* and the people-centred approach focus of his theory, which is seen as his major contribution in the development field (Cruz et al. 2009; Spiering and del Valle Barrera 2021; Bissolati 2022; Brand-Correra and Steinberger 2022; Mora-Motta et al. 2022). The nine FHNs are regarded as finite, few, classifiable and relevant to all human beings irrespective of culture and context. 'Satisfiers' of needs, on the other hand, are unique and different in cultures, over time and according to context and may thus change (Max-Neef 1991).

Satisfiers of needs are often described as basic necessities, such as food, shelter, health, education, employment and safety. According to Max-Neef, these aspects are *satisfiers* of the FHNs. For example, the FHN for subsistence can be met by satisfiers, such as food, water and housing; the FHN for protection can be met by adequate health and safety, insurance, family and social cohesion; and the FHN for affection by the receipt of sufficient care and concern, family and social cohesion. Kissoon's (2018) clean and noise-free landfill will be a satisfier for the FHN of protection, while job creation is a satisfier for the FHN for creation. As can be seen

Table 8.1 Max-Neef's matrix of FHNs

	Being	Having	Doing	Interacting
Subsistence				
Protection				
Identity				
Freedom				
Idleness				
Participation				
Creation				
Understanding				
Affection				

Source: Max-Neef (1991)

from the examples, satisfiers do not satisfy only one FHN but can contribute to the satisfaction of several such needs. To be part of the family can satisfy the FHNs for protection, affection, understanding, idleness and identity. Not all families – or family life – satisfy the same needs.

Regarding needs and satisfiers, Holm et al. (2005) remarked that, for Max-Neef, the term 'need' refers to *deprivation* (what people do not have or the poverties they experience) and the term 'satisfier' refers to the *potential* to satisfy the need and contribute to the enhancement of well-being. Max-Neef developed a grid for the development of satisfiers in collaboration with the communities. Holm et al. (2005) refer to these satisfiers as existential categories which encompass a way of being (qualities), doing (actions), having (things) and interacting (settings) and which people employ to actualise their needs (Table 8.1).

However, Max-Neef emphasises that not all satisfiers are synergic in the satisfaction of FHNs or well-being. They can also produce opposite effects. Max-Neef classified these satisfiers in the following five categories:

1. *Synergic satisfiers* satisfy a given need, simultaneously contributing to the fulfilment of other needs. These synergic satisfiers share the attribute of being anti-authoritarian and democratic in nature. The satisfier should lead to self-production and self-reliance (Max-Neef 1991). Living in a democratic dispensation, for example, satisfies the FHNs for participation, understanding, identity and freedom. Max-Neef's well-known example is one of breastfeeding as synergic satisfier of subsistence, affection and protection.
2. *Singular satisfiers* are those that satisfy only one particular need. The satisfier is often symptomatic and not systemic. Well-intentioned handouts of clothes and food often fall into this category as they do not necessarily enhance the development of self-reliance.
3. *Pseudo-satisfiers* provide a false sense of satisfaction, such as fashion and fads, as well as exploitation of natural resources for the short-term benefit of income and wealth.
4. *Destructive satisfiers* (or destroyers/violators of needs) can be authoritarian decisions imposed on people which impair the satisfaction of their needs. An example of this is demonstrated by municipalities who moved waste pickers from landfills to material recovery facilities with a full-time, protected, decent working and supervised environment and a monthly payment. This action resulted in the waste pickers leaving the full-time job to move back to the landfill. During research into the issue of landfill waste pickers, the latter indicated that they can earn more, enjoy the freedom of choosing when they want to work, are self-employed and not supervised and can access more than just recyclables (which they can sell and/or use), such as food and construction material (Schenck et al. 2019).
5. *Inhibiting satisfiers* are those that curtail the possibility of satisfying other needs, such as deep-rooted cultural and religious customs, habits and rituals. In our studies, diaper and textile dumping were linked to beliefs that witchcraft can be practised if diapers and textiles are disposed of in the dustbin or at a spot where

others can link the textile or baby diaper to the original owner. By dumping these in a river or open area, the odds of linking the waste material to the original owner are diminished.

It is due to the application element in HSD that Spiering and del Valle Barrera (2021), as well as Spiering (2022), argue that HSD can be regarded as *transformative science*. Transformation research is seen as concerned with understanding and analysing transformation processes, while the goal of *transformative science* addresses problems arising from the challenges of unsustainability by developing possible or potential solutions (Spiering and del Valle Barrera 2021).

There is an emerging awareness in the sustainability discourse that waste and waste management are strongly linked to human well-being. In this chapter, the holistic and dynamic understanding of well-being found in Max-Neef's HSD framework is used to highlight the transformative potential of waste management on/in the lives of residents.

The next section will illustrate the nine FHN as social indicators for sustainability in the context of waste management in lower-income areas in South Africa. This will be done by discussing five waste management case studies conducted in low-income areas in South Africa.

8.4 Waste Management in South Africa

South Arica is regarded as a developing country with the typical characteristics of developing countries such as rapid urbanisation, the highest inequalities in the world, a struggling economy, diverse cultures, corrupt political landscapes and ineffective governance, in particular on local government level (Brand-Correa et al. 2018).

South Africa, as a developing country, has well-developed regulations, strategies and legislation for waste management but lacks proper and effective consistent implementation and enforcement. Collection services vary significantly between provinces, municipalities and often between adjacent suburbs. Urbanisation and the increase in informal housing put pressure on the system in particular as it means that fewer ratepayers pay for municipal services (Kalina 2020, 2021; Schenck et al. 2022). In the latest Household Survey in 2019 (StatsSA 2020), it was reported that 30.8% of South African households have to manage their own waste, while only 58.8% (in 2016 it was 61% households) had their waste collected by a municipal collection service. Poor waste management and complex socio-political challenges are major contributors to the dirty state of the cities and towns in South Africa and the resultant compromised well-being of its citizens.

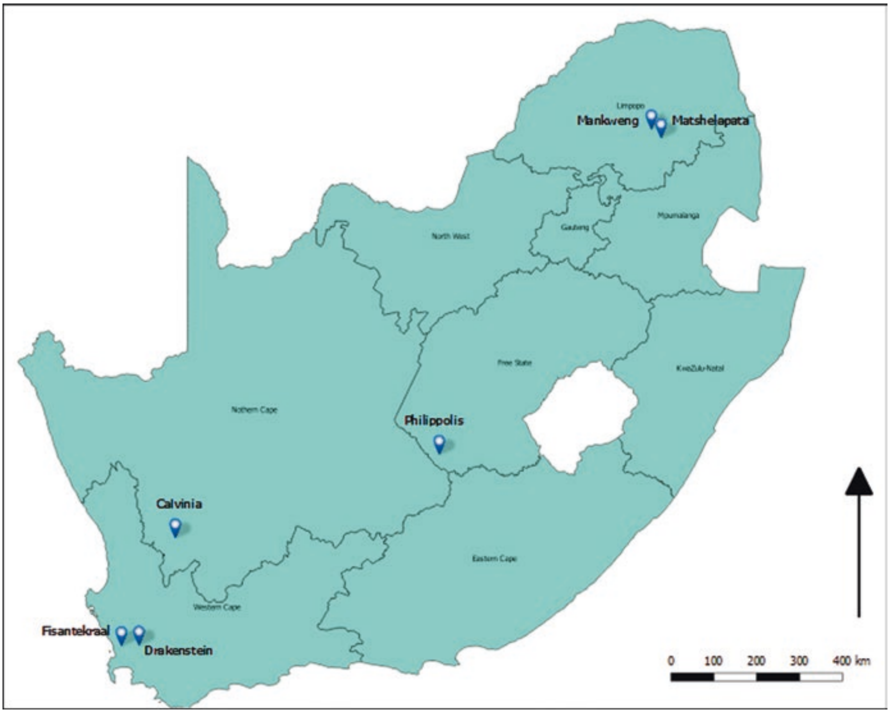

Fig. 8.2 Study area map indicating the focus areas. (Source: Alex Kimani)

8.5 Research Setting

For the collective case-study research, eight townships in five municipalities in four of South Africa's provinces were selected: the townships of Matshelapata and Mankweng in the Polokwane Municipality (Limpopo Province), the township Calvinia-West in the Hantam Municipality (Northern Cape Province), the Bergmanshoogte and Poding Tse Rolo townships in Philippolis, which fall under the Kopanong Municipality (Free State Province), and the townships Paarl East and Mbekweni in the secondary city of Paarl in the Drakenstein Municipality (Western Cape Province). Fisantekraal, a township falling under the City of Cape Town Metropolitan Municipality, was also included in the study. The map (Fig. 8.2) illustrates the location of the townships involved in the research which took place between 2019 and 2021.

The participating townships were chosen due to their lower socio-economic status within the municipalities as they experience greater problems in the management of their waste than the more affluent areas do. All townships are characterised by high unemployment and grant dependency. The townships were selected because of the differences in waste management service delivery, which will be described briefly in Table 8.2 below.

Table 8.2 Summary of the townships studied

	Focus areas	Level of waste management service rendered (2019–2021)
Name of category B local municipality		
Drakenstein	Mbekweni and Paarl East	Weekly door-to-door waste collection by the municipality. Daily mini drop-off waste collection by the municipality. Black bags and wheelie bins provided by the municipality
Hantam	Calvinia West, Calvinia	Weekly door-to-door waste collection by the municipality. No bins and black bags provided
Kopanong	Poding Tse Rolo and Bergmanshoogte, Philippolis	Irregular weekly door-to-door waste collection by municipal workers and trucks, if and when available, alternatively by local residents Collection services funded by the Philippolis Concerned Citizens group as a result of corrupt and bankrupt municipality
Polokwane	Mankweng and Matshelapata	Mankweng: Waste removal privately done Matshelapata: No waste collection services rendered by the municipality. Residents responsible for their own waste management
Name of category A municipality		
City of Cape Town	Fisantekraal	Weekly door-to-door waste removal in areas with formal housing Bins and bags provided to formal houses Informal areas not provided with bins and bags Drop-off areas available for informal and formal areas for waste streams that are not collected by the municipality such as garden/organic waste

Source: Research data

8.6 Data Collection

A multiple/collective case-study research design with a mix of quantitative and qualitative data collection methods was used to build the case studies (Creswell 2014). The data were collected between April 2019 and November 2021. During 2020 and 2021, the data were collected between the waves of COVID-19 outbreaks.

Quantitative data collected included:

- *Household surveys:* Determining household waste perceptions and behaviour. A total of 877 questionnaires were completed in the selected townships.
- *Household waste characterisation studies:* Which consisted of 5-week household waste characterisation studies, analysing the waste generated by 230 households.
- *Illegal dumping mapping:* All illegal dumpsites were mapped in each township. Geospatial data were collected by making use of the mobile application *field area measure.* Coordinates and the size of each illegal dumpsite were captured, and the types of waste in/on the dumpsites were recorded and listed. Photos were taken of each illegal dumpsite. Maps were made using ArcGIS software (Kimani 2020).

Qualitative data collected included:

- *Household interviews:* In total 322 semi-structured open-ended interviews exploring perceptions of the reasons for littering and illegal dumping were completed with one member per household.
- *Interviews with taxi drivers and commuters:* In the central business districts of Drakenstein Municipality (Paarl and Wellington) and Polokwane Municipality (Mankweng), semi-structured questionnaires were used to interview taxi drivers while they were waiting in the queues to pick up passengers and commuters. Philippolis and Calvinia do not have taxi ranks. A total of 71 taxi drivers and 120 taxi commuters available and willing to participate in the study were interviewed in both areas until data saturation.
- *Interviews with street vendors:* These were interviewed in Paarl CBD and Mbekweni. The other towns did not have street vendors to be interviewed.
- *Interviews with key informants:* Key informants in the communities were interviewed, such as the local waste managers, the municipal manager, members of business chambers, ministers of religion, NGOs, interested people and teachers.
- *Observations:* These were noted and photos taken.

8.7 Fieldworkers: Students and Residents

To collect the data, the services of trained postgraduate students from the University of the Western Cape (UWC) and the University of Limpopo (UL) were engaged. Data were also collected by well-trained unemployed residents of the townships – referred to as participant researchers. The benefit of their paid assistance was twofold: they enabled easier access to the communities and enhanced the credibility of the research process among the residents of the townships. In addition to developing skills, the project's financial support also established goodwill in the community.

8.8 Ethical Considerations

The Human and Social Science Research and Ethics Committee (HSSREC) of the University of the Western Cape provided ethical clearance for the research project.

8.9 Illustrating the FHNs as Social Indicators

The indicators will be described briefly after which the results and findings of the study will be used to illustrate how the indicators can be employed as a proxy for social sustainability in the waste management context.

8.9.1 Indicator 1: Subsistence

8.9.1.1 Definition

Subsistence denotes the most fundamental form of needs, referring to the basic means of survival, such as food, shelter and water (Max-Neef 1991; Cruz et al. 2009; Nel et al. 2021), and, when fulfilled, contribute to the physical and mental health and well-being of the person (Max-Neef 1991).

8.9.1.2 Example

Waste removal services and waste infrastructure for a clean environment affect the satisfaction of subsistence needs. The expectation of regular, effective, efficient and local relevant waste removal services and well-maintained infrastructure was expressed by all communities. The communities receiving insufficient/ineffective waste management service delivery spoke of the need for regular waste removal or at least infrastructural support. They struggle to manage waste without support, information and infrastructure – in particular certain difficult waste fractions, such as bulky waste and used disposable diapers which cannot be buried and burnt. Research has shown that engineered-driven waste removal seems to be sufficient for more affluent suburbs, but lower-income communities without resources, such as sufficient storage opportunities, space and access to private transport, have different infrastructural needs. Locally innovative approaches need to be developed *with* the community. Infrastructure limitations, such as the lack of space to store waste due to small and overpopulated houses and stands, which then leads to roaming dogs, pigs and goats eating and spreading uncollected waste, create difficulties for households to manage their waste effectively.

Transport and transport costs appear to be major hindrances to managing waste and establishing efficient waste governance systems in developing countries. Thus, in addition to high transport costs for municipalities, the lack of transport was highlighted as a major obstacle to managing waste in the lower-income areas despite the fact that regular waste collection is done in certain townships.

It also became clear that the dumping of waste in low-income areas is not necessarily an *indiscriminate* act but rather a *discriminate* or *intentional* act: an attempt to keep the household's immediate surroundings clean. In all areas there were particular requests for waste management solutions for the difficult waste fractions which residents struggle to dispose of effectively and legally. These waste fractions were identified as *yard waste* (garden/organic waste), dead animals (in particular, dead dogs), bulky waste (fridges, old furniture) and construction and demolition (C&D) waste (bricks, cement, concrete). Most of these waste fractions, which cannot typically fit into a bin, are not taken away during regular waste collection (if and where available). The removal of such waste is manageable if access to transport, finances and/or infrastructure, such as drop-off facilities, is available. Inequalities are pertinent when in low-income areas residents are not able, or do not have the means, to manage difficult waste fractions themselves and, as a result, dump, burn or bury such waste in or just outside their immediate environment. Due to the lack of or access to transport, waste fractions not collected by the municipality were moved with wheelbarrows and dumped in selected sites if there was no landfill or mini drop-off within walking distance. These results agree with the findings of Wang et al. (2018) that the distance from a residence to a waste collection facility has a significant impact on waste management in rural areas. Furthermore, in one area with regular waste removal, but high prevalence of backyard dwellers (due to shortage of housing and the need for additional income to the households), the municipality provided bins and bags only to the households and not to the backyard dwellers. This decision resulted in significant dumping by the backyard dwellers who did not have space to keep the waste nor the means to transport it to landfills. In another area the municipality built mini drop-off facilities or provided skips to the community. However, solutions, such as mini drop-offs or skips, can degenerate into opportunities for dumping if not well managed and regularly cleaned. The case study described by Schenck et al. (2021) also highlighted that not well-managed mini drop-offs and skips become destructive satisfiers and sources of vandalism or crime and may hold more threats than answers.

8.9.1.3 Application of Satisfiers

Satisfiers for the *subsistence* indicator would include increasing holistically provided waste management alongside sufficient other infrastructural subsistence needs, such as shelter and access to water, food, electricity and roads. The neglect of any of the infrastructural satisfiers will contribute to poverty of subsistence.

Appropriate, efficient, sufficient and inclusive waste management systems and infrastructure will also contribute to the satisfaction of other needs, such as affection, protection, identity, creation and understanding, as will be illustrated.

8.9.2 Indicator 2: Affection

8.9.2.1 Definition

Nel et al. (2021) explain that the need for *affection* refers to caring and being cared for, as well as meaningful relationships, networks and interactions (Pauw 2006). Acts of caring and being cared for relate closely to identity and self-esteem.

8.9.2.2 Example

During interviews with the participants in the studies, experiences of a non-caring government (in all three spheres of government, i.e. local, provincial and national spheres) were expressed as one of the reasons for dumping of waste and littering ('The Government doesn't care – why should I care?'*)*. Due to experiences of lack of service delivery and lack of communication in some municipalities, as well as the levels of corruption, the need for the development of affection (caring and trust) and collaboration was clearly not met.

During conversations the lack of care, collaboration, trust and social cohesion *within* the communities and among each other (Schenck et al. 2022) were highlighted. Poverty, crime, political differences, inequalities and limited support and safety networks were given as some of the reasons why experiences of care and collaboration were limited. These observations corroborate Brandt's (2017) description of socially disorganised communities as a major contributor to the mismanagement of waste.

8.9.2.3 Application of Satisfiers

Waste management as satisfiers for *affection* would include increased experiences of effective, equal and holistic service delivery, as well as regular and appropriate communication between government/institutions and communities. Affection and care would be increasingly met with the facilitation or fostering of improved social cohesion, networking, active citizenry and communication within communities.

8.9.3 Indicator 3: Participation

8.9.3.1 Definition

For Max-Neef (1991), *participation* as FHN is a truly effective – or valid – way of promoting human well-being, and social justice can only be achieved through real and effective citizen participation. Dempsey et al. (2011) also emphasise participation as social indicator for sustainability, which relates to concepts, such as social capital, social networking, social coherence, accessibility and sense of community.

8.9.3.2 Example

In all communities involved in the study, there were requests for increased collaborative and inclusive planning to address waste management issues, appropriate communication, collaboration and engagement between the municipality, other stakeholders and the community, as well as among community members and within communities. Participants did not see the responsibility of area cleansing only as a municipal responsibility but as an opportunity for community engagement (FHN of affection), building social cohesion and creating opportunities for, for instance, income generation (due to high unemployment and poverty levels).

Interesting were the results when we explored the best method of communication which municipalities should employ when informing or engaging with communities. Municipalities and waste management companies rightfully make use of social media, such as Facebook, WhatsApp and monthly notices, to communicate with their residents. The results from our studies show that a mix of media should be used to accommodate those who do not have access to social media mainly due to the unaffordability of data. In two of the areas, fewer than half of the residents indicated that they can afford the data needed for social media. Media, such as community meetings, radio, pamphlets and a roaming vehicle with a loud hailer, are preferred in addition to social media. Interesting was the popularity of a local radio station in one township where it was indicated that most residents listen to that particular radio station. While interviewing participants outside their residences for the purpose of data collection, the radio was audible in the background. Of significance is the fact that all the communities emphasised engagements, such as community forums, as important in order to have a platform to voice their concerns and be part of planning waste management and other service delivery issues. One area still has traditional leaders such as a chief and nduna with established engagement structures in place, and the community meetings were indicated as the preferred mode of communication.

8.9.3.3 Application of Satisfiers

Satisfiers with regard to *participation* should include increased collaborative and participatory planning and implementation of locally relevant waste management programmes.

The implementation of participatory methods in planning and collaborative execution, management and monitoring of waste management might assist in the development of appropriate and applicable methods and infrastructures to deal with the waste management hindrances which communities experience. Forms of 'citizen science'[1] could produce and offer valuable information which authorities and researchers could use for an in-depth understanding of difficult waste issues (Goldin et al. 2021).

[1] Citizen science refers to nonscientists who are actively involved in generating information and knowledge to their benefit.

8.9.4 Indicator 4: Creation

8.9.4.1 Definition

Creation as a FHN refers to opportunities – as well as the skills, abilities and capabilities – to be creative, invent, design and work (Max-Neef 1991; Nel et al. 2021).

8.9.4.2 Example

One of the major themes extracted from interviews with residents in the townships was the need for the creation of work and income opportunities due to the high poverty levels and unemployment rates in all the townships. Managing waste was considered such an opportunity. In fact, their perception is that people litter and dump 'to create jobs'. They believe that persons, such as those who work on Expanded Public Works Programme[2] (EPWP), would lose their jobs if residents were to dispose of their waste in bins instead of littering or dumping. The only research outside South Africa which refers to job creation as a possible reason for littering and dumping was an article by Salvia et al. (2021), who reported on their study in Kisumu, Kenya. Kisumu's residents also mentioned littering behaviour as sustaining job and income creation.

8.9.4.3 Application of Satisfiers

Satisfiers towards *creation* could include an increase in formal and informal job, income and business opportunities in waste management within local communities. Based on the previous indicators, the planning for work and income opportunities should be done in collaboration with the communities through open and transparent processes. Thus, increased opportunities for self-employment, entrepreneurship and SMMEs form part of this indicator. Appropriate policies and legislation which can facilitate these processes should be put in place.

8.9.5 Indicator 5: Understanding

Understanding relates to critical thinking, formal and informal education, skills training, enhancing capabilities and gaining knowledge and skills to be able to understand and interact with the world (Nel et al. 2021). Paulo Freire (1998) refers to the ability to 'read the world'.

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[2] EPWP programmes are government-led temporary job creation programmes. One such opportunity is the cleaning of streets in certain areas.

8.9.5.1 Example

Participants in the study highlighted the lack of education and awareness about waste, waste management and the importance of clean environments as reasons for people littering and dumping and not knowing how to manage waste, in particular the difficult waste fractions. They further recommended a variety of educational and awareness opportunities for school children, youth, adults and the aged. For instance, children and the youth at schools should be taught how to clean their environment and why it is important to live in clean environments. The wish to educate adults on matters such as how to store waste and what to do about the aforementioned difficult waste fractions. They asked for information regarding income opportunities from waste and waste recycling, as well as communication regarding the logistics of waste collection.

8.9.5.2 Application of Satisfiers

Satisfiers of *understanding* related to waste management would include an increase in the variety of modes of education and awareness to establish foundational knowledge and skills regarding waste and waste management as determined by the residents. Active participation in waste management activities towards cleaner environments would also be evident.

8.9.6 Indicator 6: Idleness

8.9.6.1 Definition

The FHN for *idleness* refers to time and opportunities to rest or to play or for recreation (Nel et al. 2021).

8.9.6.2 Example

Members of the communities expressed concerns regarding dirt and dumped waste, as this renders open and recreational spaces unpleasant (and even dangerous), inhibits freedom of movement and limits opportunities for idleness – particularly for children to play.

In one particular area with no waste management and with a high prevalence of venues which attract crowds, such as taverns and shebeens, the environment was strewn with so much observable broken glass, as well as dumped, soiled, disposable diapers, that children and youth could not play in the veld and open spaces, nor could they swim in the rivers and dams. This situation/scenario, combined with limited demarcated recreational facilities and opportunities, resulted in illegal dumpsites becoming the playground for children and the gathering places for offenders, drug users and other criminal activities. For Dempsey et al. (2011), such a physical environment, instead of providing experiences that create a healthy sense of place, community and attachment, will lessen interaction and participation.

8.9.6.3 Application of Satisfiers

Effective waste management creates cleaner environments with increased opportunities and facilities for *idleness.* The ability to use open spaces, rivers and dams for recreational opportunities would also contribute to some of the other FHNs, such as participation (being part of sport and recreation), creation (generating income opportunities) and understanding (using these spaces and opportunities for educational and awareness purposes).

8.9.7 Indicator 7: Protection

Protection refers to having access to aspects, such as adequate and reliable protection systems which would include reliable policing, a safe environment, social security, health and food systems, safety nets and relationship networks (Nel et al. 2021). Social cohesion and well-being cannot be met in unsafe and unprotected environments (Dempsey et al. 2011).

8.9.7.1 Example

Waste management is first and foremost a satisfier of the need for protection from dirty environments, unhealthy contexts and unhealthy waste management practices, such as dumping and the open burning of waste. Protection includes waste management which enhances good health and clean physical environments.

Ma and Hipel (2016) conducted a systematic literature review to explore the social dimension of municipal solid waste management. They highlighted the finding that unmanaged waste renders people's health, environment, well-being and the economy vulnerable.

The participants who experience the lack of effective and appropriate waste management expressed their vulnerability and exposure to dirty and unhealthy environments. All communities were marked by serious and extensive illegal dumping. This created particular concern with regard to the children's health as they resorted to playing on these illegal dumpsites. In addition there were concerns around children and adults collecting recyclables on landfills, as well as dumped glass and diapers in open fields, rivers and watercourses which, in turn, pollute their own and their animals' water sources.

8.9.7.2 Application of Satisfiers

Satisfiers towards *protection* should include increased and improved engaged waste management services and programmes, cleaner environments, fewer health concerns and less prevalence of the creation of nuisance conditions, such as flies, vermin and windblown litter.

8.9.8 Indicator 8: Freedom

8.9.8.1 Definition

Freedom exists when people experience equal rights, participation and access – including the access to services, opportunities and a clean environment. Freedom includes a wider range of choices, freedom of movement, critical thinking, being allowed a critical voice and increased levels of self-esteem and self-reliance. Max-Neef's concept of freedom as a FHN resonates with Sen's (1999) notion that personal and societal development is the realisation of freedoms and the abolition of unfreedoms, such as poverty, famine and lack of political rights, as well as aspects of political, religious or cultural traditions which constrain people's ability to develop. Thus, an increase in human capabilities facilitates freedoms.

8.9.8.2 Example

Freedom in the low-income communities was experienced as restricted due to poverty and unemployment, corruption, ineffective and unequal service delivery, dirty environments and limited access to facilities and opportunities – even bad roads, overcrowded housing and limited access to water were mentioned. The challenge of dealing effectively with difficult waste fractions was another concern. Those communities without waste management had to deal with their own waste on a daily basis. As mentioned before, dirty environments limit freedom of access to open areas, rivers and participation in education and awareness. Consequently, effective communication and thus the participation in collective decision-making are hampered. Access to possible job and income creation opportunities are equally limited.

In one of the townships, a young member of the community made the comment that 'they have taken our eyes away': limited freedom and opportunities are available to the residents of the communities.

8.9.8.3 Application of Satisfiers

Regarding waste and waste management *freedom* as indicator would be met by increasing levels of cleanliness, access to good waste removal and waste management opportunities, as well as other types of service delivery. Furthermore, access to income opportunities in relation to waste matters would mean a step in the direction of freedom from extreme poverty. The freedom to participate and consider various choices with regard to methods of waste management and greater participation in planning, decision-making and implementation would engender self-esteem and self-reliance within the community. Finally, improved government services in general would significantly contribute to a sense of freedom among the residents of the townships researched and discussed.

8.9.9 Indicator 9: Identity

Living in a clean environment, experiencing care and concern for each other and the authorities, being educated and the fulfilment of all the FHNs contribute to the formation of a person's and a community's *identity*. Identity speaks to the sense of belonging and the sense of place within a community and environment (Dempsey et al. 2011).

8.9.9.1 Example

Waste and clean – or dirty – environments form part of our identity and the identity of a community. In the townships studied, community members were uncomfortable with the environment. When asked about reasons for the littering and dumping, reference was made to the 'others' who are *not well educated*, *careless*, *lazy* and *not well raised* – *those from the other countries/provinces*, *those from other cultures*, *the municipality.* Seldom did residents acknowledge participation in the act of littering and dumping. 'This is not how we are raised'. From the interviews with the minibus taxi drivers, their uneasiness about the littered taxi and taxi ranks was expressed 'I feel dirty myself' and 'I feel disrespected'.

8.9.9.2 Application of Satisfiers

Many identity and self-perception measurements exist in psychology. Developing this indicator can measure an individual's and a community's experiences of themselves in relation to waste and waste management, as well as clean or dirty environments. Engaged and effective waste management will show respect towards residents. Nurturing an identification with clean environments, cultivating personal responsibility and agency with regard to a clean environment, can facilitate sense of pride and belonging.

8.10 Discussion and Conclusion

The aim of this chapter was to explore Max-Neef's nine universal and finite FHNs as social indicators for sustainability in the context of waste and waste management in South Africa. The rationale is that, according to Max-Neef, these FHNs, if satisfied, enhance all human beings' self-reliance and well-being. Efficient, consistent and appropriate waste management can be considered a synergic satisfier of all nine FHNs (or indicators) if implemented in an engaged and participatory manner so that it creates greater socio-economic opportunities, increases social cohesion, improves communication, engenders experiences of care and affection and leads to a sense of place, pride and freedom (Murray and Pauw 2022). Conversely, inappropriate and ineffective waste management can hinder the satisfaction of needs and experience of well-being. According to Oteng-Ababio (2014: 12), the endeavour to satisfy these FHNs can be enhanced through engagement and incentives to do 'the right thing'. Facilitative policies, plans and programmes should be evaluated against the criteria of synergic satisfiers and should be developed with the residents. Clube and Tennant (2020) advise that Max-Neef's matrices be used as decision support tools to ensure that circular economy (CE) and sustainable initiatives maximise need satisfaction. Building on the completed research, the participatory completion of the matrices would be the next step in the development of the social indicators for sustainability in the context of waste and waste management.

References

C. Bissolati, *Recovery as Social Human Development: An Assessment of Streetscapes Community Based Rehabilitation Programme*. Master's Thesis (Department of Sociology, University of Cape Town, Cape Town, 2022)

L. Brand-Correra, J. Steinberger, Max-Neef and sustainability: Theoretical, methodological and empirical contribution. Int. J. Sustain. Dev. **25**, 114 (2022)

L.I. Brand-Correra, J. Martin-Ortega, J.K. Steinberger, Human scale energy services: Untangling the "golden threat". Energy Res. Soc. Sci. **38**, 178–187 (2018). https://doi.org/10.1016/j.erss.2018.01.008

A.A. Brandt, *Illegal Dumping as an Indicator for Community Social Disorganization and Crime*. Master's Thesis (Department of Environmental Studies. San Jose State University, San Jose, 2017). https://doi.org/10.31979/etd.9hq7-yrq7

K.M. Clube, M. Tennant, The circular economy and human needs satisfaction: Promising the radical, delivering the familiar. Ecol. Econ. **177**, 106772 (2020). https://doi.org/10.1016/j.ecolecon.2020.106772

J.W. Creswell, *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches* (SAGE Publishing, Thousand Oaks, 2014) https://fe.unj.ac.id/wp-content/uploads/2019/08/Research-Design_Qualitative-Quantitative-and-Mixed-Methods-Approaches.pdf

I. Cruz, A. Stahel, M. Max-Neef, Towards a systemic development approach: Building on the human scale development paradigm. Ecol. Econ. **68**(7), 2021–2030 (2009). https://doi.org/10.1016/j.ecolecon.2009.02.004

N. Dempsey, G. Bramley, S. Power, C. Brown, The social dimension of sustaible development: Defining urban social sustainability. Sustain. Dev. **19**(5), 289–300 (2011). https://doi.org/10.1002/sd.417

P. Freire, *Pedagogy of Freedom: Ethics, Democracy and Civic Courage* (Rowman & Littlefield Publishers, Lanham, 1998)

F.M. Gimelli, B.C. Rogers, J.J. Bos, Linking water services and human well-being through the fundamental human needs framework: The case of India. Water Altern. **12**(2), 715–733 (2019) https://www.water-alternatives.org/index.php/alldoc/articles/vol12/v12issue3/524-a12-2-7/file

J. Goldin, R. Mokomela, T. Kanyerere, K.G. Villholth, Diamonds on the soles of their feet: Groundwater monitoring in the Hout catchment, South Africa. J. Educ. Sustain. Dev. **15**(1), 25–50 (2021). https://doi.org/10.1177/09734082211014435

D.E. Holm, M. Murray, C J. Pauw, *The House as a Satisfier for Human Needs: A Framework for Analysis, Impact, Measurement and Design*. XXXIII IAHS World Congress on Housing, 27–30 September 2005. "Transforming Housing Environments through Design" (University of Pretoria, 2005). Available: https://repository.up.ac.za/handle/2263/10419

M. Kalina, Waste management in a more unequal world: Centring inequality in our waste and climate change discourse. Local Environ. **25**(8), 612–618 (2020). https://doi.org/10.1080/13549839.2020.1801617

M. Kalina, As South Africa's cities burn: We can clean up, but we cannot sweep away inequality. Local Environ. **26**(1), 1186–1191 (2021). https://doi.org/10.1080/13549839.2021.1967900

A. Kimani, *GIS Mapping of Community Perceptions of Illegal Dumping in Mbekweni, Paarl.* Master's Thesis (Department of Geography, Environmental & Tourism Studies. University of the Western Cape. Cape Town, 2020). Available: http://etd.uwc.ac.za/handle/11394/8251

S. Kissoon, *The Advancement of the Waste Resource Optimisation and Scenarion Evaluation (WROSE) Model: The Inclusion of the Socio-Economic and Institutional Indcators*. Master of Science Thesis (Department of Civil Engineering. University of KwaZulu-Natal (UKZN), Durban, 2018)

J. Ma, K.W. Hipel, Exploring the social dimensions of municipal solid waste management around the globe: A systematic literature review. Waste Manag. **56**, 3–12 (2016). https://doi.org/10.1016/j.wasman.2016.06.041

M.A. Max-Neef, *Human Scale Development: Conception, Application and Further Reflections* (The Apex Press, New York, 1991) Available: http://www.wtf.tw/ref/max-neef.pdf

A. Mora-Motta, T. Stellmacher, M. Del Valle Barrera, Fundamental human needs and socio-ecological transformation: A reflection on participatory action research in a context of tree plantations in Chile. Int. J. Sustain. Dev. **25**, 53 (2022)

M. Murray, C. Pauw, A novel tool for quality-of-life assessment in the household context. Int. J. Sustain. Dev. **25**, 95 (2022)

H. Nel, H. Louw, R. Schenck, R. Skhosana, *Introduction to Participatory Community Practice* (Unisa Press, Pretoria, 2021)

M. Oteng-Ababio, Rethinking waste as a resource: Insights from a low-income community in Accra, Ghana. City Territory Architect. **1**(10), 1–14 (2014) Available: file:///C:/Users/Admin/Downloads/Rethinking_waste_as_a_resource_insights%20(2).pdf. https://doi.org/10.1186/2195-2701-1-10

C.J. Pauw, *Die sistematiese teologiese betekenig van menslike behoeftes*. Doctor of Divinity thesis (Faculty of Theology and Religion. University of Pretoria, Pretoria, 2006). https://repository.up.ac.za/bitstream/handle/2263/28275/Complete.pdf

G. Salvia, N. Zimmerman, C. Willan, J. Hale, H. Gitau, K. Muindi, E. Gichana, M. Davies, The wicked problem of waste management: An attention-based analysis of stakeholder behaviours. J. Clean. Prod. **326**, 129200 (2021). https://doi.org/10.1016/j.jclepro.2021.129200

R. Schenck, N. Roman, C. Erasmus, D. Blaauw, J. Ryan, Homeless in observatory, Cape Town, through the lens of Max-Neef's fundamental human needs taxonomy. Soc. Work **53**(2), 266–287 (2017). https://doi.org/10.15270/52-2-568

C.J. Schenck, P.F. Blaauw, E.C. Swart, J.M.M. Viljoen, N. Mudavanhu, The management of South Africa's landfills and waste pickers on them: Impacting lives and livelihoods. Dev. South. Afr. **36**(1), 80–98 (2019). https://doi.org/10.1080/0376835X.2018.1483822

C.J. Schenck, L. Grobler, H. Tyrrell, *Managing Waste in Lower-Income Communities by Formalizing Illegal Dump Sites: Learnings from Drakenstein Municipality* (International Union for the Conservation of Nature (IUCN), 2021). Available: https://www.researchgate.net/publication/355586461_Managing_waste_in_lower-income_communities_by_formalising_illegal_dump_sites_Learnings_from_Drakenstein_Municipality

R. Schenck, D. Blaauw, C. Nell, Waste management in rural South Africa: Perspectives from Mannfred Max-Neef's human scale development framework. Int. J. Sustain. Dev. 25, 1/2 (2022). Special edition. https://dx.doi.org/10.1504/IJSD.2022.10051423

A. Sen, *Development as Freedom* (Oxford Press, Oxford, 1999)

S. Spiering, Self-reflexive practice through the human scale development approach competencies needed for transformative science research. Int. J. Sustain. Dev **25**, 132 (2022)

S. Spiering, M. Del Valle Barrera, Testing the quality of transformative science methods: The example of the human scale development approach. Sustain. Sci. **16**, 1439–1457 (2021). https://doi.org/10.1007/s11625-021-00966-3

Statistics South Africa (StatsSA), *General Household Survey 2019* (StatsSA, Pretoria, 2020) http://www.statssa.gov.za/publications/P0318/P03182019.pdf

A. Talan, R.D. Tyagi, R.Y. Surampalli, Social dimension of sustainability, in *Sustainability, Fundamentals and Applications*, ed. by R. Surampalli, T. Zhang, M.K. Goyal, S. Brar, R. Tyagi, (2020). https://doi.org/10.1002/9781119434016.ch9

S. Torjmam, *The Social Dimension of Sustainable Development* (Caledon Institute of Social Policy, 2000). Available: https://maytree.com/wp-content/uploads/1-894598-00-8.pdf

F. Wang, Z. Cheng, A. Reisner, Y. Liu, Compliance with household solid waste management in rural villages in developing countries. J. Clean. Prod. **202**(20), 293–298 (2018). https://doi.org/10.1016/j.jclepro.2018.08.135

Chapter 9
Urban Mining and Circular Economy in South Africa: Waste as a Resource for New Generation of Hybrid Materials

Noredine Mahdjoub

9.1 Introduction

Driven by a philosophy of exponential consumerism, excess of availability, and rapid manufacturing of new products, highly unsustainable levels of waste generation have arisen in the South African context. It converges to the crucial need to adapt the way waste is managed (Rootes 2009; Arora et al. 2017; Silva et al. 2017).

Conventional waste management solutions partake in the surge of rejected materials that end up either dumped in non-engineered landfill or incinerated to become ashes. This leads to reconsidering conventional methods and brainstorming for more sustainable system that could require the use of further materials that could be found through extraction and mining of discarded and rejected materials. Traditional and accepted conventional waste management methods are currently colluded towards unsustainability and the inevitable need for redesign to achieve satisfactory environmental outcomes for sustainable development and waste minimisation.

The South African waste sector, public and private, is an underutilised resource of materials and energy. The focus on waste has intrinsic economic value, and the formal and informal recycling systems are fundamental to the South-African waste management system (Karani and Jewasikiewitz 2007; Arora et al. 2017).

The movement of reforms of traditionalist waste management bases has already started in some developing countries, while some countries considered to be part of the "first world" are fundamentally reconceptualising and reframing their waste management systems (Lauridsen and Jørgensen 2010; Cramer 2013; Silva et al. 2017).

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Waste and society, consumption behaviours, and circular economy concepts reinforce the drive for renewed adapted standards in governance structures, waste policies, and contextualized waste scenarios. Circular economy concepts provide greater social and environmental benefits when juxtaposed to the South African context and its formal and informal ecosystems (Cossu 2013; Cossu and Williams 2015; Ghisellini et al. 2016).

In most developed countries, urban mining concepts are being applied on a large and global scale to recuperate resources from anthropogenic mines. In countries from the global south like South Africa, secondary resource can be perceived as both a challenge and an opportunity for material recovery towards resource benefits, environmental savings, and economic benefits as well.

South African sustainable cities should not differentiate between waste and resources. They need to consider innovative philosophies that include secondary resource utilisation. Urban mining could be specifically relevant to the four high priority waste streams identified by the South African RDI waste roadmap: municipal solid waste, waste plastic, organic waste, and waste tyres.

This contribution is a compendium of preliminary experimental studies conducted in the KwaZulu-Natal province. The research compiles investigations conducted in the KwaZulu-Natal province, on the municipal solid waste (glass) streams, the waste tyres waste stream, paper mill sludge (PMS) waste, and food waste. Urban Mining

"Closing Loop" has become a trendy subject of conversation in the waste management expert's community; it is becoming a subject of conversation even outside the sphere of the waste management sector. Recycling, recovery of resource, landfill diversion, and waste minimisation are terms used in debates and conversations between politicians, national governance systems, businesses, and industries. This diverse groups are now evolving the conversation to material recovery, zero waste, and circular economy while drifting to more concepts such as urban mining and landfill mining. Due to social media and easier way of communication, waste management or waste awareness exists and has become a viral topic. Societies are more aware of waste resource management, and they acknowledge the importance of the resources still present in what is considered as waste. In the context of South Africa, many reasons can explain this momentum; as a developing country, South Africa has seen an increase in consumerism as well as a shortage of raw materials for example, and many landfilled are starting encountering a lack of space availability for waste disposal. Moreover, GHG emissions mitigation has become a priority in South Africa, as a consequence the need for control of environmental contaminations, such as the use of proper engineering landfill systems, and the need of proper waste treatment have become priorities.

The circular economy model rejects the linear "take-make-waste" approach (Cossu 2013; Cossu and Williams 2015). This model strives to maintain products' usage for a longer time via reusing waste and reducing waste generation. It also consists in utilising as much as secondary raw materials as possible while in production cycles to promote economic growth and to create new job opportunities.

The concept of Materials Recycling fits within an idea of transformation of selected wastes into new generation of materials that become usable in the manufacture of other products. This recovered materials are reintroduced in production cycles.

All activities relating to the extraction and processing of wastes previously stocked, in particular, kinds of deposits (e.g. municipal landfills) is called landfill mining. As the natural continuation of this concept, urban mining is the extension of landfill mining. It expands the process of reclaiming compounds and elements from any kind of anthropogenic stocks, including buildings, infrastructure, industries, products (in and out of use), and environmental media receiving anthropogenic emissions (Cossu 2013; Cossu and Williams 2015).

As defined by R.Cossu and I.Williams, from an etymological point of view, urban mining should refer to the exploitation of anthropogenic stocks; however, today the term is widely used for describing almost any sort of material recycling (Cossu 2013; Cossu and Williams 2015).

9.2 The Case of South Africa

Several factors have contributed to the rise of consumerism in South Africa: population growth, extensive urbanisation, economic and industrial growth, and shift of income bracket via rising incomes. Consumption of materials in South Africa and in countries of the global south is still low compared to developed countries (Arora et al. 2017).

In most developed countries, urban mining concepts are being applied on a large and global scale to recuperate resources from anthropogenic mines. In countries from the global south like South Africa, secondary resource can be perceived as both a challenge and an opportunity for material recovery towards resource benefits, environmental savings, and economic benefits as well.

South African sustainable cities should not differentiate between waste and resources. They need to consider innovative philosophies that include secondary resource utilisation. Urban mining could be specifically relevant to the four high priority waste streams identified by the South African RDI waste roadmap: municipal solid waste, waste plastic, organic waste, and waste tyres.

9.3 Municipal Solid Waste (Glass)

This study considers the feasibility of utilising waste glass as a partial replacement of natural aggregates in concrete. As the chemical and physical properties of cullet are similar to fine aggregate, cullet used in concrete can reduce the amount of waste glass that ends up in landfills (Umapathy et al. 2014; Senthil Kumar and Baskar 2015a, b), including colored glass which is typically not recycled. However, currently there are very few applications of waste glass in concrete due to lack of knowledge and long-term data on the behaviour of concrete containing glass aggregate (Senthil Kumar and Baskar 2015a, b). The Glass Recycling Company (TGRC) was established in South Africa in 2006 as a glass industry association body with the overall objective of reducing the total volume of glass being sent to landfills. There are however numerous challenges faced by TGRC. The logistics involved in transportation of waste glass poses a great challenge due to its weight and shape. Although recycling of waste is a top priority in the waste hierarchy, the cost of producing glass has decreased substantially over the past few years; hence, recycling is becoming as expensive or even more expensive than producing new glass from virgin resources. This has led to a decrease in price paid for glass and an increased focus on potential alternative applications for this waste stream. Since the main component of glass is sand, the properties and specifications are very similar, and concrete containing glass aggregate meets the requirements of conventional concrete (The Clean Washington Centre, 1996). A potential problem recognised by Stanton (1940) is the effect of the alkali-silica reaction (ASR) which may occur between the cement which is alkaline and reactive silica, theoretically creating "silica gel" which is prone to microscopic cracking in the presence of moisture. However, the presence of ASR gel may not necessarily result in destruction of the concrete; it is however considered as a possible risk and should be mitigated effectively (Swamy 1992). Positive effects of glass introduction were reported, whereby particles smaller than 1.18 mm showed lower expansion than natural fine aggregates and particles smaller than 75 μm in size showed an increase strength development, which could possibly attribute to the cementitious properties of glass powder (Liang et al. 2007, 2021). In South Africa, this unconventional way of producing concrete may receive scepticism because it is perceived that waste materials are inferior to virgin materials, and for this reason, more extensive testing is important to demonstrate the benefits and provide technical confidence.

9.4 Waste Tyres

The rapid expansion of the automobile industry throughout the globe has led to an increase in demand for natural and synthetic materials. The large number of vehicles present today has led to the accumulation of waste tyres worldwide. Rubber tyres are one of the most widely used materials in the transport industry; however, the disposal of used tyres is difficult due to their characteristics and properties (Torretta et al. 2015). There are approximately one and a half billion tyres manufactured annually throughout the globe (Pilusa et al. 2014). In South Africa, there are fourteen million tyres sold annually (Department of Environmental Affairs 2018). Due to the non-biodegradable properties of the tyres, the disposal of the used tyres in a sustainable way becomes challenging (Bisht and Ramana 2017). It is estimated that there are approximately 30 million to 60 million tyres in stockpiles throughout South Africa (Department of Environmental Affairs 2018). The latest waste tyre statistics show that approximately 27.01% of waste tyres collected in South Africa were recycled for the first 6 months in 2019.

Incineration of these tyres releases toxic chemicals such as carbon monoxide, sulphur, and nitrogen oxides into the atmosphere, which are detrimental to the health of organisms and the environment (Ziadat and Sood 2014; Bisht and Ramana 2017). Disposal of tyres at landfills and stockpiles pose many hazards as they promote the breeding of pest and bacteria (Eldin and Senouci 1994). Due to the chemical composition of tyres, they are highly combustible. Therefore, the accumulation of tyres is regarded as a fire hazard as they are difficult to extinguish if set alight (Ziadat and Sood 2014). The ambient grinding process is one of the material recovery methods used to convert waste tyres into crumb rubber. The rubber component of the tyre is shredded into coarse-sized particles which are used in a variety of applications. The steel found in the tyre is removed and recycled. However, polymer fibres that are used as tyre reinforcement are disposed at landfill sites.

The concept of using fibres for concrete reinforcement is not a new one. Previous studies investigated the effects of incorporating fibres in concrete, for example, using fibre derived from recycled PET drink bottles. Generally, addition of fibres to concrete would act as crack inhibitors and substantially increase the tensile strength, cracking resistance, impact strength, wear and tear, fatigue resistance, and ductility of concrete (Kandasamy and Murugesan 2011; Koo et al. 2014; Al-Hadithi and Alani 2015).

Shi Yin et al. describe this a sewing effect, increasing the ductility; it is also at times defined as a "bridging" effect (Yin et al. 2015). Furthermore, they noted when testing beams that plain concrete beams failed almost instantaneously with the occurrence of the first crack, but the fibre beams (polypropylene fibre) failed over a period of additional bending as the bending force was transmitted to the fibres once the first cracks occurred; this was a result of the matrix action that is attributed due to the concrete mixed with the fibres (Pešić et al. 2016).

Trois et al. explored a possible solution for the reuse of tyre fibres by adding them as a performance enhancement material in low strength concrete. Experiments were conducted using different masses of contaminated and partially cleaned tyre fibres as a replacement for fine aggregates in the concrete (Naicker et al. 2015).

The tyre fibres were substituted by percentage mass for fine aggregates in the concrete mixes, while all other components remained constant. The following concrete mixes were designed for the investigation:

1. 0% Tyre fibre mix (control)
2. 2% Partially clean fibre mix
3. 5% Partially clean fibre mix
4. 2% Contaminated fibre mix (contaminated with crumb rubber from the tyres)
5. 5% Contaminated fibre mix (contaminated with crumb rubber from the tyres)

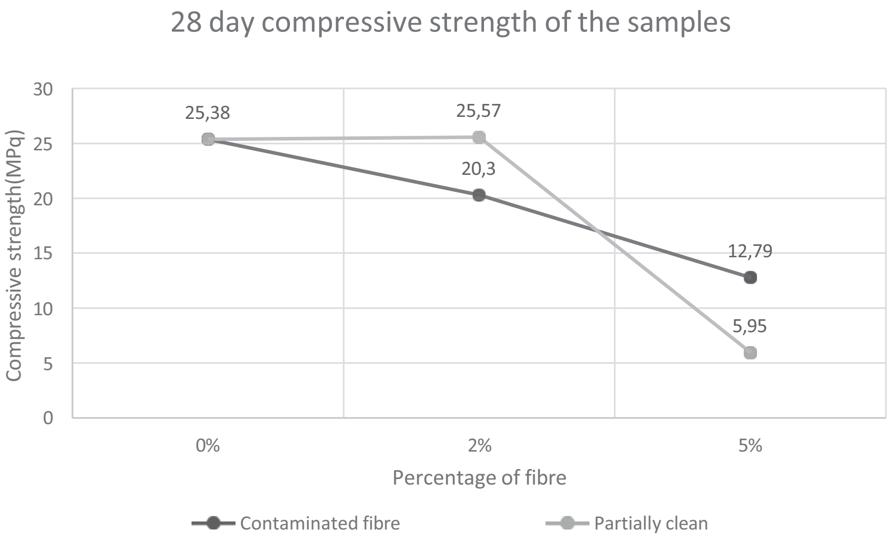

Fig. 9.1 28-day results for compression strength for the different concrete mixes. (Naicker et al. 2015)

9.4.1 Compression Strength Test

The results obtained from the compression strength test are presented in Fig. 9.1. Three cubes were cast for each concrete mix, and an average value was used as the final strength of the mix.

From Fig. 9.1, it can be noted that the target strength of 25 MPa was achieved for the control mix. The concrete mix containing 2% partially cleaned fibres displayed an increased compressive strength of 0.19 MPa when compared to the control mix. A large transition was recorded between concrete mixes containing 2% and 5% partially cleaned fibres. The concrete mix containing 5% partially cleaned fibres was relatively dry when compared to the other mixes. One of the reasons for the phenomena is the absorption of the water by the partially cleaned fibres. A gradual decline in the compressive strength of concrete mixes containing contaminated fibres was experienced. This trend was also experienced in experiments conducted on concrete incorporated with contaminated tyre fibres (Pešić et al. 2016; Baričević et al. 2018). The high volume of crumb rubber may influence the strength of the concrete. Past literature mentions that as the volume of crumb rubber increases, the compressive strength of the concrete decreases (Al-Tayeb et al. 2013; Dong et al. 2013; Hunag et al. 2016; Bisht and Ramana 2017).

As it is exhibited in Fig. 9.1, for the 5% partially cleaned fibre concrete mix, the compressive strength for the third cube does not lie within 15% of the average; therefore, the results for the mix is not valid. This would suggest that more samples will be required to evaluate the compressive strength of the concrete mix and improve the validity of the results.

9.4.2 Splitting Tensile Test

The results from the splitting tensile test are presented in Fig. 9.2. Three cylinders were casted, and an average splitting tensile strength was calculated for each concrete mix.

As observed in Fig. 9.2, there is an increase of 0.15 MPa in the tensile strength for the concrete mix containing 2% partially cleaned fibres, when compared to the control mix. A sharp decline is noted in the tensile strength between 2% and 5% partially cleaned concrete mixes. The concrete mixes containing contaminated fibres experienced a gradual decline in the tensile strength of the concrete as the percentage of fibre added increased. During the tests, it was noted that the samples did not split completely into two separate pieces. A crack could be noted; however, the fibres held the samples together.

9.4.3 Flexural Test

The results obtained from the flexural test of the concrete samples are presented in Fig. 9.3. Three beams were cast for each concrete mix, and an average of the results for each mix was used as the final value.

It can be observed in Fig. 9.3, for 2% fibre, that there was an increase in the flexural strength of 0.15 MPa and 0.03 MPa for partially cleaned and contaminated fibre

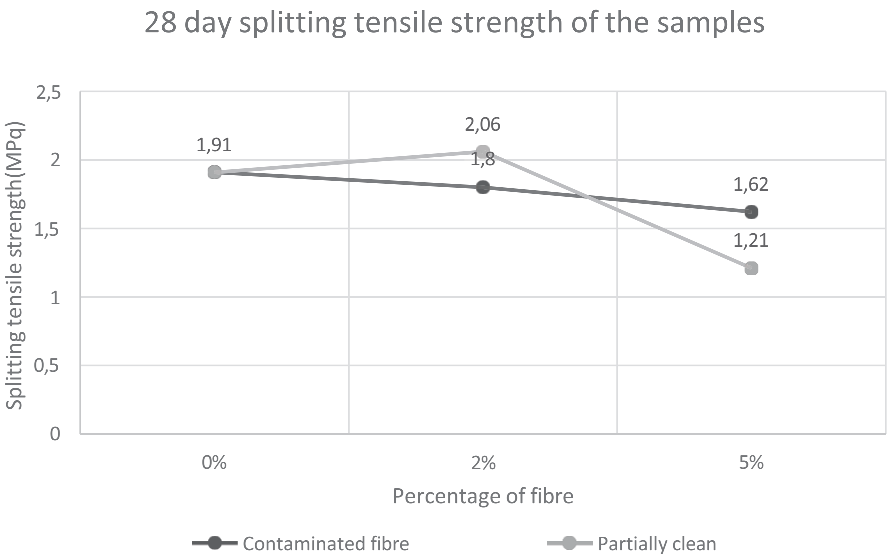

Fig. 9.2 28-day results for splitting tensile strength for the different concrete samples. (Naicker et al. 2015)

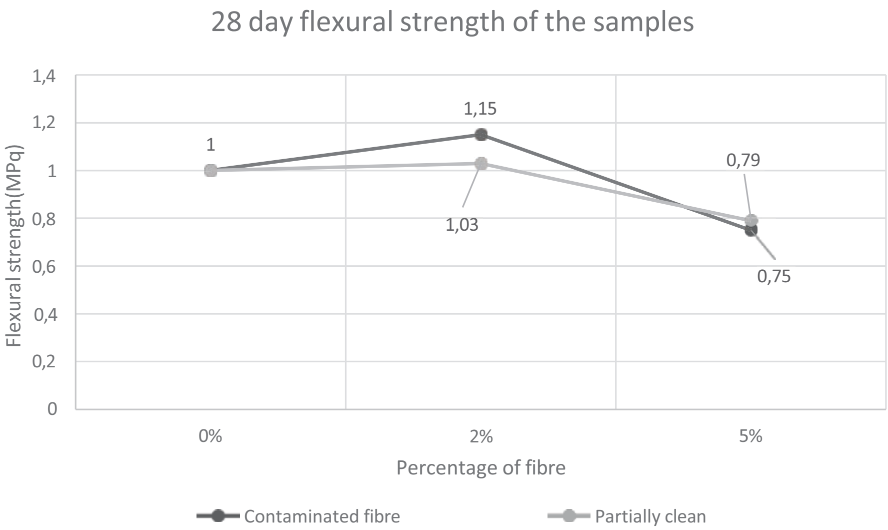

Fig. 9.3 28-day results for flexural strength of the different concrete samples. (Naicker et al. 2015)

respectfully when compared to the control mix. This was followed by a decline in the flexural strength in both partially clean and contaminated fibres, for the 5% fibre concrete samples. A similar trend was observed in the results published by Baricevic et al. (2018), with wet spray, air-entrained concrete. It is clear that more tests are required to identify the effects of increasing amounts of tyre fibres in concrete on the flexural strength of the material. During the tests, it was observed that the beams did not split into two separate pieces.

9.5 Paper Mill Sludge (PMS)

Pulp and paper mill residual solids (also called sludge) are composed mainly of cellulose fibers, moisture, and papermaking fillers (mostly kaolinitic clay and/or calcium carbonate) (Bajpai 2015). The main methods of disposing this type of sludge have been land application and land filling. Landfilling costs in Europe have risen due to the increasingly strict laws, taxes and decreasing capacities of landfills (Ochoa de Alda 2008). Paper mill sludge is also often incinerated in order to reduce the volume of the waste disposal and to recover heat (Fava et al. 2011).

Paper sludge has high water absorption. This property of paper sludge reduces its flow properties when used in cement mortar and concrete. Research conducted by Segui et al. (2012) included the use of paper sludge as hydraulic binder, the result of this experiement revealed that paper sludge as an hydraulic binder provided satisfactory strength as a whole. The use of PMS in clay bricks is one of the most researched applications of paper sludge reuse. Sutcu and Akkurt et al. (Segui et al. 2012) found that paper sludge in clay material reduced the combustion load during the firing process of bricks. In more recent studies, paper sludge was also used in energy recovery techniques. This includes pyrolysis, direct liquefaction, steam reforming, anaerobic digestion, and gasification (Singh et al. 2018). Many different ways of re-using waste PMS have been researched. These various applications include hydraulic binders, cementitious materials, polymer reinforcement, and fibreboards. These applications were researched due to PMS containing gehlenite, tricalcium aluminate, belite, metakaollinite, and mayenite (Singh et al. 2018). Any source of calcite and kaolin can be used as a pozzolanic addition in the manufacturing of cement. The pozzolanic reaction of PMS is as good as that of natural metakaolin. The presence of CaO and MgO in sludge creates volume instability. This limits the partial replacement of cementitious binder by sludge to 10%.

In South Africa, approximately 500,000 tons per annum of sludge is produced from pulp, tissue, and paper mills. This sludge waste is mostly landfilled, discharged into the ocean via a sea outfall pipeline, or incinerated. Implementation of environmental legislation, such as the National Environmental Management: Waste Act, 2008 (Act 59 of 2008) places the sector under considerable pressure to find better management practices for mill sludge disposal. However, apart from legislative pressure, pulp and paper mills can benefit from finding alternative methods of sludge management by producing value-added products to supplement the mills' income and reduce their carbon footprint. The difficulty with pulp and paper mill sludge is the variants in process conditions (from mill to mill) and the type of fibre feedstock (virgin fibre or recycled fibre), which result in the properties of mill sludge being different. Therefore, a single solution for mill sludge diversion from landfill is not realistic, and some beneficiation options might be better suited to certain mill types than others. A typical sludge contains about 60% organic matter and 40% inorganic matter. The inorganic matter can be beneficiated through the manufacture of bricks, whereas the organic matter can be beneficiated by the separation of fibres and converting them to nanocrystalline cellulose, as well as by the microbial processing of the sludge to produce biopolymer plastics (Godfrey et al. 2022; Jele et al. 2022).

This study was undertaken at the South African Research Chair Waste and Climate Change hosted at the University of KwaZulu-Natal headed by Prof C. Trois. We considered the elaboration of hybrid materials in the making of concrete bricks using PMS as a performance enhancer. All the sample testing undertaken were hardened state tests of concrete samples. All the tests were conducted after 28 days of curing and consisted of compressive strength test, splitting tensile strength tests, and flexural strength test (beam test). All testing was done in accordance with the South African National Standards.

9.5.1 Compressive Strength

As shown in Table 9.1, the concrete sample that contained 2% PMS fibres showed a 15.03 MPa reduction in compressive strength, which is a 35.04% loss in strength from the control sample. The concrete sample with 5% PMS fibres showed a reduction of 18.87 MPa in compressive strength, which is a 44% loss in compressive strength from the control sample. The concrete sample that contained 10% PMS fibres showed a significant loss of 37.73 MPa, which resulted in 87.97% reduction in compressive strength from the control sample. The loss in compressive strength of the samples with PMS fibres means that these samples cannot be graded as the same grade of concrete as the control mix.

For the test of the samples to be valid, the range between the compressive strengths of the samples needs to be within 15% of the mean compressive strength of the samples. It can be seen that all the samples fell within the required range of 15% and the tests are considered valid.

9.5.2 Splitting Tensile Strength

The concrete samples containing 2 and 5% PMS fibres both showed an increase of splitting tensile strength from the control sample (see Table 9.2). The sample with 2% PMS and 5% PMS samples showed a 1.27 MPa (59.53%) and 0.42 MPa (19.61%) increase in splitting tensile strengths, respectively, whereas the sample with 10% PMS showed a 0.9 MPa reduction in splitting tensile strength, which is a 42.51% reduction from the splitting tensile strength of the control mix.

It can be seen that the increase in PMS fibres in 2 and 5% concentration increased the average splitting tensile strength of the concrete. There is a drop in average splitting tensile strength from 2% PMS substitution to 10% PMS substitution. According to the concrete institute, one of the factors that affect concrete strength is the surface texture of aggregates. The PMS fibres consisted of inconsistent surface texture, as they were hand shredded and not uniform. This could have had aided in the increase in the splitting tensile strength of the concrete.

The decrease in tensile strength from the 2% PMS to 5% PMS to the 10% PMS samples can be attributed to the inconsistent size and geometry of the PMS fibres.

Table 9.1 Summary of 28-day compressive strength results. (Naicker et al. 2015)

Mix	Average 28-day compressive strength (MPa)	Percentage change in compressive strength (%)
0% PMS	42.89	0.00
2% PMS	27.86	35.04 Decrease
5% PMS	24.02	44.00 Decrease
10% PMS	5.16	87.97 Decrease

Table 9.2 Summary of 28-day splitting tensile strength results. (Naicker et al. 2015)

Mix	Average 28-day splitting tensile strength (MPa)	Percentage change in splitting tensile strength (%)
0% PMS	2.13	0.00
2% PMS	3.40	59.53 Increase
5% PMS	2.55	19.61 Increase
10% PMS	1.23	42.51 Decrease

Table 9.3 Summary of 28-day flexural strength results. (Naicker et al. 2015)

Mix	Average 28-day flexural strength (MPa)	Percentage change in flexural strength (%)
0% PMS	5.89	0.00
2% PMS	5.23	11.21 Decrease
5% PMS	4.80	18.49 Decrease
10% PMS	2.42	58.92 Decrease

The PMS fibres were hand shredded, and large unsorted PMS fibres have probably reduced concrete strength with higher concentrations of PMS.

9.5.3 Flexural Strength (Beam Test)

As shown in Table 9.3, the sample with 2% PMS showed a 0.66 MPa reduction in flexural strength, which is a 11.21% loss in flexural strength from the control sample. The 5% PMS samples showed a reduction of 1.09 MPa in flexural strength, which is 18.49% loss in strength from the control samples. The sample with 10% PMS fibers showed a 3.47 MPa reduction in flexural strength, which is a 58.92 loss in strength from the control sample.

9.6 Food Waste

Sharma et al. (2019) put forward the various problems that result from the inadequate management of organic waste. These include pollution of the natural environment, eutrophication, aesthetic degradation, greenhouse gas emissions, and impacts on public human health. Of the potential waste valorisation applications, organic pollutants release heavy metals that are a health hazard to both people and the environment (Sharma et al. 2019). Composting using organic waste has proven to be shown to reduce the amount of organic waste sent to landfills (Sharma et al. 2019). This agricultural recycling of organic waste ensures that landfilling costs are reduced, transportation costs of the waste are avoided, and conventional fertilisers that may be imported are substituted (Sharma et al. 2019).

One type of organic waste that has a good potential for alternative building materials within urban mining is bone. Research suggests that the use of bone within concrete production in its various forms is feasible. According to Bhat et al. (2012), bone is a slow-deteriorating, hard but light material with an extracellular matrix.

Bovine bone waste is widely produced within South Africa. Currently, the overwhelming majority of this waste stream is landfilled, contributing to waste management costs for local municipalities, as well as contributing to South Africa's climate change emissions through methane emitted from landfill. Thus, there is significant scope to valorise this waste stream within a South African context.

Using bone waste as an additive during the production of concrete has numerous benefits, including the preservation of natural resources and landfill airspace reduction (Abubakar et al. 2016). Some of the other benefits from the implementation of crushed bovine bones in concrete production are the improvement of livelihoods as valorisation of bone waste has the potential for job creation and consequentially improve the lives of those that generate bone waste which has demonstrated to be a resource. Another benefit from the implementation of crushed bovine bones in concrete production is the improvement of livelihoods as valorisation of bone waste has the potential for job creation. Bone waste has proved/shown to be a resource and has the potential to improve the lives of those that generate it. Furthermore, if this waste stream is successfully valorised, butcheries nationwide or markets such as bovine-head markets within informal markets sectors will economically benefit from selling bone waste for construction purposes. The addition of bone in concrete results in a light weight concrete with many structural benefits; lightweight concrete means that elements of structures such as beams, columns, and foundations may be designed at reduced sizes (Bhat et al. 2012).

Though this study has a broad national application, this work will speak to the study area of the bovine-head market at Warwick Junction Informal Market in Durban, South Africa. The market sells bovine-head meat and dumplings daily to the public in the Durban Central Business District (CBD). A total of 20 traders work at the market, and their tasks are divided into cookers and skinners. The market's most significant waste streams are bovine-head bones, skin, and residual wastes resulting from the market's activities.

The Warwick Junction Informal Markets (WJIM) are the biggest collection of informal markets in Southern Africa. WJIM comprise of nine markets of which two are the early morning market and the BHM. The BHM is a facility run by 20 traders who prepare bovine head meat and sell it to customers in the Durban CBD. One of the traders revealed that the bovine heads are acquired from various butcheries in the near vicinity. The current method of disposal at the market is direct disposal to the local municipal sanitary landfill, and the implications of this disposal method are undesirable. This case study aims to create a crushed bone hybrid concrete that is a sustainable alternative for conventional concrete while diverting this organic waste from landfills and mining this particular type of waste stream.

Table 9.4 Summary and comments on compressive strength test

Compressive strength		
%CBB in concrete mix	28-day CS (MPa)	Comments
0%	40.2	The 28-day compressive strength decreased with an increase in %CBB content as observed in previous literature. Overall, compressive strengths were greater than those achieved in previous literature
10%	33.7	
15%	29.7	
20%	27.6	

9.6.1 Experimental Investigation and Discussion

The compressive strengths achieved in MPa ranged between 27.6 and 40.2, as seen in Table 9.4. When compared to the range of 16.49 MPa to 24.29 MPa achieved in a study by Ogarekpe et al. (2017), this preliminary results surpassed expectations. The differences in strengths may have been influenced by type of bovine bones used. The bones used in this study were jaw bones, and because the study by Ogarekpe et al. does not specify which kind of bovine bones were used, a comparison in this regard cannot be made. Compressive and flexural strength (Table 9.5) in this study result decreased with an increase in the percentage of CBB content, and this was the predicted outcome observed in previous studies. According to South-African Standards, low-strength, medium-strength, and high-strength concretes have strengths of 15 MPa, 25 MPa, and 30 MPa, respectively. The 20% CBB concrete achieved a strength of 27.6 MPa which was above the medium-strength concrete strength; hence, concrete with a 20% CBB content could be applied as a medium-strength concrete. The applications of medium-strength concrete according to South African standards are footpaths, reinforced foundations, patio slabs, light-duty house floors, garage floors, and driveways. The flexural strength results as seen in Table 9.5 fluctuated with the 15% CBB content achieving a maximum strength of 3.3 MPa. The control specimens yielded greater strengths in comparison to the all the hybrid CBB concrete specimens.

9.7 Viability of the Waste Resource from the Different Waste Streams for Bricks

In terms of average compressive strength, some of the bricks incorporated with waste performed better than the control sample. Using South African standards for building requirements, a number of practical applications become apparent (see Table 9.6).

Table 9.5 Summary and comments on flexural strength test

Flexural strength		
%CBB in concrete mix	28-day FS (MPa)	Comments
0%	3.9	Flexural strength at 28 days reduced with an increase in CBB content and this relationship followed the same trend found in previous literature
10%	2.3	
15%	3.3	
20%	3.2	

Table 9.6 Suggested bricks with waste for various applications in functions of their compressive strength. (Mahdjoub et al. 2021)

Possible applications	Average required compressive strength for solid units (MPa)	Proposed brick specification
Single storey or the upper storey of a double storey building	4.0	Cow bones, glass, paper Mill Sludge, tyres nylon fibers
Lower storey of a double storey building	10.0	Cow bones, glass, paper mill sludge, tyres nylon fibers
Infill panels in concrete and steel-framed buildings of four storeys or less	4.0	Cow bones, glass, paper mll sludge, tyres nylon fibers
Free standing, retaining, parapet, and balustrade walls	5.0	Cow bones, glass, paper mill dludge, tyres nylon fibers

9.8 Conclusion

Waste from a broad perspective is a subject of concern for most emerging countries. In the context of Africa, the newly defined etymological terms of urban mining and circular economy are supposedly considered to be new concepts.

However, historically speaking, or traditionally speaking, African people have always applied, not knowingly, the concepts of urban mining and waste recovery as a secondary source of materials. Since the recognition of these concepts from the developing countries, more African countries have started reconsidering their modern approach to waste and materials and are now consciously moving towards urban mining.

This collection of investigation has articulated some possibilities for waste utilisation as a source of material for the creation of hybrid materials. Testing revealed that incorporation of waste into building material was viable, and this incorporation should be perceived as a performance enhancer method through urban mining. Developing this process could lead to income generation for the local economy of some developing countries. It could also initiate consistent and intensive waste mining adapted to the context of emerging states.

References

M. Abubakar, M. Abdullahi, J. Aguwa, Probability based design of concrete mixes with cow-bone ash admixed cement. **28**, 31–42 (2016)

A.I. Al-Hadithi, M.F.A. Alani, Mechanical properties of high performance concrete containing waste plastic as aggregate. Journal of Engineering **21**(8), 100–115 (2015)

M.M. Al-Tayeb, B.H. Abu Bakar, H.M. Akil, H. Ismail, Performance of rubberized and hybrid rubberized concrete structures under static and impact load conditions. Experimental Mechanics : An International Journal **53**(3), 377–384 (2013)

R. Arora, K. Paterok, A. Banerjee, M.S. Saluja, Potential and relevance of urban mining in the context of sustainable cities. IIMB Management Review **29**(3), 210–224 (2017)

P. Bajpai, *Generation of waste in pulp and paper mills* (Springer, Management of Pulp and Paper Mill Waste, 2015), pp. 9–17

A. Baričević, M. Jelčić Rukavina, M. Pezer, N. Štirmer, Influence of recycled tire polymer fibers on concrete properties. Cement and Concrete Composites **91**, 29–41 (2018)

A. Baricevic, M. Pezer, M. Jelcic Rukavina, M. Serdar, N. Stirmer, Effect of polymer fibers recycled from waste tires on properties of wet-sprayed concrete. Construction and Building Materials **176**, 135–144 (2018)

J.A. Bhat, R.A. Qasab, A. Dar, Machine crushed animal bones as partial replacement of coarse aggregates in lightweight concrete. ARPN Journal of Engineering and Applied Sciences **7**, 1202–1207 (2012)

K. Bisht, P.V. Ramana, Evaluation of mechanical and durability properties of crumb rubber concrete. Construction and Building Materials **155**, 811–817 (2017)

R. Cossu, The Urban Mining concept. Waste Manag **33**(3), 497–498 (2013)

R. Cossu, I.D. Williams, Urban mining: Concepts, terminology, challenges. Waste Management **45**, 1–3 (2015)

J. Cramer, Material efficiency: from top-down steering to tailor-made governance. Philosophical Transactions of the Royal Society A, Mathematical, Physical and Engineering Sciences (2013)

Department of Environmental Affairs, South Africa State of Waste Report. A report on the state of the environment. D. o. E. Affairs. Pretoria, Department of Environmental Affairs, 2018

Q. Dong, B. Huang, X. Shu, Rubber modified concrete improved by chemically active coating and silane coupling agent. Construction & Building Materials. **48**, 116–123 (2013)

N.N. Eldin, A.B. Senouci, Measurement and prediction of the strength of rubberized concrete. Cement and Concrete Composites **16**(4), 287–298 (1994)

G. Fava, M.L. Ruello, V. Corinaldesi, Paper mill sludge ash as supplementary cementitious material. Journal of Materials in Civil Engineering **23**(6), 772–776 (2011)

P. Ghisellini, C. Cialani, S. Ulgiati, A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production **114**, 11–32 (2016)

L. Godfrey, M. John, G. Mturi, S. Muniyasamy, Transitioning to a circular economy in South Africa: The role of innovation in driving greater waste valorization, in *Circular economy and waste valorisation*, Industrial ecology and environmental management, ed. by J. Ren, L. Zhang, vol. 2, (Springer, Cham, 2022). https://doi.org/10.1007/978-3-031-04725-1_7

L.-J. Hunag, H.-Y. Wang, Y.-W. Wu, Properties of the mechanical in controlled low-strength rubber lightweight aggregate concrete (CLSRLC). Construction and Building Materials **112**, 1054–1058 (2016)

T. Jele, B. Sithole, P. Lekha, J. Andrew, Characterisation of pulp and paper mill sludge for beneficiation. Cellulose **29**, 1–15 (2022)

R. Kandasamy, R. Murugesan, Fibre reinforced concrete using domestic waste plastics as fibres. ARPN Journal of Engineering and Applied Sciences **6**(3), 75–82 (2011)

P. Karani, S.M. Jewasikiewitz, Waste management and sustainable development in South Africa. Environment, Development and Sustainability **9**(2), 163–185 (2007)

B.-M. Koo, J.-H.J. Kim, S.-B. Kim, S. Mun, Material and structural performance evaluations of Hwangtoh admixtures and recycled PET fiber-added eco-friendly concrete for CO2 emission reduction. Materials **7**(8), 5959–5981 (2014)

E.H. Lauridsen, U. Jørgensen, Sustainable transition of electronic products through waste policy. Research Policy **39**(4), 486–494 (2010)

H. Liang, H. Zhu, E. A. Byars, *Use of waste glass as aggregate in concrete*. 7th UK CARE Annual General Meeting. UK Chinese Association of Resources and Environment, Greenwich 2007.

G. Liang, H. Li, H. Zhu, T. Liu, Q. Chen, H. Guo, Reuse of waste glass powder in alkali-activated metakaolin/fly ash pastes: Physical properties, reaction kinetics and microstructure. Resources, Conservation and Recycling **173**, 105721 (2021)

N. Mahdjoub, M. Kalina, A. Augustine, E. Tilley, Innovating traditional building materials in Chembe, Malawi: Assessing post-consumer waste glass and burnt clay bricks for performance and circularity. International Journal of Sustainable Engineering **14**(4), 874–883 (2021)

J.A.G. Ochoa de Alda, Feasibility of recycling pulp and paper mill sludge in the paper and board industries. Resources, Conservation and Recycling **52**(7), 965–972 (2008)

N. Ogarekpe, J. Agunwamba, F.O. Idagu, E. Bejor, O. Eteng, H.E. Ndem, E.O. Oloko, Suitability of burnt and crushed cow bones as partial replacement for fine aggregate in concrete. Nigerian Journal of Technology (NIJOTECH) **36**, 686–690 (2017)

N. Pešić, S. Živanović, R. Garcia, P. Papastergiou, Mechanical properties of concrete reinforced with recycled HDPE plastic fibres. Construction and Building Materials **115**, 362–370 (2016)

J. Pilusa, M. Shukla, E. Muzenda, Economic assessment of waste tyres pyrolysis technology: A case study for Gauteng Province, South Africa, 2014

C. Rootes, Environmental movements, waste and waste infrastructure: An introduction. Environmental Politics **18**(6), 817–834 (2009)

P. Segui, J.-E. Aubert, B. Husson, M. Measson, Characterization of wastepaper sludge ash for its valorization as a component of hydraulic binders. Applied clay science **57**, 79–85 (2012)

K. Senthil Kumar, K. Baskar, Briefing: Shear strength of concrete with E-waste plastic. Proceedings of the Institution of Civil Engineers-Construction Materials **168**(2), 53–56 (2015a)

K. Senthil Kumar, K. Baskar, Development of ecofriendly concrete incorporating recycled high-impact polystyrene from hazardous electronic waste. Journal of Hazardous, Toxic, and Radioactive Waste **19**(3), 04014042 (2015b)

B. Sharma, B. Vaish, U.K. Singh, P. Singh, R.P. Singh, Recycling of organic wastes in agriculture: An environmental perspective. International Journal of Environmental Research **13**(2), 409–429 (2019)

A. Silva, M. Rosano, L. Stocker, L. Gorissen, From waste to sustainable materials management: Three case studies of the transition journey. Waste Management **61**, 547–557 (2017)

S.K. Singh, S. Kulkarni, V. Kumar, P. Vashistha, Sustainable utilization of deinking paper mill sludge for the manufacture of building bricks. Journal of Cleaner Production **204**, 321–333 (2018)

T. Naicker, V. Tramontin, C. Trois, Green Concrete: an investigation into the effects of waste materials available In South Africa on concrete performance. Journal of Construction **8**, 27–37 (2015)

R.N. Swamy, *Fibre reinforced cement and concrete: Proceedings of the fourth RILEM international symposium* (CRC Press, 1992)

V. Torretta, E.C. Rada, M. Ragazzi, E. Trulli, I.A. Istrate, L.I. Cioca, Treatment and disposal of tyres: Two EU approaches. A review. Waste Management **45**, 152–160 (2015)

U. Umapathy, C. Mala, K. Siva, Assessment of concrete strength using partial replacement of coarse aggregate for waste tiles and cement for rice husk ash in concrete. International Journal of Engineering Research and Applications (2014) ISSN: 2248-9622

S. Yin, R. Tuladhar, F. Shi, M. Combe, T. Collister, N. Sivakugan, Use of macro plastic fibres in concrete: A review. Construction and Building Materials **93**, 180–188 (2015)

A.H. Ziadat, E. Sood, An environmental impact assessment of the open burning of scrap tires. Journal of Applied Sciences **14**(21), 2695–2703 (2014)

Chapter 10
Composting: An Alternative with Marked Potential for Organic Waste Management

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10.1 Description of Composting Process and Technology

Composting is a widely accepted method to transform organic waste into a valuable stable soil amendment, also called compost. Compost is a non-toxic and non--pathogenic product that can be applied as an appropriate fertiliser and soil conditioner to support plant growth, used by rural farmers for centuries. Compost enriches the soil with macronutrients and micronutrients over a prolonged period, as opposed to synthetic fertilisers, promoting a sustainable agriculture.

Furthermore, composting is an interesting valorisation methodology of organic waste, friendly with environment, which prevents the climate change and improves the circular economy. Organic waste composting is a task of municipal solid waste (MSW) management, which is preceded by other management tasks such as production, source separation, temporary storage, collection, and transport. Furthermore, all of the mentioned activities are associated with sustainability aspects, such as policy, regulation, institutional frameworks, public participation, financial and corporate governance, and technological aspects (Sharma and Sharma 2020).

With regard to implanted technology, several types of facilities with different level of development and complexity can be found installed worldwide. In general terms, these facilities include from window systems that consist of the simple accumulation of compost piles, which usually are 1.5–3.0 m high and 3.0–6.0 m wide (but the cross-sectional dimensions vary with feedstock and turning equipment), to in-vessel systems or bioreactors, which are most of the technologies currently used in developed countries. Although windrows are opened systems that require low

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installation and maintenance costs, the emissions generated (aerosols, odour and leachate) cannot be correctly managed. In these rows, the compostable material is generally aerated by turning to improve its porosity and oxygen content, moisture, and temperature, which are relevant to monitor the composting process properly. Sometimes, windrows are dotted with forced aeration systems, but this involves an added cost to the composting process. Generally, in-vessel systems consist of tanks where moisture, airflow, and temperature can be more readily controlled, ensuring, and adequate for aerobic development of the process and the sanitation of the final product. These systems are dotted with air circulation systems that allow pressurised fresh air to be injected and the exhaust to be extracted through a biofilter to minimise or remove volatile compound and the odour associated to these emissions. However, this technology is not considered applicable in developing countries due to cost and maintenance reasons (Couth and Trois 2012).

10.2 Implementation Status of Composting in Developed Countries

The urban waste management models have been gradually materialised in recent years towards circular economy in the productive cycle of our society, where waste is beginning to be considered as resource. It is undeniable that social concern for the immediate environment is increasingly relevant, especially due to the consequences of climate change with direct and indirect negative effects worldwide. In this context, the European Union (EU) has clearly marked the steps that all members states must take to move towards an improvement in the management of urban waste, starting with minimisation and prevention and, as the last option, leaving energy recovery of waste and landfill, as stated by the Landfill Directive (1999/31/EC) and Waste Framework Directive (2008/98/EC). However, one of their fundamental strategies is to establish differentiated management of organic waste from household origin and organic nature substrates generated in the municipalities such as parks, gardens, and fresh market waste, all called "biowaste" (Ravindran et al. 2021). The target for recycling municipal waste by 2035 is set to 65% in the revised legislative framework on waste. In this regard, the EU promotes the implementation of precise measures and actions among its members in order to enhance current conditions and build a legal framework for the proper MSW management (Comesaña et al. 2017). As a result, the amount of recycled waste (material recycling and composting) increased from 39 million tons in 1995 to 116 million tons in 2017, at an average annual rate of 5.0%. In some countries, there are explicit and detailed rules set by legislation under waste law. However, the standards on the use and quality of compost differ considerably within EU members, mostly due to differences in soil policies (Cesaro et al. 2015). Platform like the European Compost Network (www.compostnetwork.info) brings all European biowaste organisations and their operating plants, research, policy making, consultants, and authorities together and creates a network for sustainable recycling practices in composting (Bruni et al. 2020).

Concretely, Spain made public the transposition of this obligation to Law 22/2011 and of waste and contaminated soils. However, at this moment, different situations can be found among the autonomous communities. Catalonia especially, but also Euskadi and Navarra, stands out as those that already integrate the collection and segregated treatment of biowaste as part of its urban waste management model, although it has not reached the entire population yet. In the rest of the communities, in the best of cases, selective collection has only begun in some municipalities, but without having specific treatment facilities at the moment (Campos-Alba et al. 2021; Füleky and Benedek 2010). Despite the composting history and accumulated information about the need for organic waste recycling, currently in the EU most of the municipal waste is still deposited in landfills (45%). In Spain, landfilling currently accounts for 57.8% of urban waste generated, while composting of selectively collected biowaste does not exceed 0.8% (Indicadores – Serie Territorial – Dosieres España – UE n.d.).

In terms of process scaling, composting can be broadly applied at centralised large-scale plants that are complex and serve vast geographic areas and sectors, at community-scale plants that serve primarily residential neighbourhoods or community levels, and home-scale operations that serve individual housing units (Pai et al. 2019). It should be marked that the development of the different scale operations depends mainly on policies and governmental promotions, but also geographical situation of the areas, culture, traditional routines, and climate conditions determines the kind of facilities as well as the scale operation. Despite the advanced technological development of many of the composting plants located in Spain, others do not meet the objectives for which they were or should have been built. In fact, in some cases, they are inadequately managing organic waste as a result of very low production yields, high liquid and gaseous emissions, poor quality products, and consequently little reduction in the amount diverted to landfill (Moreno and Moral 2008).

In developed countries, special attention is paid to the separate collection on the initial stages of waste management to optimise the global management process of organic fraction of municipal solid waste (OFMSW) also improving the composting process and obtaining a high-quality final product. The requirements for compost quality depend on its destination, which includes agriculture, horticulture, and urban landscaping. Several countries and public and private organisations have established quality standards for compost, where certain properties are prioritised, and different limits are established according to the end use. However, there is a need to homogenise such criteria at international level (Cesaro et al. 2015; Oviedo-Ocaña et al. 2019).

It is worth noting that different countries have addressed strategies for reducing the environmental impacts of composting processes and evaluated new analytical and microbiological approaches to define compost quality (Greff et al. 2022). Furthermore, the current strategies should prioritise the adequate management of composting processes to minimise excessive emissions of ammonia (NH_3), greenhouse gases such as nitrous oxide (N_2O), and methane (CH_4) (Bernal et al. 2017).

10.3 Implementation Status of Composting in Developing Countries

The general situation in developing countries is marked by a high generation of solid waste motivated by the development in urban areas over rural ones in a process called urbanisation. For example, in Africa, the average population growth rate in urban areas is more than three times as high as in rural areas. The projection is that by 2030 there will be 41 countries in sub-Saharan Africa (SSA) with higher urban than rural populations (Cofie et al. 2009), or Asia with 4.2 billion inhabitants will likely experience smaller proportional increase than Africa. However, the usual unplanned urbanisation growth will lead to an increased demand for proper and healthy municipal services. Specifically, the urbanisation involves a high amount and variety waste generation, which demands the development of appropriate norms to promote available methods and facilities to manage large amount of organic solid waste, such as composting facilities. In this context, the implementation status of composting processes in developing countries is extremely varied. As an example, in Egypt, which is an African Middle East Arab country, 75% of the MSW is generated in urban areas. Total estimated MSW for 2025 is expected to reach 33 million tons for a growth rate of 3.2%, based on 2001 records. Collection services cover less than 30% of urban and rural areas. A portion of 8% of the total collected MSW is sent to composting facilities, but the rest is sent to uncontrolled landfills putting at risk the public health and the environment (GIZ 2014). In Latin America, the daily MSW generation is estimated to be approximately 436,000 tonnes (0.93 kg/person·d) and with a predicted generation of 1.5 kg/person·d, by 2025, mainly coming from the urban population (Oviedo-Ocaña et al. 2017). This situation is similar in other developing countries in Southeast Asia, Africa, and Latin America. These evidences reveal an inefficient waste collection, improper segregation, and poor community participation in developing countries, which are the major restriction in the implementation of MSW recycling policy that is usually under control of non--sufficiently efficient sectors (Silpa Kaza and Lisa Yao 2018; Suthar et al. 2016).

Due to poor public acceptability, budget constraints, infrastructure insufficiency, and lack of self-sustaining approaches, waste minimisation, recycling, reuse, and waste-to-energy could not gain much attention in developing counties (Ferronato and Torretta 2019). Many studies reported possible solutions for improving the solid waste management in developing countries, such as organic waste valorisation programs, with compost or biogas production (Hettiarachchi et al. 2018), implementation of energy recover plans and technologies (Ouda et al. 2016), production of energy from biomass waste by making briquettes (Sawadogo et al. 2018), and involvement of the integration of human waste pickers with legal incentives (Ghisolfi et al. 2017), among others. Kumar et al. (2008) reported an assessment of the status of municipal solid waste management in 59 selected cities in India and highlighted the need to promote processing technologies such as composting or vermicomposting to treat the biodegradable fraction of waste. These initiatives have been recommended to recover valuable resources from such waste streams under circular economy models, providing high opportunities for the socioeconomic development of the countries. However, many barriers still remain for improving formal collection, treatment, or valorisation and final disposal (Matter et al. 2015). Specifically, because of the numerous advantages that composting process involves, some strategies should be promoted to encourage organic waste management through this process in developing countries: (1) to further home composting, that is, a productive option for treating organic waste at source (Loan et al. 2019), due to its many benefits such as reducing pressure on landfills, minimising garbage collection and transportation costs (Tanaka 2007), reducing loss of organic resources derived from landfilling (Smith and Jasim 2009), and generating high added value products with intrinsic value by improving soil structure and fertility (Andersen et al. 2011; Barrena et al. 2014); (2) to popularise composting through marketing approaches; and (3) to encourage well-regarded businesses and hotels to fertilise their lawns with compost to raise public awareness of the benefits and simplicity of composting.

On balance, the implementation of a waste management program that prioritises composting has the potential to create jobs in the waste management sector. Popularising composting would also provide farmers with unlimited quantities of organic fertiliser at low or no cost. Therefore, increased public awareness of the benefits of composting in developing countries is vital to both supporting environmental sustainability and reducing poverty (Ibáñez-Forés et al. 2019).

10.4 Residual Substrates for Organic Waste Composting

10.4.1 Urban Solid Waste

According to recent estimates, about 2.01 billion tons of solid waste are produced per year in the world, with a high percentage of garbage ending up in landfills. Moreover, the fastest growing regions are sub-Saharan Africa, South Asia, and the Middle East and North Africa where, by 2050, total waste generation is expected to nearly triple, double, and double, respectively, which will have vast implications for the environment, health, and prosperity, thus requiring urgent action. Knowledge of waste composition is of particular importance for decision makers to determine proper MSW management options, which is influenced by economics. Food waste has the largest content in MSW, accounting for 44% followed by paper and cardboard trash (17%), plastic (12%), glass (5%), and metal (4%) (Silpa Kaza and Lisa Yao 2018). The content of organic waste generated in developing countries is much higher than that contained in the waste derived from developed countries (Kumar et al. 2008). Recent studies reported the evaluation of paper and paperboard recycling possibilities (Suthar and Kishore Singh 2022). Landfilled paper waste could be valorised by applying a suitable composting mechanism to breakdown such complex lignocellulosic substances into nutrient-rich manure for agronomic applications (Rai and Suthar 2020).

On the other hand, sewage sludge (SS) is also a potential residual substrate to be valorised through composting due to its high production worldwide. It is estimated that, considering that the daily amount of domestic SS generated per person on a dry basis is 60 g and the rate of population served by wastewater treatment plants in total population is 70%, the annual amount of SS is 1.24 million tons per year, on a dry basis, in Turkey (Turkstat 2021). In a comparative manner, Toamasina is the second largest city in Madagascar with a population of 326,286 and produces about 14,100 m^3 faecal sludge per year (Dirix et al. 2021), which is stored in latrines without a post-treatment. Developing countries (like India) have constructed millions of toilets with on-site sanitation technologies (OSTs). However, these OSTs lack the required management system for collection, transportation, and disposal of faecal sludge (sludge getting accumulated in OST), leading to considerable water and soil pollution (Chandana and Rao 2022). Furthermore, the presence of pathogenic organisms in this waste may pose health risks, limiting the direct application of sludge to soil fertilisation as well as the prohibited legislation in many countries such as Turkish national legislation (Şevik et al. 2018). Therefore, SS treatment by methods such as composting before they are applied to the soil is mandatory, allowing stabilisation of the organic material with both a reduction in mass and volume and obtaining an enrich in nutrients hygiene product (Kulikowska 2016). Composting of SS can contribute to the antibiotics persistence removal in the primary sludge improving the agricultural recycling of this waste (Couth and Trois 2012). Furthermore, physicochemical properties of SS such as high content of organics, nitrogen, phosphorus, and trace elements make this organic substrate play a key role in composting processes.

In addition, Eftoda and McCartney (2004) reported that the compact structure and high moisture content of SS demand the addition of bulking materials to create a more properly compostable structural support with interparticle cavities that allow the material aeration during composting process. By adding bulking agent to the composting mixture, substrate properties such as moisture content, C/N ratio, particle size, and pH values of mixtures are adjusted to optimum conditions (Cies¨lik et al. 2015; Ingelmo et al. 2012; Zittel et al. 2018). Leaves, wood, straw (Amir et al. 2005), sawdust (Kebibeche et al. 2019), or lignocellulosic crop waste (Greff et al. 2022) have been generally reported in the literature as bulking agents in the composting of SS.

10.4.2 *Agro-Industrial and Fishery Waste*

Management of agro-waste derived from agricultural practices has emerged as a significant global problem also in developing countries. Identically, handling raw animal manure in a hygienic and eco-friendly process appears tedious too. For example, in India, approximately 700 million tons of organic waste materials per year are disposed unsafely in the respective surrounding environment (Sofia

Vizhimalar et al. 2021). As a consequence, there is an emergent need for cleaner and safe production methods of organic manures from biowastes (Ravindran et al. 2021).

Similarly, disposal of dairy manure by inappropriate manage methods also causes environmental problems such as the spread of bad odours, infiltration of nitrates, and other pollutants into the groundwater causing eutrophication due to an excess of nitrogen and phosphorus (Zhao et al. 2021). Turkey, which is the country of agriculture and animal husbandry, has 12.4 million animal, and it is estimated that approximately 226 million tons of dairy manure are produced annually. In order to mitigate this problem, Şevik et al. (2018) proposed the co-composting of SS, dairy manure, and tomato stalks evaluating the effects of free air space, due to compact structure of SS and C/N ratios.

Sofia Vizhimalar et al. (2021) reported the composting of agro-waste with cow and mule dung, obtaining final composts characterised by good stability and maturity index after 90 days of process. The effect of obtained composts on *Raphanus sativus* was evaluated, and they reported germination of *Raphanus sativus* L. seeds and vigorous plant growth parameters, which confirmed the non-pathogenic phytotoxic-free nature of finished composts. Some authors mixed poultry manure with different proportions of rice hulls and/or sawdust being these substrates two common C-rich wastes derived from rice and timber agro-industries in subtropical NE Argentina. In the Mesopotamia region of NE Argentina, considerable amounts of C-rich wastes are generated from timber and rice agro-industries. Considering the high proportion of sandy or highly weathered soils in this region under humid subtropical climate, this study proposed composting like an interesting alternative for processing those wastes. However, neither rice hulls nor sawdust can be composted alone, because of their high C/N ratio (higher than 100), high cellulose and lignin concentration, and very low nutrient concentrations. Thus, they must be composted in mixtures with materials rich in nutrients, especially N, and easily decomposable C (Leconte et al. 2009; Rynk 1992). As a novel study, Alavi et al. (2019) researched the removal of tetracycline from chicken manure in Khuzestan Province, Iran, by using abundant bulking material (bagasse) in the composting process (Alavi et al. 2019). Furthermore, utilisation of sugarcane bagasse in composting offers numerous advantages such as maintenance of water content of the organic mixture by forming porous spaces in the composting mass to increase the availability of oxygen and reduces the loss of static (Aranganathan et al. 2019). On the other hand, *Musa* spp. banana is cultivated over 130 countries in tropical and subtropical areas and specially in South America, Africa, and Asia, being the second largest produced fruit, after citrus (Díaz et al. 2021). From the whole fruit, only 20–30% is consumed, whereas the remnant fraction includes peel, pseudostem, foliar residues, and rachis or stems should be valorised. Because of the generation around four tons of lignocellulosic waste per ton of harvested fruit by the banana industry alone, several studies proposed the composting of banana peel with other waste such as orange peel waste and fish waste (Isibika et al. 2021) or with arecanut waste (Chanakya and Sreesha 2012).

Regarding fishery waste, seafood processing sector generates large quantities of biological waste that are dumped in landfills and even discarded in open sea waters that create health and environmental problems. These kinds of waste are characterised by a high N and P content and organic matter. Furthermore, fishery waste does not contain any toxic or carcinogenic agents compared to municipal and industrial effluents (Aranganathan et al. 2019).

Finally, it is worthy to note the importance of these types of waste as they offer the opportunity to be composted in situ or even co-composted with other wastes from nearby areas improving the sustainability of the process.

10.4.3 Food Waste

Food waste is characterised by having strong potential to be valorised through composting due to the high organic matter content susceptible to be biodegraded by aerobic microorganisms. The huge proportion of food waste generated should be the reason for promoting the implementation of waste separation at sources and their collection at homes, hotels, and restaurants with the aim of promoting the installation of facilities for collection and adequate treatment of OFMSW. However, food waste treatment sites are currently operating only in large and developed countries. On the contrary, developing countries have significant limitations in bringing food waste to centralised facilities for recycling (Tai et al. 2011). For example, Jamaica depends on private sector to the activate recycling systems. In Nigeria, there are no policies or regulations on food waste recycling and management, and therefore, recycling operations are carried out mostly by informal sectors; specifically, only 8% of total food waste generation is recycled and used to produce compost (Ogwueleka 2009). In the future, the growth of innovative technologies might contribute to addressing the food waste treatment. Moreover, the transfer of technologies and lessons learned from developed countries would also definitely give developing countries simplified methodologies to comprehend their food waste management systems (Mbuligwe et al. 2002; Suthar et al. 2016). Sometimes, governments encourage people to separate food waste at sources in some cities to reinforce 3R (Reduce, Reuse, and Recycle) implementation, including composting programs. In Thailand, the government encouraged increasing organic waste utilisation by 50% before 2026 (Sharp and Arun 2012). Following this purpose, the government provided free organic waste bins for Thai people. However, until the present, their food waste recycling system has not obtained significant achievements, mainly due to the underdeveloped food waste treatment system, poor markets for food waste products, and insignificant economic incentives. In a similar manner, India generates a large amount of food waste, but their recycling activities are poor, and the dump sites are mostly used to dispose organic wastes (Agarwal et al. 2021). Following the purpose of improving food waste management, Bharucha (2018) proposed some key solutions such as implementing initiatives in restaurants to allow clients to take away leftovers and choose their serving size, training staff to minimise wastage, hiring food waste auditors, or reducing prices for end stock or offering sales to minimise waste.

10.5 Potential Improvements in the Composting Process

10.5.1 Co-composting

Co-composting process can be considered an adequate strategy to valorise waste generated in nearby areas and dotted with complementary physicochemical properties. The use of different wastes in composting process as input material helps to optimise process conditions (Alavi et al. 2017). The selection of residual substrates in co-composting processes should be promoted by (1) material quality in terms of C/N ratio, pH, moisture, nutrient content, and porosity; (2) the availability of the compostable material; (3) the acquisition cost: purchasing the material should be at a minimum cost, so that operational costs for the composting facility is not increased; (4) minimum recollection distance from composting facility; and (5) material handling facilities should not lead to major operational changes in the composting facility (i.e. material conditioning in sorting and grading, drying, and shredding activities) (Oviedo-Ocaña et al. 2017). In developing countries, these aspects should be considered to achieve the organic waste valorisation by minimising the management costs. The literature reports many studies in which co-composting is the selective treatment approach to valorise different waste generated in a local area. Although technological development is not highly advanced on an industrial scale, numerous studies about co-composting are being carried out in developing countries.

Specifically, the co-composting is widely used to treat SS, which is known to be hazardous waste containing a high load of organic and chemical pollutants such as dangerous pathogens, toxic heavy metals, pesticides, carcinogens, and other substances with a high odour nuisance (Białobrzewski et al. 2015). In addition to the production of SS, another serious environmental problem arises nowadays in Tunisia, the olive oil extraction industry. It represents a substantial share of the economies of Mediterranean countries but leads to serious environmental problems by producing huge amounts of wastes within a short production period. For this reason, Asses et al. (2018) proposed two mixtures of SS with olive mill waste or green waste, respectively, obtaining in both cases hygienic compost with proper agronomic quality. Moreover, compost application in peat amended at ratios equal to 30% and 50% improved the growth speed and fresh biomass of maize and tomato plants. Other authors reported the co-composting of SS with dairy manure by using tomato stalks as bulking agent in order to valorise some waste agricultural by--products generated in Turkey (Şevik et al. 2018). The co-composting of SS with sawdust and wheat straw was also evaluated to obtain a final compost without bacterial pathogens and low heavy metals concentration. The obtained results indicated that the addition of wood sawdust increases the nitrogen content leading to slightly alkaline compost, which influences seeds germination by reducing the phytotoxicity of SS (Kebibeche et al. 2019). Soto-Paz et al. (2019) evaluated the co-composting of biowaste with sugarcane filter cake and star grass collected from the processing of sugar cane and from the areas surrounding the composting facility, respectively. In this study, biowaste was obtained from a municipality in Colombia where source selection and selective collection are applied.

Many studies in developing countries are promoted by specific local needs, specifically the valorisation of agricultural waste with low possibilities of being valorised alone without being mixed with other waste. Jalili et al. (2019) proposed co-composting as an appropriate strategy for agricultural waste recycling, including the pistachio de-hulling waste. This study evaluated the co-composting at laboratory scale, by mixing this agricultural waste, cattle manure, and municipal dewatering SS. However, in some occasions, these studies are not extrapolated at real scale due to the lack of financial support and/or the necessary technical knowledge, which make difficult the safe disposal and/or treatment of the waste (Jara-Samaniego et al. 2015).

Finally, some studies reported novel research in co-composting processes such as the use of the black solider fly (BSF larvae (*Hermetia illucens* (L.) Diptera: Stratiomyidae) in the composting of banana peel and orange peel waste with fish waste. Co-composting fibre or carbohydrate-rich fractions with fractions that have, e.g. higher protein content is another way of improving the BSF larvae composting efficiency of these substrates (Isibika et al. 2021). Lopes et al. (2020) also determined the impact of BSF larvae co-composting of two rather high-quality waste fractions, that is, whole fish carcasses of rainbow trout (*Oncorhynchus mykiss*) and reclaimed bread.

Other novel research proposed the use of rice husk biochar amendment (0, 2, 4, 6, 8, and 10%) in the presence of salts for the co-composting of food waste and swine manure. Concretely, biochar was co-composted with olive mill waste. The prominent characteristics of the biochar, high porosity, and sorption capacity with low density improve the aeration, making it a desirable amendment material for composting process. The results revealed that biochar amendment improved the degradation rates by microbial activities in comparison with control. The final compost quality was improved by reducing the bulk density (29–53%), C/N ratio (29–57%), gaseous emissions (CO_2, CH_4, and NH_3), and microbial pathogens (*Escherichia coli* and *Salmonella* sp.) (Aycan Dümenci et al. 2021).

10.5.2 Technological Innovation

In general terms, the future of composting technology should be developed through the establishment of technology centres at large scale to manage the organic waste generated in extended areas. In fact, the advantage of technology installations such as closed tunnels or bioreactors that optimise the management of composting process and the obtaining of high-quality product should be also more promoted in developed countries. Furthermore, the development of more restrictive legislation about the quality of final product is necessary for the country globally.

Although composting is predominantly carried out at home scale in developing countries, there is some exceptions such as India, where there are more than 70 composting facilities treating mixed MSW, which recycle up to 5.9% of total food waste and generate about 4.3 million tonnes of compost each year. As an exception, two plants in Vijayawada and Suryapetare are known to handle source-separated organic wastes (Kumar et al. 2008). Moreover, there are also initiatives to promote composting of MSW from universities and technological centres. For example, KwaZulu-Natal University initiated the first mechanical biological pre-treatment of MSW in South Africa in collaboration with the eThekwini Municipality, in the city of Durban. The Durban pilot project involved waste pre-treatment in passively aerated windrows, using the Dome Aeration Technology, and prolonged passive aeration in shallow landfills using the pre-treatment aeration and flushing model (Cossu et al. 2003).

10.6 Strategies for Composting Development in Developing Countries: Africa, South America, and Asia

The strategies to be implemented in developing countries should focus on encouraging the selective collection of waste and the implementation of facilities to develop proper waste management, to promote the composting of all organic waste with appropriate characteristics, and to improve the obtaining of high-quality final product. All the purposes depend not only on technological aspects but also on factors related to municipal waste management such as social, institutional, politic, regulatory, economics, and funding aspects (Zurbrügg et al. 2012). This situation leads to stablish protocols of action as follows:

(a) The establishment of business management principles in the administration of composting systems.
(b) The development of studies to stablish product quality standards in accordance with the different uses and applications.
(c) The development of demonstration projects involving the agricultural sector to promote the compost use.
(d) The development of research studies to evaluate the environmental impacts associated with organic waste composting in comparison with other alternative options. To do this, public policy for the valorisation of organic waste should be formulated. Furthermore, incentive policies should be promoted due to the environmental benefits associated with composting processes such as the decrease of greenhouse gas (GHG) emissions in landfills.
(e) The development of pilot projects and social strategies for the implementation of source separation and selective collection, as well as for the identification of strategies to increase community participation in the different stages of bio-waste composting projects.

Details of some strategies and/or plans implemented in different developing countries in Africa, South America, and Asia are described further.

10.6.1 Africa

In Africa, in general terms, composting has failed in cities such as Dakar (Senegal) and Abidjan (Cote d'Voire) due to the lack of demand for the final product. However, some environmental, economic, and health factors encourage composting of organic waste in governmental plans. From an environmental point of view, GHG emission factors for waste management are increasingly used, but such factors are very scarce for developing countries. Some studies promoted the composting of garden waste to contribute in the development of composting strategies in South Africa. Friedrich and Trois (2013) proposed the composting of garden waste as a net GHG emitter, releasing 172 and 186 kg CO_2 equivalent per tonne of wet garden waste, for aerated and turned windrow composting, respectively.

Some International NGOs have programs to subsidise the costs for developing countries to establish small scale composting to enhance awareness of food waste recycling in some African countries such as Benin, Cameroon, Kenya, Zambia, and Nigeria (Marmolejo et al. 2012). In Cameroon, governmental policies establish strategies for environmental protection and promotion of conservation of materials through an adequate disposal and recovery of MSW; however, in practice, management is focused on collection and disposal on the land (Manga et al. 2008).

10.6.2 Asia

In Southeast Asian Nations, composting is supported by governments due to high operation and maintenance costs, the high cost of the final product with respect to commercial fertilisers, and the available market. In the case of Malaysia, the government undertook vermicomposting as a primary national plan to use food waste to produce bio-fertiliser. However, in fact, there still remain some inefficiencies of composting production caused by impurified waste feedstock, which results from the incomplete separated food waste system in source in most developing countries obtaining composts that need to be enriched with various chemical fertilisers (Thi et al. 2015). In India, composting is a tradition mainly in rural areas; utilisation of large-scale and centralised composting plants had not been economically feasible due to the lack of selective collection in source. In Jordan, even with a high fraction of biodegradable organic solid waste generated in the country, composting has not been considered as an option for solid waste management (Ikhlayel et al. 2016).

10.6.3 South America

According to the World Bank Report "What a Waste 2.0" (Silpa Kaza and Lisa Yao 2018) worldwide, only 5.5% of waste is composted and in Chile only 0.4%. On the other hand, the report Food Wastage Footprint: Impacts on Natural Resources (FAO

2013) affirmed that home composting can potentially recover up to 150 kg of food waste per household per year. In this line, Ludlow et al. (2021) reported that achieving net-zero greenhouse gas emissions by 2050 in Latin America requires a step change in resource management and the utilisation of organic waste, which is currently an untapped opportunity. This study carries out a quantitative and qualitative assessment of organic waste-to-energy potentials including annual crop residues, horticulture residues, livestock manure, and OFMSW by region in Chile. First, it produces a comprehensive quantification of organic waste. The stakeholder elicitation concluded that financial, technical, and institutional barriers prevent waste utilisation, highlighting the needs to address elevated investment costs and high reliance on landfilling practices, which together with public policies could enable the full exploitation of these resources to ensure energy security and resource efficiency. The aim of these strategies is to stablish the organic waste recycling in Chile through the installation of composting plants or, as alternative, anaerobic digestion. Furthermore, the increase of awareness in the community about the positive impact that sustainable waste management generates on the environment should be also enhanced.

In 2017, the US Environmental Protection Agency (U.S. EPA), on behalf of the Clean Air & Climate Coalition's Waste Initiative, conducted a waste characterisation study at the Naucalpan (Mexico) transfer station. The study indicated that approximately 69% of the waste handled at the transfer station could be recycled or otherwise diverted from the landfill and that more than half of the waste could be used as feedstock in composting or anaerobic digestion projects. The city is using the results of this study to inform decision-making on project design and procurement options (US EPA 2020).

Finally, the strategies should also be focused on promoting and ensuring the obtaining of high-quality final products in composting processes. In this sense, some studies evaluated the characteristics of the obtained compost in comparison with those obtained in more developed countries. Oviedo-Ocaña et al. (2017) examined the compost produced in five biowaste composting facilities in Valle del Cauca (Colombia) and compared the results with local and international standards, finding deficiencies in the chemical characteristics. Jara-Samaniego et al. (2017) obtained similar results at the composting facility of Chimborazo (Ecuador).

10.7 State of Legal Regulations on Compost Quality and Its Application

In developing countries, the statutory standards of compost quality have been developed at regional and national levels by considering different issues, with environmental issues being the most relevant to its agronomic value. In general terms, the existing standard for organic fertiliser considers the compost quality in a general class without further classification. In fact, concern about the organic waste in developing countries is mainly focused on their management more than their

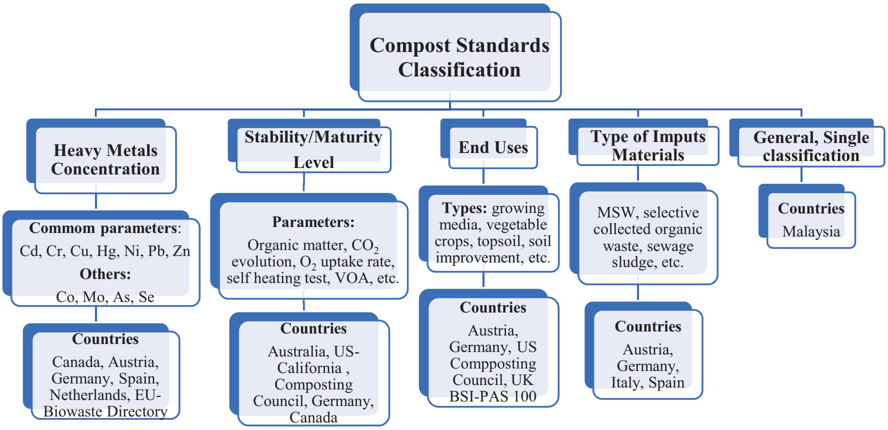

Fig. 10.1 Compost standards classification in different countries. (Van Fan et al. 2016)

valorisation through composting, although both management and composting might be promoted and powered by common policies.

Many developed countries have considered the concentration levels of Cd, Cu, Cr, Hg, Ni, Pb, and Zn; however, most developing countries, such as Malaysia Standards (2012)-MS 1517:2012, do not include Cu and Zn, whose excessive concentration might pose a threat to public health when they are transferred to the food (Van Fan et al. 2016). In Indonesia, the proposed compost standards and guidelines were created to meet all environmental regulations throughout the country and to assure the public that the compost is safe for use. However, these guidelines do not propose a stringent and expensive testing regime, including the control of some parameters such as heavy metal concentration to be applied in agricultural soils (Hoornweg et al. 1999).

Figure 10.1 summarises the classification of compost standards in different countries based on different criteria including heavy metals concentration, maturity/stability level, end uses, or types of input materials.

In the same countries, the composts are classified into three categories based on maturity and stability level for the standard set by US-California Compost Quality Council (CCQC 2001) and Canada-BNQ. Canada-BNQ also classified the compost based on the organic matter (OM) content, while CCQC 2001 classified the compost based on CO_2 evolution, O_2 uptake rate, self-heating test, volatile organic acids (VOA), seed germination, etc. A similar approach is adopted in the Australia Standard AS 4454–2012 for composts, soil conditions, and mulches. Even if the compost is not classified mainly based on the heavy metal limits, in all cases, most countries have set the safety limit of heavy metals for compost. The British Standards Institution Publicly Available Specification (BSI-PAS 1002012) covers a wide range of general quality criteria to be first fulfilled followed by further classifications based on the end use (Cesaro et al. 2015).

References

M. Agarwal, S. Agarwal, S. Ahmad, R. Singh, K.M. Jayahari, Food loss and waste in India: The knowns and the unknowns. World Resour. Inst. (2021). https://doi.org/10.46830/wriwp.20.00106

N. Alavi, M. Daneshpajou, M. Shirmardi, G. Goudarzi, A. Neisi, A.A. Babaei, Investigating the efficiency of co-composting and vermicomposting of vinasse with the mixture of cow manure wastes, bagasse, and natural zeolite. Waste Manag. **69**, 117–126 (2017). https://doi.org/10.1016/j.wasman.2017.07.039

N. Alavi, K. Sarmadi, G. Goudarzi, A.A. Babaei, R. Bakhshoodeh, P. Paydary, Attenuation of tetracyclines during chicken manure and bagasse co-composting: Degradation, kinetics, and artificial neural network modeling. J. Environ. Manag. **231**, 1203–1210 (2019). https://doi.org/10.1016/j.jenvman.2018.11.003

S. Amir, M. Hafidi, G. Merlina, J.C. Revel, Sequential extraction of heavy metals during composting of sewage sludge. Chemosphere **59**, 801–810 (2005). https://doi.org/10.1016/j.chemosphere.2004.11.016

J.K. Andersen, A. Boldrin, T.H. Christensen, C. Scheutz, Mass balances and life cycle inventory of home composting of organic waste. Waste Manag. **31**, 1934–1942 (2011). https://doi.org/10.1016/J.WASMAN.2011.05.004

L. Aranganathan, S.R.R. Rajasree, T.Y. Suman, R.R. Remya, S. Gayathri, C. Jayaseelan, M.G. Karthih, M. Gobalakrishnan, Comparison of molecular characteristics of Type A humic acids derived from fish waste and sugarcane bagasse co-compost influenced by various alkaline extraction protocols. Microchem. J. **149**, 104038 (2019). https://doi.org/10.1016/j.microc.2019.104038

N. Asses, A. Farhat, S. Cherif, M. Hamdi, H. Bouallagui, Comparative study of sewage sludge co-composting with olive mill wastes or green residues: Process monitoring and agriculture value of the resulting composts. Process. Saf. Environ. Prot. **114**, 25–35 (2018). https://doi.org/10.1016/j.psep.2017.12.006

N. Aycan Dümenci, O. Cagcag Yolcu, F. Aydin Temel, N.G. Turan, Identifying the maturity of co-compost of olive mill waste and natural mineral materials: Modelling via ANN and multi-objective optimization. Bioresour. Technol. **338** (2021). https://doi.org/10.1016/j.biortech.2021.125516

R. Barrena, X. Font, X. Gabarrell, A. Sánchez, Home composting versus industrial composting: Influence of composting system on compost quality with focus on compost stability. Waste Manag. **34**, 1109–1116 (2014). https://doi.org/10.1016/J.WASMAN.2014.02.008

M.P. Bernal, S.G. Sommer, D. Chadwick, C. Qing, L. Guoxue, F.C. Michel, Current approaches and future trends in compost quality criteria for agronomic, environmental, and human health benefits, in *Advances in Agronomy*, (Academic, 2017), pp. 143–233. https://doi.org/10.1016/bs.agron.2017.03.002

J. Bharucha, Social media and young consumers behavior. Int. J. Supply Chain Manag. **7**, 72–81 (2018)

I. Białobrzewski, M. Mikš-Krajnik, J. Dach, M. Markowski, W. Czekała, K. Głuchowska, Model of the sewage sludge-straw composting process integrating different heat generation capacities of mesophilic and thermophilic microorganisms. Waste Manag. **43**, 72–83 (2015). https://doi.org/10.1016/j.wasman.2015.05.036

C. Bruni, C. Akyol, G. Cipolletta, A.L. Eusebi, D. Caniani, S. Masi, J. Colon, F. Fatone, Decentralized community composting: Past, present and future aspects of Italy. Sustainability (2020). https://doi.org/10.3390/SU12083319

C.M. Campos-Alba, J.C. Garrido-Rodríguez, A.M. Plata-Díaz, G. Pérez-López, The selective collection of municipal solid waste and other factors determining cost efficiency. An analysis of service provision by spanish municipalities. Waste Manag. **134**, 11–20 (2021). https://doi.org/10.1016/J.WASMAN.2021.07.039

A. Cesaro, V. Belgiorno, M. Guida, Compost from organic solid waste: Quality assessment and European regulations for its sustainable use. Resour. Conserv. Recycl. **94**, 72–79 (2015). https://doi.org/10.1016/j.resconrec.2014.11.003

H.N. Chanakya, M. Sreesha, Anaerobic retting of banana and arecanut wastes in a plug flow digester for recovery of fiber, biogas and compost. Energy Sustain. Dev. **16**, 231–235 (2012). https://doi.org/10.1016/j.esd.2012.01.003

N. Chandana, B. Rao, A critical review on sludge management from onsite sanitation systems: A knowledge to be revised in the current situation. Environ. Res. **203**, 111812 (2022). https://doi.org/10.1016/j.envres.2021.111812

B.M. Cies¨lik, J. Namies¨nik, P. Konieczka, Review of sewage sludge management: Standards, regulations and analytical methods. J. Clean. Prod. (2015). https://doi.org/10.1016/j.jclepro.2014.11.031

O.O. Cofie, P. Drechsel, S. Agbottah, R. van Veenhuizen, Resource recovery from urban waste: Options and challenges for community-based composting in sub-Saharan Africa. Desalination **248**, 256–261 (2009). https://doi.org/10.1016/j.desal.2008.05.063

I.V. Comesaña, D. Alves, S. Mato, X.M. Romero, B. Varela, Decentralized composting of organic waste in a European rural region: A case study in Allariz (Galicia, Spain), in *Solid Waste Management in Rural Areas*, (IntechOpen, 2017). https://doi.org/10.5772/intechopen.69555

R. Cossu, R. Raga, D. Rossetti, The PAF model: An integrated approach for landfill sustainability. Waste Manag. **23**, 37–44 (2003). https://doi.org/10.1016/S0956-053X(02)00147-2

R. Couth, C. Trois, Cost effective waste management through composting in Africa. Waste Manag. **32**, 2518–2525 (2012). https://doi.org/10.1016/j.wasman.2012.05.042

S. Díaz, Z. Ortega, A.N. Benítez, D. Costa, F. Carvalheiro, M.C. Fernandes, L.C. Duarte, Assessment of the effect of autohydrolysis treatment in banana's pseudostem pulp. Waste Manag. **119**, 306–314 (2021). https://doi.org/10.1016/j.wasman.2020.09.034

D. Dirix, F. Rossi, H. van der Hoek, Faecal sludge management in Toamasina, Madagascar: Emptying – Transport – Treatment. J. Environ. Manag. **281**, 111808 (2021). https://doi.org/10.1016/j.jenvman.2020.111808

G. Eftoda, D. McCartney, Determining the critical bulking agent requirement for municipal biosolids composting. Compost Sci. Util. **12**, 208–218 (2004). https://doi.org/10.1080/1065657X.2004.10702185

FAO, *Food Wastage Footprint Impact on Natural Resources* (FAO, 2013)

N. Ferronato, V. Torretta, Waste mismanagement in developing countries: A review of global issues. Int. J. Environ. Res. Public Health **16** (2019). https://doi.org/10.3390/ijerph16061060

E. Friedrich, C. Trois, GHG emission factors developed for the recycling and composting of municipal waste in South African municipalities. Waste Manag. **33**, 2520–2531 (2013). https://doi.org/10.1016/j.wasman.2013.05.010

G. Füleky, S. Benedek, *Composting to Recycle Biowaste* (Springer, Dordrecht, 2010), pp. 319–346. https://doi.org/10.1007/978-90-481-3333-8_12

V. Ghisolfi, G.L. de Diniz Chaves, R. Ribeiro Siman, L.H. Xavier, System dynamics applied to closed loop supply chains of desktops and laptops in Brazil: A perspective for social inclusion of waste pickers. Waste Manag. **60**, 14–31 (2017). https://doi.org/10.1016/j.wasman.2016.12.018

GIZ, *Country Report on the Solid Waste Management in Occupied Palestinian Territories* (SWEEP-Net, 2014)

B. Greff, J. Szigeti, Á. Nagy, E. Lakatos, L. Varga, Influence of microbial inoculants on co--composting of lignocellulosic crop residues with farm animal manure: A review. J. Environ. Manag. **302** (2022). https://doi.org/10.1016/j.jenvman.2021.114088

H. Hettiarachchi, J.N. Meegoda, S. Ryu, Organic waste buyback as a viable method to enhance sustainable municipal solid waste management in developing countries. Int. J. Environ. Res. Public Health **15**, 1–15 (2018). https://doi.org/10.3390/ijerph15112483

D. Hoornweg, L. Thomas, L. Otten, Urban waste management. Composting and its applicability in developing countries (1999). Published for the Urban Development Division. The World Bank, Washington DC

V. Ibáñez-Forés, M.D. Bovea, C. Coutinho-Nóbrega, H.R. de Medeiros, Assessing the social performance of municipal solid waste management systems in developing countries: Proposal of indicators and a case study. Ecol. Indic. **98**, 164–178 (2019). https://doi.org/10.1016/j.ecolind.2018.10.031

M. Ikhlayel, Y. Higano, H. Yabar, T. Mizunoya, Introducing an integrated municipal solid waste management system: Assessment in Jordan. J. Sustain. Dev. **9**, 43 (2016). https://doi.org/10.5539/jsd.v9n2p43

Indicadores – Serie Territorial – Dosieres España – UE [WWW Document] (n.d.), https://www.mapa.gob.es/es/ministerio/servicios/analisis-y-prospectiva/Territorial_Espapa_UE_Mundo.aspx. Accessed 24 Feb 2022

F. Ingelmo, M.J. Molina, M.D. Soriano, A. Gallardo, L. Lapeña, Influence of organic matter transformations on the bioavailability of heavy metals in a sludge based compost. J. Environ. Manag. **95**, S104–S109 (2012). https://doi.org/10.1016/j.jenvman.2011.04.015

A. Isibika, B. Vinnerås, O. Kibazohi, C. Zurbrügg, C. Lalander, Co-composting of banana peel and orange peel waste with fish waste to improve conversion by black soldier fly (Hermetia illucens (L.), Diptera: Stratiomyidae) larvae. J. Clean. Prod. **318**, 128570 (2021). https://doi.org/10.1016/j.jclepro.2021.128570

M. Jalili, M. Mokhtari, H. Eslami, F. Abbasi, R. Ghanbari, A.A. Ebrahimi, Toxicity evaluation and management of co-composting pistachio wastes combined with cattle manure and municipal sewage sludge. Ecotoxicol. Environ. Saf. **171**, 798–804 (2019). https://doi.org/10.1016/j.ecoenv.2019.01.056

J. Jara-Samaniego, M.R. Moral, D. Perez-Murcia, C. Paredes, L. Gálvez-Sola, I. Gavilanes-Terán, M.Á. Bustamante, Urban waste management and potential agricultural use in South American developing countries: A case study of Chimborazo Region (Ecuador). Commun. Soil Sci. Plant Anal. **46**, 157–169 (2015). https://doi.org/10.1080/00103624.2014.988587

J. Jara-Samaniego, M.D. Pérez-Murcia, M.A. Bustamante, A. Pérez-Espinosa, C. Paredes, M. López, D.B. López-Lluch, I. Gavilanes-Terán, R. Moral, Composting as sustainable strategy for municipal solid waste management in the Chimborazo Region, Ecuador: Suitability of the obtained composts for seedling production. J. Clean. Prod. **141**, 1349–1358 (2017). https://doi.org/10.1016/j.jclepro.2016.09.178

H. Kebibeche, O. Khelil, M. Kacem, M. Kaid Harche, Addition of wood sawdust during the co-composting of sewage sludge and wheat straw influences seeds germination. Ecotoxicol. Environ. Saf. **168**, 423–430 (2019). https://doi.org/10.1016/j.ecoenv.2018.10.075

D. Kulikowska, Kinetics of organic matter removal and humification progress during sewage sludge composting. Waste Manag. **49**, 196–203 (2016). https://doi.org/10.1016/j.wasman.2016.01.005

S. Kumar, J.K. Bhattacharyya, A.N. Vaidya, T. Chakrabarti, S. Devotta, A.B. Akolkar, Assessment of the status of municipal solid waste management in metro cities, state capitals, class I cities, and class II towns in India: An insight. Waste Manag. **29**(2), 883–895 (2008). https://doi.org/10.1016/j.wasman.2008.04.011

M.C. Leconte, M.J. Mazzarino, P. Satti, M.C. Iglesias, F. Laos, Co-composting rice hulls and/or sawdust with poultry manure in NE Argentina. Waste Manag. **29**, 2446–2453 (2009). https://doi.org/10.1016/j.wasman.2009.04.006

L.T.T. Loan, Y. Takahashi, H. Nomura, M. Yabe, Modeling home composting behavior toward sustainable municipal organic waste management at the source in developing countries. Resour. Conserv. Recycl. **140**, 65–71 (2019). https://doi.org/10.1016/j.resconrec.2018.08.016

I.G. Lopes, C. Lalander, R.M. Vidotti, B. Vinnerås, Using Hermetia illucens larvae to process biowaste from aquaculture production. J. Clean. Prod. **251** (2020). https://doi.org/10.1016/j.jclepro.2019.119753

J. Ludlow, F. Jalil-Vega, X. Schmidt Rivera, R.A. Garrido, A. Hawkes, I. Staffell, P. Balcombe, Organic waste to energy: Resource potential and barriers to uptake in Chile. Sustain. Prod. Consum. **28**, 1522–1537 (2021). https://doi.org/10.1016/j.spc.2021.08.017

V.E. Manga, O.T. Forton, A.D. Read, Waste management in Cameroon: A new policy perspective? Resour. Conserv. Recycl. **52**, 592–600 (2008). https://doi.org/10.1016/j.resconrec.2007.07.003

F.L. Marmolejo, P. Diaz Torres, M. Garci, Perspectives for sustainable resource recovery from municipal solid waste in developing countries: Applications and alternatives. Waste Manag. Integr. Vis. (2012). https://doi.org/10.5772/52303
A. Matter, M. Ahsan, M. Marbach, C. Zurbrügg, Impacts of policy and market incentives for solid waste recycling in Dhaka, Bangladesh. Waste Manag. **39**, 321–328 (2015). https://doi.org/10.1016/j.wasman.2015.01.032
S.E. Mbuligwe, G.R. Kassenga, M.E. Kaseva, E.J. Chaggu, Potential and constraints of composting domestic solid waste in developing countries: Findings from a pilot study in Dar es Salaam, Tanzania. Resour. Conserv. Recycl. **36**, 45–59 (2002). https://doi.org/10.1016/S0921-3449(02)00009-5
J. Moreno Casco y Raúl Moral Herrero. Compostaje. MundiPrensa (España) (2008). ISBN 13: 9788484763468, ISBN 10: 8484763463
T.C. Ogwueleka, Municipal solid waste characteristics and management in Nigeria6. J. Environ. Health Sci. Eng. **6**, 173–180 (2009)
O.K.M. Ouda, S.A. Raza, A.S. Nizami, M. Rehan, R. Al-Waked, N.E. Korres, Waste to energy potential: A case study of Saudi Arabia. Renew. Sust. Energ. Rev. (2016). https://doi.org/10.1016/j.rser.2016.04.005
E.R. Oviedo-Ocaña, L.F. Marmolejo-Rebellon, P. Torres-Lozada, Avances en investigación sobre el compostaje de biorresiduos en municipios menores de países en desarrollo. Ing. Investig. y Tecnol. **18**, 31–42 (2017). https://doi.org/10.22201/fi.25940732e.2017.18n1.003
E.R. Oviedo-Ocaña, I. Dominguez, D. Komilis, A. Sánchez, Co-composting of green waste mixed with unprocessed and processed food waste: Influence on the composting process and product quality. Waste Biomass Valoriz. **10**, 63–74 (2019). https://doi.org/10.1007/s12649-017-0047-2
S. Pai, N. Ai, J. Zheng, Decentralized community composting feasibility analysis for residential food waste: A Chicago case study. Sustain. Cities Soc. **50** (2019). https://doi.org/10.1016/j.scs.2019.101683
R. Rai, S. Suthar, Composting of toxic weed Parthenium hysterophorus: Nutrient changes, the fate of faecal coliforms, and biopesticide property assessment. Bioresour. Technol. **311** (2020). https://doi.org/10.1016/j.biortech.2020.123523
B. Ravindran, N. Karmegam, A. Yuvaraj, R. Thangaraj, S.W. Chang, Z. Zhang, M. Kumar Awasthi, Cleaner production of agriculturally valuable benignant materials from industry generated bio--wastes: A review. Bioresour. Technol. (2021). https://doi.org/10.1016/j.biortech.2020.124281
R. Rynk, On-Farm Composting Handbook. Monogr. Soc. Res. Child Dev. **77**, 132 (1992)
M. Sawadogo, S. Tchini Tanoh, S. Sidibé, N. Kpai, I. Tankoano, Cleaner production in Burkina Faso: Case study of fuel briquettes made from cashew industry waste. J. Clean. Prod. **195**, 1047–1056 (2018). https://doi.org/10.1016/j.jclepro.2018.05.261
F. Şevik, İ. Tosun, K. Ekinci, The effect of FAS and C/N ratios on co-composting of sewage sludge, dairy manure and tomato stalks. Waste Manag. **80**, 450–456 (2018). https://doi.org/10.1016/j.wasman.2018.07.051
N.K. Sharma, S. Sharma, Municipal solid waste management in developing countries: Future challenges and possible opportunities. J. Green Eng. **10**, 8788–8797 (2020). https://doi.org/10.5772/16438
A. Sharp, J.S. Arun, *A Guide for Sustainable Urban Organic Waste Management in Thailand : Combining Food, Energy, and Climate Co-Benefits* (Institute for Global Environmental Strategies, 2012)
Silpa Kaza, P.B. Lisa Yao, What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050 – Tata, Frank Van Woerden – Google Books (2018)
S.R. Smith, S. Jasim, Small-scale home composting of biodegradable household waste: Overview of key results from a 3-year research programme in West London. Waste Manag. Res. **27**, 941–950 (2009). https://doi.org/10.1177/0734242X09103828
A. Sofia Vizhimalar, M. Vasanthy, C. Thamaraiselvi, M. Biruntha, J.A.J. Paul, A. Thirupathi, S.W. Chang, Z. Xu, S. Al-Rashed, G. Munuswamy-Ramanujam, B. Ravindran, Greener pro-

duction of compost from agricultural biomass residues amended with mule dung for agronomic application. Chemosphere, 132561 (2021). https://doi.org/10.1016/j.chemosphere.2021.132561

J. Soto-Paz, E.R. Oviedo-Ocaña, P.C. Manyoma-Velásquez, P. Torres-Lozada, T. Gea, Evaluation of mixing ratio and frequency of turning in the co-composting of biowaste with sugarcane filter cake and star grass. Waste Manag. **96**, 86–95 (2019). https://doi.org/10.1016/j.wasman.2019.07.015

S. Suthar, N. Kishore Singh, Fungal pretreatment facilitates the rapid and valuable composting of waste cardboard. Bioresour. Technol. **344**, 126178 (2022). https://doi.org/10.1016/j.biortech.2021.126178

S. Suthar, P. Rayal, C.P.S. Ahada, Role of different stakeholders in trading of reusable/recyclable urban solid waste materials: A case study. Sustain. Cities Soc. **22**, 104–115 (2016). https://doi.org/10.1016/j.scs.2016.01.013

J. Tai, W. Zhang, Y. Che, D. Feng, Municipal solid waste source-separated collection in China: A comparative analysis. Waste Manag. **31**, 1673–1682 (2011). https://doi.org/10.1016/J.WASMAN.2011.03.014

M. Tanaka, Waste management for a sustainable society, in *Journal of Material Cycles and Waste Management*, (Springer, 2007), pp. 2–6. https://doi.org/10.1007/s10163-006-0164-7

N.B.D. Thi, G. Kumar, C.Y. Lin, An overview of food waste management in developing countries: Current status and future perspective. J. Environ. Manag. (2015). https://doi.org/10.1016/j.jenvman.2015.04.022

Turkstat. TURKSTAT Corporate [WWW Document]. Foreign Trade Stat December 2020 (2021). https://data.tuik.gov.tr/Bulten/Index?p=Waste-Statistics-2020-37198&dil=2. Accessed 2 Jan 2022

US EPA, INTER Mejores prácticas para la gestión de residuos sólidos: Una Guía para los responsables de la toma de decisiones en los países en vías de desarrollo. Epa 530-R-20-002-S 169 (2020)

Y. Van Fan, C.T. Lee, J.J. Klemeš, C.P.C. Bong, W.S. Ho, Economic assessment system towards sustainable composting quality in the developing countries. Clean Techn. Environ. Policy **18**, 2479–2491 (2016). https://doi.org/10.1007/s10098-016-1209-9

B. Zhao, Y. Wang, L. Ma, Y. Li, Y. Deng, X. Chen, Z. Xu, Adding an appropriate proportion of phosphogypsum ensured rice husk and urea composting to promote the compost as substrate utilization. Bioresour. Technol., 126301 (2021). https://doi.org/10.1016/j.biortech.2021.126301

R. Zittel, C. Pinto da Silva, C.E. Domingues, T.R. de Oliveira Stremel, T.E. de Almeida, G. Vieira Damiani, S. Xavier de Campos, Treatment of smuggled cigarette tobacco by composting process in facultative reactors. Waste Manag. **71**, 115–121 (2018). https://doi.org/10.1016/j.wasman.2017.10.023

C. Zurbrügg, M. Gfrerer, H. Ashadi, W. Brenner, D. Küper, Determinants of sustainability in solid waste management–the Gianyar waste recovery project in Indonesia. Waste Manag. **32**(11), 2126–2133 (2012). https://doi.org/10.1016/j.wasman.2012.01.011

Chapter 11
Appropriate Biochemical Conversion Technology for Organic Waste Recovery in Developing Countries

Hassan El Bari, Sanae Habchi, Fadoua Karouach, and Nabila Lahboubi

11.1 The Biochemical Biomass Conversion Technologies

Growing energy consumption, increasing fossil fuel trends, escalating fuel prices, and rising levels of CO_2 and other greenhouse gases are some of the main drivers for the search for alternative energy sources (Nanda et al. 2016). Numerous biomass conversion technologies are used to valorize all components of a raw material. These technologies include a wide spectrum of biological/biochemical processes to generate products such as biofuels and value-added products. These processes are generally defined as fermentative, although each of them requires specific operating conditions (e.g., anaerobic environment, light supply) and/or specific microorganisms (bacteria, yeast, cyanobacteria, algae) (Gouveia and Passarinho 2017).

11.1.1 Anaerobic Digestion of Biomass

Every year, millions of tons of biomass waste are produced, with disposal posing a challenge. Over 88% of the world's electrical and thermal energy consumption is met by non-renewable resources, namely petroleum and natural gas (Ziemiński and Frąc 2012). Anaerobic digestion (AD) is a biological process that uses anaerobic bacteria to degrade organic substrates in an oxygen-free environment. The end-products of AD are biogas and residue named digestate. The biogas contains mostly

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of methane and is considered as a renewable energy (Bakraoui et al. 2020b; Lahboubi et al. 2021).

The conversion of cellulose and hemicellulose to bioethanol, methane, and hydrogen is more efficient when the digestibility of lignocellulosic biomass is improved (Boontian 2014). The AD process is a potential process for digesting biomass waste into large amounts of methane, which can be utilized directly as a source of energy or converted to hydrogen (Albertson et al. 2006). Due to current environmental issues, such as global warming, high-rate methane and hydrogen fermentation from renewable biomass has received a lot of interest recently (Demirel et al. 2010). Figure 11.1 shows the process of AD from different organic wastes. The by-products of AD are biogas and digestate (Beniche et al. 2021; Habchi et al. 2022). The biogas is used to produce thermal or electrical energy and also the biofuels, and the digestate is used as fertilizer for the soil and can also be used by the thermochemical conversion. Methane production can be improved using different pretreatment methods (Lahboubi et al. 2022; Habchi et al. 2022) or by co-digestion (Beniche et al. 2020; Karouach et al. 2021).

11.1.1.1 The Stages of Anaerobic Digestion

It is critical to know and understand the process, technological elements, biochemistry, and microbiology of AD in order to ensure proper design and implementation of anaerobic treatment systems. Several sequential, simultaneous, and complex biological and chemical reactions are involved in the AD process. The substrates of one group of microbes are the products of the next.

Anaerobic degradation is divided into four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Kerrou et al. 2021). Various microorganism populations are involved in the degrading process. Different steps in the biosynthesis of methane can be distinguished according to the substrates utilized by these bacteria and the products they create (Moletta 2006). They are shown in the diagram below Fig. 11.2.

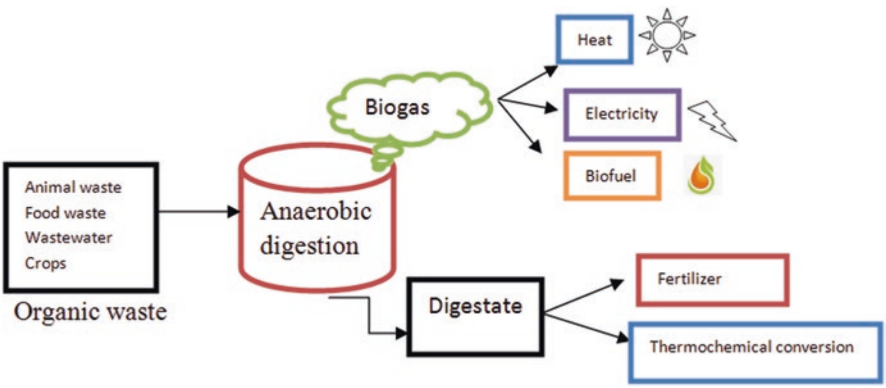

Fig. 11.1 The process of anaerobic digestion

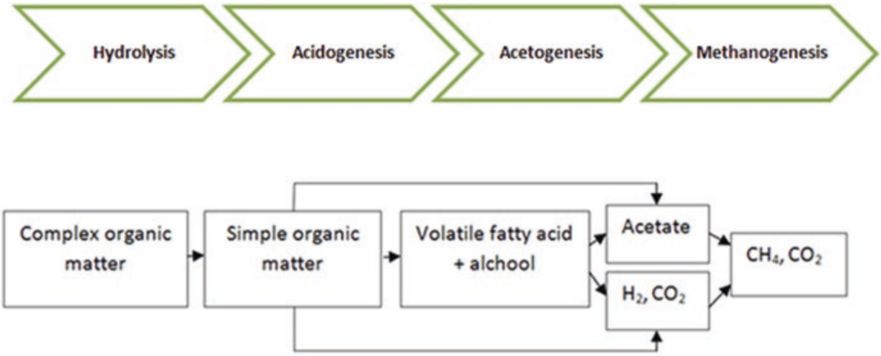

Fig. 11.2 The stages of anaerobic digestion

Hydrolysis
Hydrolysis is an extracellular process that converts complex polymers (proteins, polysaccharides, lipids, cellulose, and soon) that are inaccessible to microbes into simple, soluble molecules (amino acids, simple sugars, fatty acids, glycerol, etc.). As a result, the hydrolysis process seeks to break down organic macromolecules into smaller components that acidogenic bacteria can utilize (Ostrem 2004).

Acidogenesis
The acidogenesis stage entails the conversion of monomers from the hydrolysis stage into a variety of chemicals, including organic acids, volatile fatty acids (VFAs), alcohols, hydrogen, carbon dioxide, ammonium, and so on. There are two types of acidogenesis: hydrogenation and dehydrogenation. Acetates, CO_2, and H_2 are the primary transformation products, with additional acidogenesis products playing a minor role (Chynoweth et al. 1998). The methanogenic bacteria could employ the new products as substrates and energy sources immediately after these changes. The bacteria's response to an increase in hydrogen concentration in the solution is the build-up of electrons by molecules such as lactate, ethanol, propionate, butyrate, and higher volatile fatty acids. The novel products are incompatible with methanogenic bacteria and must be transformed by obligatory hydrogen-producing bacteria in a process known as acetogenesis (Ziemiński and Frąc 2012).

Acetogenesis
The action of acetogenic bacteria permits the transformation of acids produced during the acidogenesis phase into acetic acid, hydrogen, and carbon dioxide during the acetogenesis stage. Acetic acid is particularly significant in methanization since it can account for up to 70% of the methane generated (Ntaikou et al. 2010). The oxidation of the substrates (propionic and butyric acids, as well as ethanol) is accompanied by the generation of acetate, hydrogen, and carbon dioxide at this stage. Two species of bacteria are involved in this process:

- Hydrogen-producing bacteria (OHPA) are anaerobic bacteria that produce hydrogen ("obligate hydrogen-producing acetogens"). They can make acetate and hydrogen from decreased acidogenesis products like propionate and butyrate. It is worth noting that these bacteria have a considerable multiplication time, ranging from 1 to 7.5 days.

- Non-syntrophic acetogenic bacteria: these bacteria's metabolism is primarily focused on the generation of acetate. They thrive in high-CO_2 conditions, which are common in anaerobic habitats. Non-syntrophic acetogenic bacteria are divided into two categories.
- Bacteria that create acetate, butyrate, and other chemicals from simple sugars make up the first category. Acetate is made from hydrogen and carbon dioxide.

Methanogenesis

Methanogenic archaea transform the products of the previous stage into methane and carbon dioxide in this final step. To create methane, they fundamentally use acetate, formate, carbon dioxide, and hydrogen as substrates. There are two main mechanisms for methane generation for this purpose, both involving strict anaerobic archaea (Moletta 2006):

- Acetoclast methanogens: Acetate + $H_2 \leftrightarrow CO_2 + CH_4$
- Hydrogen-trophic methanogens: $CO_2 + 4H_2 \leftrightarrow 2H_2O + CH_4$

In anaerobic digesters, about 60–70% of methane is produced by acetoclast methanogens (Batstone et al. 2002).

11.1.1.2 Operating Conditions for Anaerobic Digestion

Several factors influence AD, including the physical system and biogas generation (CH_4 and CO_2). It is therefore critical to keep the experiment under controlled circumstances in order to produce a decent biogas yield.

To ensure process stability, the following parameters can be managed and maintained at acceptable intervals. Temperature, pH, alkalinity, residence time, waste composition, and inhibitor presence are all factors to consider. The relevance of each parameter must be understood because any variation from the permissible range can cause the system to shut down.

Temperature

Temperature is a crucial element in biological processes because it impacts microorganism growth kinetics and material transfer. AD requires continuous environmental conditions, preferably close to the process optimum, to get the best biogas yield. Frequently, a significant portion of the biogas produced is used to provide process energy. The anaerobic digester can be heated via coupling solar energy and biodigester (Ouhammou et al. 2019). According to the authors, the coupled system provides a 100% reduction in energy usage for nearly 10 months of the year and a 70% reduction for 2 cold months. Microorganisms are categorized into three types based on the temperature range in which they can proliferate (Cresson et al. 2006). The temperature phases are as follows:

- Psychrophilic: T < 20 °C
- Mesophilic: 20 °C < T < 45 °C with optimum for 35 °C
- Thermophilic: 45 °C < T < 65 °C with optimum for 55 °C

pH and Alkalinity

pH is an essential parameter in AD because each of the microbial groups involved in the reactions has a specific pH range for optimal growth. It is therefore important to monitor the pH and, if necessary, adjust it in the feed or automatically regulate it in the digester. The optimum pH for AD is around neutral, between 6.5 and 8.5 (Lahboubi et al. 2020). If the acceptable operating range of a reactor is between 6.5 and 8.5, the ideal values for methanogenic microorganisms vary between 7.0 and 7.2. A drop in pH below 5.0 is lethal to these organisms. The use of pH as an indicator of the process is normally based on the fact that a drop in pH corresponds to the accumulation of VFA (Bakraoui et al. 2020a). An important element in maintaining pH is the alkalinity of the digester (Wilson 2004).

Alkalinity (Alk) measures the buffering capacity in the digester and thus its ability to maintain a stable pH (Batstone et al. 2002). Alkalinity is usually expressed in terms of equivalent calcium carbonate concentration (mg CO_3Ca/L). An alkalinity value greater than 1000 mg CO_3Ca/L is recommended so that methanogenic populations are not inhibited. It should be noted that pH and alkalinity in an AD system are affected by the concentration of CO_2 in the upper void space of the digester (in the biogas) (Wilson 2004).

Volatile Fatty Acids

One of the most essential markers in monitoring the AD process is VFA concentration. Acidogenic and acetogenic bacteria create VFAs, which are then eaten by methanogenic bacteria). It is widely assumed that their concentration in the digester indicates a methanation process fault (Wilkinson 2011). It is widely assumed that their collection in the digester indicates a digestive process dysfunction. The main cause of toxicity and reactor failure in the AD process is the reduction in pH that occurs as VFAs accumulate (Hill and Bolte 1989).

Retention Time

The retention time (RT) also known as residence time is the amount of time the substrate spends in the reactor on average. It is determined using the volumetric loading rate of a reactor while it is in operation. A longer retention time should theoretically result in a more complete deterioration of the feedstock. The reaction rate, on the other hand, diminishes as retention duration increases (Boe and Batstone 2005). Each type of substrate has a different retention period, which spans from 14 to 30 days for most dry procedures to as little as 3 days for wet processes. According to a research, a decrease of 64–85% of volatile matter in a reactor can be achieved in less than 10 h for specific wastes; however, the retention time is longer (Sakar et al. 2009).

Organic Loading Rate

The pace at which organic matter can be delivered into a digester is known as the organic loading rate (OLR). Overloading could lead to system failure due to the accumulation of inhibitory chemicals; hence the OLR is an important control parameter in AD. In this situation, the system's feed rate should be lowered (Lettinga 2001).

Figure 11.3 resumed the most important parameters (Alk, T, pH, OLR, RT, and VFA) of the AD control.

Fermentation of Biomass

The current global energy picture emphasizes nonconventional energy sources. Biomass has established itself as a reliable unconventional feedstock for bioethanol production (Khan and Dwivedi 2013). Biomass resources are classified into four groups around the world. Wood scraps are currently the most abundant biomass source for energy production. It comes from the paper mills, sawmills, and furniture making industries. Agriculture residues and dedicated energy crops are the next largest, followed by municipal solid trash. Dedicated energy crops appear to be the greatest and most promising future biomass resource among these biomass resources, which include short-rotation woody crops and herbaceous crops, especially tall grasses. This is due to the potential to get several harvests from a single planting, which lowers the average annual cost of establishing and managing energy crops dramatically, especially when compared to traditional crops.

In some emerging nations, the production of fuels, chemicals, and power from trees, crops, and agricultural and forestry wastes is already underway. Executive orders have been passed to exploit such resources for the development of clean energy in several wealthy nations as well (Shah and Rehan 2014).

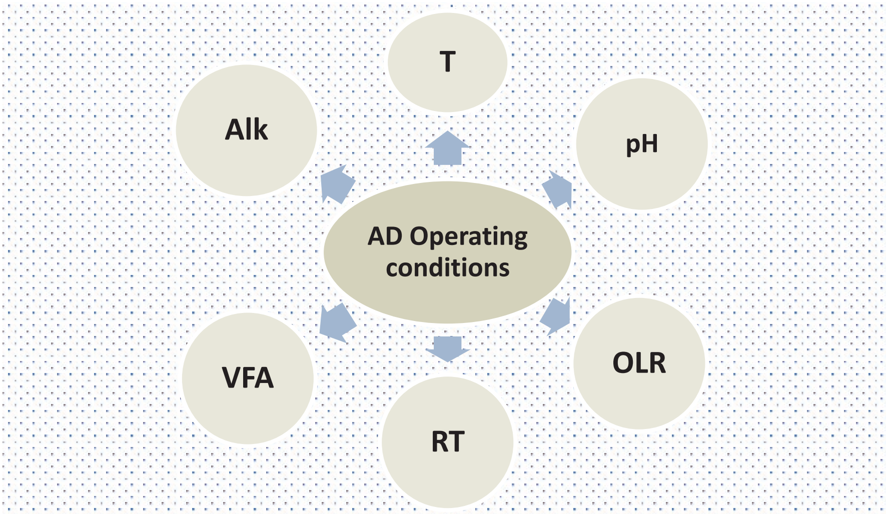

Fig. 11.3 Anaerobic digestion operating conditions

11.1.1.3 First-Generation Bioethanol Production

First-generation biofuels are made from biomass that is commonly utilized in the food industry, such as corn, soy, and sugar cane. These biofuels are created by fermenting or chemically converting the oils, sugars, and starches found in biomass into liquid fuels. Bioethanol production utilizing first-generation feedstock is a well-established technology with high bioethanol productivity and output; the method is associated with the food-to-fuel controversy and a high environmental effect due to land use charge (Ayodele et al. 2020). Moreover, an integrated biorefinery technique can be used as an efficient strategy to lower the bioethanol minimum selling price in half, according to a techno-economic analysis published in the literature by Aghaei et al. (2022) on the production of bioethanol from corn stover residue by applying pretreatment techniques. The saccharification and fermentation pretreatments showed their positive effect on the first-generation bioethanol production process in terms of yield and cost. Figure 11.4 depicts the bioethanol manufacturing process using sugar-based feedstocks high in sugar or starch that are fermented to produce bioethanol.

In order to meet the Kyoto Protocol's carbon dioxide reduction targets and lessen reliance on the supply of fossil fuels, governments around the world have carefully considered and directed state policies toward the improved and affordable utilization of biomass for meeting their future energy demands. Brazil and the USA produce the majority of the world's bioethanol, contributing 26.72% and 56.72%, respectively (Gupta et al. 2015).

Assessing the sustainability of first-generation bioethanol is not an easy task, as it depends on several factors related to the economic situation of the country in terms of food security and agricultural activities.

11.1.1.4 Second-Generation Bioethanol Production

In order to produce second-generation bioethanol, a wide range of non-edible agricultural and industrial lignocellulosic wastes are used, such as rice husk, wheat straw, maize stalks, olive pomace, bagasse, coconut husk, paper pulp industry waste, and even fruit peels.

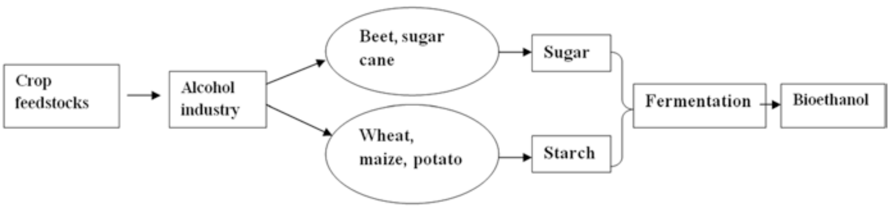

Fig. 11.4 First-generation bioethanol production

Table 11.1 Composition of the sugar cane molasses

Water content, %	Soluble solids content, %	Total sugar, %	Total nitrogen content, %	Mineral substances content, %	pH	References
18,2	81,8	54,6	0,5	6,2	7,6	Elena et al. (2009)
18,85	81,15	48,87	0,90	13,82	5,3	Hashizume et al. (1966)
–	88,67	51,36	0,39	10,45	5,1	Hassan et al. (2019)

Agricultural waste can be exploited, and the demand for fossil fuels can be alleviated, in particular, molasses, a by-product obtained during the refining of sugar cane (Ghorbani et al. 2011). In the commercial production of bioethanol, manufacturers most often use sugarcane molasses as feedstock because of its abundance and low cost. The most commonly used microorganisms for fermentation are *Saccharomyces cerevisiae* yeasts because of their ability to hydrolyze sucrose from sugarcane molasses into glucose and fructose and too easily identifiable hexoses (Elena et al. 2009). Molasses has been of great interest for bioethanol production because it is cheap, rich in sucrose, which is a substrate that does not require pre-treatment before fermentation (Bouallagui et al. 2013). Table 11.1 presents the composition of the sugarcane molasses; we notice that the sugar content is higher than 50% for the three examples presented. That means it is a suitable feedstock since the sugar is a key element for the bioethanol production.

In Pakistan, bioethanol produced from sugarcane molasses has been evaluated for its potential for availability, energy efficiency, and environmental sustainability. The current potential of molasses-based bioethanol was found to be sufficient to replace about 7% of the nation's total gasoline usage. Pakistan is the eighth largest producer of sugar in the world and the fifth largest producer of sugarcane (Ghani and Gheewala 2021).

In Mexico, an estimated yearly need of 3 billion liters is expected to be produced primarily from sugarcane, knowing that bioethanol is now being introduced as a fuel oxygenator (Lopez-Ortega et al. 2021). This study shows how the Brazilian experience gained over 40 years of successful transformation of its biorefinery sector. This long experience could be used to transform the Mexican sugar industry by redeveloping sugar mills to produce bioethanol from molasses first and then using juice to sustainably increase bioethanol production (Lopez-Ortega et al. 2021).

11.1.2 Sustainability of Second-Generation Bioethanol Production

Increasing energy demand, growing debates about whether first-generation biomass should be used for food or fuel, and market pressure for environmental sustainability are forcing bioethanol supply chain decision-makers to use non-edible second-generation biomass feedstocks while reducing carbon emissions. Most biofuel manufacturers now use edible first-generation biomass feedstocks. Motivating them to move to a second-generation feedstock, from both an economic and environmental standpoint appears to be critical in this context (Esmaeili et al. 2020a). From a sustainability standpoint, first-generation biofuels have both benefits and drawbacks in terms of environmental and socioeconomic implications.

In African case, for several reasons, the bioethanol business has been rapidly expanding for use as an alternative motor fuel. This sector of the economy is still developing in South Africa (Amigun et al. 2011) (Table 11.2).

The production of bioethanol is in direct function with the raw material used. For Brazil, it uses sugar cane as raw material to produce bioethanol; the production was 44.9% billion liters in 2006 as shown in Table 11.3; this is the most important production compared to other countries. In order to produce an important quantity of bioethanol, the choice of the raw material to be used is a very important step which allows us a good management of the waste more precisely in the developed countries. In 2018, global bioethanol output hit 108.6 billion liters (Table 11.3). The United States and Brazil together generate 84% of the world's bioethanol, with the EU accounting for 5% and China for 4% (Table 11.3). Sugarcane, corn, and sugar beets are the most commonly used crops for bioethanol production (Sydney et al. 2019).

To reduce dependence on fossil fuels, sustainable energy requires renewable energy sources. Corn has been used to make first-generation bioethanol as a renewable energy source. However, the creation of such a biofuel raises corn-based food prices, leading to heated arguments over food vs fuel. First-generation bioethanol producers would be enticed to switch to second-generation bioethanol production by financial incentives (Esmaeili et al. 2020b). Along with better technologies, residues from the second-generation process (e.g., unreacted lignocellulosic material) could be used as fuels, increasing the amount of surplus bagasse. Instead of biodigestion to produce biogas, pentose fermentation to bioethanol will result in increased

Table 11.2 Commercial first- and second-generation biofuels compared at present technology levels

	First generation	Second generation
Source of energy	Starch, sugar, and oil are examples of fuel-producing substances	Mostly lignocellulose is turned into fuel
Source of biomass	Only the principal crop product (e.g., grain, sugar, or oil-seed component of the plant) is used to make the fuel; the rest of the plant is not utilized	Produced from whole plants, crop wastes, forestry residues, or waste from wood processing
Crops	Corn, wheat, sugar cane and sugar beet, rapeseed, oil palm, and soybean are all annuals	Switchgrass, Miscanthus, Coppice Willow, and Alfalfa are examples of perennials
Prospects	N_2O emissions, which are generally doomed, contribute to global warming	Genetic engineering is closely tied to development, and its widespread use endangers food security and exacerbates climate change

Adapted from Ponti and Gutierrez (2009)

Table 11.3 Bioethanol production for different countries

Country	Feedstock	Bioethanol production of 2006[a] (% billion liters)	Bioethanol production of 2018[b] (million liters)
USA	Primarily corn	46.9	60,000
Brazil	Sugarcane	44,9	28,000
Canada	Corn, wheat, straw	0,5	–
China	Corn, wheat, cassava, sweet, sorghum	2,6	–
EU	Wheat, other grains, sugar beets, wine, alcohol	4,1	–
India	Molasses, sugarcane	0,8	–

[a]Ponti and Gutierrez (2009)
[b]Sydney et al. (2019)

bioethanol production, increasing the process' energy demand and, as a result, reducing the amount of excess lignocellulosic material available (Dias et al. 2013).

Bagasse might thus be used for second-generation bioethanol production, with the cogenerated by-product being applied to the soil to create a sustainable second-generation bioethanol production system that improves soil carbon stocks and nutrient bioavailability (Inglett et al. 2021).

Given the drawbacks and benefits of both kinds first and second generations of bioethanol, an integrated approach of both technologies is recommended. Ayodele et al. (2020) reported that combining 2G and 1G bioethanol production in a single facility delivers technological, economic, and environmental benefits, compared to a stand-alone 2G bioethanol production method. Bioethanol synthesis from 1G feedstock has the advantage of producing a lot of bioethanol. However, there are concerns about the food-to-fuel debate as well as significant environmental consequences. Due to the abundance of lignocellulosic biomass resources and its potential as a cleaner and ecologically friendly biofuel, bioethanol production from 2G feedstocks has gotten a lot of attention, but is initial investment and end-product cost still too high. The integrated approach leads to reduce the operational and the end-product cost and to preserve the environment, which makes it a cost-effective and a sustainable approach. In the same context, Ferreira et al. (2018) reported that incorporating second-generation feedstocks into first-generation facilities can have favorable technological, economic, and environmental outcomes. These possibilities can affect waste management by constructing suitable biorefineries and circular economies, in addition to realizing bioethanol production from second-generation feedstocks. This strategy entails enhancing first-generation bioethanol plants by the valorization of intrinsic waste streams, the integration of cogeneration systems, and the incorporation of lignocellulosic materials and other wastes.

In another study related to the same field, conducted by Furlan et al. (2012), based on first- and second-generation bioethanol synthesis from sugarcane, a modeling using a process simulator for four case studies. The results revealed the importance of appropriate bagasse partitioning for the process energy self-sufficiency.

Sugarcane bagasse is currently primarily used to provide electric and thermal energy to the process. The creation of second-generation bioethanol raises heating demands by at least 25%, limiting the decision range for how much bagasse may be redirected to second-generation fuel production. Furthermore, the surplus of electric power has decreased by at least 31%, which might have a significant influence on process economics because it is sold as part of the industry goods portfolio.

Bioethanol manufacturing is currently progressing to the third generation. Third-generation biofuels are made from algal biomass, which has a considerably different growth yield than traditional lignocellulosic biomass. Because of its high protein content and high hexose content (15.29% of the raw material on a dry basis), *Sargassum muticum* is a good feedstock for third-generation bioethanol production (10.55%) (del Río et al. 2019).

It is clear that there are certain criteria that need to be met to improve and optimize bioethanol production. These criteria include, for example, process quality certificates, which guarantee the efficiency of alternative energy sources, and are becoming increasingly popular as a result of the promotion of biofuels, particularly bioethanol, in the industrial or agro-industrial sector. In developing countries, the biggest problems with biofuel production, however, go beyond the consequences of utilizing subpar technology or not relying on its advancement. To increase the production of bio-ethanol sustainably and efficiently, while also balancing the needs of society and the environment, the industrial sector must encourage and implement innovative techniques, tools, and infrastructure. Extensive research and government investments are required to support the best growth of biofuel production. The development of bioethanol needs to be encouraged by tax breaks and financial aid provided to biofuel companies.

11.2 Organic Waste Management and Recovery in Developing Countries

Many developing countries are today confronted with major development issues, which may be aggravated if old development programs are maintained. Following the recent global economic crises, development issues are projected to worsen as a result of the negative impact on rich countries' ability to provide required support to poor countries. Urbanization is accompanied by an increase in the number of people living in cities. The number and complexity of created wastes and overburdens, especially solid wastes, will increase as a result of the growth. The mismanagement of these wastes can damage the environment and lead to different problems. Thus, different developing countries opt to treat solid wastes by specific treatment, according to the nature and characteristics of the waste, to produce valuable product that can be used.

11.2.1 Appropriate Biogas Technology for Developing Countries

In developing countries, the common digesters implanted are the fixed dome (Chinese type), floating cover (Indian type), and a balloon digester (Fig. 11.5).

Figure 11.5 shows the common applications of biogas used in the developing countries. The use of biogas in these countries is restricted to cooking and lighting. In Syria, the size of digesters implanted is between 14 and 100 m^3, with an annual production of 4.6 billion m^3 of biogas and 341 million tons of high quality organic fertilizer (Jafar and Awad 2021). In Nepal, more than 431,000 biogas digesters family sizes (4–10 m^3) were installed with an annual biogas production of 3.04 billion m^3 (Lohani et al. 2021). Farmers with a medium or high income were more likely to adopt the technology than lower farmers income (Mwirigi et al. 2009).

In fact, different studies in the literature suggest that food waste (FW) can produce biogas using AD processes as an alternative source of energy.

Using local material for building a rural biodigesters can minimize construction costs. The AD technology did not just provide cooking energy but also contributed to the sanitation system (Ogwang et al. 2020). The latest author declares that AD has an important effect on reducing chemical oxygen demand (COD) from FW by about 58%. The authors mention that the process can reduce 99% of pathogens from FW.

11.2.1.1 Fixed Dome

The fixed dome is popularly used in developing countries as a biodigester to recover organic waste and produce biogas and digestate. Figure 11.6 shows the scheme of fixed dome digester and its accessories. It consists of underground digester with inlet for feeding material and two outlets: one for collecting biogas and the second

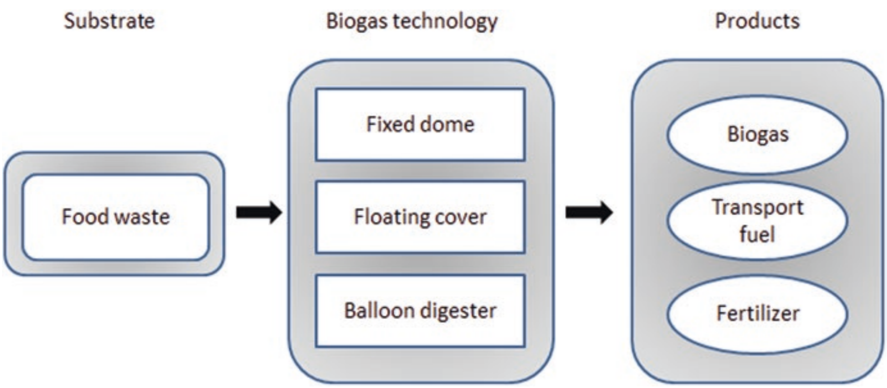

Fig. 11.5 Biogas plant technology for food waste and their products

one for collecting the digestate. In general, the food wastes can be co-digested with cattle manure in a wet fermentation process. Fixed dome digesters provide different positive impact on the environment, but there are limitations in biogas production in winter due to the decrease of temperature which leads to the drop-down of produced biogas volume (Lohani et al. 2021). The main advantages of the fixed dome digester are relatively low cost for construction and a lifespan of more than 10 years. The most disadvantage of the fixed dome digester is that it needs a highly qualified technical constructor to limit the problems of pressure fluctuation. In a research carried out with the design of Chinese Fixed Dome Digesters (CFDD) for the construction of a small-scale digester design that is optimized for rural South Africa, the authors compared a prototype digester with two experimental design features (Ogwang et al. 2020). They found out that the optimized digestion generated 9.3 NL CH_4/KgVS (about 10% more biomethane) than the control digester.

11.2.1.2 Floating Cover

The floating cover digester consists of an above or shallow ground digester made of concrete and steel. The principal design of the floating cover digester is the same as the fixed dome digester. The wastes are fed from the inlet of the digester, and the biogas was collected using a flexible floating cover where the gas is stored (Fig. 11.7). Figure 11.7 shows the scheme of the floating cover digester and its accessories. The most advantage of the floating cover digester is the operation can be visually seen due to the cover which rises and falls with the fluctuation of the gas pressure. The disadvantages of the floating cover digester are the steel utilized in the

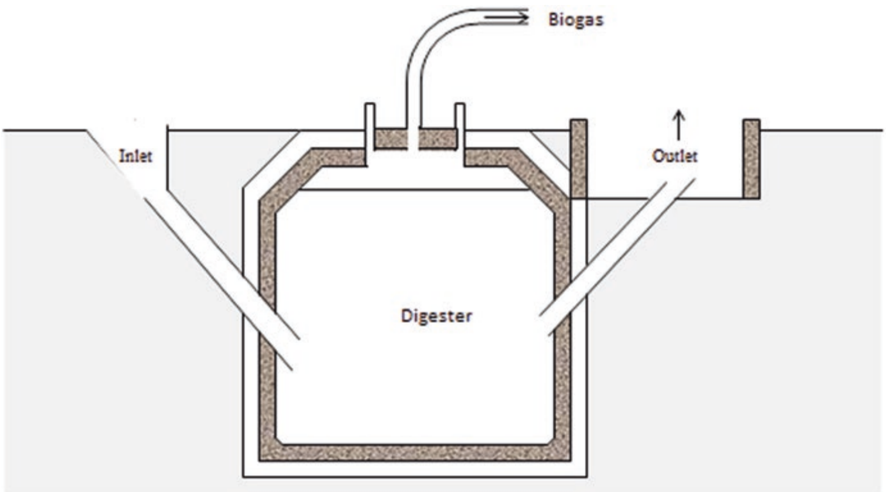

Fig. 11.6 Scheme of fixed dome digester

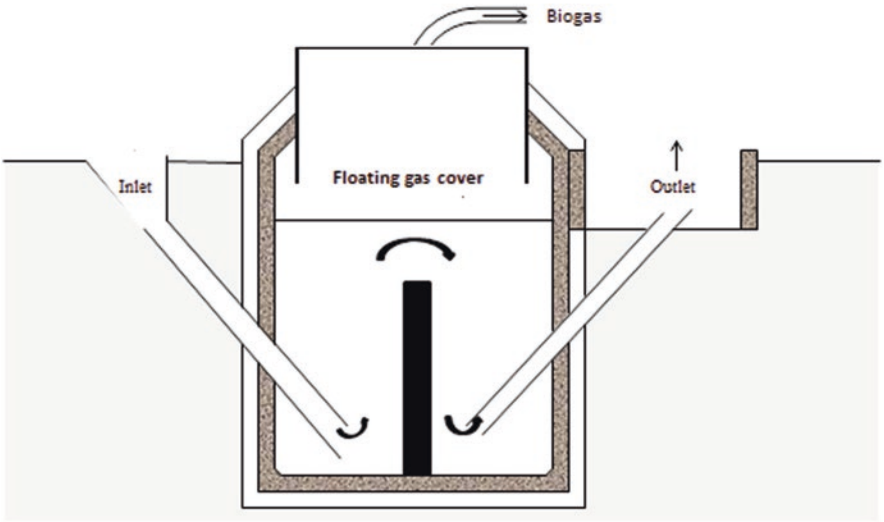

Fig. 11.7 Scheme of floating covers digester

building design is highly expensive; its life duration is relatively limited; and it requires regular maintenance due to corrosion (Orhorhoro et al. 2019).

11.2.1.3 Balloon Biodigester

A balloon biodigester is a plant that combines a digester and a gas holder in a heat-sealed plastic or rubber bag. Figure 11.8 shows the scheme of the balloon biodigester and its accessories. The gas is collected in the balloon's upper section. The inlet and outlet are directly linked to the balloon's skin. Weights can be placed on the balloon to boost gas pressure. The skin may be damaged if the gas pressure surpasses the capacity of the balloon. As a result, safety valves are necessary. A gas pump is required if higher gas pressures are required. Specially stabilized, reinforced plastic or synthetic caoutchoucs are preferred since the material must be weather and UV resistant (Ghiandelli 2017). RMP (red mud plastic), Trevira, and butyl are some of the other materials that have been effectively used. Typically, functional life-span does not exceed 5 years (Zaki et al. 2021). The balloon biogas plants are advised if local maintenance is or can be made possible and the cost advantage is significant.

The advantages of the balloon biodigester include low-cost prefabrication (Kabyanga et al. 2018) and construction sophistication; transportation convenience; shallow installation for use in places where the groundwater table is high; high-temperature digesters are used in hot areas; cleaning without difficulty and sample; and safe maintenance and emptying.

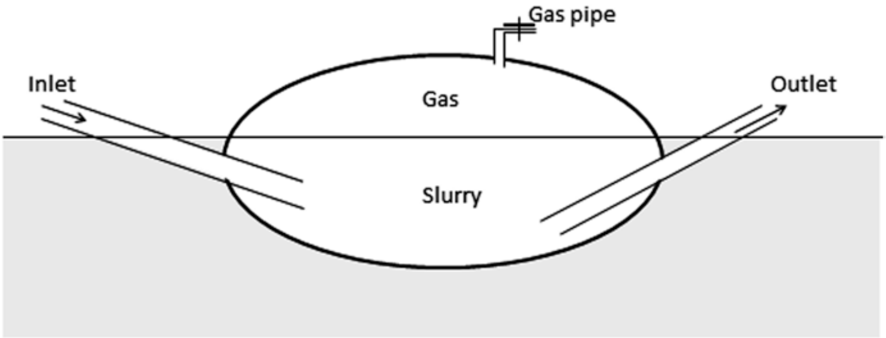

Fig. 11.8 Scheme of balloon digester

The balloon biodigester may necessitate the use of gas pumps for low gas pressure; scum cannot be removed during operation; the plastic balloon has a limited useful life and is subject to mechanical damage; and it is usually not accessible locally. Furthermore, local craftsmen are rarely capable of repairing a broken balloon. There is little opportunity for local employment development and thus low self-help potential.

11.2.2 Rural Biogas and Poverty Reduction in Developing Countries

11.2.2.1 Effect of Biogas on the Developing Countries

Through many biogas applications, biogas technology may contribute to the reduction of poverty in developing countries (Fig. 11.9). Figure 11.9 represents how biogas may be used to reduce poverty. On the one hand, biogas may be used for cooking or heating. Instead of buying wood or charcoal, inhabitants can use it for free in their kitchens. Biogas, on the other hand, may be converted into energy and used to lighting the house or power devices. As a result, citizens would refrain from paying their electrical bills. Some households may go larger distances to obtain hardwoods from a forest or park; but, with biogas technology, they will not have to go as far and also it can help minimizing deforestation. Biogas digesters, according to Shaibur et al. (2021), minimize the time necessary to collect wood for cooking, allowing individuals to pursue education and employment elsewhere. For example, in Nepal, rural household biodigesters can save 2 h/day of time for women and children (Katuwal and Bohara 2009).

Small-scale biogas systems would also help to accomplish the sustainable development goals: SDGs 1: no poverty; SDG 3: good health and well-being; SDG 5: gender equality; SDG 7: affordable and clean energy; SDG 13: climate action; and SDG 15: living on land, according to Lohani et al. (2021). The production of biogas requires working power for the production, collection, and transport of raw

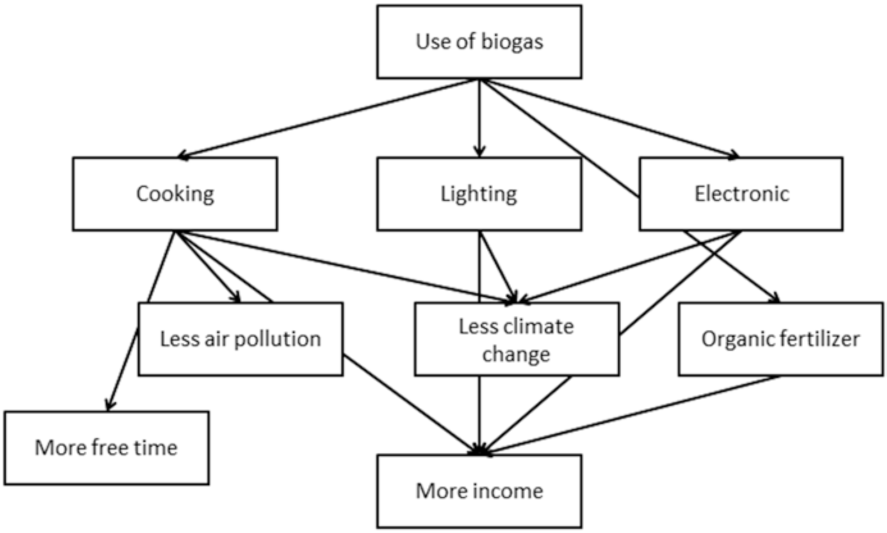

Fig. 11.9 The application of biogas

materials; this implies that the creation of a regional biogas sector helps to generate new jobs. A research shows that, in developing countries, biogas technology can decrease the poverty gap and increase the incomes for biogas adopters more than non-adopters (Rahman et al. 2021). For example, in Bangladesh, biogas adopters had a household poverty gap of around 16% smaller than non-adopters. The authors declare that biogas adopters have a per capita household income between 13% and 27% more than non-adopters. A study showed that a 10 m^3 fixed dome digester can produce up to 2.5 m^3 per day of biogas, which is equivalent to 13 kg of firewood (Diouf and Miezan 2019). In a recent study, we find that five families (each with eight individuals) have constructed a fixed dome digester utilizing co-digested cassava and vegetable and fruit waste in the design of a household biogas digester (Sawyerr et al. 2020). With a mass of incoming biomass of 465.12 kg/day, the installed digester generates 10 m^3 biogas/day. The digester's material cost is estimated to be at R 121 136.09 (South African Rands) by the authors (which is equivalent to 7 792.75 USD) .

The production of the rural population, which lives below the national poverty line, is mainly dependent on traditional biomass fuels such as wood and dung cake (dried cattle manure) (Rahman et al. 2019). The biogas digester for domestic use can contribute to achieving the UN Millennium Development Goal (MDG). Among these MDG, we can (i) cite reduction in poverty and hunger (MDG 1), (ii) empower women and maintain gender equality (MDG 3), and (iii) ensure environmental sustainability (MDG 7) (Amigun and von Blottnitz 2010). As domestic biodigesters increase employment, they can also enhance the quality of living. The domestic biodigester improves the sanitary facilities that can eradicate different diseases and cause annual numbers of deaths.

11.2.2.2 Recommendations to Promote Biogas Technology in Developing Countries

Various significant government engagements are necessary to understand what caused domestic biogas plants to operate successfully or unsuccessfully and to investigate potential obstacles (Bond and Templeton 2011). Biogas stoves look to have fresh development potential in light of the current push to minimize indoor air pollution by promoting cleaner cookstoves. According to the authors, low-cost designs with greater resilience, functionality, and simplicity of building, operation, and maintenance would help biogas plants gain market share. Furthermore, small-scale bioreactors that successfully digest accessible substrates in both rural and urban settings are required to move beyond a reliance on animal dung.

In a study carried out to bring attention to the state of energy usage in developing nations, they have mentioned the role that AD for biogas generation may and does play in satisfying these countries' energy and waste management demands (Surendra et al. 2014). The author states that developing countries have a big challenge in terms of the construction of biogas digesters and its maintenance costs. The authors recommend that construction costs must be reduced and that the direct and indirect costs and advantages of biogas technology should be evaluated and assessed. Provisions for financial services (soft loans) should be made accessible, according to the authors, to increase rural communities' access to biogas technology. Microfinance institutions set up in selected regions might be one option to consider so that impoverished people have simple access to a range of financial services. The authors give an example in Nepal; over 260 microfinance organizations provide financing to households that cannot afford the upfront cost of a biogas system.

Government agencies and non-governmental organizations (NGOs) might play an important role in encouraging digester owners to install new efficient digester technology, optimize critical operational parameters, and better manage digesters and locally accessible feedstocks (Khan and Martin 2016). The authors indicate that

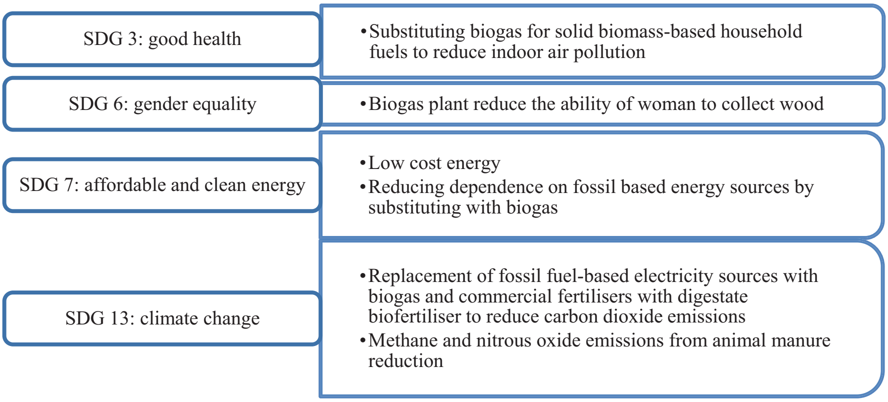

Fig. 11.10 Biogas plant contribution to achieve sustainable development goals

it is critical to make a gradual adjustment in attitudes and policies in order to replace the chemical fertilizer assistance program. According to the authors, in rural Bangladesh, biogas competes primarily with (free) solid biomass financial investments, and the biogas may fail to break even over time. Developing a sustainable biogas energy system in rural regions necessitates extensive changes in all techno-economic, social, and policy elements and is one of the most important investments in the future Fig. 11.9. .

11.3 Main Obstacles to Overcome for Biogas Technology Promotion

In order to promote biogas technology in a given country or region, it would be necessary to be aware of the main obstacles that hinder the development of biogas as a renewable energy source. It is important to know what are the largest obstacles the region/country needs to overcome so that the biogas industry can reach its full potential. In general, six types of obstacles and barriers can be found in the literature: (i) institutional, (ii) technical, (iii) economic, (iv) market, (v) environmental, and (vi) sociocultural (Nevzorova and Kutcherov 2019). These authors compare these barriers in developed and developing countries.

The promotion of biogas technology may be based on a country's geographical data, development level, and weather; thus, it is critical for each country's biogas strategy to determine its particular obstacles.

In this paragraph, we will first give a bibliographical review on these different obstacles that hinder the development of the biogas sector in developing countries. In particular, we will indicate, according to this bibliographical study, the priority ranking according to different authors and countries. Then, the priority order for each of the six types of barriers according to different authors and studies will be determined. In this context, different methodologies were used to realize these research studies. In a recent study, the analysis of the financial, technical, social-cultural, and institutional impediments to biogas transmission, in sub-Saharan Africa, was done (Rupf et al. 2015).

In other research, the authors summarize the primary barriers to adoption found during stakeholder interviews, as well as suggestions for how to overcome each of them, based on the lessons gained (Mukeshimana et al. 2021; Budiman 2021).

Biogas diffusion obstacles in India were identified using composition analysis. Financial, information, market, social, and cultural hurdles, as well as regulatory and institutional, technological, and infrastructural barriers, were all cited as major roadblocks (Mittal et al. 2018). The authors compared these hurdles in India's rural and urban areas. This suggests that biogas penetration barriers vary depending on the use area, substrate, resource potential, technological maturity, and scale. These variables may differ by country or region.

In Africa, biogas generation stands out as a viable solution with various advantages, particularly in terms of reducing health risks, indoor air pollution, and deforestation, which is rapidly becoming a severe issue in the country. However, the majority of biogas production initiatives have failed because more than 40% of the population lives in rural areas where firewood is the primary source of heat, cooking, and other necessities (Dahunsi et al. 2020).

In a recent study, the importance of the obstacles was ranked using the Analytical Hierarchy Process (AHP). This research revealed that financial barriers are the most powerful, with high capital costs and a lack of finance mechanisms ranking high among all hurdles (Mukeshimana et al. 2021).

The priority ranking of the four categories of barriers is shown in Fig. 11.10. Fig. 11.11. Financial constraints were placed first, followed by institutional impediments, with technical and sociocultural barriers ranking third and fourth, respectively.

In another study, the purpose was to determine systemic obstacles to biodigester adoption by looking at the landscape of biogas governance in Indonesia, its fragmentation, and its relevance for biodigester adoption (Budiman 2021). This research reveals impediments to technology adoption that go beyond the user/individual level. It depicts the interaction of various aspects such as policy, technology transfer governance, technical production concerns, and sociocultural issues.

11.3.1 Financial and Economic Barriers

In developing countries, high capital costs combined with widespread poverty are major economic barriers. Biogas systems are unique in that almost all costs are incurred up front, while operational costs are minimal.

In Africa, biodigesters' high initial costs are a significant obstacle to implementation. Increased access to finance is one strategy now being used to address the high initial investment costs (Meyer et al. 2021).

In fact, the initial costs of building a biogas plant, such as construction, labor, and equipment, are relatively high for rural households. The entire cost of installing a family biogas plant varies depending on the size, location, and model.

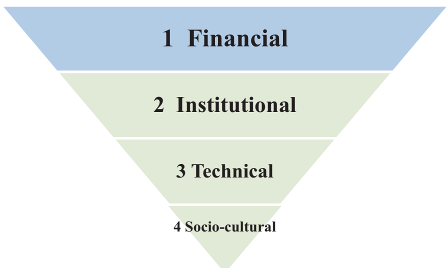

Fig. 11.11 The priority ranking of the four categories of barriers. (Adapted from Mukeshimana et al. 2021)

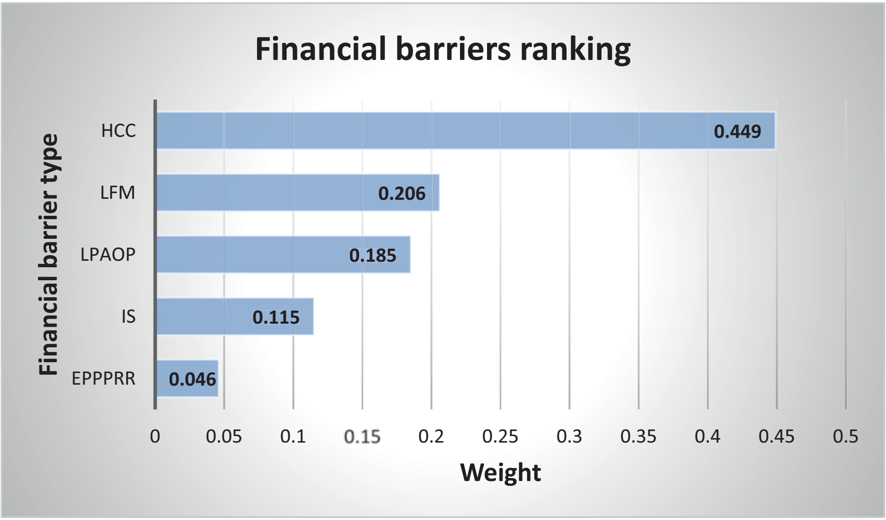

Fig. 11.12 Financial barriers ranking. (Adapted from Mukeshimana et al. 2021)

As shown in Fig. 11.12, *high capital costs (HCC)* were the most highly regarded financial barrier, followed by a *lack of financial mechanisms (LFM)*. Meanwhile, *lack of paying ability owing to poverty (LPAOP)* and *insufficient subsidies* (IS) were rated third and fourth, respectively, while the *extended payback period and poor rates of return (EPPPRR)* were ranked last. The expense of technology installation was noted by many stakeholders as a problem in biogas generation (Budiman 2021).

11.3.2 Institutional Barriers

According to literature assessment, government intervention is still necessary. In many cases, political support and particular programs to promote biogas technology are lacking. The National Biogas and Manure Management Program, launched by the Indian federal government, takes a top-down strategy. The program is inefficiently targeted because owning 2–3 cattle is one of the criteria for receiving capital subsidies to establish a biogas plant under the program (Mittal et al. 2018).

The most significant policy barrier to biogas adoption in Bangladesh was found to be a "no feed-in tariff policy." "Lack of concrete biogas policy" and "Insufficient attention from government" were the other major policy hurdles, followed by "Lack of financial policy" (Hasan et al. 2022). The governance problem inside biogas projects has an impact on production and consumption barriers (Budiman 2021).

11.3.3 Technical Barriers

The lack of locally sourced biogas technologies can make it difficult to deploy biogas as a source of energy. Biogas plant production is influenced by operator expertise, professional employees, and well-trained workers (Nevzorova and Kutcherov 2019). Poor design and lack of standards for biogas construction, insufficient feedstock supply, and a lack of technical services and research and development facilities are all examples of technical barriers (Mukeshimana et al. 2021). The results show that "lack of waste treatment and storage facilities," "lack of feedstock supply," and "planning and installation challenges" were the most significant technical barriers to biogas technology deployment (Hasan et al. 2022).

11.3.4 Sociocultural Barriers

Biogas adoption in rural areas is hampered by a number of social and cultural hurdles. First, due to the associated social shame, people and plant owners are hesitant to employ night soil/human excreta in biogas plants (personal communication E). Second, in rural households, women are generally responsible for cooking and are thus exposed to indoor air pollution induced by solid fuel combustion (Mittal et al. 2018). Most of the social obstacles can be overcome by taking social and cultural considerations into account when designing systems, as well as properly communicating with potential biogas users about the suitable use and benefits of biogas technology to fulfil their needs (Rupf et al. 2015).

The consumption barrier is linked to community social difficulties. People's socioeconomic acceptance of biodigesters also contributed to low demand (Budiman 2021).

11.3.5 Market Barriers

Lower fossil fuel prices and a higher price for biogas are major market hurdles. Biogas is more expensive than natural gas, which worries users because they will pay more than "normal." In order for biogas to reach the public sector, its price must be competitive with other available fuels (Nevzorova and Kutcherov 2019). Another difficulty in obtaining organic biomass feedstock in villages is the lack of local markets for these feedstocks (Mittal et al. 2018). Since conversion losses are minimized with biomethane injection into the natural gas grid, it is an effective delivery system.

In Bangladesh, the most significant market hurdle to biogas deployment was described as an "immature biogas market." "Lack of involvement in the global carbon market" and "unsettled energy market" are two additional important impediments mentioned. In the Bangladesh biogas market, “low primary-end-user demand” and “competition with fossil fuels” are deemed less important (Hasan et al. 2022).

11.3.6 Environmental Barriers

Despite the fact that biogas has a number of important environmental benefits, few authors address potential negative factors such as noise pollution, odor complaints, and the necessity for ample water supplies for biogas digesters (Nevzorova and Kutcherov 2019). AD necessitates a large volume of water, with a ration of water and manure to be placed into the digester of 1:1 (Kelebe 2018). As a result, while biogas generation may not be a problem during the rainy seasons, but it may be a problem during the dry seasons, particularly where the distance to water supply is great and in areas where water is scarce (Kelebe 2018).

Soil biodiversity, water storage and retention capacity, erosion management, and agricultural yield stability are all directly connected to soil organic matter concentration (Pirelli et al. 2021). As a result, the author mentions that monitoring and evaluating soil organic carbon (SOC) as an indicator for soil quality is critical for determining the long-term viability of bioenergy crops and defining appropriate management techniques.

11.4 Conclusion

Several biomass conversion technologies are used to valorize organic wastes. These technologies cover a wide range of biological/biochemical processes that produce biofuels and value-added goods, among other things. The promotion of biofuels, particularly bioethanol, in the industrial or agro-industrial sector has led to a rise in the need for process quality certificates, which attest to the efficacy of alternative energy sources. The largest issues with producing biofuel in developing nations, however, go beyond the negative effects of using subpar technology or ignoring its growth. The industrial sector has to support and put in place innovative methods, devices, and infrastructure for boosting bioethanol production effectively while juggling societal and environmental demands. Government funding and extensive research are needed to promote the best expansion of the biofuel industry. Tax concessions and financial aid for biofuel companies must be used to promote the growth of bioethanol.

Note that assessing the sustainability of first-generation bioethanol is not an easy task, as it depends on several factors related to the economic situation of the country in terms of food security and agricultural activities.

Poor management of significant amounts of organic waste has the potential to harm the ecosystem and cause major problems. AD is used to treat these wastes and can produce biogas and digestate. Fixed dome, floating cover, and balloon digesters are the most popular digesters used in developing countries. Through various biogas applications, such as cooking or heating, as well as energy for lighting the house or the usage of electronics, biogas technology may aid in the reduction of poverty in developing countries.

In recent years, there has been a lot of interest in the existing obstacles to the widespread use of biogas as an energy source. Thus, awareness of the hurdles to wider adoption of biogas is important to handle, as well as their potential impact on the energy industry as a whole. The general barriers can be defined as six interrelated sets of constraints in both established and emerging economies. These barriers are technical, economic, market, institutional, sociocultural, and environmental. High capital costs and widespread poverty are significant economic obstacles in developing countries. Political support and targeted initiatives to advance biogas technology are frequently absent. Biogas production is influenced by skilled operators, qualified staff, and trained employees. People and plant owners are hesitant to use night soil or human excreta in biogas plants, which influences biogas adoption. Because biogas is more expensive than natural gas, users are concerned that they will end up paying more than necessary. Even though biogas has a number of significant environmental advantages, there are different inconvenient factors, such as odor complaints, noise pollution, and the need for sufficient water supply for biogas digesters.

References

S. Aghaei, M. KarimiAlavijeh, M. Shafiei, K. Karimi, A comprehensive review on bioethanol production from corn stover: Worldwide potential, environmental importance, and perspectives. Biomass Bioenergy **161**, 106447 (2022). https://doi.org/10.1016/j.biombioe.2022.106447

M. Albertson, A. Pruden, R.T. Oliver, Enhanced anaerobic digestion of biomass waste for optimized production of renewable energy and solids for compost. Int. Congr. Ser. **1293**, 221–229 (2006). https://doi.org/10.1016/j.ics.2006.01.007

B. Amigun, H. von Blottnitz, Capacity-cost and location-cost analyses for biogas plants in Africa. Resour. Conserv. Recycl. **55**(1), 63–73 (2010). https://doi.org/10.1016/j.resconrec.2010.07.004

B. Amigun, D. Petrie, J. Görgens, Economic risk assessment of advanced process technologies for bioethanol production in South Africa: Monte Carlo analysis. Renew. Energy **36**, 3178–3186 (2011). https://doi.org/10.1016/j.renene.2011.03.015

B.V. Ayodele, M.A. Alsaffar, S.I. Mustapa, An overview of integration opportunities for sustainable bioethanol production from first- and second-generation sugar-based feedstocks. J. Clean. Prod. **245**, 118857 (2020). https://doi.org/10.1016/j.jclepro.2019.118857

M. Bakraoui, Y. El Gnaoui, N. Lahboubi, F. Karouach, H. El Bari, Kinetic study and experimental productions of methane production from UASB reactor treating wastewater from recycled pulp and paper for the continuous test. Biomass Bioenergy **139**, 105604 (2020a). https://doi.org/10.1016/j.biombioe.2020.105604

M. Bakraoui, F. Karouach, B. Ouhammou, N. Lahboubi, Y. El Gnaoui, O. Kerrou, M. Aggour, H. El Bari, Kinetics study of methane production from anaerobic digestion of sludge and wastewater recycled pulp and paper. IOP Conf. Ser. Mater. Sci. Eng. **946** (2020b). https://doi.org/10.1088/1757-899X/946/1/012009

D.J. Batstone, J. Keller, I. Angelidaki, S.V. Kalyuzhnyi, S.G. Pavlostathis, A. Rozzi, W.T.M. Sanders, H. Siegrist, V.A. Vavilin, The IWA anaerobic digestion model no 1 (ADM1). Water Sci. Technol. **45**(10), 65–73 (2002)

I. Beniche, H. El Bari, J.A. Siles, A.F. Chica, M.Á. Martín, Methane production by anaerobic co-digestion of mixed agricultural waste: Cabbage and cauliflower. Environ. Technol., 1–9 (2020). https://doi.org/10.1080/09593330.2020.1770341

I. Beniche, J. Hungría, H. El Bari, J.A. Siles, A.F. Chica, M.A. Martín, Effects of C/N ratio on anaerobic co-digestion of cabbage, cauliflower, and restaurant food waste. Biomass Convers. Biorefinery **11**(5), 2133–2145 (2021). https://doi.org/10.1007/s13399-020-00733-x

K. Boe, D. Batstone, *Optimisation of Serial CSTR Biogas Reactors Using Modeling by ADM1*. In Proceedings of the first international workshop on the IWA anaerobic digestion model no. 1 (ADM1) (2005), pp. 219–221

T. Bond, M.R. Templeton, History and future of domestic biogas plants in the developing world. Energy Sustain. Dev. **15**(4), 347–354 (2011). https://doi.org/10.1016/j.esd.2011.09.003

N. Boontian, Conditions of the anaerobic digestion of biomass. World Academy of Science, Engineering and Technology, Open Science Index 93. Int. J. Environ. Ecol. Eng. **8**(9), 1036–1040 (2014)

H. Bouallagui, Y. Touhami, N. Hanafi, A. Ghariani, M. Hamdi, Performances comparison between three technologies for continuous ethanol production from molasses. Biomass Bioenergy **48**, 25–32 (2013). https://doi.org/10.1016/j.biombioe.2012.10.018

I. Budiman, The complexity of barriers to biogas digester dissemination in Indonesia: Challenges for agriculture waste management. J. Mater. Cycles Waste Manage. **23**(5), 1918–1929 (2021). https://doi.org/10.1007/s10163-021-01263-y

D.P. Chynoweth, A.C. Wilkie, J.M. Owens, *Anaerobic Processing of Piggery Wastes: A Review*. In ASAE annual international meeting; 12–16 July (American Society of Agricultural Engineers (ASAE), Orlando/St. Joseph 1998), 38 pp

R. Cresson, H. Carrère, J.P. Delgenès, N. Bernet, Biofilm Formation during start upperiod of an anaerobic biofilm reactor – Impact of nutrient complementation. Biochem. Eng. J. **30**(1), 55–62 (2006). https://doi.org/10.1016/j.bej.2006.02.002

S.O. Dahunsi, O.O. Fagbiele, E.O. Yusuf, Bioenergy technologies adoption in Africa: A review of past and current status. J. Clean. Prod. **264**, 121683 (2020). https://doi.org/10.1016/j.jclepro.2020.121683

P.G. del Río, E. Domínguez, V.D. Domínguez, A. Romaní, L. Domingues, G. Garrote, Third generation bioethanol from invasive macroalgae Sargassummuticum using autohydrolysis pretreatment as first step of a biorefinery. Renew. Energy Elsevier **141**(C), 728–735 (2019). https://doi.org/10.1016/j.renene.2019.03.083

B. Demirel, P. Scherer, O. Yenigun, T.T. Onay, Production of methane and hydrogen from biomass through conventional and high-rate anaerobic digestion processes. Crit. Rev. Environ. Sci. Technol. **40**(2), 116–146 (2010). https://doi.org/10.1080/10643380802013415

M.O.S. Dias, T.L. Junqueira, C.E.V. Rossell, R.M. Filho, A. Bonomi, Evaluation of process configurations for second generation integrated with first generation bioethanol production from sugarcane. Appl. Energy **109**, 72–78 (2013). https://doi.org/10.1016/j.apenergy.2013.03.081

B. Diouf, E. Miezan, The biogas initiative in developing countries, from technical potential to failure: The case study of Senegal. Renew. Sust. Energ. Rev. **101**, 248–254 (2019). https://doi.org/10.1016/j.rser.2018.11.011

P. Elena, R. Gabriela, B. Camelia, H. Traian, *Bioethanol Production from Molasses by Different Strains of. Saccharomyces cerevisiae*. The Annals of the University Dunarea de Jos of Galati Fascicle VI – Food Technology, New Series Year III (XXXIII) Paper presented at the International Symposium Euro - aliment 2009, 9th–10th of October 2009, Galati – ROMANIA (2009)

S.A.H. Esmaeili, A. Sobhani, J. Szmerekovsky, A. Dybing, G. Pourhashem, First-generation vs. second-generation: A market incentives analysis for bioethanol supply chains with carbon policies. Appl. Energy **277**, 115606 (2020a). https://doi.org/10.1016/j.apenergy.2020.115606

S.A.H. Esmaeili, J. Szmerekovsky, A. Sobhani, A. Dybing, T.O. Peterson, Sustainable biomass supply chain network design with biomass switching incentives for first-generation bioethanol producers. Energy Policy **138**, 111222 (2020b). https://doi.org/10.1016/j.enpol.2019.111222

Furlan FF, Costa CB, Fonseca GC, Soares RP, Secchi AR, Gonçalves da Cruz AG, Giordano RC, (2012) Assessing the production of first and second generation bioethanol from sugarcane through the integration of global optimization and process detailed modeling, Computers & Chemical Engineering, Vol 43, 1-9, https://doi.org/10.1016/j.compchemeng.2012.04.002.

J.A. Ferreira, P. Brancoli, S. Agnihotri, K. Bolton, M.J. Taherzadeh A review of integration strategies of lignocelluloses and other wastes in 1st generation bioethanol processes. ProcessBiochem **75**, 173–186 (2018). https://doi.org/10.1016/j.procbio.2018.09.006

H.U. Ghani, S.H. Gheewala Environmental Sustainability Assessment of Molasses-based Bioethanol Fuel in Pakistan. Sustain Prod Consum **27**, 402–410 (2021). https://doi.org/10.1016/j.spc.2020.11.013

M. Ghiandelli, *Development and Implementation of Small-Scale Biogas Balloon Biodigester in Bali, Indonesia* (KTH School of Industrial Engineering Management Energy Technology EGI2017-0066-MSC, 2017), p. 68

F. Ghorbani, H. Younesi, A. Esmaeili Sari, G. Najafpour, Cane molasses fermentation for continuous ethanol production in an immobilized cells reactor by Saccharomyces cerevisiae. Renew. Energy **36**(2), 503–509 (2011). https://doi.org/10.1016/j.renene.2010.07.016

L. Gouveia, P.C. Passarinho, Biomass conversion technologies: Biological/biochemical conversion of biomass. Biorefineries, 99–111 (2017). https://doi.org/10.1007/978-3-319-48288-0_4

N. Gupta, M. Pal, M. Sachdeva, M. Yadav, A. Tiwari, Thermophilicbiohydrogen production for commercial application: The whole picture. Int. J. Energy Res. **40** (2015). https://doi.org/10.1002/er.3438

S. Habchi, N. Lahboubi, F. Karouach, I. Naim, Y. Lahlou, M. Bakraoui, B. Sallek, H. El Bari, Effect of thermal pretreatment on the kinetic parameters of anaerobic digestion from recycled pulp and paper sludge. Ecol. Eng. Environ. Technol. **23**(1), 192–201 (2022). https://doi.org/10.12912/27197050/143568

A.S.M.M. Hasan, M.A. Kabir, M.T. Hoq, M.T. Johansson, P. Thollander, Drivers and barriers to the implementation of biogas technologies in Bangladesh. Biofuels **13**(5), 643–655 (2022). https://doi.org/10.1080/17597269.2020.1841362

T. Hashizume, S. Higa, Y. Sasaki, H. Yamazaki, H. Iwamura, H. Matsuda, Constituents of cane molasses: Part I. Separation and identification of the nucleic acid derivatives. Agric. Biol. Chem. **30**(4), 319–329 (1966). https://doi.org/10.1080/00021369.1966.10858603

S.H.A. Hassan, A.e.N.A. Zohri, R.M.F. Kassim, Electricity generation from sugarcane molasses using microbial fuel cell technologies. Energy **178**, 538–543 (2019). https://doi.org/10.1016/j.energy.2019.04.087

D.T. Hill, J.P. Bolte, Digester stress as related to iso-butyric and iso-valeric acids. Biol. Wastes **28**(1), 33–37 (1989). https://doi.org/10.1016/0269-7483(89)90047-5

T.B.K.S. Inglett, P.W. Inglett, L. Vardanyan, A.C. Wilkie, G.A. O'Connor, K.R. Reddy, Comparing first- and second-generation bioethanol by-products from sugarcane: Impact on soil carbon and nitrogen dynamics. Geoderma **384**, 114818 (2021). https://doi.org/10.1016/j.geoderma.2020.114818

R. Jafar, A. Awad, State and development of anaerobic technology for biogas production in Syria. Clean Eng. Technol. **5**, 100253 (2021). https://doi.org/10.1016/j.clet.2021.100253

M. Kabyanga, B.B. Balana, J. Mugisha, P.N. Walekhwa, J. Smith, K. Glenk, Economic potential of flexible balloon biogas digester among smallholder farmers: A case study from Uganda. Renew. Energy **120**, 392–400 (2018). https://doi.org/10.1016/j.renene.2017.12.103

F. Karouach, M. Bakraoui, A. Zguani, A. Hammadi, H. El Bari, Co-digestion of industrial recycled pulp and paper sludge with vinasse wastewater: Experimental and theoretical study. Int. J. Environ. Sci. Technol. (2021). https://doi.org/10.1007/s13762-020-03111-2

H. Katuwal, A.K. Bohara, Biogas: A promising renewable technology and its impact on rural households in Nepal. Renew. Sust. Energ. Rev. **13**(9), 2668–2674 (2009). https://doi.org/10.1016/j.rser.2009.05.002

H.E. Kelebe, Returns, setbacks, and future prospects of bio-energy promotion in northern Ethiopia: The case of family-sized biogas energy. Energy Sustain. Soc. **8**(1), 30 (2018). https://doi.org/10.1186/s13705-018-0171-2

O. Kerrou, N. Lahboubi, M. Bakraoui, F. Karouach, Y.E. Gnaoui, A. Schüch, W. Stinner, H. El Bari, Methane production from anaerobic digestion of date palm leaflet waste in Morocco. J. Mater. Cycles Waste Manage. **23**, 1599–1608 (2021). https://doi.org/10.1007/s10163-021-01238-z

Z. Khan, A.K. Dwivedi, Fermentation of biomass for production of ethanol: A review. Univers J Environ Res Technol **3**, 1–13 (2013)

E.U. Khan, A.R. Martin, Review of biogas digester technology in rural Bangladesh. Renew. Sust. Energ. Rev. **62**, 247–259 (2016). https://doi.org/10.1016/j.rser.2016.04.044

N. Lahboubi, O. Kerrou, F. Karouach, M. Bakraoui, A. Schüch, K. Schmedemann, W. Stinner, H. El Bari, A. Essamri, Methane production from mesophilic fed-batch anaerobic digestion of empty fruit bunch of palm tree. Biomass Conv. Bioref. **12**, 3751–3760 (2020). https://doi.org/10.1007/s13399-020-00864-1

N. Lahboubi, F. Karouach, M. Bakraoui, H. El Bari, A. Essamri, *Energetic Potential of Palm Waste: Empty Fruit Bunch* (AIP Proceeding, Khouribga, 2021), p. 020015. https://doi.org/10.1063/5.0049397

N. Lahboubi, F. Karouach, M. Bakraoui, Y. El Gnaoui, A. Essamri, H. El Bari, Effect of alkali-NaOH pretreatment on methane production from anaerobic digestion of date palm waste. Ecol. Eng. Environ. Technol. **23**(2), 77–88 (2022). https://doi.org/10.12912/27197050/144846

G. Lettinga, Digestion and degradation, air for life. Water Sci. Technol. **44**, 157–176 (2001). https://doi.org/10.2166/wst.2001.0489

S.P. Lohani, B. Dhungana, H. Horn, D. Khatiwada, Small-scale biogas technology and clean cooking fuel: Assessing the potential and links with SDGs in low-income countries – A case study of Nepal. Sustain. Energy Technol. Assess. **46**, 101301 (2021). https://doi.org/10.1016/j.seta.2021.101301

M.G. López-Ortega, Y. Guadalajara, T.L. Junqueira, I.L.M. Sampaio, A. Bonomi, A. Sánchez, Sustainability analysis of bioethanol production in Mexico by a retrofitted sugarcane industry based on the Brazilian expertise. Energy **232**, 121056 (2021). https://doi.org/10.1016/j.energy.2021.121056

E.L. Meyer, O.K. Overen, K.C. Obileke, J.J. Botha, J.J. Anderson, T.A.B. Koatla, T. Thubela, T.I. Khamkham, V.D. Ngqeleni, Financial and economic feasibility of bio-digesters for rural residential demand-side management and sustainable development. Energy Rep. **7**, 1728–1741 (2021). https://doi.org/10.1016/j.egyr.2021.03.013

S. Mittal, E.O. Ahlgren, P.R. Shukla, Barriers to biogas dissemination in India: A review. Energy Policy **112**, 361–370 (2018). https://doi.org/10.1016/j.enpol.2017.10.027

R. Moletta, *Gestion des problèmes environnementaux dans les industries agroalimentaires* (2e éd.). In: Libr. Lavoisier (2006). https://www.lavoisier.fr/livre/environnement/gestion-des-problemes-environnementaux-dans-les-industries-agroalimentaires-2e-ed/moletta/descriptif-9782743008321. Accessed 6 June 2022

M.C. Mukeshimana, Z.-Y. Zhao, M. Ahmad, M. Irfan, Analysis on barriers to biogas dissemination in Rwanda: AHP approach. Renew. Energy **163**(C), 1127–1137 (2021). https://doi.org/10.1016/j.renene.2020.09.051

J.W. Mwirigi, P.M. Makenzi, W.O. Ochola, Socio-economic constraints to adoption and sustainability of biogas technology by farmers in Nakuru Districts, Kenya. Energy Sustain. Dev. **13**(2), 106–115 (2009). https://doi.org/10.1016/j.esd.2009.05.002

S. Nanda, J.A. Kozinski, A.K. Dalai, Lignocellulosic biomass: A review of conversion technologies and fuel products. Curr. Biochem. Eng. **3**(1), 24–36 (2016). https://doi.org/10.2174/2213385203666150219232000

T. Nevzorova, V. Kutcherov, Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. Energy Strategy Rev. **26**, 100414 (2019). https://doi.org/10.1016/j.esr.2019.100414

I. Ntaikou, G. Antonopoulou, G. Lyberatos, Biohydrogen production from biomass and wastes via dark fermentation: A review. Waste Biomass Valoriz. **1**, 21–39 (2010). https://doi.org/10.1007/s12649-009-9001-2

J.O. Ogwang, M.R. Kalina, N. Mahdjoub, C. Trois, *Integrated Biogas Systems as Rural Sanitation Solutions: Reflections From Five Institutional Interventions in Ndwedwe, Kwazulu-Natal*. Conference Water Institute South Africa 2020 Online Conference. Virtual Event (2020)

E. Orhorhoro, A. Erameh, A Comprehensive Review on Anaerobic Digestion Plant.Nigerian Journal of Engineering Science Research **2**, 13–28 (2019)

K. Ostrem, Greening waste: Anaerobic digestion for treating the organic fraction of municipal solid wastes. Dep. Earth. Environ. Eng. Fu. Found. Sch. Eng. Appl. Sci. Columbia Univ. **59** (2004)

B. Ouhammou, M. Aggour, Â. Frimane, M. Bakraoui, H. El Bari, A. Essamri, A new system design and analysis of a solar bio-digester unit. Energy Convers. Manag. **198**, 111779 (2019). https://doi.org/10.1016/j.enconman.2019.111779

T. Pirelli, A. Chiumenti, M.M. Morese, G. Bonati, S. Fabiani, G. Pulighe, Environmental sustainability of the biogas pathway in Italy through the methodology of the Global Bioenergy Partnership. J. Clean. Prod. **318**, 128483 (2021). https://doi.org/10.1016/j.jclepro.2021.128483

L. Ponti, A.P. Gutierrez, Overview on biofuels from a European perspective. Bull. Sci. Technol. Soc. **29**(6), 493–504 (2009). https://doi.org/10.1177/0270467609349048

K.M. Rahman, D.J. Edwards, L. Melville, H. El-Gohary, Implementation of bioenergy systems towards achieving United Nations' Sustainable Development Goals in rural Bangladesh. Sustainability **11**(14), 3814 (2019). https://doi.org/10.3390/su11143814

M.S. Rahman, M.K. Majumder, M.H.K. Sujan, Adoption determinants of biogas and its impact on poverty in Bangladesh. Energy Rep. **7**, 5026–5033 (2021). https://doi.org/10.1016/j.egyr.2021.08.027

G.V. Rupf, P.A. Bahri, K. de Boer, M.P. McHenry, Barriers and opportunities of biogas dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India, and Nepal. Renew. Sust. Energ. Rev. **52**(C), 468–476 (2015). https://doi.org/10.1016/j.rser.2015.07.107

S. Sakar, K. Yetilmezsoy, E. Kocak, Anaerobic digestion technology in poultry and livestock waste treatment. Waste Manag. Res. **27**(1), 3–18 (2009). https://doi.org/10.1177/0734242X07079060

N. Sawyerr, C. Trois, T.S. Workneh, O. Oyebode, O.M. Babatunde, Design of a household biogas digester using co-digested cassava, vegetable and fruit waste. Energy Rep. **6**, 1476–1482 (2020). https://doi.org/10.1016/j.egyr.2020.10.067

N. Shah, T. Rehan, Bioethanol Production from Biomass. J. Chem. Biochem. **2**(2), 10.15640/jcb.v2n2a8 (2014)

M.R. Shaibur, H. Husain, S.H. Arpon, Utilization of cow dung residues of biogas plant for sustainable development of a rural community. Curr. Res. Environ. Sustain. **3**, 100026 (2021). https://doi.org/10.1016/j.crsust.2021.100026

K.C. Surendra, D. Takara, A.G. Hashimoto, S.K. Khanal, Biogas as a sustainable energy source for developing countries: Opportunities and challenges. Renew. Sust. Energ. Rev. **31**, 846–859 (2014). https://doi.org/10.1016/j.rser.2013.12.015

E. Sydney, L. Letti, S. Karp, A. Sydney, L. Vandenberghe, J. De Carvalho, A. Woiciechowski, A. Medeiros, V. Thomaz-Soccol, C. Soccol, Current analysis and future perspective of reduction in worldwide greenhouse gases emissions by using first and second generation bioethanol in the transportation sector. Bioresour. Technol. Rep. **7**, 100234 (2019). https://doi.org/10.1016/j.biteb.2019.100234

A. Wilkinson, *Anaerobic Digestion of Corn Ethanol Thin Stillage for Biogas Production in Batch and By Downflow Fixed Film Reactor*. PhD Thesis (Université d'Ottawa/University of Ottawa, 2011)

M.B.A.M. Zaki, R. Shamsudin, M.Z.M. Yusoff, M.Z. Mohd Yusoff, Portable bio-digester system for household use – A review. Adv. Agric. Food Res. J. **2**(2), a0000148 (2021). https://doi.org/10.36877/aafrj.a0000148

K. Ziemiński, M. Frąc, Methane fermentation process as anaerobic digestion of biomass: Transformations, stages and microorganisms. Afr. J. Biotechnol. **11**(18), 4127–4139 (2012). https://doi.org/10.4314/ajb.v11i18

P. Wilson, Anaerobic Treatment of Agricultural Residues and Wastewater Application of High-Rate Reactors. PhD Thesis (Lund University, 2004)

Chapter 12
Suitable Thermochemical Conversion Technology for Organic Waste Recovery in Developing Countries

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Nomenclature and AbbreviationsAbbreviations

AC	Activated Carbon
AFR	Air-Fuel Ratio
BET	Brunauer, Emmett et Teller theory
DE	Densification Energy ratio
DHW	Domestic Hot Water
EY	Energy efficiency
E_a	Activation Energy
FAR	Fuel-Air-Ratio
FC	Fixed Carbon
HHV	High Heat Value
HTC	HydroThermal Carbonization
k	Heating rate
LHV	Low Heat Value
m	Mass (or flow rates)
MC	Moisture content
MGW	Municipal green waste
OP	Olive Pomace
PW	The Process Water
R	Gas constant
R_0	Hydrothermal severity
SI	Severity Index

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T	Temperature
t	Time
VM	Volatile Matter

Greek Symbols

λ	Air factor
Φ	Equivalence ratio
ω	Empirical parameter

Subscripts

0	Reference
a	Air
b	Burnout
c	Combustible/Fuel
i	Ignition
max	Maximum rate of mass loss
s	Stoichiometric conditions

12.1 Introduction

In the future decades, developing countries will be confronted with rising fossil fuel prices and climate change. To adequately and coherently overcome these challenges, they will certainly need an energy transition and resilient pathways through which they can achieve economic growth. This transition needs to promote clean and energy-saving (or energy-efficient) technologies, especially those of renewable resources (solar, wind, and hydropower) and biomass. Bioenergy is the largest form of renewables in use today. It is used in the industrial and transportation sectors, as well as for heating, cooking, and power generation through appropriate technologies (combustion and/or gasification). In developing countries, biomass and various wastes are abundant renewable resources that could reduce greenhouse gas emissions when used in efficient conversion systems compared to fossil fuels. Furthermore, the use of these products would increase farm incomes and improve soil quality. The competitiveness of biomass energy depends mainly on conversion system technologies and the availability of low-cost feedstocks, such as straw, crop waste, and agricultural or forestry residues. For these reasons, capacity factors for bioenergy plants are varied. Thus, between 2010 and 2019, the global

Table 12.1 Evolution of solid biomass use for energy in the IEA bioenergy member countries and comparison with the domestic forest areas

Country	GJ solid biomass/capita				GJ/hectare forest (2019)
	2005	2010	2015	2019	
Brazil	9.86842	12.23684	12.85088	13.24561	7.41176
China	4.82456	3.46491	2.80702	2.80702	21.41176
India	4.84277	5.72327	5.34591	5.59748	132.58824
South Africa	6.28931	6.79245	5.59748	5.59748	19.76471
Sweden	33.33333	39.90826	38.3792	40.21407	14.82353
USA	7.03364	6.88073	6.88073	7.49235	8.23529
EU28	6.72783	8.7156	9.02141	9.78593	32.11765

Adapted from IEA bioenergy countries' Report-update 2021 (Pelkmans 2021)

weighted-average capacity factor for bioenergy projects ranged from a low of 65% in 2012 to a high of 86% in 2017 (IRENA 2020). In 2019, the levelized cost of electricity (LCOE) ranged from a low of 0.057$/kWh in India and 0.059$/kWh in China to 0.08$/kWh in Europe and 0.099$/kWh in North America (IRENA 2020).

To clarify expectations, the solid biomass potential is presented in Table 12.1. This category of organic waste consists of wood and its derivatives and agricultural residues such as bagasse and straw. It remains the dominating type of biomass used for energy in all countries which have a high domestic forest area per capita and considerable wood processing industries. It shows that the highest energy levels from solid biomass (per capita) are reached in Sweden (developed country), whereas developing countries (Brazil, China, India, and South Africa), the USA, and the European Union (EU28) have low energy levels. The last right column of Table 12.1 also exhibits the amount of solid biomass used for energy in 2019 in terms of domestic forest areas.

The organic wastes conversion is quite often carried out by using different thermochemical conversions, namely pyrolysis, torrefaction, combustion, gasification, and hydrothermal carbonization

12.2 Organic Wastes Characterization

The conversion of energy from biomass to other forms of energy needs the knowledge of the physicochemical properties of each biomass predisposed to be a candidate for the chosen conversion technology. This technology could account for differences in the physical characteristics of the biomass and the proximate composition which can vary greatly in terms of moisture and ash content. Moreover, many conversion technologies are in need of ultimate analysis (elemental composition or elemental (C, H, N, S, O)) too (D. Yogi Goswami and Kreith 2008).

12.2.1 Physicochemical Properties of Biomass

12.2.1.1 Physical Characteristics

Bulk density and particle size are the two major physical properties that should be considered in designing conversion systems for biomass handling. The bulk density of a biomass is influenced by the size, shape, moisture content, particle density, and surface characteristics. For example, hollow wheat straw particles have wet and dry density bulk ranging from 24 to 111 kg.m^{-3}. This biomass is composed of cylindrical shape particles whose lengths range from 6 to 50 mm and moisture content varies from 8% to 60% wet basis (w.b) (Lam et al. 2008).

12.2.1.2 Chemical Characteristics

The chemical properties of a biomass constrain the choice of the thermochemical conversion process. The most important characteristics of biomasses concern ultimate (or elemental) and proximate analyses.

Ultimate Analysis

The chemical elements of a solid biofuel (biomass) have varying concentrations according to their types and origins. In the organic phase, the ultimate (or elemental) analysis gives the composition of biomass essentially as weight percentages of six major elements, namely carbon (C), hydrogen (H), and oxygen (O) as well as nitrogen (N), sulfur (S), and chlorine (Cl) if any one of those elements exists. In fact, the Cl significant content is present in certain biomass materials like municipal and animal wastes, herbaceous biofuels, fruit residues, and grains. During thermochemical conversion, this element (Cl) can react with other elements to form chloridric acid (HCl), Cl_2, KCl, and NaCl. Consequently, it may be a possible pollutant and corrosive agent in combustion and gasification conversion processes.

It should be noted that American Standard Testing Methods (ASTM) is usually used to carry out the elemental analysis. Furthermore, this analysis is used to determine the empirical chemical formula of a biomass and allows for establishing models for predicting its higher heat value (HHV) (Vargas-Moreno et al. 2012). In order to clarify and elucidate that issue, Tables 12.2 and 12.4 display the ultimate analysis of olive pomace, argan nut shell, and miscanthus, respectively.

Table 12.2 Elemental analysis and high heat value of olive pomace and argan nut shell

Elemental analysis (%)	C (%)	H (%)	N (%)	S (%)	O (%)	HHV (MJ/kg)
Olive pomace (Elorf et al. 2016)	59	8.5	1.5	0	31	21.3
Argan nut shell (Rahib et al.; 2021)	51.33	6.32	0.005	0	42.35	20.6

Proximate Analysis

Chemical characteristics essentially concern proximate and ultimate analyses. In addition, proximate analysis covers the determination of moisture content (MC), volatile matter (VM), and ash (Ash). As for the calculation of the fixed carbon (FC), it is given by Eq. (12.1):

$$FC(\%) = 100 - \left[MC(\%) + Ash(\%) + VM(\%) \right] \tag{12.1}$$

The proximate analysis can be done by ASTM (American Society for Testing and Materials) methods (Milne et al. 1990), thermogravimetric analysis (TGA), or differential thermogravimetric (DTG) (Klass 1998).

Usually, the high heat value (HHV) is required with proximate analysis too. HHV of a fuel sample is the higher amount of heat released when a unit mass of the fuel is burned. It is measured using oxygen bomb calorimeter in which a specified mass of sample is burned under standardized conditions. As with ultimate analysis, Table 12.4 shows an example of proximate analysis of olive pomace (OP) and miscanthus.

12.2.2 Types of Biomasses

Lignocellulosic biomass is the oldest energy source after the sun. It is the most renewable organic material such as wood, crops, plants, and animal wastes. Biomass gets its energy from the sun via the photosynthesis process since sunlight provides plants with their energy needs to convert water and carbon dioxide into oxygen and sugars. Due to its unlimited supplies, biomass is considered a renewable energy source. Developing countries have a diversified and abundant potential biomass such as rice straw (China, India, Indonesia, …), sugarcane bagasse (Brazil, India, China, …), wheat straw (China, India, Argentina, …), and maize straw (China, Brazil, Mexico, South Africa, …).

12.3 Gasification and Pyrolysis

Pyrolysis and gasification are high temperature thermochemical conversion technologies for converting biomass and waste into gaseous fuel. Different technologies are used for this purpose including fixed bed, entrained flow, and fluidized bed.

In pyrolysis, when the organic material is subjected to an intense temperature gradient, under an inert atmosphere (argon), it decomposes producing gases (pyrolysis gases: H_2, CO, CO_2, CH_4, C_2H_4, C_2H_5, C_2H_6, C_6H_6, C_3H_4, C_3H_6, C_3H_8, C_4H_{10}, H_2S, C_7H_8, C_2H_5OH, C_2H_4O) (Elorf et al. 2021) and a solid product namely char and tars (composed of a mixture of water and several hundred oxygenated organic compounds whose composition depends on the initial biomass) (Evans and Milne 1987).

Depending on the temperature and the heating rate, there are three types of pyrolysis:

- Slow pyrolysis (T = 350–600 °C and heating rate $k \leq 10$ °C/min).
- Fast pyrolysis (T = 600–800 °C, $10 \leq k \leq 50$ °C/min) generally is used to maximize the yield of liquid bio-oil products.
- Flash pyrolysis (T = 450–600 °C, $k \geq 50$ °C/min and residence time less than 1 s). Yields of flash pyrolysis oil can be as high as 60–70 wt.% under optimized conditions (Ighalo et al. 2022).

The heating rate has a great influence on the pyrolysis process. When it is high, it leads to the rapid formation of volatile matter with a high C/H ratio. Conversely, slow pyrolysis at low temperatures (between 300 and 400 °C) promotes char production.

During pyrolysis, temperature of biomass particles is highly variable. Certainly, the temperature rise is difficult to control because it is ruled by competitions between chemical kinetics and heat transfers. Heat transfers in the particle are subject to different parameters: particle size, humidity, thermal conductivity of the material, etc. Temperature and heat flux density have influence on the overall distribution of pyrolysis products. The geometry of the particles to be pyrolyzed is an important parameter if the size is too high and the residence time of the tars within the particles increases, which can cause the degradation of these tars via intraparticle secondary reactions. The mass yield of the pyrolysis products, which represents 30% of char, 30% of condensable, and 30% of gas, for a heat flux density less than 10 kW/m^2 and a temperature value less than 500 °C (primary pyrolysis), becomes approximately 60–75% of condensable for a heat flux density greater than 10 kW/m^2. When the temperature becomes greater than 700 °C (secondary pyrolysis), the gases represent more than a third of the products for a heat flux density <10 kW/m^2 and reach 80% of the pyrolysis products for heat flux density values >10 kW/m^2.

Pyrolysis is also a preliminary phase to gasification. When the oxidizing agent is present with limited quantity in the pyrolysis process, partial gasification is obtained. Conversely, when this oxidizing agent is present in sufficient quantity, the thermochemical process is a combustion phase.

12.3.1 Gasification

Like pyrolysis, gasification is a thermochemical process of converting biomass or waste into a mixture of combustible and non-combustible gases called syngas. This process takes place in a gasifier. The combustible fraction of syngas consists of methane (CH_4), carbon monoxide (CO), and hydrogen (H_2), and the non-combustible fraction consists of carbon dioxide (CO_2), moisture (H_2O), and nitrogen (N_2).

There are several types of gasifiers: moving bed gasifiers and fixed-bed gasifiers which can be classified as updraft, downdraft and double fire throated gasifiers, and bubbling or circulating fluidized bed gasifiers. Figure 12.1 provides a schematic view of some gasifier types.

The choice of gasification process type rests on several parameters such as the installation fuel consumption (in kg/h), power range (10–10,000 kW for fixed-bed gasifiers and 5–100 MW for fluidized-bed), the biomass or waste used, and the downstream gas application.

12.3.2 Fixed Bed Gasifiers

The first gasification technology that emerged is fixed-bed gasifiers. Fixed-bed processes are generally easy to make and operate. They are the most chosen for small- to medium-scale heat and power production. In updraft or downdraft fixed-bed gasifiers, the fuel, consisting of biomass or waste, forms a dense bed inside the reactor which moves vertically. Biomass is introduced at the top of the gasifier in updraft processes, the gasifying agent is introduced at the bottom, and syngas is recovered at the top. However, in a downdraft gasifier (Fig. 12.1b), the biomass is introduced at the top, as in an updraft gasifier, the gasifying agent is introduced in the middle at the level of the throat and the syngas is recovered at the bottom.

The gas produced in the updraft process is heavily laden with tar. The tar which forms during the pyrolysis phase flows upward to the cooler region. On the other hand, the downdraft process promotes tar cracking. Indeed, tar production is low because the tar produced during the pyrolysis phase crosses the combustion zone and a large part is converted. Nevertheless, to produce gas without tar or with very small quantities of tar, a cleaning system must be provided.

Finally, it can be noted that fixed bed gasifiers support large particles. The particles constituting the fuel can have a dimension ranging between 2 and several millimeters. The residence time required for gasification is counted in hours.

12.3.3 Bubbling and Circulating Fluidized Bed Gasifiers

The other category of gasifier is bubbling fluidized bed gasifiers (Fig. 12.1c) and the circulating fluidized bed (Fig. 12.1d) which suits for the medium and large scale and for which the particle sizes is limited up to 20 mm that needs the grinding of the raw material. This process requires higher fluidized bed velocity to suspend the particle bed (Grace et al. 2006) and produce a high level of mixing between biomass and bed material which makes it possible to achieve a biomass thermal conversion system of around 96% (Sansaniwal et al. 2017). This is due to the partial oxidation of most of the carbon contained in the biomass. As a result, smaller amounts of tar are generated (no more than 20 g/mm^3 for bubbling and 5 g/mm^3 for circulating fluidized bed) (Valderrama Rios et al. 2018).

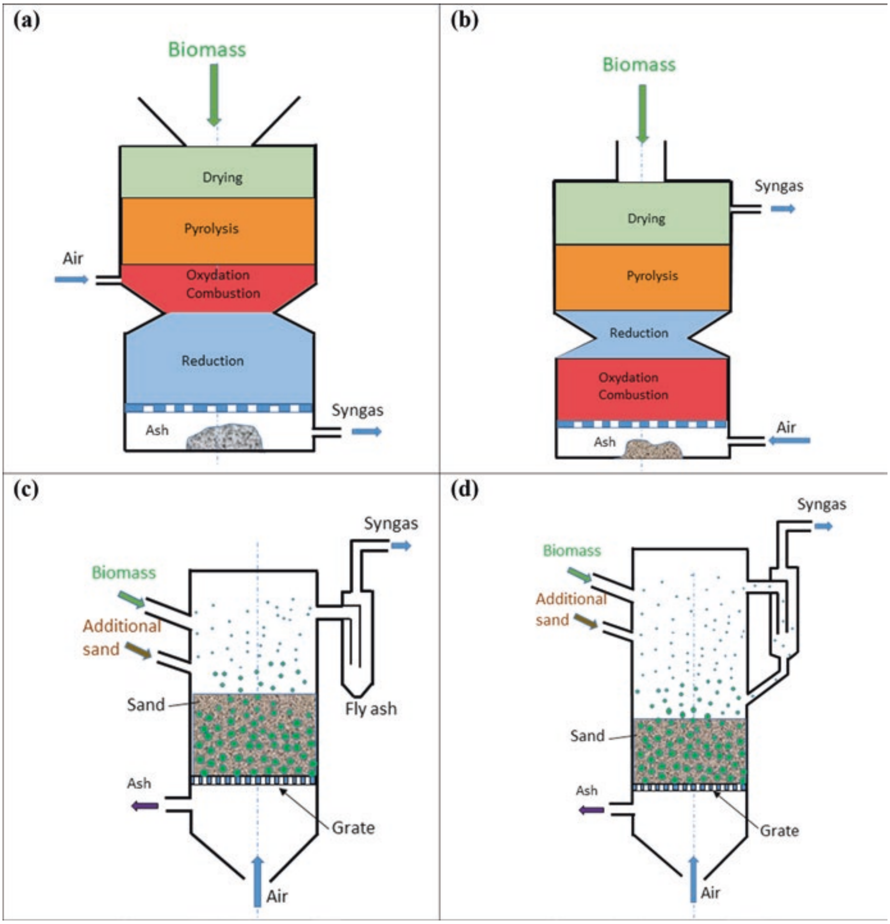

Fig. 12.1 Schematic of gasifiers: Fixed bed [(**a**) downdraft, (**b**) updraft], (**c**) bubbling fluidized bed, (**d**) circulating fluidized bed

12.3.4 Gasification Process

In a gasifier, the gasification process generally involves four phases:

- Drying in which the moisture content in the biomass or waste is vaporized and humidity is converted into steam. This step takes place up to a temperature of about 200 °C so that the moisture content drops below 20%, allowing the favorable moisture condition for gasification to be reached.
- Pyrolysis is in which biomass components are decomposed into volatile compounds (gas pyrolysis and tar) and solid residues (char).

- Oxidation or partial combustion takes place in the presence of a gasifying agent. In the gasification process, the oxygen quantity is lower than the theoretical requirement in the combustion process.
- Reduction or gasification occurs in the presence of other gasifying agents such as CO_2 and water vapor.

These phases entail reactions that happen at the same time in the gasification process (Watson et al. 2018). The main reactions in this zone during the air gasification process are as follows (Gai and Dong 2012; Mandl et al. 2010; Patra and Sheth 2015):

$$\text{Pyrolysis: } CH_xO_y \rightarrow \text{Tar} + \text{Char} + \text{Gases}\left(H_2; CO; CH_4; CO_2; H_2O; C_nH_m\right) \tag{12.2}$$

$$\text{Oxidation: } C + 0.5O_2 \rightarrow CO \qquad \Delta H = -111\,\text{kJ/mol} \tag{12.3}$$

$$C + O_2 \rightarrow CO_2 \qquad \Delta H = -394\,\text{kJ/mol} \tag{12.4}$$

$$\text{Boudouard: } C + CO_2 \leftrightarrow 2CO \qquad \Delta H = +172\,\text{kJ/mol} \tag{12.5}$$

$$\text{Water-gas: } C + H_2O \rightarrow CO + H_2 \qquad \Delta H = +131\,\text{kJ/mol} \tag{12.6}$$

$$\text{Water-gas shift: } CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = +41\,\text{kJ/mol} \tag{12.7}$$

$$\text{Methanation: } C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H = -75\,\text{kJ/mol} \tag{12.8}$$

$$\text{Methane reforming: } CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H = +206\,\text{kJ/mol} \tag{12.9}$$

In the gasification process, where several reduction reactions occur, the gas production is impacted by the reaction temperature. Endothermic reactions are thus favored when the temperature increases, which improves the process.

12.3.5 Gasification Modeling

In the gasification process, the reactions generated are complex and factors such as moisture content, biomass feedstock composition and operating parameters (temperature, pressure, air/biomass ratio, etc.) have an important effect on the gas produced. To understand the effect of each parameter on the performance of gasification systems, mathematical modeling for the gasification process has developed (kinetic models, artificial neural networks, CFD, thermodynamic equilibrium model) (Silva et al. 2019). In the stoichiometric equilibrium model, the chemical reaction equilibrium constant method is used, while the non-stoichiometric equilibrium model uses Gibbs free energy minimization. Note that the equilibrium approach is independent of the gasifier design. In the kinetic models, the reaction kinetics and species transport equations are solved, and the temperature and composition profiles of the products at different positions along the gasifier are described. In computational fluid dynamics (CFD), mass, momentum, energy, and species transport conservation equations, turbulence models, and multiphase flow models in a space-time domain of a gasifier are solved for the prediction of temperature and concentration profiles in all regions of the gasifier.

12.4 Biomass Combustion

Combustion is the thermochemical process intended to produce heat directly. Ligneous biomass is made up of forest or agri-food residues: bark, branches, straw, sawdust, wood pellets, etc. It is used as fuel to supply a boiler, a hot air generator, or a wood oven. Thus, this primary energy is used to obtain hot water, hot air, or steam. Steam is used, among other things, to produce electricity.

The use of biomass as an energy source contributes to the natural carbon cycle; the amount of carbon dioxide (CO_2) released into the atmosphere during the combustion corresponds to that absorbed by the biomass by photosynthesis. Sectors that do not require significant energy consumption to grow and process raw biomass have a favorable CO_2 balance.

Energy recovery from wood and biomass is the leading source of renewable energy in France and Europe. In the latter, wood and biomass represent approximately 65% of renewable energy consumption and in France just over 50%, including 75% of thermal energy (the second renewable energy is hydropower, used to produce electricity) (Rogaume 2009). Even though numerous research and development works aimed at developing new ways of energy recovery (pyrolysis, gasification, liquefaction, etc.), more than 95% of the current recovery is carried out by direct combustion in plants whose power and technology vary considerably. Besides, among the biomasses of plant origin, wood is the vast majority of these systems.

12.4.1 Principle of Biomass Combustion

Biomass combustion is a complex process that includes transfers of heat and matter and reactions in homogeneous and heterogeneous phases. Its main stages are as follows (Nussbaumer 2003; Rosendahl 2013):

– Drying
– Pyrolysis
– Oxidation reactions in the gas phase
– The gasification/combustion of char

During the heating of biomass, its constituents are hydrolyzed, oxidized, dehydrated, and pyrolyzed as temperature increases, forming condensable and non-condensable volatile species, as well as coal with high carbon content. At the ignition temperature of the volatile species and in the presence of oxygen, exothermic reactions (combustion) are triggered. The major combustion products (CO_2 and H_2O) can also react with the residual char during its oxidation.

The stoichiometric combustion (ideal combustion) of a $C_\alpha H_\beta O_\gamma$ hydrocarbon with air can be expressed by the following equation:

$$\mathbf{C}_a\mathbf{H}_b\mathbf{O}_g + \left(a+\frac{b}{\mathbf{4}}-\frac{g}{\mathbf{2}}\right)\left(\mathbf{O_2}+\mathbf{3.76N_2}\right) \rightarrow a\mathbf{CO_2}+\frac{b}{\mathbf{2}}\mathbf{H_2O}+\mathbf{3.76}\left(a+\frac{b}{\mathbf{4}}-\frac{g}{\mathbf{2}}\right)\mathbf{N_2} \tag{12.10}$$

The coefficients associated with each species in Equation (12.10) (marked in **bold**) are called stoichiometric reaction coefficients. The amount of air needed to burn a stoichiometric mixture is called stoichiometric or theoretical air. The approximate standard composition of dry air is about 21% oxygen and 79% nitrogen, hence the value of 3.76.

In fact, the combustion is non-stoichiometric, i.e., the fuels are often burned with a quantity of air different from the theoretical ratio. If less than the stoichiometric air is used, the mixture is described as rich in fuel. If excess air is used, the mixture is considered as lean in fuel. For this reason, it is convenient to quantify the combustible mixture using the two main relations: equivalence ratio (ER or Φ) and fuel-air ratio (FAR).

The air-fuel ratio, AFR, is defined as the mass of air supplied to a combustion system per unit mass of fuel during combustion, namely:

$$\mathrm{AFR} = \frac{\mathrm{Air\ used\left(kg/time\ \ unit\right)}}{\mathrm{fuel\ \ used\left(kg/time\ \ unit\right)}} = \frac{\mathrm{m_a}}{\mathrm{m_c}} \tag{12.11}$$

where m_a and m_c are the respective masses (or flow rates) of air and fuel.

The inverse of AFR is also used, fuel-to-air ratio, **FAR = 1/AFR.** The equivalence ratio (Φ) of a system is defined as the ratio of the real fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio. Mathematically,

$$\Phi = \frac{\mathrm{FAR_{real}}}{\mathrm{FAR_s}} \tag{12.12}$$

The subscript "s" indicates a value under stoichiometric conditions. For $\Phi < 1$, the mixture is considered lean; for $\Phi = 1$, the mixture is stoichiometric; and for $\Phi > 1$, the mixture is considered rich. The inverse of Φ is also used, air factor, $\boldsymbol{\lambda = 1/\Phi}$.

Generally, combustion products include many different species in addition to the main species (CO_2, H_2O, N_2, O_2). The equilibrium of the stoichiometric equation requires the use of thermodynamic equilibrium relations. If the combustion products contain only major species (complete combustion) and excess air, the overall lean combustion equation ($\Phi < 1$) is written as follows:

$$C_\alpha H_\beta O_\gamma + \frac{1}{\Phi}\left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right)(O_2 + 3.76\,N_2) \rightarrow \alpha\,CO_2 + \frac{\beta}{2}H_2O + \frac{3.76}{\Phi}$$
$$\left(\alpha + \frac{\beta}{4} - \frac{\gamma}{22}\right)N_2 + \left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right)\left(\frac{1}{\Phi} - 1\right)O_2 \tag{12.13}$$

As a result of the combustion process, different types of pollutants can be distinguished:

- Unburnt pollutants such as CO, C_XH_Y, PAH, tar, soot, unburnt carbon, H_2, HCN, NH_3, and N_2O
- Pollutants from complete combustion such as NO_x (NO and NO_2), CO_2, and H_2O
- Ash and contaminants such as ash particles (KCl, etc.), SO_2, HCl, PCDD/F, Cu, Pb, Zn, Cd, ...

12.4.2 Used Technologies

Burning waste is an old process that reduces its volume and recovers energy. The mastery of this technology in a closed fireplace is much more recent. Indeed, the first urban waste incinerators date back to the beginning of the last century in Europe. This technology then developed with the inexorable increase in the quantity of urban waste throughout the twentieth century. It makes it possible to reduce the volume of this waste by around 90%, recover energy from this waste, and restrict landfilling to final waste only.

Energy recovery from biomass through combustion has benefited from the development of the thermal waste treatment chain. This processing chain is made up of five elements:

1. The combustion equipment supply system
2. The combustion equipment (furnace, burner)
3. A possible energy recovery system
4. A flue gas analysis and treatment device
5. A storage space for solid residues after combustion

The varying shapes and characteristics of the solids to be burned require different combustion plants. The most used technologies are (Tillman 1987) the following:

- Grate kilns
- Fluidized bed kilns
- Rotary kilns
- Pulverized carbon kilns

The grate kiln is the most used incineration process for urban waste. The block diagram is shown in Fig. 12.2. Generally, the combustion zone can be divided into three parts as shown in Fig. 12.2. The distribution of the primary air under the grate is done by means of boxes, the number of which varies according to the installations.

For units with a high treatment capacity, it is generally a furnace-boiler assembly. Several types differ in shape, size, or even the inclination of the grid, thus giving different movements to the waste. Grid dimensions depend on the heat value of the fuel and the load

12.4.3 Technical Issues Related to Biomass Combustion

Three main phenomena can occur during the combustion of biomass and affect the operation of the combustion equipment used, or even damage it: the formation of bottom ash, the fouling of the heat exchange zones, and corrosion (Demirbas 2007; Khan et al. 2009; Sommersacher et al. 2012).

12.4.3.1 Formation of Bottom Ash

Bottom ash is a pile of partially melted ash. The bottom ash formation process is associated with the phenomenon of sintering (agglomeration of particles under heat effect) and partial melting of ash particles. Bottom ash deposit on a burner for pulverized biomass boilers can cause burner ignition problems or other operational difficulties and affect combustion performance. On the heat exchange surfaces of the combustion chamber, the bottom ash reduces the heat absorption capacity of the furnace. Among the compounds that promote the formation of bottom ash, we can

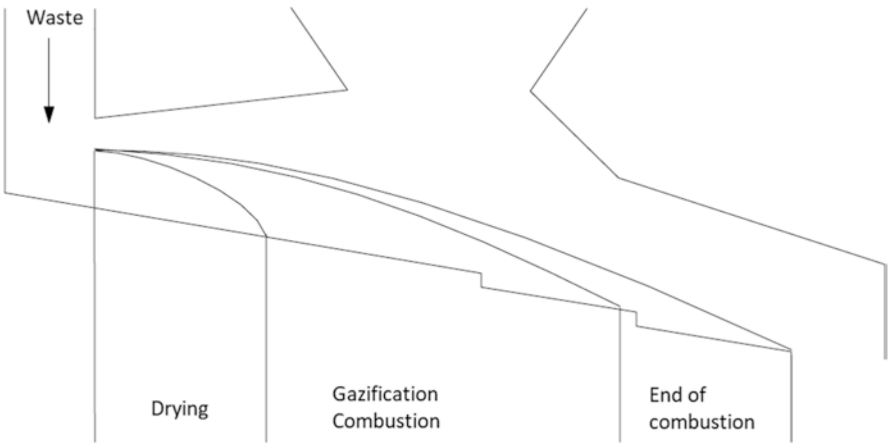

Fig. 12.2 Schematic diagram of a grate kiln

mainly mention alkalis, mainly potassium (K) and sodium (Na), silica (Si), sulfur (S), and chlorine (Cl).

The design of the boiler/furnace can limit the appearance of bottom ash. Temperature close to the combustion chamber wall should, for example, be low enough to avoid the melting of ash on these walls, the starting point for the formation of bottom ash.

12.4.3.2 Fouling of Heat Exchange Zones

Ash deposition "fouling" can occur in the convection zones of boilers on the heat exchange surfaces where the temperature of the flue gases decreases. This causes the reduction of heat absorption capacity of the convection zones of the boilers and an increase in the gas outlet temperature. If the fouling is severe, it can increase the pressure drop in the heat exchanger tubes. The main technical means of destroying ash deposits in convective zones is the use of compressed air or steam guns, which by mechanical impact and thermal shocks allow the breaking of deposits to eliminate them.

12.4.3.3 Corrosion

The corrosion is caused by different mechanisms: the direct attack of gaseous HCl or Cl2 on the heat exchange surfaces; the formation of chloride and/or alkaline sulfate deposits, which dissolve the oxide layer protecting the heat exchange surfaces; and the sulfation of chlorides of alkali metals and heavy metals deposited on the exchange tubes, which results in the release of Cl, which can then attack the surface of the tube and lead to its corrosion. Among the technical solutions to prevent corrosion, we can mention the use of specific alloys or coatings. Lowering the temperature of the water or water vapor in the heat exchange tubes also makes it possible to reduce the temperature of their metal surface and thus reduce the rate of corrosion.

12.4.4 Biomass Combustion: CNRS-ICARE Boiler

12.4.4.1 Experimental Setup

As part of the VERA 2015–2018 project (France – Morocco), we developed a biomass boiler (Fig. 12.3) for the combustion of agricultural residues, and, in particular, olive pomace and argan nut shells. The biomass supply is done by the supply tank (biomass storage hopper) and an endless screw to convey the fuel inside the chamber. In the boiler, the biomass is distributed with a rotating leveler at the bottom of the chamber. The air supply is done by a fan driven by a variable speed motor and, therefore, an adjustable airflow after calibration. The flame develops vertically along the chamber; the combustion products pass through a cyclone and then a

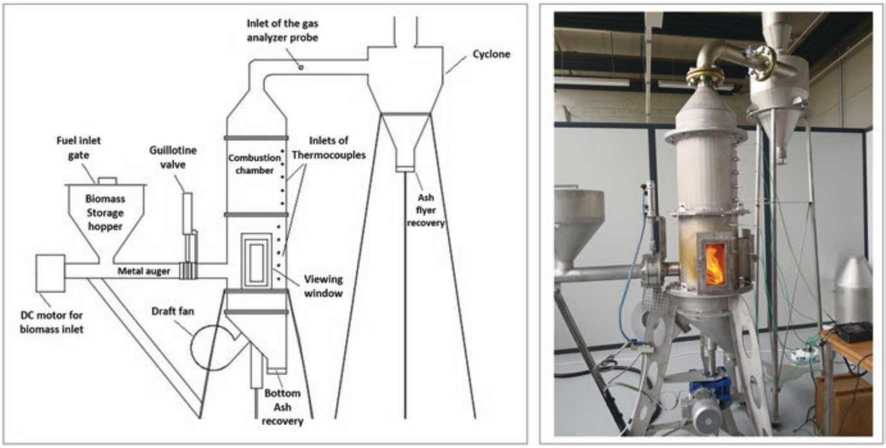

Fig. 12.3 VERA biomass boiler developed at ICARE-CNRS, diagram of the entire installation (left), photo of the boiler (right)

Table 12.4 Properties of selected biomass materials

	OP	Miscanthus
Proximate analysis (%)		
MC	7.4	9.8
VM	74.2	69.4
FC[a]	16.1	20.4
Ash	2.3	0.4
Ultimate analysis (%)		
Carbon	53.5	53.4
Hydrogen	6.8	4.4
Nitrogen	1.1	0.48
Sulfur	–	0.3
Oxygen[a]	38.6	41.3
HHV[b] (MJ/kg)	22.5	16.8

Jayaraman and Gökalp (2015) and Missaoui et al. (2017a, b)
MC moisture content, *VM* volatile matter, *FC* fixed carbon
[a]By difference
[b]Higher heating value

smoke scrubber to remove particles and possibly odors. The boiler has a viewing window, full-height thermocouples, and a multi-gas analyzer installed at the chamber outlet.

Many thermo-physical analyses were performed (TGA, elemental analyses, heat value measurements) to determine the properties of the biomasses used before the combustion stage (Bennini et al. 2019; Elorf et al. 2016; Rahib et al. 2021). As an example, Table 12.2 gives the elemental analysis results (C, H, N, S, O) and the caloric value for given samples of olive pomace and argan nut shells (ANS). Note that the calorific value is high, which allows two biomasses to be a substitute for wood or coal in heat production systems. Elemental analysis gives high levels of carbon and oxygen and relatively low levels of hydrogen and nitrogen. No trace of sulfur is observed in these types of biomasses.

12.4.4.2 Combustion of Olive Pomace

Figure 12.4 illustrates examples of flames obtained according to the granulometry of olive pomace: raw particles (1–20 mm), medium size (1–5 mm), and fine size (<1 mm). It was observed that the flame develops better with raw- or medium-sized biomass compared to that obtained with fine particles. This is due probably to the high density of the biomass bed with the fine particles that somehow weakens the injection of air into the combustion zone, which leads to poor mixing between the reactants.

Figure 12.5 shows the maximum temperatures obtained as a function of AFR (air-fuel ratio) for the combustion of 1 kg of raw olive pomace. The Ti readings indicate values above 600 °C in the combustion products. These results are extremely

Fig. 12.4 Example of flames obtained according to the particle size of olive pomace

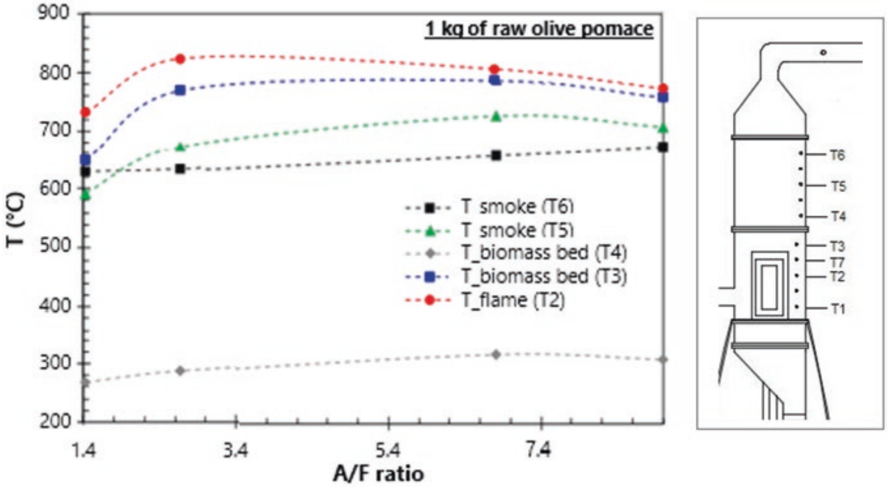

Fig. 12.5 Temperature variation according to the AFR (air-fuel ratio) at initial injection

Table 12.3 Variation of gas emissions according to AFR and particle sizes

Mass	0.5 kg raw pomace		0.5 kg medium particles		0.5 kg fine particles		
Total time (min)	09:00		10:00		13:00		
Measurement time	02:00	04:00	02:00	06:00	04:00	08:00	10:00
Air flow rate (m^3/h)	10		9	22	8		21
AFR	3.5		3.5	8.7	3.5		10.7
O_2%	7.1	13.7	11.4	15.8	…	…	…
CO_2%	14.27	9.43	10.8	5.35	5.38	3.1	2.03
CO%	1.264	0.622	0.498	0.713	0.356	0.286	0.27
NO ppm	138	199	155.5	82	44	34	64
NO_2 ppm	2	0	9.5	9	18	40	10
NO_x ppm	139	199	165	91	61	75	74

promising for use in heating/DHW and eventually to produce steam which can be used with a micro turbine to produce electricity (Creyx et al. 2016).

Table 12.3 shows the evolution of pollutant emissions for three samples of olive pomace with different grain sizes: raw particles, medium-diameter particles (1–5 mm), and small-diameter particles (<1 mm). Experiments were conducted by sometimes varying the air flow (from rich to the lean regime), knowing that the stoichiometric AFR is estimated at 6.9. In general, relatively correct NO_x emissions are observed, between 50 and 200 ppm depending on the flow conditions, size of biomass, and measurement time. CO emissions globally are high, but the rate naturally decreases with excess air. These rates are usually obtained for biomass boilers. This high CO in the fumes is probably due to poor mixing in the biomass bed. The air would not necessarily pass through all the areas where biomass particles are present on the perforated air inlet plate. It would be better to modify the air intake plate by making more holes with fewer gaps. Note that the combustion of this biomass visibly produces a lot of soot, given the color of the flame, the high presence of the CO level, and the recovery of small black particles at the level of the cyclone. The formation of soot depends strongly on the nature of the fuel, the behavior of the flame, and the local equivalence ratio (Desgroux et al. 2013) which is linked to input parameters such as the air flow rate and the size of particles.

Experiments were also done on argan nut shell biomass (ANS) as presented in Rahib et al. (2021).

12.5 Hydrothermal Carbonization (HTC)

12.5.1 General Concept

HTC is a process that uses water and heat to transform biomass or residues into carbon compounds (Fig. 12.6). This transformation results in decarboxylation and hydrolysis reactions but also polymerization reactions allowing the production of secondary hydrochar (Zhao et al. 2014). The biomass-to-water mass ratio can vary from 1:2 to 1:10, making it possible to work with wet residues such as sewage sludge, olive pomace, bagasse, and also fishery waste, algae, and animal waste. This hydrothermal treatment on wet residues avoids the drying phase needed in the case of pyrolysis or gasification or direct combustion of biomass.

Water plays the role of solvent, but HTC exploits the physicochemical properties of water which evolve with temperature. HTC is usually produced in closed reactors that produce autogenous pressure. Note that water at 180 °C has an equilibrium pressure of 1 MPa and about 4 MPa at 250 °C. The technology used should therefore take into account the rise in pressure. This pressure management makes HTC

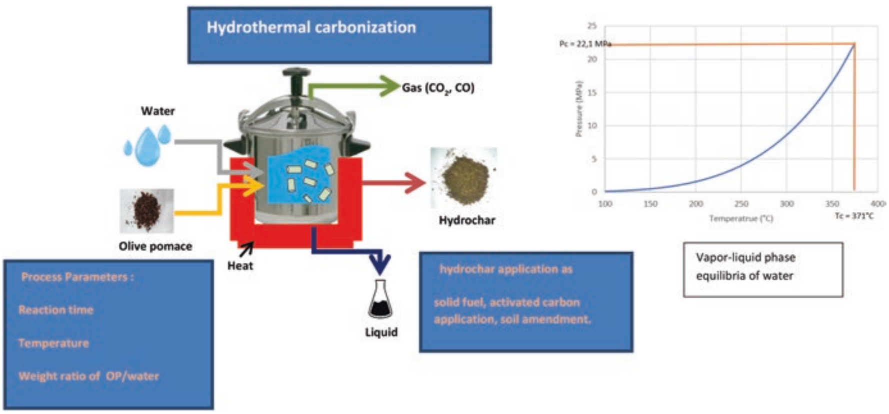

Fig. 12.6 Schematic illustration of the hydrothermal carbonization process

more constraining to gasification or pyrolysis. Furthermore, the water reaches supercritical conditions for a temperature of 371 °C and a pressure of 221 bars. Under these conditions, the density of water is about 0.3 g/cm^3. This density is about 3 times less dense than water at 25 °C and about 1000 times denser than water in the vapor state at 1 bar. The ionization constant of the water can reach a value of 10^{-11} mol^2.kg^{-1} corresponding to a value of 1000 times greater than that obtained at ambient temperature. This evolution increases the concentration of protons and free hydroxyl ions by 30 times, thus favoring catalytic reactions. Moreover, the evolution of the dielectric constant (ε) is surprisingly observed. This constant decreases to 2.5 at 250 bars and for a temperature of 400 °C giving it a polarity equivalent to that of acetone. These conditions allow solubilizing of the organic compounds (Kruse and Dinjus 2007).

Water also denatures plant cell walls and degrades the main biomass constituents which are hemicellulose, cellulose, and lignin. In the biomass compounds not mentioned, we have extractable compounds (which are soluble compounds in toluene or acetone according to the protocols put in place to quantify the three major compounds), proteins, lipids, and mineral compounds. The decomposition phases will be different depending on the chemical families. For the three main compounds, their decompositions are carried out by the first hydrolysis which will release molecules of lower molecular weight. Thus, α-cellulose (polymer consisting of glucose units bound together by alpha 1–4 bonds) decomposes into polysaccharides and hexoses (glucose, fructose). These oses then undergo dehydration to form furfurals and organic acids (Bobleter 1994; Wang et al. 2018). At the same time, these furfurals can condense to make polymers. These polymers will form secondary char (Sangare et al. 2022). For hemicellulose, the more complex polymer of pentoses xylose and hexoses, its decomposition pathways are quite similar, but the carbohydrate unit obtained is a pentose called xylose. In contrast to cellulose and hemicellulose, lignin has an aromatic structure based on three compounds: the p-coumaryl, coniferyl, and sinapyl alcohol. Thus, its decomposition path is different. In a simplified way, part of this lignin will solubilize in oligomers which will give phenolic compounds, and aldehydes. These compounds will form polymers giving an aromatic hydrochar. On the other hand, some of the lignin will not solubilize. This insoluble part is also a polyaromatic hydrocarbon similar to that obtained by pyrolysis, which may be called primary carbon. So, the contents of cellulose, hemicellulose, and lignin have a significant influence on the hydrochar porosity, surface functional group, and thermal stability. For example, this is observed during TG analyses, by the values of the characteristic peak of decomposition of hemicellulose which is around 295 °C; for cellulose 350 °C and for lignin, its characteristic peak is wider between 360 and 700 °C.

Moreover, hydrothermal treatments generate three different phases: a solid phase called hydrochar, an oil phase called biocrude or bio-oil, and a gas phase. In the range of process temperatures between 180 and 260 °C, the largest phase is solid. This is hydrothermal carbonization (HTC). For temperatures between 260 °C and the supercritical temperature (371 °C), the major phase will be the biocrude. This is hydrothermal liquefaction. Its application allows the production of biofuels that must undergo treatment for their use (Deuber et al. 2021). Finally, for temperatures above the supercritical temperature, the main phase will be the gas whose composition will mainly be CO, CO_2, CH_4, and H_2 (syngas) which are the ultimate stage of decomposition of the main biomass compounds. It is the supercritical water gasification (SCWG) (Graz et al. 2016; Kruse 2008).

12.5.2 Potential Hydrochar Applications

In the context of the HTC, hydrochar has several ways of valorization which are the use as solid fuel, as an activated carbon, or as soil remediation.

12.5.2.1 Solid Fuel Application

To assess the quality of the hydrochars, the following combustion characteristics are used: the HHV (in MJ/kg), the volatile matter (VM), fixed carbon (FC), and ash fractions (in %) which are obtained owing to the proximate analysis. However, we can also determine the ignition (T_i), maximum reaction rate (T_m), and burnout temperature (T_b) by identifying the relevant point of (TG-DTG) analyses. T_i is associated with which the fuel is likely to self-ignite. T_b corresponds to the temperature stabilized for a rate loss of weight less than 1%/min when the sample is completely oxidized (Sangare et al. 2020; Zhang et al. 2020). Furthermore, a combustibility index (SN) can be expressed, and the more its value is high, the better the combustion characteristic.

12.5.2.2 Activated Carbon Application

Hydrochar has a great interest as carbon materials are used, for example, as absorbents for gas purification, water treatment, and energy storage. The textural properties of the activated carbon (AC) prepared from hydrochar were studied by N_2 and CO_2 gas adsorption to give the surface areas and the pore volumes. The treatments studied focus on their impact on their BET surface and the volume of pores generally. For instance, BET surface values of 673 m^2/g were obtained for hydrochar produced from glucose (Fechler et al. 2013).

12.5.2.3 Soil Amendment

The hydrochar can be used as a soil amendment to sequester carbon and enhance soil quality by improving the soil structure and the water retention and enhancing the cation exchange capacity. For example, studies have shown that poultry litter-derived hydrochar seems to be an adequate amendment for sandy soils (Mau et al. 2020).

12.5.2.4 The Process Water (PW)

The HTC liquid treatment represents the largest mass of the outgoing effluent of HTC process. By reutilization of the PW, the amount of contaminated wastewater can be strongly reduced. However, the process temperature influences hydrochar and PW composition during PW recirculation. In the case of green municipal waste (MGW), the PW after HTC was fully reused up to 11 times (Köchermann et al. 2018). Results showed that hydrochar mass yield increases with progressing PW recirculation. However, the HHV was not affected by it. The liquid contains molecules such as furfurals and acids obtained from the degradation of the main components of biomass.

Some studies have examined the potential of PW for biochemical methane production. This liquid may also be a source of nitrogen and humic acid which improves soil fertility (Gupta et al. 2021). The process water can also be used for microalgae production and provides some necessary nutrients without inhibiting the growth of microalgae (Özçimen et al. 2022).

The fate of this water must be taken into account in the whole process. Furthermore, this water affects the energy balance of the process. In order to have a favorable balance, it is necessary to seek to work with the highest biomass/water mass ratio. In the case of olive pomace, it has been shown that this ratio must be at least equal to 1/5 in order to allow an energy balance favorable to the process (Missaoui et al. 2017a, b).

12.5.3 HTC Process

The three main operating parameters of HTC are the temperature (*T*), the reaction time (*t*), and the weight ratio biomass/water. Other factors may affect biomass degradation such as the feedwater pH and the concentration of substrate.

In the case of temperature and reaction time, there is an interaction between these two quantities. A conversion rate depends on the reaction time and its kinetics which varies with the temperature. So, some studies used a term of hydrothermal severity (R_0) which takes into account these two parameters.

$$R_0 = t \times \exp\left[\left(T - 100\right) / \omega\right] \tag{12.14}$$

with T = process temperature (°C); t = reaction time (min); ω is an empirical parameter that relates to the gas constant (R), the activation energy (E_a), and the reference temperature. Its value is equal to 14.75 when lignocellulosic biomasses are involved.

This term can be also called severity index (SI) expressed by the following equation:

$$SI = \int_{t}^{0} e^{\left(\frac{-E_a}{R}\right)\times\left(\frac{1}{T}-\frac{1}{T_0}\right)} dt \tag{12.15}$$

with T_0 = reference temperature.

Most studies focus on the influence of T and t. For t, it is very variable, since it can range from 0 min to 24 h of treatment. In general, the longer the time increases, the lower the mass yield of the hydrocarbon, but the higher its HHV and its fixed carbon content.

To show these relations, the following application relates HTC processing of olive pomace collected from a three-phase centrifugation system of a semi-industrial unit in Morocco. In this application, the biomass/water mass ratio is 1/3. A Doelhert design was implemented in view to study the influence of T and t. The studied domain was for T between 180 and 250 °C and t between 0 and 60 min. In fact, t = 0 min corresponds to the time at which the solution remains at the desired temperature. t = 0 min allows showing the impact of the heating rate. Owing to Doelhert's design, we are able to represent the main effect graphic also the response surface modeled from factors on specific responses (as in Fig. 12.7) owing to a model as

$$Y = b_0 + b_1X_1 + + b_2X_2 + b_{11}X_{12} + + b_{22}X_{22} + + b_{12}X_1X_2 \tag{12.16}$$

With X_i factors, Y response and b_i model coefficients.

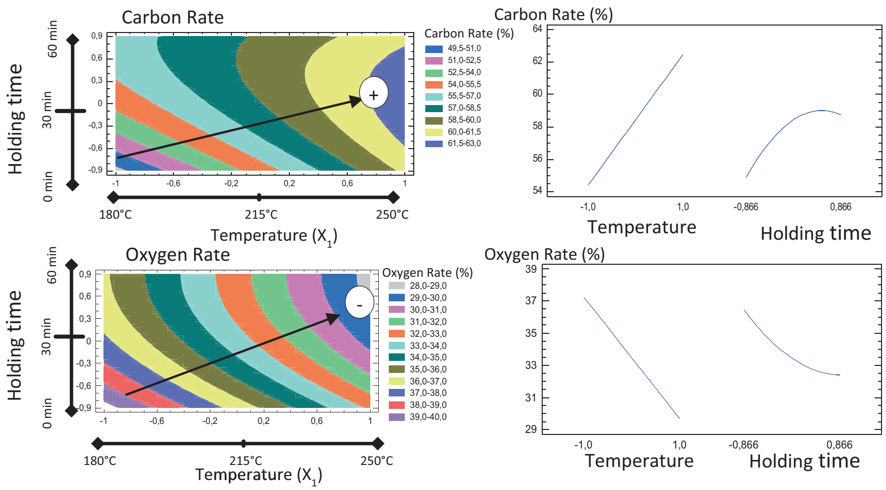

Fig. 12.7 The main effects (on the right) and 2D contour plots (on the left) of temperature and holding time on carbon and oxygen rates

Figure 12.7 reveals that the carbon rate increases with *t* and *T* contrary to the oxygen rate. So, the ratio O/C decreases with increasing factors favorable pour fuel application. The same trend is shown with the HHV allowing to have a value of 20% greater than the raw olive pomace. On the other hand, the hydrochar mass yield decreases to a minimum value of 66%.

The energy efficiency (EY) makes it possible to take into account this antagonistic evolution by the fact that its calculation is carried out with the following formula:

$$\mathrm{EY}\left(\%\right) = \mathrm{Mass\ \ yield} \times \mathrm{Densification\ \ energy\ \ ratio} \tag{12.17}$$

and densification energy ratio:

$$\mathrm{DE}\left(-\right) = \frac{\mathrm{HHV}_{\mathrm{dried\ hydrochar}}}{\mathrm{HHV}_{\mathrm{dried\ olive\ pomace}}} \tag{12.18}$$

The EY values were between 80% and 92%. Moreover, the energy balance, which takes into account the energy recovery minus the energy consumption, can be considered positive in all the domains favoring the introduction of such a process.

12.6 Characterization of Gaseous Products Evolved from Biomass Fuels During Thermochemical Conversion Using TGA-µGC

12.6.1 Introduction

The production of new clean and sustainable fuels from biomass thermochemical conversion has enhanced the demand for in-depth characterization of the evolved gases upon thermal decomposition. In order to apply these processes, the thermal degradation must be properly characterized for mass loss, temperature, and the nature and composition of the gases evolved during the thermal conversion of biomass.

Thermogravimetric analysis (TGA) coupled with micro-gas chromatography (micro-GC or µGC) allows determining precisely and in a short time the key parameters required for the process design of thermochemical conversion technologies.

This section describes a practical application of the thermal degradation of two biomass wastes in a Netzsch TGA instrument coupled with a 3-module micro-gas chromatograph (SRA Instruments), and the results presented illustrate the investigation of fuel production from olive pomace (OP) and miscanthus.

12.6.2 Theory and Operating Principles of TGA and Simultaneous Evolved Gas Analysis

12.6.2.1 Thermogravimetric Analysis

TGA is a thermo-analytical technique that combines gravimetric measurements with furnace heating to measure the mass of a sample as a function of temperature in a defined atmosphere (Dunn 2002). The sample (usually a solid) undergoes thermal degradation and subsequent gas–solid heterogeneous reactions that result in the evolution of gaseous, liquid (tars), and residue by-products. In TGA, the gaseous products are removed by a flowing gas, and the changes in the remaining mass of the sample can be presented in two different plots, as depicted in Fig. 12.8a.

Gasifying agent: air at an equivalence ratio of 0.20 from 700 to 1000 °C. (a) TGA curves and black and red (solid) lines represent the TG and DTG profiles, respectively. (b) Main volatile decomposition products over time and temperature, dash-dotted line: temperature program from room temperature to 1000 °C; color lines: releasing profile of target gas products (CO, CO_2, CH_4, and H_2).

The thermogravimetric (TG) curve (in wt.%) is a plot of the mass of the sample against time or temperature. Similarly, the derivative of TGA data can be plotted as a derivative thermogravimetric (DTG) curve (in wt.%/min or wt.%/°C), which is a plot of the rate of change of mass with respect to temperature or time against temperature or time (Dunn 2002). This allows for the determination of mass-loss stages and specific decomposition temperatures, such as the temperature of the maximum rate of mass loss (T_{max}) at which the material decomposes or reacts (DTG peak). Onset (ignition, T_i) and final (burnout, T_b) degradation temperature data can also be evaluated from TG plots (ASTM 2011; Sangare et al. 2020).

Therefore, TGA is extensively used for assessing the reactivity phenomena involving biomass and solid wastes. It can provide valuable information on compositional changes and enables a wide range of experimental conditions (i.e., sample

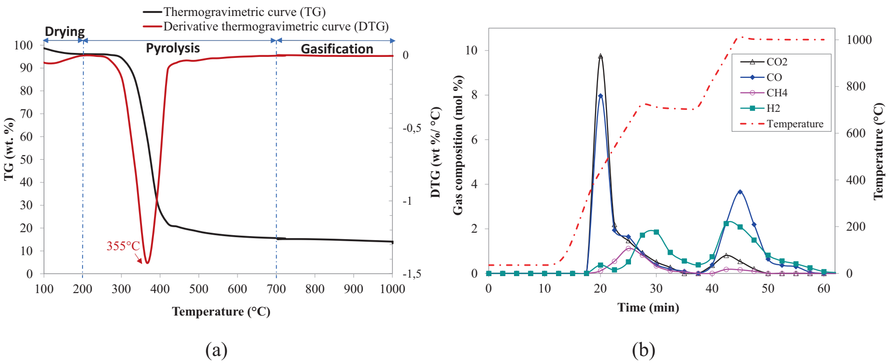

Fig. 12.8 Thermogravimetric and evolved gas analysis of the pyrolysis-char gasification process of cellulose upon heating at 40 °C/min. Char resulting from cellulose pyrolysis at 700 °C in flowing argon (20 mL/min)

mass, heating rate, specific atmosphere, final temperature, holding time, nature, and flow rate of the reactive gas) to be adapted to the feedstock composition to which TGA is applied, which is done through analysis of characteristic TG and/or DTG profiles (Fig. 12.8a).

Furthermore, detailed information like moisture loss and volatile matter (VM), fixed carbon (FC), and ashes content can also be determined using TGA standardized analytical procedures (ASTM 2014).

12.6.2.2 Simultaneous Thermogravimetric and Micro-Gas Chromatography (TGA-µGC) Analysis

TGA can be used simultaneously or separately, depending on the research objective, for the analysis of dehydration, thermal decomposition, oxidization, and other processes which are involved in the energy conversion of biomass and waste management. By combining TGA with other analytical methods, additional information can be obtained from one sample. In particular, TGA coupled with micro-GC enables both qualitative and quantitative analyses of biomass and organic waste samples.

The operation principle of a micro-GC analysis system is based on miniaturized chromatographic separations to provide rapid and in situ characterization in gas mixtures (Regmi and Agad 2018). The composition of evolved gases enriched in hydrogen (H_2), carbon monoxide (CO), and methane (CH_4) can be studied by micro-GC analysis (Fushimi et al. 2003; Xu et al. 2011, 2020; Yang et al. 2007; Zhu et al. 2018). Carbon dioxide (CO_2), nitrogen (N_2), and oxygen (O_2), if released, can also be detected and quantified.

Figure 12.9 summarizes the flow of operating procedure of the TGA-µGC system. Simultaneous TGA and micro-GC measurements are carried out in three steps: *(i)* the sample is first heated on the TGA, *(ii)* the evolved gaseous effluent is directed to the micro-GC through the transfer line, *(iii)* the target gas species eluting from the micro-GC columns are identified and quantified by comparing the peak area signal and retention times with those of calibration standards under the same conditions as the samples. The thermogravimetric and chromatographic data are continuously recorded on a computer over the course of the experimental run.

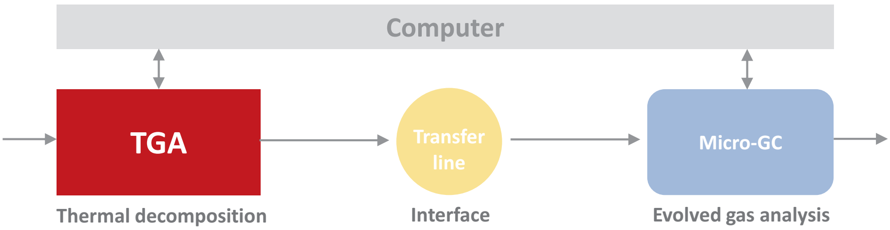

Fig. 12.9 TGA and micro-GC coupling principle

The experimental setup consists of a Netzsch STA 449 F3 Jupiter thermogravimetric analyzer coupled with a micro-gas chromatograph (Micro GC SOLIA 490, SRA Instruments). The micro-GC device is equipped with micro-packed columns and three thermal conductivity detector (TCD) channels. The experimental procedures were based on the methodology developed by Sangaré et al. (2022). The TGA-μGC coupling requires the synchronization of the operating conditions of both instrumental devices. The setup optimization was obtained by following manufacturers' specifications for the Solia 490 micro-GC and performing preliminary TGA-μGC measurements on cellulose as a reference case. The micro-GC starts with the TGA at the beginning of the run, and the complete gas composition is obtained in less than 3 min (~150 s analysis time) for H_2, CH_4, CO, and CO_2, by optimizing the heating rate, final temperature, and carrier gas (type and flow rate) experimental conditions. Three consecutive runs were conducted, which demonstrated a maximum standard deviation of less than 2.3% for the peak area of all compounds of interest. The detailed operating conditions can be found elsewhere (Sangaré et al. 2022).

As an example, the pyrolysis and gasification outputs of cellulose under argon and air atmospheres are presented in Fig. 12.8. Firstly, a dehydration stage took place due to evaporation of moisture below 150 °C. This was followed by a primary pyrolysis step that produces char, followed by air gasification of that char from 700 to 1000 °C with an equivalence ratio of 0.20. A single mass-loss stage in the temperature range between 300 and 415 °C, and a maximum decomposition rate (1.42 wt.%/°C) was reached at ~355 °C (DTG peak), which is in agreement with the results reported in the literature (Yang et al. 2007). The devolatilization rate shows that cellulose is converted mainly to volatiles. Approximately 85 wt.% of cellulose was devolatilized up to 700 °C (Fig. 12.8a). To quantitatively characterize the effect of temperature on gas release, the analysis of the gas evolution over time and temperature was made by online TGA-μGC measurements.

Figure 12.8b shows the effects of pyrolysis and gasification temperature on the composition of gas products of cellulose. CO, CO_2, H_2, and CH_4 are the main gas products. The content of CO, CO_2, H_2, and CH_4 in the pyrolysis gases accounted for more than 36 mol%. As the temperature increased, the H_2 content in the product gases increased from 5.83 mol% at 700 °C to 8.31 mol% at 1000 °C, while CO, CO_2, and CH_4 evolution exhibited the opposite trend. The H_2/CO ratio was increased from 0.45 to 0.87 at 700 °C and 1000 °C, respectively. The lower heating value (LHV) of the product gases from cellulose was 6.5 MJ/Nm^3, as estimated by Xie et al. (2012).

TGA-μGC coupling is considered to be an effective technique to identify and easily quantify the main compounds causing a mass loss during thermal decomposition. The resulting data can contribute to determining the utilization of a biomass sample or mixture as an energy source in thermochemical processes or other applications.

In the following, a comparative case is presented to support biomass and waste management valorization opportunities using thermochemical conversion technologies for social development in rural areas of developing countries.

12.6.3 Case Study

Two examples are presented to illustrate the simultaneous characterization of biomass thermal decomposition and analysis of the evolved gas, in a single run, using TGA-μGC coupling.

The first is the gasification of olive pomace (OP), and the other is the gasification of miscanthus. In terms of waste characteristics, the proximate analysis, ultimate analysis, and heating values of miscanthus and OP are given in Table 12.4. The OP composition is almost comparable with miscanthus. So, OP and miscanthus opted for the present comparative study.

The influence of the feedstock type on the gasification process through TGA of the biomass samples is depicted in Fig. 12.10. As can be seen in this figure, both samples involve a major mass loss step that occurred at 250–415 °C, with approximately 30% of solid residue left for the OP and 20% for miscanthus at 1000 °C. The DTG showed a maximum weight loss rate (0.80 wt.%/°C) at 350 °C for OP, and two observable peaks (~1.51 and 0.92 wt.%/°C) attained for miscanthus at 325 °C and 365 °C, respectively. This suggests that this region could be divided into two stages corresponding to different thermochemical reactions, in which the main weight loss is due to removal of the volatile matters of the biomass. In both cases, the differences in the intrinsic chemical and structural features of the two biomass samples possibly account for the different gasification behaviors observed (McKendry 2002; Yang et al. 2007).

The gas data in Fig. 12.10 show that the CO_2 evolved during gasification was lower for miscanthus, while CO production was increased and CH_4 and H_2 were

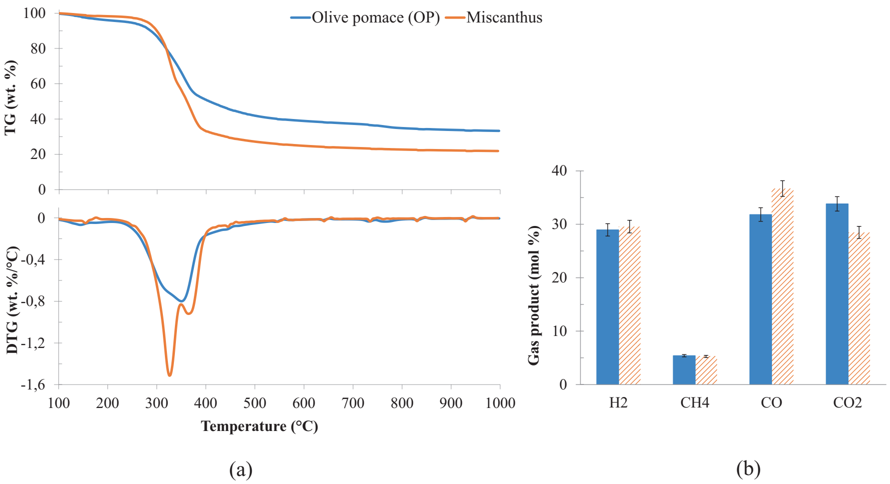

Fig. 12.10 Thermogravimetric and evolved gas analysis of the gasification process of OP and miscanthus upon heating at 40 °C/min in flowing nitrogen (20 mL/min). Gasifying agent: air at an equivalence ratio of 0.10 from 110 to 1000 °C. (**a**) TGA curves: TG and DTG profiles, respectively. (**b**) Main gas products (H_2, CH_4, CO, and CO_2)

much similar for both study cases. The produced gases had a LHV of 9.1 MJ/Nm^3 and 9.7 MJ/Nm^3, respectively, for OP and miscanthus, at this temperature range (250–1000 °C).

12.6.4 Summary

The measurements presented show that the combination of TGA and micro-GC analyses allows determining accurately (±2.3% standard deviation) and in a short time (~150 s analysis time) the amounts of the target gases, such as H_2, CH_4, CO, and CO_2, produced during the pyrolytic and gasification processes. The pyrolysis of cellulose was used here as an example. Under similar measurement conditions, within one test series, a comparative evaluation of the gasification products of OP and miscanthus was presented. The effect of measurement conditions, including temperature, heating rate, feedstock composition, and blending ratios, as well as the type and flow rate of the carrier gas must be considered when performing simultaneous TGA-μGC studies. Finally, the proposed methodology can contribute to expanding the analytical techniques used in thermochemistry and broaden the assessment of waste sources for the production of synthetic fuels in developing countries.

References

ASTM, *ASTM E2550-11, Standard Test Method for Thermal Stability by Thermogravimetry* (West Conshohocken, 2011)

ASTM, *ASTM E1131–08, Standard Test Method for Compositional Analysis by Thermogravimetry* (West Conshohocken, 2014)

M.A. Bennini, A. Koukouch, I. Bakhattar, M. Asbik, T. Boushaki, B. Sarh, et al., Characterization and combustion of olive pomace in a fixed bed boiler: Effects of particle sizes. Int. J. Heat Technol. **37**, 229–238 (2019). https://doi.org/10.18280/ijht.370128

O. Bobleter, Hydrothermal degradation of polymers derived from plants. Prog. Polym. Sci. **19**, 797–841 (1994). https://doi.org/10.1016/0079-6700(94)90033-7

M. Creyx, E. Delacourt, C. Morin, S. Lalot, B. Desmet, Energetic and exergetic analysis of a heat exchanger integrated in a solid biomass-fuelled micro-CHP system with an Ericsson engine. Entropy **18** (2016). https://doi.org/10.3390/e18040154

A. Demirbas, Combustion of biomass. Energy Source A Recover Util. Environ. Eff. **29**, 549–561 (2007). https://doi.org/10.1080/009083190957694

P. Desgroux, X. Mercier, K.A. Thomson, Study of the formation of soot and its precursors in flames using optical diagnostics. Proc. Combust. Inst. **34**, 1713–1738 (2013). https://doi.org/10.1016/j.proci.2012.09.004

R.D.S. Deuber, D.S. Fernandes, J.M. Bressanin, J. Watson, M.F. Chagas, A. Bonomi, et al., Techno-economic assessment of HTL integration to the Brazilian sugarcane industry: An evaluation of different scenarios. Ind. Crop. Prod. **173** (2021). https://doi.org/10.1016/j.indcrop.2021.114139

J. Dunn, Thermogravimetric analysis, in *Characterization of Materials*, ed. by E.N. Kaufmann, (The University of Toledo, Toledo, 2002)

A. Elorf, N.M. Koched, T. Boushaki, B. Sarh, J. Chaoufi, S. Bostyn, et al., Swirl motion effects on flame dynamic of pulverized olive cake in a vertical furnace. Combust. Sci. Technol. **188**, 1951–1971 (2016). https://doi.org/10.1080/00102202.2016.1214419

A. Elorf, J. Kandasamy, V. Belandria, S. Bostyn, B. Sarh, I. Gökalp, Heating rate effects on pyrolysis, gasification and combustion of olive waste. Biofuels **12**, 1157–1164 (2021). https://doi.org/10.1080/17597269.2019.1594598

R.J. Evans, T.A. Milne, Molecular characterization of pyrolysis of biomass. 1. Fundamentals. Energy Fuel **1**, 123–138 (1987)

N. Fechler, S.A. Wohlgemuth, P. Jäker, M. Antonietti, Salt and sugar: Direct synthesis of high surface area carbon materials at low temperatures via hydrothermal carbonization of glucose under hypersaline conditions. J. Mater. Chem. A **1**, 9418–9421 (2013). https://doi.org/10.1039/c3ta10674h

C. Fushimi, K. Araki, Y. Yamaguchi, A. Tsutsumi, Effect of heating rate on steam gasification of biomass. 2. Thermogravimetric-mass spectrometric (TG-MS) analysis of gas evolution. Ind. Eng. Chem. Res. **42**, 3929–3936 (2003). https://doi.org/10.1021/ie0300575

C. Gai, Y. Dong, Experimental study on non-woody biomass gasification in a downdraft gasifier. Int. J. Hydrog. Energy **37**, 4935–4944 (2012). https://doi.org/10.1016/j.ijhydene.2011.12.031

J.R. Grace, B. Leckner, J. Zhu, J.R. Grace, Fluidized beds, in *Multiphase Flow Handbook*, ed. by C.T. Crowe, (CRC Press, New York, 2006)

Y. Graz, S. Bostyn, T. Richard, P.E. Bocanegra, E. De Bilbao, J. Poirier, et al., Hydrothermal conversion of Ulva macro algae in supercritical water. J. Supercrit. Fluids **107**, 182–188 (2016). https://doi.org/10.1016/j.supflu.2015.07.038

D. Gupta, S.M. Mahajani, A. Garg, Hydrothermal carbonization of household wet waste – Characterization of hydrochar and process wastewater stream. Bioresour. Technol. **342**, 125972 (2021). https://doi.org/10.1016/j.biortech.2021.125972

J.O. Ighalo, F.U. Iwuchukwu, O.E. Eyankware, K.O. Iwuozor, K. Olotu, O.C. Bright, et al., Flash pyrolysis of biomass: A review of recent advances. Clean Techn. Environ. Policy, 1–15 (2022)

IRENA, *Renewable Power Generation Costs in 2019 – Key Findings* (International Renewable Energy Agency, 2020), p. 160

K. Jayaraman, I. Gökalp, Pyrolysis, combustion and gasification characteristics of miscanthus and sewage sludge. Energy Convers. Manag. **89**, 83–91 (2015). https://doi.org/10.1016/j.enconman.2014.09.058

A.A. Khan, W. de Jong, P.J. Jansens, H. Spliethoff, Biomass combustion in fluidized bed boilers: Potential problems and remedies. Fuel Process. Technol. **90**, 21–50 (2009). https://doi.org/10.1016/j.fuproc.2008.07.012

D.L. Klass, *Biomass for Renewable Energy, Fuels, and Chemicals* (Academic, London, 1998). https://doi.org/10.5860/choice.36-4508

J. Köchermann, K. Görsch, B. Wirth, J. Mühlenberg, M. Klemm, Hydrothermal carbonization: Temperature influence on hydrochar and aqueous phase composition during process water recirculation. J. Environ. Chem. Eng. **6**, 5481–5487 (2018). https://doi.org/10.1016/j.jece.2018.07.053

A. Kruse, Supercritical water gasification. Biofuels Bioprod. Biorefining Innov. Sustain. Econ. **2**, 415–437 (2008)

A. Kruse, E. Dinjus, Hot compressed water as reaction medium and reactant. Properties and synthesis reactions. J. Supercrit. Fluids **39**, 362–380 (2007). https://doi.org/10.1016/j.supflu.2006.03.016

P.S. Lam, S. Sokhansanj, X. Bi, C.J. Lim, L.J. Naimi, M. Hoque, et al., Bulk density of wet and dry wheat straw and switchgrass particles. Appl. Eng. Agric. **24**, 351–358 (2008)

C. Mandl, I. Obernberger, F. Biedermann, Modelling of an updraft fixed-bed gasifier operated with softwood pellets. Fuel **89**, 3795–3806 (2010). https://doi.org/10.1016/j.fuel.2010.07.014

V. Mau, G. Arye, A. Gross, Poultry litter hydrochar as an amendment for sandy soils. J. Environ. Manag. **271**, 110959 (2020). https://doi.org/10.1016/j.jenvman.2020.110959

P. McKendry, Energy production from biomass (part 1): Overview of biomass. Bioresour. Technol. **8**, 37–46 (2002)

T.A. Milne, A.H. Brennan, B.H. Glenn, *Sourcebook of Methods of Analysis for Biomass and Biomass-Conversion Process* (Elsevier, London, 1990)

A. Missaoui, S. Bostyn, V. Belandria, B. Cagnon, B. Sarh, I. Gökalp, Hydrothermal carbonization of dried olive pomace: Energy potential and process performances. J. Anal. Appl. Pyrolysis **128**, 281–290 (2017a). https://doi.org/10.1016/j.jaap.2017.09.022

A. Missaoui, S. Bostyn, V. Belandria, B. Sarh, I. Gökalp*, Assessing the Heat and Energy Balances of Hydrochar Production via Hydrothermal Carbonization of Olive Pomace*. In 25th European biomass conference exhibition (2017b)

T. Nussbaumer, Combustion and co-combustion of biomass: Fundamentals, technologies, and primary measures for emission reduction. Energy Fuel **17**, 1510–1521 (2003). https://doi.org/10.1021/ef030031q

D. Özçimen, B. Inan, A.T. Koçer, S. Bostyn, I. Gökalp, Hydrothermal carbonization processes applied to wet organic waste streams. Int. J. Energy Res. (2022). https://doi.org/10.1002/er.8304

T.K. Patra, P.N. Sheth, Biomass gasification models for downdraft gasifier: A state-of-the-art review. Renew. Sust. Energ. Rev. **50**, 583–593 (2015). https://doi.org/10.1016/j.rser.2015.05.012

L. Pelkmans, *IEA Bioenergy Countries' Report-Update 2021: Implementation of Bioenergy in the IEA Bioenergy Member Countries* (2021), pp. 1–28

Y. Rahib, T. Boushaki, B. Sarh, J. Chaoufi, Combustion and pollutant emission characteristics of argan nut shell (ANS) biomass. Fuel Process. Technol. **213**, 106665 (2021). https://doi.org/10.1016/j.fuproc.2020.106665

B.P. Regmi, M. Agah, Micro gas chromatography: An overview of critical components and their integration. Anal. Chem. **90**, 13133–13150 (2018)

Y. Rogaume, *La combustion du bois et de la biomasse*. Pollut Atmosphérique, Clim Santé, Société (2009); Numéro spé:65–82.

L. Rosendahl (ed.), *Biomass Combustion Science, Technology and Engineering* (Woodhead Publishing, Oxford, 2013)

D. Sangare, A. Missaoui, S. Bostyn, V. Belandria, M. Moscosa-Santillan, I. Gökalp, Modeling of Agave Salmiana bagasse conversion by hydrothermal carbonization (HTC) for solid fuel combustion using surface response methodology. AIMS Energy **8**, 538–562 (2020)

D. Sangaré, S. Bostyn, M. Moscosa Santillán, P. García-Alamilla, V. Belandria, I. Gökalp, Comparative pyrolysis studies of lignocellulosic biomasses: Online gas quantification, kinetics triplets, and thermodynamic parameters of the process. Bioresour. Technol. **346** (2022). https://doi.org/10.1016/j.biortech.2021.126598

D. Sangare, A. Chartier, M. Moscosa-Santillan, I. Gökalp, S. Bostyn, Kinetic studies of hydrothermal carbonization of avocado stone and analysis of the polycyclic aromatic hydrocarbon contents in the hydrochars produced. Fuel **316** (2022). https://doi.org/10.1016/j.fuel.2022.123163

S.K. Sansaniwal, K. Pal, M.A. Rosen, S.K. Tyagi, Recent advances in the development of biomass gasification technology: A comprehensive review. Renew. Sust. Energ. Rev. **72**, 363–384 (2017). https://doi.org/10.1016/j.rser.2017.01.038

I.P. Silva, R.M.A. Lima, G.F. Silva, D.S. Ruzene, D.P. Silva, Thermodynamic equilibrium model based on stoichiometric method for biomass gasification: A review of model modifications. Renew. Sust. Energ. Rev. **114**, 109305 (2019). https://doi.org/10.1016/j.rser.2019.109305

P. Sommersacher, T. Brunner, I. Obernberger, Fuel indexes: A novel method for the evaluation of relevant combustion properties of new biomass fuels. Energy Fuel **26**, 380–390 (2012). https://doi.org/10.1021/ef201282y

D.A. Tillman, Biomass combustion, in *Biomass Regeneration Energy*, ed. by D.O. Hall, R.P. Overend, (Wiley, New York, 1987), pp. 203–219

M.L. Valderrama Rios, A.M. González, E.E.S. Lora, O.A. Almazán del Olmo, Reduction of tar generated during biomass gasification: A review. Biomass Bioenergy **108**, 345–370 (2018). https://doi.org/10.1016/j.biombioe.2017.12.002

J.M. Vargas-Moreno, A.J. Callejón-Ferre, J. Pérez-Alonso, B. Velázquez-Martí, A review of the mathematical models for predicting the heating value of biomass materials. Renew. Sust. Energ. Rev. **16**, 3065–3083 (2012). https://doi.org/10.1016/j.rser.2012.02.054

T. Wang, Y. Zhai, Y. Zhu, C. Li, G. Zeng, A review of the hydrothermal carbonization of biomass waste for hydrochar formation: Process conditions, fundamentals, and physicochemical properties. Renew. Sust. Energ. Rev. **90**, 223–247 (2018). https://doi.org/10.1016/j.rser.2018.03.071

J. Watson, Y. Zhang, B. Si, W.T. Chen, R. de Souza, Gasification of biowaste: A critical review and outlooks. Renew. Sust. Energ. Rev. **83**, 1–17 (2018). https://doi.org/10.1016/j.rser.2017.10.003

Q. Xie, S. Kong, Y. Liu, H. Zeng, Syngas production by two-stage method of biomass catalytic pyrolysis and gasification. Bioresour. Technol. **110**, 603–609 (2012)

Q. Xu, S. Pang, T. Levi, Reaction kinetics and producer gas compositions of steam gasification of coal and biomass blend chars, part 1: Experimental investigation. Chem. Eng. Sci. **66**, 2141–2148 (2011). https://doi.org/10.1016/j.ces.2011.02.026

D. Xu, Y. Xiong, J. Ye, Y. Su, Q. Dong, S. Zhang, Performances of syngas production and deposited coke regulation during co-gasification of biomass and plastic wastes over Ni/γ-Al_2O_3 catalyst: Role of biomass to plastic ratio in feedstock. Chem. Eng. J. **392**, 123728 (2020). https://doi.org/10.1016/j.cej.2019.123728

H. Yang, R. Yan, H. Chen, D.H. Lee, C. Zheng, Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel **86**, 1781–1788 (2007). https://doi.org/10.1016/j.fuel.2006.12.013

D. Yogi Goswami, F. Kreith, *Energy Conversion* (2008). https://doi.org/10.1007/978-3-030-56164-2_7

X. Zhang, Y. Li, M. Wang, L. Han, X. Liu, Effects of hydrothermal carbonization conditions on the combustion and kinetics of wheat straw hydrochar pellets and efficiency improvement analyses. Energy Fuel **34**, 587–598 (2020). https://doi.org/10.1021/acs.energyfuels.9b03754

P. Zhao, Y. Shen, S. Ge, K. Yoshikawa, Energy recycling from sewage sludge by producing solid biofuel with hydrothermal carbonization. Energy Convers. Manag. **78**, 815–821 (2014). https://doi.org/10.1016/j.enconman.2013.11.026

L. Zhu, Y. Zhang, H. Lei, X. Zhang, L. Wang, Q. Bu, et al., Production of hydrocarbons from biomass-derived biochar assisted microwave catalytic pyrolysis. Sustain. Energy Fuels **2**, 1781–1790 (2018). https://doi.org/10.1039/c8se00096d

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H. El Bari, C. Trois (eds.), *Waste Management in Developing Countries*, Waste as a Resource, https://doi.org/10.1007/978-3-031-28001-6