Solid waste management

Aparcana Robles, Sandra Roxana

Published in:
Climate technologies in an urban context

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Aparcana Robles, S. R. (2021). Solid waste management. In *Climate technologies in an urban context* (pp. 46-73). UNEP DTU Partnership.

4. Solid waste management

Flickr

The municipal solid waste management sector represents a major challenge for developing countries due to significant environmental and socioeconomic issues involving rapid urbanization, inappropriate municipal solid waste management practices, and the existence of the informal waste sector. in these countries, municipal solid waste management systems are often inefficient and operate to low standards (1, 2). Municipal solid waste management is characterized by low collection rates and the lack of appropriate waste treatment and final disposal, contributing not only to global climate change[1] and other critical environmental impacts, but also having negative economic and social effects. Most impacts related to waste management occur during the final disposal phase.

Dumping untreated solid waste on uncontrolled landfills and open sites is still the most prevalent method of waste disposal in the cities of developing countries. For example, a study analysing waste-management systems in 36 urban areas in 22 developing countries revealed the common use of open dumps without leachate treatment, treatment gases or any other necessary infrastructure. In addition, in 61 percent of the cities analysed open burning of waste by households was extensively practised (3). Uncontrolled waste-disposal practices can lead to the spread of vector-borne diseases, and the disposal of waste containing hazardous materials can be harmful to workers in the waste sector, nearby communities, and the environment. Environmental impacts in the municipal solid waste management sector include, but are not limited to, global warming, acidification, eutrophication, and human and eco-toxicity.

These are only some of the impacts that waste-management practices can have on cities. In the following section we will go further into the municipal solid waste management systems of developing countries and their stakeholders, and provide an overview of the current municipal solid waste management technologies and approaches that are available.

Typically, municipal solid waste management systems in developing countries are run by both the formal and informal sectors. Nevertheless, the stakeholders and their role are similar, despite the existence of possibly different contexts. There is a wide range of stakeholders involved in municipal solid waste management systems, and their different roles depend on the step in the waste management value chain in which they are acting (generators, waste management operators, law and policy-makers, etc.). Also, there is sometimes a blurred line between the two sectors, the same stakeholders possibly being responsible for both informal and formal roles and activities in the system.

National governments are mostly responsible for establishing national waste-management policies, strategies ensuring that local governments have the necessary enforcement capacity, and the resources for effective solid-waste management. Municipalities and other local authorities are responsible for the provision of solid-waste collection and disposal services. In addition, local governments are typically responsible for implementing waste-management legislation and regulations. If there is cooperation with the formal private sector, local governments regulate and control the appropriate

[1] In 2012, the municipal solid waste management sector accounted for around 5 percent of global greenhouse gas emissions, primarily driven by disposal in open dumps and landfills without landfill-gas collection systems (1).

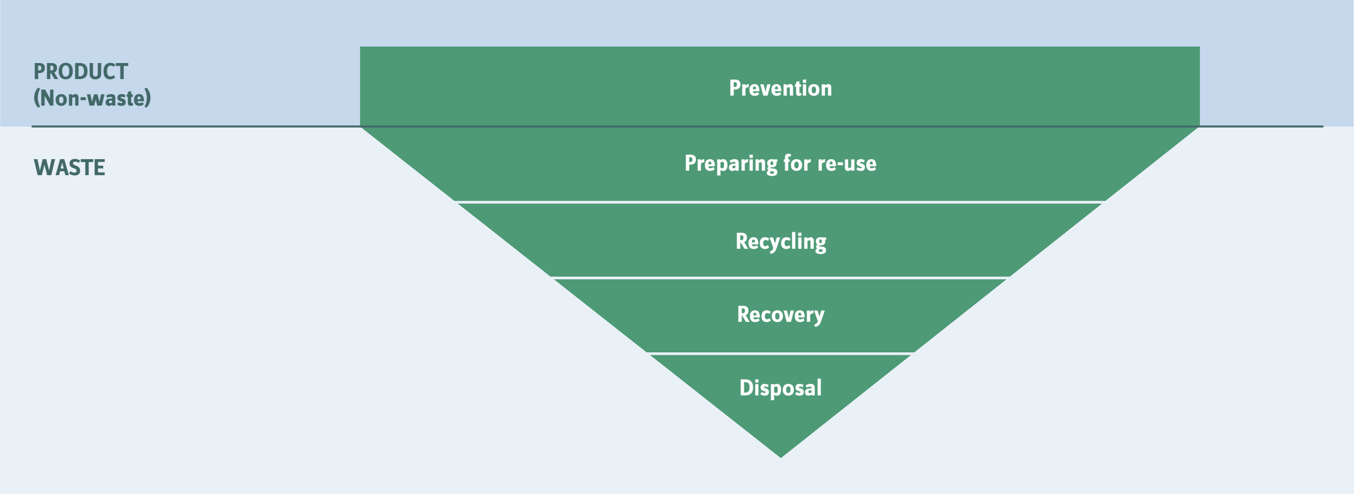
provision of waste management services by means of formal private companies, registered entities with an organized labour force and some capital investment, and covering a wide range of enterprise types. Their main motivation is to generate profits on their investments in waste services (collection, transfer, treatment, recycling and disposal).

The lack of municipal solid waste management services creates a need for alternative ways of handling and disposing of the waste, causing the development of informal waste activities (called ‘informal sector’ or IS) in developing countries. The informal private sector comes into play when formal waste management services are not provided, perhaps in rural areas or areas that are difficult to access, or when there is lack of financial capacity or willingness to pay for waste-collection fees. The informal sector commonly consists of individuals, groups and small enterprises that typically operate in inadequate and uncontrolled conditions and belong to socially disadvantaged individuals or groups working in informal recycling (e.g. children, women, and the elderly) (5). Frequently, the informal sector carries out waste separation and recycling, thus also reducing greenhouse gas emissions and other environmental impacts by reducing the volume of waste disposed of in landfills while at the same time creating local added value through the recycling market and informal jobs. However, despite these positive impacts, informal waste-management activities are also associated with negative social and economic conditions, such as poverty, inappropriate occupational and health-related working conditions, exploitation, discrimination, child labour, social rejection, and a lack of education (5).

Households and commercial establishments are waste-generators and waste-management service-users. Their waste composition and characteristics tend to be very similar and to be treated as municipal solid waste. Sometimes they could be involved in the city’s source-segregation activities. Other possible stakeholders present in waste management systems are non-governmental organizations and external support agencies, both of which aim at supporting and facilitating the implementation of more sustainable waste management practices. This support can be provided by, for example, capacity-building, financial assistance to formalized waste workers, technical assistance for implementing separate collections, technology transfers, etc. (6).

The boundary between formal and informal stakeholders is not always clear. Recyclable materials are recovered by informal waste-workers who sell them to formal recycling companies. Municipal employees who load waste into municipal trucks (municipal waste-collection crews) may also separate recyclables as they load and sell what they find unofficially to informal sector dealers. Co-operatives consisting of informal-sector workers may undertake some formal work under contract to a municipal authority while also being involved in informal recycling (7). The next section will describe the most common working and interaction mechanisms between the two sides, as well as the waste-management technologies and approaches that link them.

Figure 1. Waste hierarchy



Source: European Waste Framework Directive, 2008

4.1. Overview of technology options

There are different options for tackling diverse issues related to municipal solid waste management that are problematic for developing countries, ranging from strategic and management-oriented options to purely technical solutions. Often, both sorts of scheme should be combined in order to optimize their results. Currently, countries in general are formulating their national goals and targets and development road-maps for the sector around resource efficiency based on waste-minimization principles. A key pillar of these is the so-called "waste hierarchy", which targets waste prevention/reduction, reuse and recycling (and the intermediate steps that link them), recovery and disposal (see Figure 1). This concept outlines an order of preference within waste-management practices. There are different variations of the waste-management hierarchy (3Rs, 5Rs, 9Rs) (8, 9, 10), but they are all very similar and are focussed on preventing waste generation as the topmost and most important aspect of the hierarchy. The Waste Hierarchy considers waste reduction and waste prevention to be the most sustainable waste management practice, as it is very critical to decoupling waste generation from economic growth (11). Waste reuse is ranked as the second best option, this being followed by waste-recycling, recovery, and disposal. Landfilling and further final disposal practices are the least sustainable options and are therefore placed at the bottom of the hierarchy.

While the waste hierarchy focuses on resource efficiency and waste minimization as the main goals, there are other waste management approaches that incorporate it as a key pillar but that also contemplate waste management more holistically. They give importance not only to the efficiency of materials and energy flows, but also to country context, with multiple actors participating in municipal solid waste management systems and the particularities of their interactions towards sustainability. Among of these approaches are:

- **Integrated waste management**, which adopts the waste hierarchy as a cornerstone, but also focuses on stakeholder participation, the integration of political and social factors, and other interrelated processes in the waste system (6).

- **Participatory waste management** pays more attention to the social aspects of waste management than integrated waste management. This approach aims to achieve solidarity within stakeholders in waste management systems and strongly supports the social and economic integration and empowerment of the informal waste sector.

In terms of the greenhouse gas mitigation potential of each waste management practice, there are a number of life cycle assessment-based studies estimating the greenhouse gas emissions of different waste management practices and comparing them in terms of their mitigation potential. In this sense, waste prevention has been proved to reduce greenhouse gas emissions by reducing raw-material extraction and energy use in production activities, as well as from avoided waste treatment and disposal. Generally, greenhouse gas emissions from waste-prevention measures are lower than any other waste-management practice. A comparative study of the greenhouse gas mitigation potential of different waste-management practices in Organization of Economic Cooperation and Development countries demonstrated that source-reduction and prevention and recycling provide the highest reductions in greenhouse gas emissions per metric tonne of diverted municipal solid waste compared with baselines practices in 2030 (13).

After waste prevention and re-use, waste-recycling is the next option for cities to consider according to the waste hierarchy. In developing countries, the mitigation potential from recycling is driven by the informal sector, which also has very interesting potential in terms of greenhouse gas mitigation. Commonly, due to the informal nature of these activities and the lack of data, it is difficult to measure the avoided environmental impacts related to informal recycling. However, some experiences were able to estimate this mitigation potential: see Table 1 for some examples.

Table 1. Examples of greenhouse gas emissions reductions from informal waste-recycling

Location	Materials	Greenhouse gas emissions saved
India	Paper, plastics, metals and glass	962,000 tonnes carbon dioxide/year
Six cities in Peru, India, Egypt, Romania, Zambia and Philippines	-	28,900 - 496,700 tonnes carbon dioxide
São Paulo, Brazil	Paper and cardboard	1,443–2,720 tonnes carbon dioxide/year
Ormoc, the Philippines	Dry recyclables	7,750 tonnes carbon dioxide/year

Source: Aparcana and Hinostroza, 2015; King and Gutberlet, 2013; Hetz el al. 2011

After waste-prevention and waste-recycling, cities have further options targeting the final steps of the waste hierarchy. The election of these technologies will depend, among other things, on the waste's physical and chemical characteristics and the amounts generated. Among of these technologies are:

- **Composting:** this is a technological and economical accessible option that simultaneously generates aggregated value to organic waste and contributes to greenhouse gas mitigation, mainly by diverting untreated organic waste from landfills and the substitution of chemical fertilizers. The latter represents greenhouse gas savings of around 8 kg carbon dioxide e/ton of composted waste (11, 6). Furthermore, compost may also act as a carbon stock (it has a high carbon-storage capacity due to its slow carbon-mineralization process). There is consensus about this role, but not about the quantification of this potential.

- **Anaerobic digestion/biodigestion:** this is used to degrade organic waste, the main inputs of this process being biogas (methane as the main component) and digestate. Biogas has a number of uses depending on the size of the biodigestor (therefore, the amount of biogas obtained) and the quality of the biogas. Usually, small-scale biogas plants convert the gas into heat and use this energy for cooking, heating, drying of grains, etc. Bigger plants with a more complex technologies can generate electricity and heat through cogeneration. Small-scale biogas plants are more frequent in developing countries, due to their easy-to-implement technology and low construction and operating costs. The greenhouse gas mitigation potential of anaerobic digestion may vary depending on the end-use of the energy (gas, electricity, heat, transport, etc.), local energy grids, technology, etc. Anaerobic Digestion projects planned for Chile and the Dominican Republic are expected to achieve greenhouse gas savings of 6 million metric tonnes of carbon dioxide/year,[2] and in twenty years an accumulated reduction of around 51 million metric tonnes of carbon dioxide (6).

- **Mechanical biological treatment:** this usually involves a first treatment phase, corresponding to the separation and sorting of recyclable materials (mechanical phase), and a second biological one, which could be anaerobic digestion or composting for the organic fraction. Due to the high construction and operating costs, mechanical biological treatment plants are more common in developed countries (11). Owing to the combination of different treatment processes (see more in Section 2), mechanical biological treatment plants have an interesting greenhouse gas mitigation potential, depending on the technology, waste composition, type of waste, local energy grid, use of final outputs, etc. However, compared to landfill, mechanical biological treatment plants may save around 90 percent of methane emissions (11). In Organization of Economic and Cooperation and Development countries, mechanical biological treatment could reduce the amount of municipal waste diverted from landfill (relative to baseline practices in 2030) from 500 to around 2,000 kg carbon dioxide e/ton (13).

---

[2] Million metric tons of carbon dioxide.

- **Incineration:** this technology is widely applied in developed countries (80 percent of all plants at global level), but in developing countries its implementation is still low, mainly due to inadequate waste composition (water content too high), lack of adequate legal and regulatory frameworks, and high investments and operating costs (16). Moreover, when it comes to circularity and sustainable waste management, incineration would be the last option to consider, as energy recovery comes at one of the last steps in the implementation of the waste hierarchy. municipal solid waste incineration can save greenhouse gas emissions through avoided landfilling and energy recovery (electricity and heat). For each tonne of municipal solid waste incinerated in an incineration plant with combined heat and power units, the equivalent of 1,010 kg of carbon dioxide can be avoided by diverting that waste from landfill without using methane gas (16).

- **Gasification and pyrolysis:** these are treatments carried out under oxygen-controlled conditions, during which pyrolysis gas and a solid coke are formed. The heat values of pyrolysis gas typically lie between 5 and 15 MJ/m^3 from processing municipal waste. Pyrolysis technology is constantly being developed, and some countries in Europe are introducing this technology in the form of pilot plants and demonstration plants. Other countries (e.g. Japan) are using it already on a commercial basis. However, this technology still has only a small share of the overall treatment capacity when compared to incineration and is used to process selected waste materials only (17).

- **Landfill:** this is considered the last waste management option, after waste prevention, recycling and recovery. A sanitary landfill includes landfill gas and leachate capture and treatment systems. A landfill without gas utilization would emit around 1,610 Kg carbon dioxide eq/tonne municipal solid waste (16); however, if landfill gas is used for energy recovery, it can compensate emissions in favour of greenhouse gas emission reductions. Landfill gas typically contained around 50 percent of methane and can be captured and burned in combined heat and power units to generate electricity and heat. The Environmental Protection Agency reports that approximately 60 to 90 percent of the methane emitted from a landfill can be recovered and used, depending on system design and effectiveness (18).

Although waste management treatment options are already known and well-established, there is still a lack of knowledge about them and their applicability in developing countries, which is strongly linked to the lack of understanding about the main characteristics of municipal solid waste management systems and the technical conditions required to operate certain technologies under particular contexts.

4.2. Selected technologies

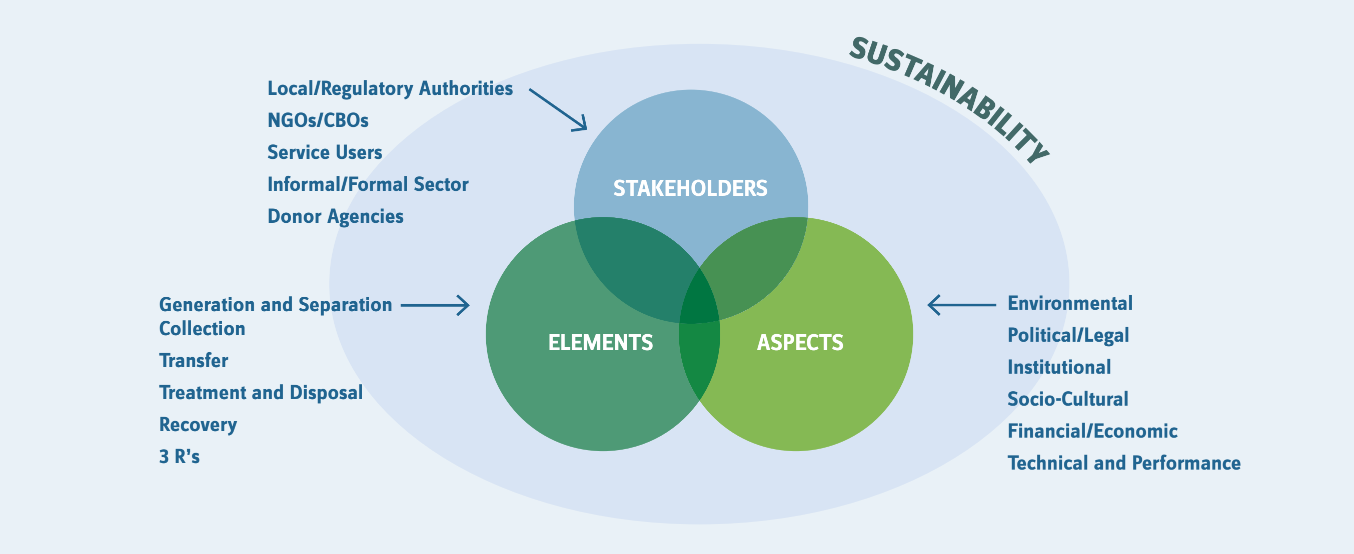
As described in the previous section, there are several waste-management options that can be selected according to particular contexts, such as waste characteristics, economic and financial restrictions, the institutional and policy-related aspects, etc.

Frequently, in order to address the particularities of each municipal solid waste management system, it is necessary to combine sustainable waste management approaches with adequate technical and operational solutions. This chapter describes waste management approaches and technology options that, when combined, can reduce the negative impacts linked to inappropriate waste management practices.

4.2.1. Integrated Waste Management and Integration of the Informal Waste Sector

The Integrated waste management approach adopts the waste hierarchy as its cornerstone by focusing on the management of material and energy flows within of the waste management system and the links outside it. Integrated waste management can be used to optimize existing systems, as well as to design and implement a new one (19). In contrast to conventional waste management systems, which mainly focus on improving the operational aspects (waste collection, transport, disposal) and increasing their efficiency, integrated waste management focuses also on stakeholder participation, waste in neighbourhoods, cities, etc. integrated solid waste management goes beyond the technical level to focus on the integration of the political and social factors, and other interrelated processes into the waste strategy (6).

Figure 2. Integrated waste management



Source: Hoornweg and Bhada-Tata, 2012

Integrated solid waste management is based on four principles: equality for all citizens regarding access to waste-management systems: ability to remove the waste safely; ability to maximize the benefits; ability to minimize the costs and optimize the use of resources; and sustainability of the system from the technical, environmental, social, economic, financial, institutional, and political perspectives. The implementation of integrated waste management involves three dimensions: 1. stakeholders, 2. waste-system elements and 3. aspects. The stakeholders are people or organizations involved in the waste-management system in both the formal and informal sectors. Waste-management elements refer to the operational dimensions of the system: waste-collection, transport, treatment and final disposal, including recycling and waste-prevention measures. The context aspects encompass the reality around a waste management system with regard to the financial, economic, environment, politico-legal, institutional arrangements, and socio-cultural aspects. This context can be changed to enable sustainability (2). The concept of integrated solid waste management considers these three dimensions to be strongly linked. Integrated solid waste management implies managing the interrelations between the contextual aspects, operational and material flow-related elements, and the stakeholders in a sustainable way. The impacts of these interactions can enable a waste management system to work or prevent it from reaching a sustainable state.

Aligned with the importance that integrated waste management gives to stakeholder involvement, including by informal actors, there have been multiple experiences in developing countries testifying to the key role of the informal waste sector and the positive economic, environmental and social impact of their inclusion within the formal waste management system. In the last few years, more and more cities in developing countries have identified the need to recognise the contribution of the informal sector and its inclusion in formal waste-management systems as an effective strategy. Governments have started to change their previous attitudes of opposition and indifference into active support (20). For this reason, in the few last years, several methods of formalization have been implemented in order to improve waste-management systems and transform them into more sustainable systems. These practical experiences have demonstrated the numerous advantages achieved through the formalisation of the informal sector (Mumbai, India; Manila, Philippines, Londrina and Diadema, Brazil; Bogota, Colombia; Cañete, Peru; among others). Among these benefits are increasing waste collection and recycling rates, poverty alleviation, reduction of health problems, job creation, women’s empowerment, cost savings for the formal sector, waste valorization, and reductions in child labour and discrimination (6).

Methods of formalization are mainly based on encouraging collection and valorization activities. They aim at the recognition of informal waste workers as important stakeholders and to embrace the environmental, social and economic benefits of informal recycling activities. Many methods of formalization organize informal waste workers into more structured groups. Local authorities support formalization through recyclers’ associations, micro- and small recycling enterprises and community-based organizations (1, 21). Often the cooperation scheme is based on the creation of public–private partnerships between the municipality and micro- and small recycling enterprises, collection and recycling contracts with recyclers’ associations, etc. (20, 22).

Some common actions and measures are recommended to enable successful formalization, for example, favourable policies and regulations enabling the informal sector to participate in the formal waste-management system. Further recommendations are acknowledgement and acceptance by authorities of the benefits of the informal sector, political and legal recognition, stakeholder communication and collaboration in the waste-management system, and diverse technical and operational measures (access to adequate infrastructure, technical assistance, improvements to the quality of recycled materials). Aligned with that, some Brazilian cities (Diadema and Sao Paulo) have successfully implemented a more comprehensive integration approach, with more participatory elements implying 'solid waste recovery, reuse and recycling practices with organized and empowered recycling cooperatives supported with public policies, embedded in a solidarity economy, targeting social equity and environmental sustainability'. This approach aims to implement public waste-management policies giving consideration to the environmental, social, and economic aspects. Livelihoods, income generation, human development and environmental protection are core aspects of this approach, which is based on achieving collective goals in the direction of common economic development (solidary economy), the formulation of democratic waste-management policies and participatory management (23).

Table 2 presents an overview of some of the key characteristics of integrated waste management, including formalization or integration of the informal sector, to be considered when looking at approaches or technologies for the waste sector.

Table 2. Overview of integrated waste management with formalization/integration of the informal sector

Scope of technology/ approach	Holistic approach to managing solid waste, considering material and energy flow optimization (waste hierarchy), socioeconomic context and interlinks, roles, and synergies among stakeholders.
Reasons for choosing this option	• Integrated waste management is a systemic framework focused on resource efficiency within the waste management system, in connection with other local value chains. • It works under strong consideration of the local socioeconomic context. • In conjunction with national policies, Integrated Waste Management can help to reach national waste management targets, but it is also related to sustainability (e.g. job creation, better working conditions, elimination of child labour, better education, gender equality). • Integrated waste management aims at achieving cooperation among all the stakeholders involved, creating economic and sustainability and at the same time reducing the environmental impacts.
Trade-offs	None
Barriers	• Absence of clear waste management policies and legal framework • Unclear roles and responsibilities of stakeholders • "Rejection" policies from municipal solid waste authorities and other stakeholders towards informal waste workers • Lack of environmental and social awareness of individuals especially regarding to their own responsibility as waste generators • In absence of formalization: competition with the informal sector for access to waste materials

Table 2. Overview of integrated waste management with formalization/integration of the informal sector

Enablers	• Clear national mandate with a focus on resource efficiency and sustainability goals. • National support for cooperation among stakeholders. • Legal framework supporting the participation of the private sector (including formalized and organized waste workers) as waste management service-providers. • Creation of financing mechanisms and business incentives for small enterprises as well.

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

4.2.2. Waste recycling

As mentioned in previous sections, sustainable municipal solid waste management strategies have the so-called "waste hierarchy" as their cornerstone. An important step facilitating the effective implementation of recycling is the introduction of waste-collection schemes that allow waste generators to separate and sort different waste fractions at source. Such schemes should be designed in accordance with the local context and conditions, for example, policies and legal framework, waste composition, waste amounts, local geography, urban distribution, population, education and environmental awareness, access roads, waste collection logistics and resources, presence of an informal waste sector, and also the treatment for each type of waste material, including the recycling market and the use of materials after their recovery.

Urban cities in developed and developing countries have different socioeconomic conditions, stakeholders, waste management regulations and policies. Waste separation at the source and collection systems can follow very detailed sorting levels, e.g. sorting of different coloured glass, type of plastics, bio-wastes and other kitchen waste, as in Germany and Austria – or it could also be designed in a simpler way. An example of this is the city of Mumbai, India, where residents separate their waste into wet and dry, corresponding to biodegradable and recyclable materials. Formalized waste workers collect the waste and proceed to treat the biodegradable fraction into compost and to sell the recyclable material (24). As in this example, waste separation and collection systems can be implemented with the support of organized waste workers' associations. As mentioned in previous chapters, informal waste workers can support municipalities in implementing and operating separate waste-collection and recycling systems as part of a formalization programme. For example, they can formalize informal waste workers by hiring them as workers in the sorting section of the manual sorting plant. Informal waste workers can identify high-quality recyclable materials more quickly and more efficiently compared with less experienced workers.

The configuration of waste separation and collection systems will influence the design and purpose of recycling facilities enormously. The layout and equipment of the recycling plant will reflect the kind of waste materials that are to be handled (e.g. sourced separated by various waste materials or only a few, or no waste separated at the source), waste input and output amounts and the expected quality of the outputs. In addition to material-related operational criteria, other criteria will also play a role when deciding the kind and degree of technology of a recycling plant. We are referring to the socioeconomic and financial aspects, such as the availability of a municipal waste management budget, access to financial mechanisms, the presence of an informal waste sector, and other socioeconomic and environmental issues that should be addressed, e.g. job creation, environmental regulations, recycling targets, local recycling value chains, integration of informal workers, etc. Additionally, it will depend on cash flow, the costs structure of the recycling plant (operational expenditure versus capital expenditure over a longer period), returns on investment and other economic aspects. For example, if the informal waste sector has a strong presence, the municipal budget for waste management is low and there is a need for local job creation and strengthening local added value for recycling, a manual recycling plant could be a more suitable option.

There are always trade-offs when choosing the level of automation. Fully automated recycling plants are frequently more expensive in terms of the initial investment, but in contrast the operating costs can be less onerous because a smaller workforce is needed compared with manual recycling plants. In addition, automated recycling plants have higher sorting efficiencies. Table 3 shows referential sorting rates for manual and automated recycling plants, highlighting the efficiencies of different plants, while Table 4 presents an overview of waste-recycling characteristics to be considered, also going a little further into some of the trade-offs.

Table 3. Manual and automated sorting efficiencies according to type of material

Materials	Manual (percent (%) recovery efficiency)	Automated (percent (%) recovery efficiency)
Newspaper and corrugated	60% - 95 %	80% / 90%
Mixed glass	70 - 95%	–
Glass – selection by colour	80 - 95%	>95%
Plastic	80 - 95%	99% (PVC); >90% others
Aluminium	80 - 95%	–

Source: Dubanowitz, 2000

Table 4. Overview of waste recycling

Scope of technology/ approach	Sorting and further mechanical treatment of recyclable materials from non-hazardous municipal solid waste; waste valorization
Reasons for choosing this option	Manual: • The best option for a city with an active recycling market and an informal waste sector. This complements integrated waste management with formalization approaches • Potentially unexpansive technology, accessible for cities with modest waste management budgets • Simple technology (for manual sorting plants) • Positive social impacts (job creation) Automated: • Best option for cities with high amounts of recyclable materials • For cities with almost no informal waste sector • Needs strong market demand for recyclable materials and stable market (amounts and prices) • For cities with high waste management budget
Trade-offs	Manual: • low investment but high operational costs • Relative fast payback period (less than five years) • Easy technology, but lower sorting efficiency Automated: • High investment but low operating costs • Payback period can be long (frequently seven to ten years) • Expensive technology, but higher sorting efficiency
Barriers	• Lack of separation at the source systems makes it more difficult to obtain good-quality recyclables • If not integrated into the municipal solid waste management system, the informal waste sector can extract valuable materials even before they reach the recycling plant, making it unfeasible technically and economically, and also creating competition • Weak local recycling market (low prices, low demand) • Lack of policies and legal framework supporting recycling
Enablers	• Waste management policies and legal framework with goals and quantitative targets for recycling, composting, anaerobic digestion, mechanical biological treatment energy from waste (also for reducing the environmental impacts from waste, such as climate change) • National policies allowing the private sector to invest in waste management and to access waste materials (including formalized and organized waste workers) • Creation of economic and financial support programmes for private investors, e.g. investment funds, low interest rates, tax exemptions for waste management to technologies, corporative taxes reduction, etc. • Long-term agreements with municipalities for allowing access to the waste (for private investors) • Involvement of formalized waste workers as waste management service providers, especially for waste collection. • Creation of quality standards for products (fertilizers, refuse derived fuel)

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

4.2.3. Composting

Composting is a controlled aerobic biodegradation process for treating organic waste, the aim being to avoid methane emissions linked to the unappropriated disposal of untreated organic matter. Composted inputs are typically food waste, agricultural waste, and the organic fraction of industrial and municipal wastes. Usually the end product is a very nutrient-rich organic fertilizer, which can be used instead of chemical fertilizers. Using compost as a fertilizer has a number of benefits: it reduce soil erosion, improves soil structure, facilitating water and air transport in the soil, and stabilizes pH, among other benefits. Composting is one of the most frequently applied technologies in treating organic waste in developing countries. It is an economically accessible option that at the same time generates aggregated value to organic waste. (6).

High-quality compost is produced from high-quality biodegradable input. In this sense, composting plants in developed countries work in conjunction with “waste separation at source” programmes. Waste generators are expected to sort “good quality clean” biodegradable waste (e.g. coffee and tea grounds, fruits peel, uncooked vegetables) from others that might be difficult to compost due to the longer composting time needed (mixed kitchen waste containing animal bones, food wrappings, etc.). In this way, biodegradable waste can be sorted in order to improve the balance of nutrients in the resulting compost and to reduce contamination with chemicals, plastics and other materials.

In addition to an appropriate input, composting depends on diverse operational parameters that should be kept in order to obtain a high-quality compost:

- Moisture content of the compost mixture (above 40 percent). Since food waste contains around 70 percent to 80 percent of moisture, it is necessary to add sawdust, rice husks or similar substances to reduce the moisture content. Moisture of between 50 percent and 60 percent has been reported to maximize respiratory activity in the composting process (26).

- Temperature: 55 – 70°C, depending on the material input to be composted and the homogeneity of the particle size.

Table 5 provides an overview of some of the key aspects of composting to be considered when using or considering it as a waste0management technology.

Table 5. Overview of composting

Scope of technology/ approach	• Treatment and valorization of biodegradable waste • Production of organic high-quality fertilizer
Reasons for choosing this option	• Low cost and simple technology • Low investment costs. Depends on the setting, low operating costs • Versatile technology (adaptability) • Very widespread in developing countries • Possible to implement centralized and decentralized • Best option if there is an active fertilizer market locally (high local demand)
Trade-offs	• Low investment • Typically higher operational cost • Lower mitigation potential (only through diverting biodegradable waste from landfilling or dumping and replacement of fossil fuel based fertilizers)
Barriers	• Needs waste separation at source • Needs quality standards for the final fertilizer • Needs a stable market • Needs clear policies and regulations allowing composting from municipal solid waste to be commercialized as compost for agriculture
Enablers	• Waste management policies and legal framework with goals and quantitative targets for recycling, composting, anaerobic digestion, mechanical biological treatment energy from waste (also for reducing environmental impacts from waste, such as climate change) • National policies allowing the private sector to invest in waste management and to access waste materials (including formalized and organized waste workers) • Creation of economic and financial support programmes for private investors, e.g. investment funds, low interest rates, taxes exemptions for waste management to technologies, corporate taxes reduction, etc. • Long-term agreements with municipalities for allowing access to the waste (for private investors) • Involvement of formalized waste workers as waste management service providers, especially for waste collection • Creation of quality standards for products (fertilizers, refuse-derived fuel)

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

4.2.4. Anaerobic digestion

Anaerobic digestion is the decomposition of organic matter through microorganisms in the absence of free oxygen. Anaerobic digestion occurs naturally under circumstances of oxygen deprivation, but the process can be replicated under controlled conditions to produce biogas to generate energy. The fermentation thereby controlled happens in a reactor called a biodigester, which provides stable and better conditions (temperature, pH, organic matter, etc.) for the microorganisms. The main outputs of the biodigestion are biogas and solid and liquid digestate. Methane is the source of the energy content in the biogas, its content usually ranging between 50 percent and 75 percent, depending on the input of waste and the operating conditions. The heating value of biogas is about two thirds that of natural gas (5.5 to 7.5 kWh/m3) (17). Biogas has a number of uses. Usually, small-scale biogas plants in developing countries convert it into heat and use this energy for cooking, heating, drying of grains, etc. However, plants with more complex technologies can generate electricity and heat through cogeneration (6).

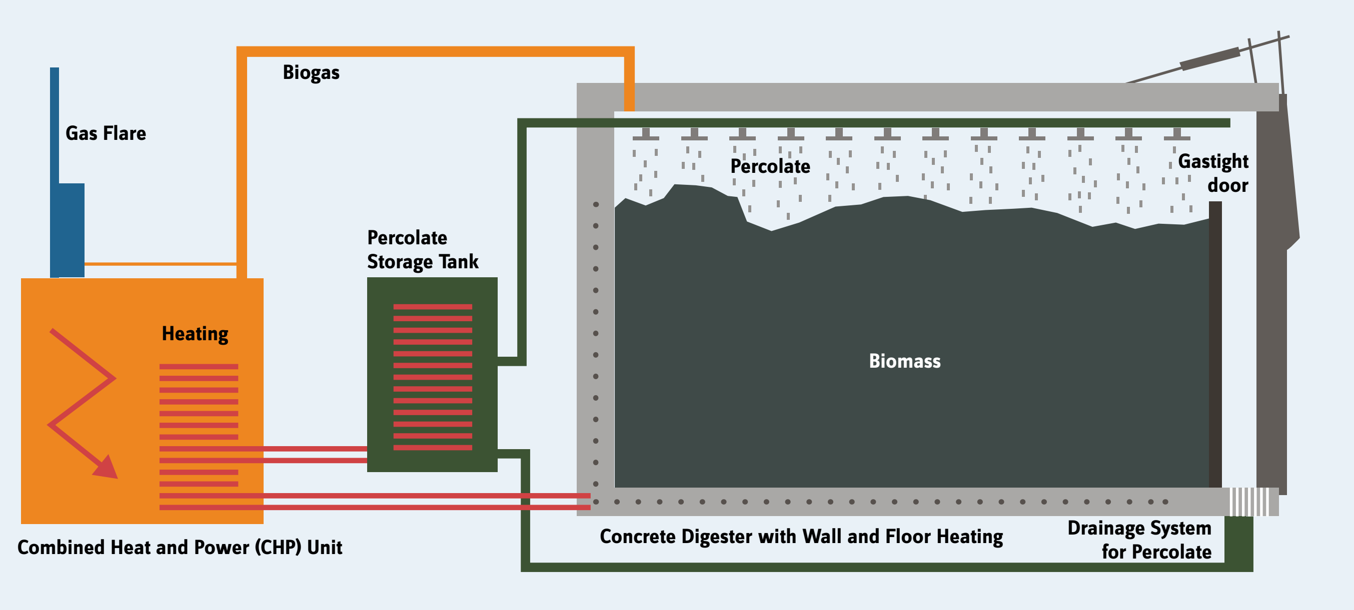
In developed countries, the organic fraction of municipal waste is treated in high-tech biogas plants. The input is source-separated in order to avoid contamination of the digestate. Large-scale biogas plants in developed countries frequently produce electricity to be sold and distributed for consumption in the national electricity grid. The heat produced during the cogeneration may be used for household heating or industrial heating. Biogas can also be cleaned and used in transport, for motor cars, gas networks, etc.

Depending on the waste input, the process flow and the main process parameters, anaerobic digestion can be categorized as:

- Psychrophilic (< 25°C), mesophilic (35-48°C) or thermophilic (> 50°C). The last is recommended when there is a risk of pathogens being produced.
- Wet fermentation or dry fermentation: waste with more than 30-40 percent dry matter (dry anaerobic digestion), waste with less than 12-15 percent dry matter (wet anaerobic digestion).
- Batch or continuous feeding: continuous feeding is common in processing liquid feedstock, such as catering waste, wastewater or industrial sludge from food-processing. Batch-feeding and batch digesters are common for solid waste input. Because most waste processed is solid waste, this is also called dry fermentation.
- One-stage and multi-stage digestion: defining the use of one or more digesters to optimize separate anaerobic digestion stages, e.g. separating the hydrolysis and acidosis from the methane-formatting phase (27).

The dry fermentation process is mostly used to treat waste inputs that are not suitable for pumping and that have a significant content of impurities that can be harmful to the stirrers and pumps in a wet fermenter. Furthermore, dry fermentation has a lower energy consumption. As a result, dry fermentation is widely used to process the organic fraction of municipal solid waste in Europe. In dry fermentation the feedstock is inoculated with digestate before each feeding cycle, and the percolate is run in circuit. The inoculum contains methanogenous bacteria, which supports the conversion of organic

Figure 3. Dry fermentation process.



Source: Qian et al., 2016

Table 6. Advantages and disadvantages of wet vs. dry fermentation

	Dry fermentation **Dry d.m. > 40 percent**	**Wet fermentation** **Wet d.m. < 15 percent**
Advantages	No need for internal mixing equipment in the reactor; strength and resistance to heavy aggregates and plastics; low loss of biodegradable organic matter in the pre-treatment; high organic loading rates; resistance to substrate concentration peaks and toxic substances; minimum and cheaper pre-treatments, reduced volume of reactors, reduced use of fresh water; minimum required heating for the reactor.	Developed technology; applicability in co-digestion with liquid waste with high organic matter content; reduced costs for pumping, mixing and pumping worldwide in the whole market: dilution of concentration of toxic substances.
Disadvantages	Less opportunity to dilute inhibitory substances and organic loads with excessive fresh water; high investment costs due to the equipment used for the treatment.	Separate phases of floating and heavy matter; abrasion of the mechanical parts due to the presence of sand and aggregate; pre-treatment of waste complex and expensive; strong sensitivity to any shocks to the presence of inhibitory substances and organic load variables; lost or organic volatile substance during pre-treatment; high investment due to equipment for the pre-treatment and for the volume of the digesters.

Source: IGWSRL (no date)

acids into methane, mainly in the digester (see Figure 3). Table 6 compares the advantages and disadvantages of wet and dry fermentation.

While biogas is frequently used to generate electricity and heat in a combined heat and power generator, the digestate can be used as fertilizer provided the waste inputs consist of source-separated, non-contaminated biodegradable waste. The solid fraction of the digestate can be dried to be used as compost, and the liquid fraction can be used as a growth stimulant for plants due to the presence of micronutrients and phytohormones. Tables 7, 8 and 9 below show some of the average indicators for biogas yields for different organic waste inputs, efficiency ratings for electricity and heat conversion by type of generator, the average electricity and heat consumption of biogas plants, and some of the general characteristics of anaerobic digestion as a waste-management technology.

4.2.5. Mechanical Biological Treatment

Mechanical biological treatment usually involves a first treatment phase, corresponding to the separation and sorting of recyclable materials (recycling plant), and a second

Table 7. Biogas and energy production for biodegradable municipal solid waste

Biodegradable waste type	Biogas yield (m^3/ton fresh)	Percent Methane	Methane yield (m^3/ton fresh)	Energy content (kWh/m^3 methane)[a]
Municipal solid waste organic fraction[b]	107	64	85	9,97
Kitchen and garden waste[c]	–	–	40 - 100	
Municipal solid waste organic fraction fresh[d]	106	–	–	
Kitchen waste[e]	80 - 120	58 - 65	–	

[a] Wirtschaftlichkeitsrechner Biogas KTBL, 2018. [b] GIZ, 2014. [c] GIZ, 2017. [d] Al Hamamre et al., 2017. [e] Austrian Umweltministerium, 2011.

Table 8. Energy conversion efficiency co-generation

Generator unit type	Gas Otto engine	Diesel engine
Electrical efficiency	34 - 42[a] 38%[b]	30–44 % 41.5%[b]
Thermal efficiency	47%[b]	42.5%[b]
Biogas plant own electricity consumption	7.6% [c] 8.1%[d]	
Biogas plant own heat consumption	28%[e]	

[a] FNR, 2016. [b] KBTL, 2018. [c] Wirtschaftlichkeitsrechner Biogas online tool, 2018. [d] Solarenergieforderverein Bayern, 2006.
[e] Wirtschaftlichkeitsrechner Biogas online tool, 2018.

Table 9. Overview of anaerobic digestion

Scope of technology/ approach	• Treatment and valorization of biodegradable waste • Energy generation (electricity and/or heat) • Production of organic high-quality fertilizer
Reasons for choosing this option	• Best option for cities with high biodegradable waste fractions and high waste flows • Anaerobic digestion is the best option for cities collecting "good quality" biodegradable waste separately from other waste streams. That would ensure high-energy production and high-quality fertilizer • High investment costs but lower operating costs • Generates up to three different valuable outputs (electricity, heat and refuse-derived fuel made from non-recyclable dry residual waste)
Trade-offs	• High investment • Low operating costs, but also low potential for job creation (workforce) • Payback period can be long (frequently seven to ten years) • More complex technology and market conditions, but it allows the economic risk to be distributed by diversifying cash flows • Higher mitigation potential (by diverting waste from landfilling, replacing fossil fuels for energy generation and replacing fossil fuel-based fertilizers)
Barriers	• Needs waste separation at the source • Needs quality standards for the final fertilizer • Needs a stable market for fertilizers and energy (e.g. national grid or private consumers) • Needs clear policies and a legal framework allowing and supporting energy generation and commercialization from waste (e.g. feed in tariffs, tax reductions, etc.)
Enablers	• Waste management policies and legal framework with goals and quantitative targets for recycling, composting, anaerobic digestion, mechanical biological treatment energy from waste (also for reducing environmental impacts from waste, such as climate change) • National policies allowing the private sector to invest in waste management and to access waste materials (including formalized and organized waste workers) • Creation of economic and financial support programmes for private investors, e.g. investment funds, low interest rates, tax exemptions for waste management to technologies, corporate tax reductions, etc. • Long-term agreements with municipalities allowing access to the waste (for private investors) • Involvement of formalized waste workers as waste management service-providers, especially for waste collection • Creation of quality standards for products (fertilizers, refuse-derived fuel)

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

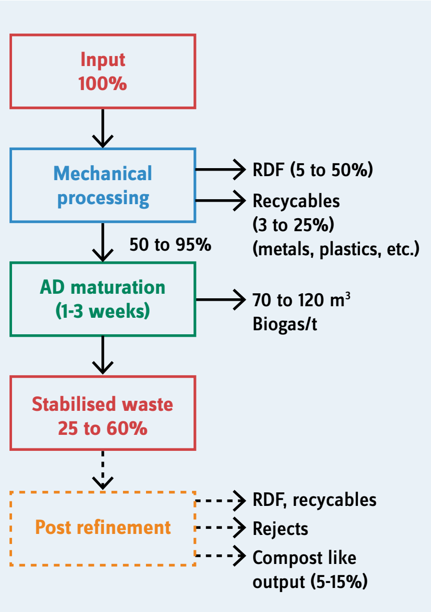
one, which could be anaerobic digestion, involving composting for the biodegradable fraction. Dry recyclable materials are sold for reutilization and the stabilized final compost-like material is landfilled or dried for its use as an alternative fuel (refuse-derived fuel or refuse-derived fuel) in incinerators or in industrial furnaces, such as cement kilns. Additionally, dry non-recyclable materials with a high calorific value (e.g. low-quality recyclables) may be also destined for energy generation as refuse-derived fuel. Due to the high construction and operating costs, mechanical biological treatment plants are mostly found in developed countries (Europe, United Kingdom and Australia) (16).

The term "refuse-derived fuel" is used to define any material that can be co-combusted and used as a secondary fuel in incineration and/or industry plants. As industrial solid waste is typically more homogeneous in its physical and chemical characteristics, industrial non-hazardous waste is frequently used as secondary/substitute fuel, e.g. waste tyres, waste oils, spent solvents, bonemeal, animal fats, sewage sludge and industrial sludge. Also homogeneous residues from industries such as plastics, textiles or the biomass industries can be used as an alternative fuel. In the context of municipal solid waste, the term "refuse-derived fuel" is used to indicate a secondary fuel derived from mixed waste fractions, different coarser grain sizes and variable physicochemical characteristics. Owing to mechanical biological treatment being able to use a combination of treatment processes and to produce different refuse-derived fuels, we will now present some of the different options:

- **Mechanical biological treatment with anaerobic digestion:** This process is ideal for generating renewable energy (e.g. electricity) for sale and distribution through the national electricity grid. Then anaerobic digestion as part of a mechanical biological treatment would represent an optimal option for waste treatment with energy recovery in a country with a favourable regulatory framework and technical conditions in place. Regarding refuse-derived fuel production, after the biodigestion, the organic fraction is dried through a composting-like process, leaving a dry, stabilized, highly mineralized organic material. This material also contains some non-recyclable dry waste, which is finally separated and used as refuse-derived fuel. Figure 2 shows the process flow of a mechanical biological treatment with Anaerobic digestion.

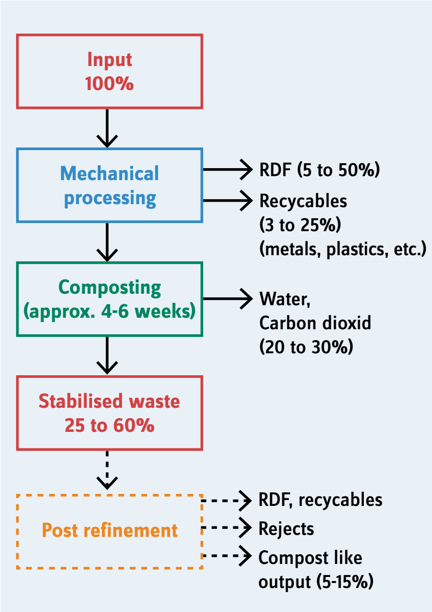
- **Mechanical biological treatment with aerobic stabilisation:** The key target of this option is mainly to treat mechanical biological treatment for further disposal, without economic dependence on other markets such us energy or refuse-derived fuel. Here, the organic fraction is stabilized, reducing the amount of biodegradable municipal waste going to landfill. Typically, the biological treatment is combined with mechanical processing to separate the refuse-derived fuel products from the waste prior to or after the biological treatment. When the refuse-derived fuel fraction is separated first, the material left after separation of the refuse-derived fuel is enriched with easily degradable components like kitchen waste and dirty paper, like tissues, which are not suitable for recycling. This material is then treated through an aerobic process (composting). This process uses some of the energy and material in the organic matter, thus generating carbon dioxide and heat. After the biological

Figure 4. Mechanical biological treatment with anaerobic digestion



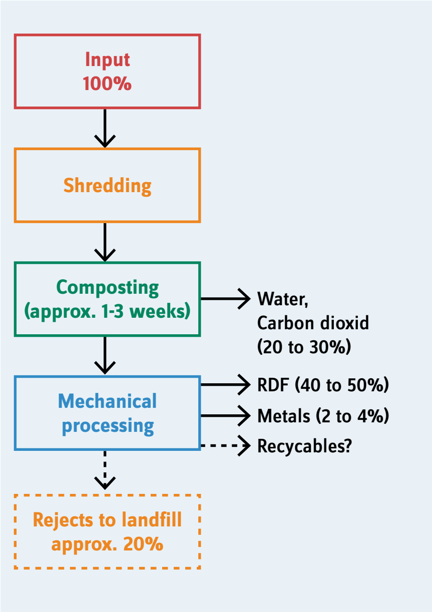
Source: 36

Figure 5. Mechanical biological treatment with stabilisation



Source: 36

Figure 6. Mechanical biological treatment with biological drying



Source: 36

hydrolysis, the waste is stabilized and ready for landfill. Further possible treatment would be a post-refinement stage, where more RDF can be separated from the stabilized compost-like material. Adding this stage depends mostly on economic feasibility more than technical issues. Figure 3 presents an example of this process, with waste streams.

- **Mechanical biological treatment with biological drying:** this combination seeks to make use of the energy content of the waste to produce a high-quality refuse-derived fuel, which can be burnt in industrial plant like cement kilns at a lower price than in a combustion facility or mass burn incineration. This "compost-like" process aims to remove the water content from the organic waste fraction by modifying the process and control parameters, thus enabling easier mechanical treatment subsequently. Müller and Bockreis (36) explain a typical mechanical biological treatment process with biological drying as follows: "The waste is shredded and placed in enclosed bio-drying boxes, where air is forced through the waste creating optimum conditions for microbiological activity, which will produce the heat for removing moisture from the waste (drying). The biological drying process is stopped at 15 percent to 20 percent water content, however, further drying can be performed by passing pre-heated air (produced with heat exchangers). With the drying of the waste the calorific value of the material is increased".

It is important to stress that the mass flows, efficiency of mass conversion, parameters and quality of the final refuse-derived fuel will depend strongly on the composition of the mechanical biological treatment, the input of the mechanical biological treatment plant. The values mentioned in Figures 4, 5 and 6 indicate a reference to what the conversion rates could be. Table 10 below presents an overview of some of the general characteristics of mechanical biological treatment when considering it as a waste-management technology.

Table 10. Overview of mechanical biological treatment

Scope of technology/ approach	• Combined process: sorting and mechanical treatment of recyclable materials • Energy and fertilizer production • Production of refuse-derived fuel as a secondary fuel
Reasons for choosing this option	• This is the best option for cities generating high waste amounts, but with a non-existent or incipient separation at the source system (collection of mixed waste) • Mechanical biological treatment maximizes material and energy recovery through refuse-derived fuel production, even after the biological treatment • Higher mitigation potential through the use of refuse-derived fuel as an alternative fuel in other industries • Best option for cities with high waste management budget (high investment costs) • Low operating costs
Trade-offs	• Due to higher investment, needs larger amounts of waste to be treated and therefore is not suitable for small cities • More energy consumption than other treatment options (more processes involved) • Greater potential to create more jobs (more complex layout that other treatment options) • Can work with mixed waste, but the quality of fertilizers is not appropriate for agriculture or others; most likely to be disposed of in a landfill • If the compost-like product is further used as refuse-derived fuel, the quality of the waste input should be monitored to generate good-quality refuse-derived fuel
Barriers	• Needs waste separation at source • Needs quality standards for the final refuse-derived fuel • Needs a stable market for refuse-derived fuel • Needs clear policies and a legal framework allowing the use of refuse-derived fuel from waste as alternative fuel • Needs cooperation with other industries (e.g. cement) to achieve attractive and stable market conditions
Enablers	• Waste management policies and legal framework with goals and quantitative targets for recycling, composting, anaerobic digestion, mechanical biological treatment energy from waste (also for reducing environmental impacts from waste, such as climate change) • National policies allowing the private sector to invest in waste management and to access waste materials (including formalized and organized waste workers) • Creation of economic and financial support programmes for private investors, e.g. investment funds, low interest rates, tax exemptions for waste management to technologies, corporate tax reductions, etc. • Long-term agreements with municipalities for allowing access to the waste (for private investors) • Involvement of formalized waste workers as waste management service-providers, especially for waste collection • Creation of quality standards for products (fertilizers, refuse-derived fuel)

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

4.3. Key policy-related issues

Typically, municipal solid waste management systems are institutionally structured on three main levels that play different but equally important roles involving national, regional and local governments. While national government responsibilities often cover general policy or strategic decisions and the establishment of institutional and legal frameworks, regional and municipal governments are frequently in charge of their actual implementation. Regional administrations might be in charge of finances and may also be involved with the protection of regional environmental health and environmental management, or supporting municipalities through the implementation of waste-management plants. They are more likely to be involved in managing regional disposal sites, especially where regional disposal facilities are used by several towns and cities. The third governance level are the municipalities, which are typically in charge of organizing, providing and regulating municipal solid waste management services (sweeping, collection, transport, etc.), as well as implementing municipal solid waste management plans. Regarding the provision of services, cooperation with the private sector is increasing. Normally, in such cases, it is the local authorities that remain responsible for regulating and controlling the private sectors’ activities.

Even though municipal solid waste management systems typically follow the structure described above, there is no doubt that they can be very different from one city to another, mainly due to their socio-economic and legal contexts. However, cities in developing countries share some common aspects or tendencies regarding their waste management problems in terms of efficiency, inappropriate waste management disposal practices, and the social, environmental and economic impacts.

These similarities allow common aspects to be identified that can be considered “key overarching enablers” for achieving sustainable municipal solid waste management systems. They could therefore be included in any waste management policy, plan or strategy:

1. Establishment of waste management policies and a legal framework (also related to waste management) with clear and measurable goals and targets, also promoting the reduction or prohibition of landfilling untreated waste. A measure like this would redirect waste materials to different treatment options. waste management targets should be measurable and legally enforced. To support their achievement and ongoing improvement, it is important to lay down legal and regulatory enforcement mechanisms. Targets should be binding, involving all relevant actors in the waste value chain, and, if possible, meeting targets should be sanctionable according to the country’s regulations.

   Following that, waste management policies should incorporate the “waste hierarchy” as the key principle of all waste-management regulation and policies and others related to resource efficiency. Establishing a waste management hierarchy makes it clearer to authorities and other relevant stakeholders what the path is to higher levels of resource efficiency. A starting point could be to introduce policies to favour waste treatment and recycling. After that, waste management policies should rise higher in the waste hierarchy, towards waste prevention and upstream waste repurposing.

2. Establishing a “healthy” municipal solid waste management cost structure and budget. Frequently, waste management service fees are defined on the basis of waste generation per capita, censuses, land registries and others, and not based on the actual waste amounts generated by consumers, nor the actual waste management costs. waste management costs tend to be under-estimated, making waste services fees are lower than the costs they should cover. In addition, municipalities do not have a functioning waste-collection scheme, and there is often great mistrust on the part of the local population and a strong unwillingness to pay waste management fees. This situation could be improved by estimating the actual waste management costs and establishing of appropriate municipal solid waste management revenue streams, as well as through adjusted waste collection and disposal fees for waste service users. This should be combined with more effective ways to collect waste management fees, such as by including them in other basic services (e.g. electricity, water) and by gradually improving waste management services to increase willingness to pay.

   Another example of measures to reduce waste management costs for the municipalities could be to allocate waste-management costs to waste generators (the “polluter pays principle[3]”) in accordance with the amount of mixed waste that is generated. Applying this might successfully encourage users to separate their waste and even modify their consumption patterns towards a more efficient use of resources.

3. Appropriate formalization or integration of the informal waste sector. Policies and legal changes allowing the formalization of the informal sector are a key aspect, especially focusing on their economic and social empowerment, which would allow their successful integration into the formal waste management system (see section 2). Policies, legal frameworks and formalization strategies should start by considering the informal waste sector as a key stakeholder when it comes to achieving the waste management targets. Some experience with formalization experience has shown the readiness of informal waste workers to be formalized as long as this happens in a participatory way that fulfils their expectations and needs regarding their working conditions, income, flexibility and empowerment, among other issues (1).

4. Incentives for the private sector to invest in waste management include establishing legal, economic and fiscal incentives, as well as companies to invest in waste management services and to participate as waste management operators. Among the incentives that could be considered are value added tax exemptions, reductions in corporate taxes, attractive conditions for concessions of waste management services, guaranteeing long-term access to waste materials, tax exemptions for technology imports, access to renewable energy prices, and business models-based extended producer responsibility schemes in cooperation with municipal waste-management systems.

[3] The principle that those causing pollution should meet the costs to which it gives rise (36).

References

5. Aparcana S. 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 Management*, 2017. Volume 61, Pages 593-607
6. Hoornweg D, Bhada-Tata P. WHAT A WASTE: A Global Review of Solid Waste Management. The World Bank. March 2012, No. 15. http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/What_a_Waste2012_Final.pdf
7. Abarca L, Maas G, Hogland W. Review: Solid waste management challenges for cities in developing countries. *Waste Management*. 2013. 33: 220–232
8. Aparcana S, Salhofer S. Development of a social impact assessment methodology for recycling systems in low income countries. *Int J Life Cycle Assess*. 2013. Doi:10.1007/s11367-013-0546-8
9. Kaza S, Yao L, Bhada-Tata P, Van Woerden F. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. *Urban Development Series*. 2018. Washington, DC: World Bank. doi:10.1596/978-1-4648-1329-0. License: Creative Commons Attribution CC BY 3.0 IGO
10. Aparcana S, Hinostroza M. Guidebook for the Development of Nationally Appropriate Mitigation Actions on Sustainable Municipal Waste Management. UNEP DTU Partnership. 2015.
11. Gunsilius E, Spies S, García-Cortés S, Medina M, Dias S, Scheinberg A, Sabry W, Abdel-Hady N, Florisbela dos Santos A, Ruiz S. Recovering resources, creating opportunities Integrating the informal sector into solid waste management. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. 2011. http://www.giz.de/de/downloads/giz2011-en-recycling-partnerships-informal-sector-final-report.pdf.
12. Potting J, Hekkert M, Worrell E, Hanemaaijer A. Circular Economy: Measuring innovation in the product chain – Policy report. PBL Netherlands Environmental Assessment Agency. 2016. 42
13. Moraga G, Huysveld S, Mathieux F, Blengini G, Alaerts L, Van Acker K, De Meester S, Dewulf J (2019) Circular economy indicators: What do they measure?, Resources, Conservation and Recycling, Volume 146
14. Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*. 2017. 127, 221–232. doi:10.1016/j.resconrec.2017.09.005
15. United Nations Environmental Programme (UNEP). Waste and Climate Change: Global trends and strategy framework. Division of Technology, Industry and Economics, International Environmental Technology Centre Osaka/Shiga. 2010. Available at: http://www.unep.or.jp/ietc/Publications/spc/Waste&ClimateChange/Waste&ClimateChange.pdf.
16. *European Waste Framework Directive. 2008* (EU).
17. Organisation for Economic Co-operation and Development. Greenhouse gas emissions and the potential for mitigation from materials management within OECD countries. Working Group on Waste Prevention and Recycling. 2012. Available at: http://www.oecd.org/env/waste/50035102.pdf.
18. King MF, Gutberlet J. Contribution of cooperative sector recycling to greenhouse gas emissions reduction: A case study of Ribeirão Pires, Brazil. *Waste Management*. 2013. Available at: http://dx.doi.org/10.1016/j.wasman.2013.07.031
19. Hetz K, Paul JG , Alfaro JC, Lemke A.The informal recycling market in Ormoc city, Philippines: Evaluation of options to enhance resources recovery and to Reduce GHG emissions. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Philippines. Proceedings of the International Conference on Solid Waste 2011- Moving Towards Sustainable Resource Management, Hong Kong SAR, P.R. China. (pages 163 - 165). Available at: http://www.iswa.org/uploads/tx_iswaknowledgebase/05_Waste_Management.pdf.
20. United Nation Environment Programme (UNEP - IETC. Waste-to-Energy: Considerations for Informed Decision-Making. International Environmental Technology Centre. 2019.

21. GIZ. Waste to Energy Options in Municipal Solid Waste Management: A Guide for Decision Makers in Developing and Emerging Countries. 2017. Available at: https://www.giz.de/en/downloads/GIZ_WasteToEnergy_Guidelines_2017.pdf
22. United States Environmental Protection Agency – EPA. Benefits of Landfill Gas Energy Projects). Available at: https://www.epa.gov/lmop/benefits-landfill-gas-energy-projects#one (accessed March 2021)
23. Seadon JK. Integrated waste management – Looking beyond the solid waste horizon. *Waste Management*. 2006. 26. 1327–1336
24. Wilson D, Velis C, Cheeseman C. Role of informal sector recycling in waste management in developing countries, *Habitat International*. 2006. 30: 797–808. Available at: DOI: 10.1016/j.habitatint.2005.09.005
25. Velis C, Wilson D, Rocca O, Smith S, Mavropoulos A, Cheeseman. An analytical framework and tool ('InteRa') for integrating the informal recycling sector in waste and resource management systems in developing countries. *Waste Management and Research* , 2012; 30: 43. DOI: 10.1177/0734242X12454934
26. Medina M. Scavenger cooperatives in Asia and Latin America. *Resources, Conservation and Recycling*. 2000; 31:51 – 89. PII: S0921-3449 (00) 00071 – 9.
27. Gutberlet J. Informal and Cooperative Recycling as a Poverty Eradication Strategy. Department of Geography, University of Victoria. *Geography Compass*, 2012; 6 (1): 19–34. Available at: DOI: 10.1111/j.1749-8198.2011.00468.x
28. Rathi S. Alternative approaches for better municipal solid waste management in Mumbai, India. *Waste Management*. 2006; 26: 1192 – 1200. DOI:10.1016/j.wasman.2005.09.006.
29. Dubanowitz A. Design of a Materials Recovery Facility (MRF) For Processing the Recyclable Materials of New York City's Municipal Solid Waste. Department of Earth and Environmental Engineering, Foundation School of Engineering and Applied Science Columbia University. 2000. Available at: http://www.seas.columbia.edu/earth/dubanmrf.pdf.
30. Kawai L, Liu C, Gamaralalage P. CCET guideline series on intermediate municipal solid waste treatment technologies: Composting. United Nations Environment Programme (UNEP). 2020.
31. United States Environmental Protection Agency – EPA. Biosolids Technology Fact Sheet Multi-Stage Anaerobic Digestion. 2006. Available at: https://www.epa.gov/sites/production/files/2018-11/documents/multistage-anaerobic-digestion-factsheet.pdf (accessed March 2021)
32. Qian M, Li R, Wedwitschka H, Nelles M, Sinner W, (2016) Industrial scale garage-type dry fermentation of municipal solid waste to biogas. Bioresource Technology 217 (2016) 82–89
33. IGWSRL. Full scale experience with dry anaerobic digestion process. No date. Available at: http://www.igwsrl.com/home/wp-content/uploads/2016/10/FULL-SCALE-EXPERIENCE-WITH-DRY-ANAEROBIC-DIGESTION-PROCESS.pdf
34. Wirtschaftlichkeitsrechner Biogas online tool. 2018. Available at: https://daten.ktbl.de/biogas/showKennzahlen.do?zustandReq=16#anwendung
35. GIZ. Zielmarktanalyse Biogas & Biomasse Kenia mit Profilen der Marktakteure. 2014. Available at: https://docplayer.org/530010-Www-exportinitiative-bmwi-de-a-zielmarktanalyse-biogas-biomasse-kenia-mit-profilen-der-marktakteure-www-export-erneuerbare-de.html
36. Al Hamamre et al. Wastes and biomass materials as sustainable: renewable energy resources for Jordan. 2017.
37. Austrian Umweltministerium. Über die Erschließung des Potenzials biogener Haushaltsabfälle und Grünschnitt zum Zwecke der Verwertung in einer Biogasanlage zur optimierten energetischen und stofflichen Verwertung. 2011.
38. Fachagentur Nachwachsende Rohstoffe e. V. Leitfaden Biogas, von der Gewinnung zur Nutzung. 2016. Available at: http://www.fnr.de/fileadmin/allgemein/pdf/broschueren/Leitfaden_Biogas_web_V01.pdf

39. Solarenergieforderverein Bayern. Der Eigenstromverbrauch von Biogasanlagen und Potenziale zu dessen Reduzierung. 2006. Available at: https://www.infothek-biomasse.ch/images//2006_SOLARENEFOERDERVER_Eigenstromverbrauch_Biogasanlagen.pdf
40. Wolfgang Müller and Anke Bockreis, Mechanical-Biological Waste Treatment and Utilization of Solid Recovered Fuels – State of the Art, 2015.
41. European Environmental Agency – EEA, Polluters Pay Principle. 2004. Available at: https://www.eea.europa.eu/help/glossary/eea-glossary/polluter-pays-principle (accessed March 2021)