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WasteGui: Guideline for organic waste treatment in East Africa

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WasteGui: Guideline for organic waste treatment in East Africa

Legal, Technical and economic guideline for dealing with organic waste as a basic strategy for politics, administration, research and the private sector for East African countries using the example of Ethiopia

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List of abbreviations and symbols

Abbreviation	Explanation
˚C	Degree celsius
a, yr	Year
AD	Anaerobic digestion
BMZ	German Federal Ministry for Economic Cooperation and Development
BtL	Biomass-to-liquid
C	Carbon
CAD	Computer-aided-design
cap	Capita
CAPEX	Capital expenditure
CHP	Combined heat and power plant
CLO	Compost like output
cm	Centimetre
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
COP	Climate change conference
Cu	Copper
d	Day
DBFZ	German biomass research centre
DIN	German national standardisation body
DS	Dry substance
e.g.	For example
EAC	East African countries
EEG	Renewable energies act
etc	Et cetera

EU	European Union
EUR	Euro
GHG	Greenhouse gases
h	Hour
H_2O	Water
Hg	Mercury
hh	Household
i.e.	That is
ICU	Engineering Consultants Environment and Construction
Inh, Inhab	Inhabitants
IPPC	Intergovernmental Panel for Climate Change
ISO	International organization for standardization
J	Joule
K_2O	Potash
kg	Kilogram
kWh	Kilowatt hour
l, ltr	Liter
LFG	Landfill gas
m^2 m^3	Square meter, cubic meter
MBS	Mechanical biological stabilization
MBT	Mechanical and biological treatment
Mg	Mega gram (= 1 ton)
MGB	Large waste containers
MJ	Megajoule
MSW	Municipal solid waste
MT	Million tons
MUDC	Ministry of Urban Development and Construction
MW	Mega watt

N	Nitrogen
NBPE	National Biogas Program – Ethiopia
Nm^3	Norm cubic meter
ODS	Organic dry substance
OPEX	Operational Expenditures
p	Page
P, P_2O_5	Phosphorus, Phosphate
PCB	Polychlorinated biphenyl
PFAS	Per- and polyfluoroalkyl substances
PJ	Petajoule
Pls	Please
POPs	Persistent organic pollutants
PPCP	Pharmaceuticals and Personal Care Product
RDF	Refuse derived fuel
resp	Respectively
SSO	Source separated organics
SWM	Solid waste management
SWOT	Strength, weaknesses, opportunities and threats
t	Ton
TPW	Tons per week
UN	United Nations
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
uPOPs	Unintentional persistent organic pollutants
VOCs	Volatile organic components
WWF	Worldwide fund for nature

Preface

This publication was elaborated in the pilot project “Guideline for organic waste treatment in East Africa” as part of a call for solutions by the PREVENT Waste Alliance. The aim of the project is to provide a general overview of the current state of organic waste management in East African countries, described in the DBFZ Report Nr. 45 (Lenhart et al. 2022), specifically using Ethiopia as an example. Based on this, DBFZ Report Nr. 47 focusses on detailed concepts for collection, transport and final treatment of organic wastes, as an additional information for politics, administration, research institutions and the private sector.

Organic wastes – as concerned in this study - appear mainly in the mixed municipal waste. Treatment options of this mixed waste to reduce the ecological damages when landfilled are described. Aside - and not less important – the separate collection of organic waste and the treatment alternatives of this material hold a relevant share of this study. This guideline should thereby serve as a profound basis to apprise decision-makers of a range of efficient and well-proven technical solutions in organic waste handling and give planners and builders a good starting point for future project development.

The project combined the learnings of the organic waste management evolution in Germany as well as input of the German organic waste recycling industry and international experts. The main inputs were elaborated by the consultants of ICU Berlin, of the Rodiek & Co. GmbH and of the INTECUS GmbH.

1 Introduction

Due to population growth as well as the growth of wealth and intensified general consumption the amount of waste - produced and disposed - is simultaneously growing. One of the problematic side effects: the rate of proper waste logistics and treatment is not growing at the same speed. Still very few and only certain types of waste are handled in a circular way by adequate recycling systems.

Regarding Solid Waste Management (SWM), attention needs to be given to the emerging economies: Countries that are shifting to a higher income level will experience a dramatic increase in per capita waste generation and an exacerbation of management difficulties due to the growth in prosperity and to the movement to urban centers (Kaza et al. 2018).

The share of organic waste in East African cities (as well as in the rural areas) is very dominant: 55 % to even 80 %. This waste composition characteristic not only demands particular attention but also offers a range of feasible management and treatment solutions. If unmanaged and not treated separately the organic matter is accountable for numerous negative environmental, health and social impacts. If landfilled or burned the general values of organics are lost: nutrient rich humus and energy potential. Improvement concepts can be relatively simple, affordable, low-tech and surprisingly effective.

Many municipalities are looking for affordable solutions and best practices (both in collection and treatment) to not only but prominently minimize the amount of landfilled material and step by step increase recycling (recognize waste as a resource). The most effective approach with numerous positive side effects: The separate handling of biodegradable waste components through natural decomposition.

Organic waste is understood as biodegradable waste that can undergo anaerobic or aerobic decomposition. In the context of this document the term biodegradable waste (biodegradables) is used equivalently to the term organic waste (organics), organic material (see definition in section 3.1).

The following guideline will offer an overview of concepts and best practices for the collection and treatment of biodegradable wastes from different sources – mainly but not only from households – developed to be adopted in East Africa, especially in Ethiopia. It is adapted to the local conditions of rural, semi- rural and urban living structures. Thereby it should help decision makers, planners and the private sector, not only by information about the various organic waste handling and treatment concepts, but also to implement a solution according to the local realities.

The structure of the document is as follows:

In chapter 2 the general waste composition in East African Countries (EAC), collection rates and trends are further analysed, actual collection and treatment practices as well as planned improvement approaches (Ethiopia) are presented.

In chapter 3 Biodegradable waste – the need for action definitions on the subject of biodegradables are given, the recent waste handling status is described as well as the negative social, environmental and health impacts of the status quo.

To solve the problems characterized in chapter 3 two main tasks are given: A functional collection of the waste and the proper treatment.

Thus, in chapter 4 the details of waste collection and logistic are described, outlining the relevant systems and influencing parameters, finally characterizing the most suitable collection and logistic systems for inner cities, semi-urban and rural areas.

In chapter 5 the options of mechanical, biological and thermal treatment are presented, referring to the two main kinds of waste – mixed waste and source separated organics. The chapter presents a range of project examples.

Chapter 6 documents in a model calculation, which high reduction of organics can be achieved in combination of separate collection and the treatment of the remaining waste.

Extracting the basics of chapter 4 and 5, chapter 7 develops specific strategies for three different settlement structures (urban, semi-urban, rural), this both for collection and treatment.

In chapter 8 the framing condition “regional availability of money” that is crucial for the selection of future concept components including a budget finding method is outlined.

Organic waste collection and treatment model projects are developed in chapter 9 – “Think big, but start small”. A conclusion is given in chapter 10.

- *Light grey boxes are used to highlight central recognitions as well as additional important information.*

2 Waste management background

Solid wastes from households and industrial, commercial and institutional actors are referred to as municipal solid waste (MSW). Most of the waste collected comes from households, which is characteristic of the region of East African Countries (EAC). However, few data are available on composition and amounts of MSW, which are generally extracted from major cities waste composition analyses.

For Ethiopia there is an estimation of 7.7 million tons of overall MSW in the year 2020. It is estimated to rise to around 10.7 million tons in 2030 to 15.1 million tons in 2040 and 21 million tons in 2050 – a growth of around plus 40 percent per decade.

The average per capita waste generation in Sub-Saharan Africa in 2016 was calculated to be less than 0.5 kg/day/capita, which is much lower than the global average of 0.74 kg per day, indicated in the report *What a Waste 2.0* (Kaza et al. 2018).

In East Africa, the average per capita MSW generation is about 22 percent higher than the Sub-Saharan average, with considerable spatial differences in the amount of waste generated which ranges from as low as less than 0.2 kg per day in Ethiopia to as high as 1.6 kg per day in the Seychelles (UNEP 2018, p. 24). Due to its large population Ethiopia is ranked as third major waste producer and contributes 12 percent of all wastes generated in East Africa.

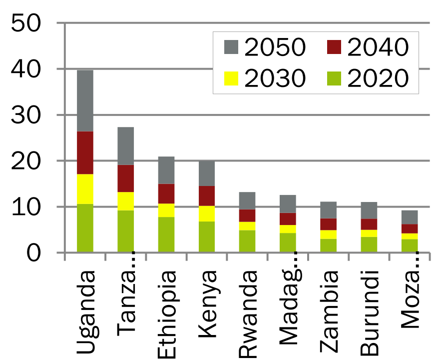

Figure 1: Waste generation growth for EAC in millions of tons per year (Lenhart et al. 2022)

Country	organic	Glass	metal	paper	plastic	other
Uganda	74.5	0.8	0.6	6	7.6	10.6
Ethiopia	87.6	0.8	1.2	3.8	2.3	4.4
Kenya	57	3	1	11.3	18.7	9
Burundi	81	2.9	2.1	7.3	3.5	3.2
Mozambique	60			25		15

Table 1: Waste composition characterization in percent (Lenhart et al. 2022)

In order to estimate the trend of MSW generation growth in the *most relevant* EAC, generation rate projections are taken from “More growth, less garbage” while population projections are those from UN Population Projections, Medium Variant, 2019 Revision (see Figure 1).

In Figure 1: Waste generation growth for EAC in millions of tons per year (Lenhart et al. 2022) different types of materials (in percent) characterizing the solid waste of East African countries as per dataset of *What a Waste 2.0* (World Bank 2019) are listed. The scarcity of data for a proper analysis and comparison is well evidenced. The data represent only the biodegradable fractions whose source is mainly MSW and some industrial food waste. Other types of biomasses such as forestry, agricultural and aquatic residues, or manure were not considered.

In low-income countries a high and dominant share of biodegradable material in the waste is very common. The share in Ethiopia of more than even 80 percent of biodegradable material in the waste composition is a strong indicator for low consumption rates. To put it simple: There is not enough wealth to buy “non-organic” products e.g. packed consumer goods, clothing, etc on a big scale.[1]

The figure 2 compares[2] the typical waste composition of different income structures with the Sub-Saharan African average and some capitals of Eastern Africa. For Addis Ababa (Ethiopia) an organic share above 60 percent was detected. In the rural area the share can be estimated to be even more dominant. Moreover, the graph shows that the proportion of “ceramics/others” is higher in some cities, which is explained by the inclusion of sand and fine particles from road cleaning (ACCP 2019, 3.5). Compared to other countries, African residual waste has a high share of mineral components. These components result from unpaved roads, which are widespread (ACCP 2019). Due to the high share of native organic matter - compared to industrialised countries - the waste has a higher water content. The high-water content, along with sand and other minerals brought in by road cleaning, influences the material and energy properties and also has an impact on waste collection and treatment (ACCP 2019; Pfaff-Simoneit 2012).

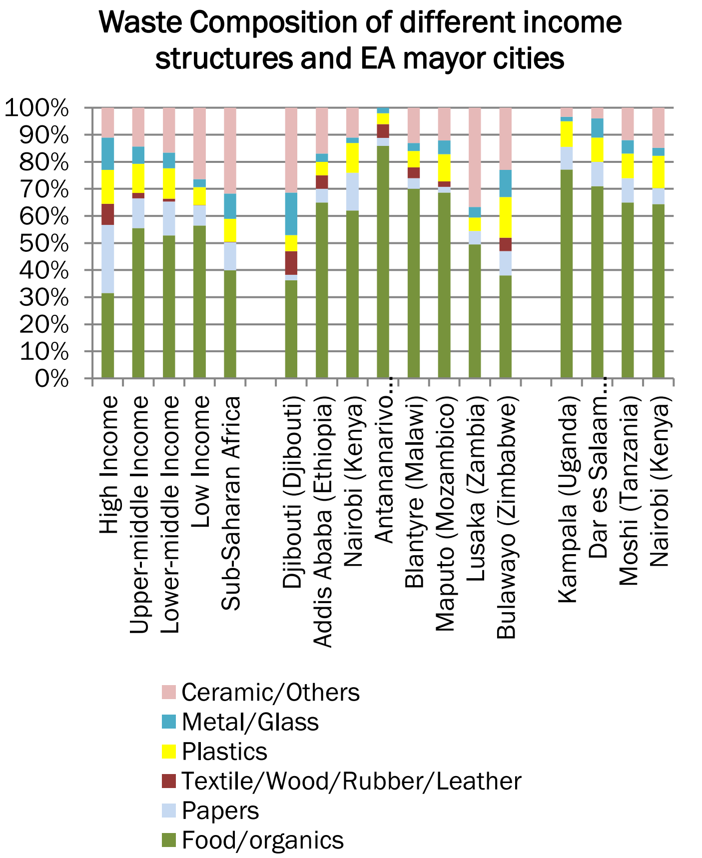

Figure 2: Waste composition in some capitals of Eastern Africa (Lenhart et al. 2022) from (ACCP 2019, 3.5) and (UNEP 2018, p. 27) and averages reported in What a Waste 2.0 (Kaza et al. 2018)

While the average collection rate for sub-Saharan Africa is between 40 and 50 %, the residual waste recycling rate for the African continent is only 4 % (Teshome 2021; Gelan 2021; ACCP 2019).

[1] Due to this - not voluntary - reduced consumption most African states are in terms of waste avoidance far ahead of industry states, which have a threefold higher amount of primarily produced waste.
[2] coarse comparison due to different methodological approaches

The waste is mostly managed as mixed waste, either collected from households or from public waste collection containers of central disposal points.

Figure 3: Public waste collection container (P. Sanders/ICU)

Looking at the capital of Ethiopia, the City of Addis Ababa with its around 5 million inhabitants, the prominent city's structure plan for the period 2017-2027 states that "about 25 % of the solid waste generated is indiscriminately dumped within residential neighbourhood, while the remaining 75 % is collected but disposed in unsanitary manner at "Repi" controlled dumping site. Waste separation at source is almost absent and only around 10 % of the MSW is reused or recycled…". The need for a more sustainable and integrated waste management system is highlighted as follows[3]:

"Successful implementation of sustainable solid waste management, however, requires separation of waste at the source and the active involvement of the public in the process. Proper implementation of such strategy creates job opportunities and minimizes burdens on the natural environment"

Specific proposals for an effective, efficient and sustainable waste management service concerning separation at source that are made by the city are the following:

- *"Ensure three-way waste separation at source (recyclable, bio-degradable and hazardous) in 2025 and five-way waste separation at source: paper, plastic, other recyclables, bio-degradable and hazardous) in 2040;*
- *Increase the percentage of recycling to 10 % in 2025 and 20 % in 2040; and*
- *Increase the percentage of organic waste transformation (e.g. composting, animal feed) to 25 % in 2025 and 40 % in 2040."*

As we know from almost everywhere in the world: Even if there is no formal separation at household level still some valuable recyclables (like metals, cans, bottles, papers) find their way out of the mixed waste stream into the recycling markets through informal ways, since these dry recyclables have a monetary value. However, this economic incentive for separate collection is not given for the biodegradable fraction (kitchen and garden wastes), resulting in huge environmental, health and social damages.

[3] Addis Ababa City Structure Plan DRAFT FINAL SUMMARY REPORT (2017-2027) AACPPO

3 Biodegradable waste and the need for action

3.1 Definition

Biodegradable waste is any native organic waste that is capable of undergoing anaerobic or aerobic decomposition. Following the definitions of the status-quo report (Lenhart et al. 2022), the presented solutions and best practices in this guideline apply to the group of *biowastes*. These are biodegradable wastes from e.g. households, gardens and parks, markets, restaurants, canteens, bars, retail premises, food processing plants as shown in Figure 4. Other biodegradable wastes, e.g. sewage sludge, wood, cardboard and paper or from the agriculture and forestry sector will not be considered. In this guideline the terms *biodegradable waste* and *organic waste* are used respectively and are referring to the group of biowaste (see Figure 4).

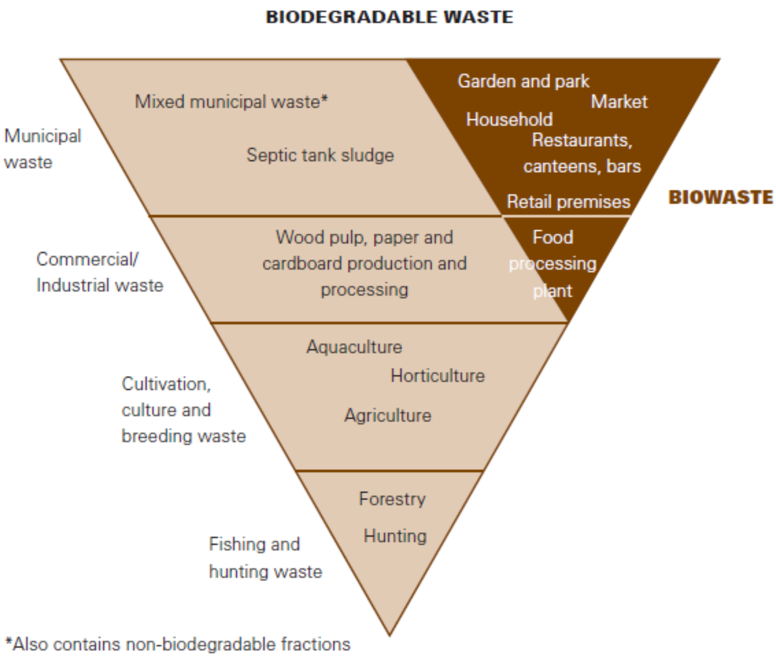

Figure 4 Potential sources of biodegradable waste and biowaste (Zabaleta et al. 2020)

Figure 5: Biodegradable waste examples. Left: Branches from street cleaning; right: Mix of kitchen and garden waste (ICU).

The spots and ways for this waste to arise are extremely varied. In principle, any place of human activity is a possible source, whereby the generated waste can be almost homogeneous in composition, but likewise contain completely different materials mixed together. This difference is important for subsequent disposal, since the overall composition and the respective properties of the waste may result in very different hazard potentials on the one hand but give way for different treatment and utilisation options on the other hand, too.

3.2 Environmental, climate, health and social impacts of the current waste management in East African

MSW with high shares of biodegradable waste components is a perfect medium for micro-organisms. Under anaerobic conditions, like in a landfill (or dumpsite), these organisms degrade the organic fraction basically into organic acids and methane. Methane is not only a very climate-relevant gas but also explosive and thereby dangerous to people who work or live in the area of a landfill. The organic acids in the landfill waste body will mobilize contaminants like heavy metals that cause a toxic leachate which purification is one of the most difficult and most expensive fields of water purification. For that reason, the reduction of biodegradable waste components in the MSW is a fundamental measure to avoid long-term health and environmental problems and additionally to contribute to mitigating climate change[4]. Moreover, the sustainable use of the contained nutrients as fertilizer can be achieved.

- *Better handling of biodegradable wastes, through implementation of simple recycling concepts, can not only offer a high number of social and health benefits, but also various renewable energy sources as well as subsidies for industrial fertilizer within the agricultural sector.*

The status quo of most places in the world is that still a very high share of landfilled or dumped mixed waste is biodegradable. The main reason is that separate collection at source-level systems or separation and treatment at disposal-level systems are not yet implemented. In addition, many landfills in the global south remain rather unmanaged and below sanitary standards (for example: uncontrolled, non-fenced, no covering, no leachate capture, no emissions capture etc.).

The causes of environmental, health and social impacts of landfilling and uncontrolled waste dumping is partly illustrated in Figure 7 and can generally be divided in:

Leachate: This pollutes drinking water resources and soil by uncontrolled emissions. Leachate in quantity is mostly influenced by percolation of rainwater, its contamination is mainly affected by the biodegradable material in the waste. While bacteria and fungi decompose the organic material other contaminating by-products are released. Any oxygen is rapidly used up, creating an anaerobic environment, the temperature rises and the pH-level falls.

Thereby, many metal ions (that are relatively insoluble at neutral-level from other waste components become dissolved in the acid leachate (Zabaleta et al. 2020; Christensen et al. 2001) and contaminate the groundwater underneath the landfill. In parallel, toxic organic compounds like oil, pesticides,

[4] Focusing just on Ethiopia, a study conducted in 2018 on available biomass residues and their bio-energy production potential calculated that within the total 750 PJ/yr bio-energy production potential, forest residues contribute with (46.6 %) of the total, crop residues 34 %) and livestock manure of 140 PJ/yr (19 %), the remaining 3.8 PJ/yr potential (0.4 %) being the share from MSW from major cities in the country (Gabisa and Gheewala 2018).

industrial residues find their way out of the corroding barrels. The emission of leachate extends much longer than the operation time of the landfill, meaning several decades after closing the landfill.

➢ *The higher the share of biodegradable material, the higher the contamination of groundwater through the percolation of leachate*[5].

Figure 6: Open dumpsite (P. Sanders/ICU)

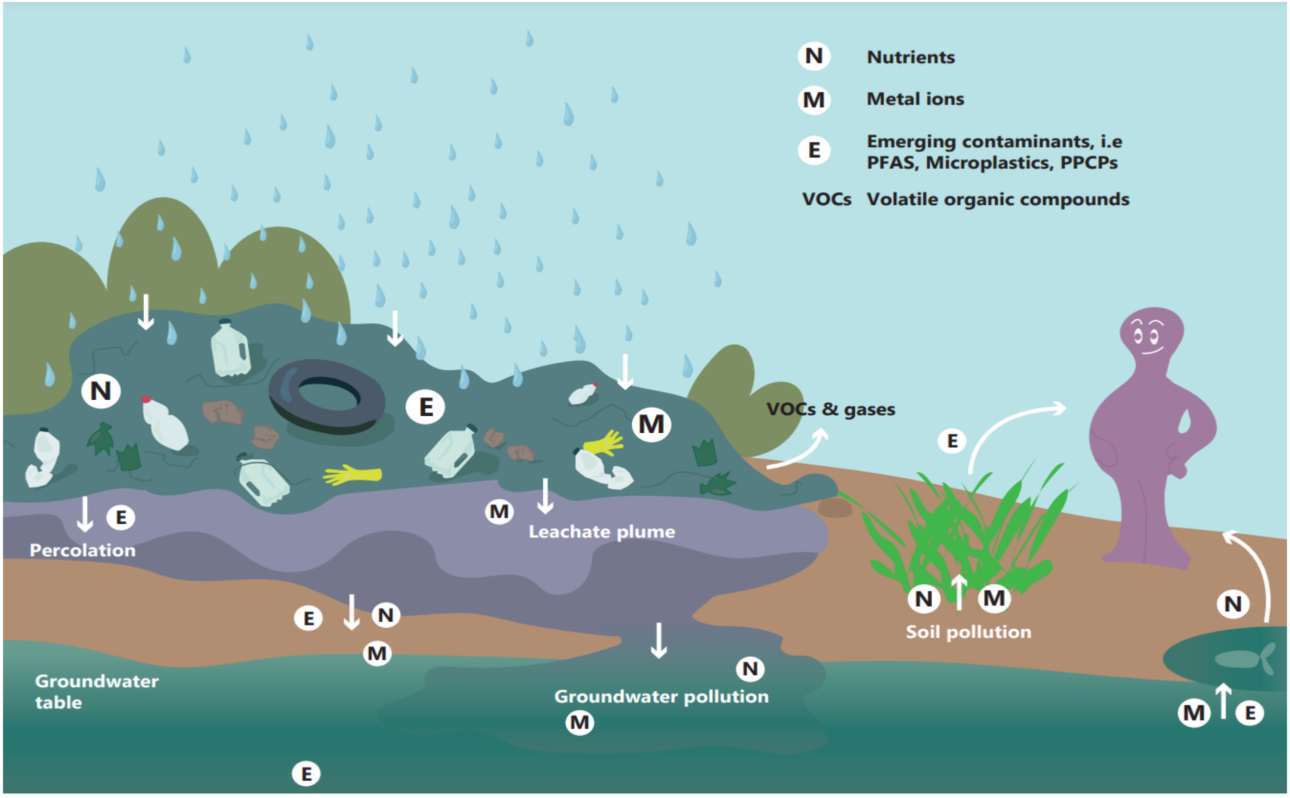

Figure 7: Visualisation of ecological effects from dumpsites and landfills (ICU)

Landfill gas (LFG): Air quality is affected by landfill gas which is emitted without any control, and causes odour problems. The organic components in the landfill-body decompose to landfill gas analogously to an anaerobic biological reactor. The landfill gas consists mainly of methane and carbon dioxide. One ton of organic waste (with 60 % moisture, 60 % organic dry substance (ODS)) produces around 60 m^3 of

[5] Applies to non-sanitary landfills

methane that can be evaluated as more than 25 times as potent as carbon dioxide in a period of 100 years, but even 86 times as potent in a period of 20 years at trapping heat in the atmosphere[6].

➢ *One ton of landfilled organics produces minimum one-ton CO_2e as a contribution to the greenhouse gas effect*

Additionally, volatile organic compounds (VOC's) are released to air. VOCs include a variety of chemicals, some of which have short- and long-term negative health effects.

Estimates[7] of methane emissions are subject to a high degree of uncertainty, but the most recent comprehensive estimate suggests that annual general global methane emissions are around 570 million tonnes (MT).

The waste related methane emissions[8] account for around 20 % (68 MT / (570 MT x *60* %)) of global *anthropogenic* methane emissions and are generally understood as "low hanging fruits" in terms of prevention.

Open burning: Another critical point is the open burning of waste instead of collection or at landfills in order to reduce volumes and/or have better access to scrap metal. This "casual thermal treatment" causes a considerable negative impact on air quality. The open burning of mixed wastes not only endangers directly the people in the close surrounding, it also emits so called (unintentional) persistent organic pollutants (uPOPs) that can air-travel long distances and therefore affect the health of humans and animals all around the world.

➢ *Anything else done with organic waste is far better than landfilling or open burning – in all considerable aspects.*

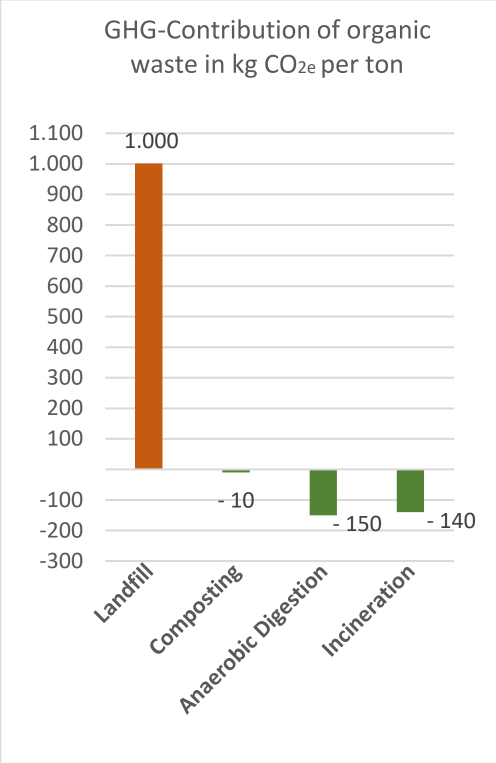

Figure 8: GHG contribution of organic waste in different treatment/disposal systems (ICU)

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[6] Methane | Climate & Clean Air Coalition (ccacoalition.org)
[7] This includes emissions from natural sources (around 40 % of emissions), and those originating from human activity (the remaining 60 % - from agriculture, energy, waste etc., known as anthropogenic emissions) (https://www.iea.org/reports/methane-tracker-2020)

[8] Methane capture at landfills is becoming more urgent as improvements in detection technologies are revealing discrepancies between methane emission estimates and reality in the industry. A new airborne methane sensor deployed by NASA, for instance, found that California landfills have been leaking methane at rates as much as six times greater than estimates from the U.S. Environmental Protection Agency. The difference has major implications for the Earth's atmosphere. (https://news.mit.edu/2022/loci-methane-emissions-landfills-0202)

Figure 9: Burning of waste to reduce volume (P. Sanders/ICU)

Direct physical impact: In many countries "scavenging" (searching for recyclables during waste collection and/or disposal, and to herd animals on landfills) is still a common practice. Consequences of this activity are: People working without any means of personal protection get hurt or sick, high danger of landfill slides, diseases occur and contaminants can enter the food chain (milk, meat). Waste slides and explosions in the waste body are relatively frequent deadly events in a lot of unmanaged landfills and dumpsites in Africa[9] and other parts of the world – including Addis Ababa Koshe landfill slide in Ethiopia.

3.3 Overview - sustainable concepts to handle biodegradable waste

What we know now: If continuously landfilled (and not used) not only nutrients, humus-building potential and alternative energy potentials are lost, but also a range of environmental, social and health damages continue to take place. Any concept that is improving resource and energy recovery and/or lowering environmental pollution is far better than the status-quo of mixed waste being dumped/landfilled or openly burned.

At COP 26 [10] in Glasgow 100 nations including Ethiopia committed to cutting methane emissions 30 % by 2030: "Participants joining the Pledge agree to take voluntary actions to contribute to a collective effort to reduce global methane emissions at least 30 percent from 2020 levels by 2030, which could eliminate over 0.2 ˚C warming by 2050. This is a global, not a national reduction target. Participants also commit to moving towards using the highest tier IPCC good practice inventory methodologies, as well as working to continuously improve the accuracy, transparency, consistency, comparability, and completeness of national greenhouse gas inventory reporting under the UNFCCC and Paris Agreement, and to provide greater transparency in key sectors" (https://www.globalmethanepledge.org/).

To improve the status-quo a range of options are available. The options will depend highly on the purity of the organic waste stream. The lower the amount of impurities (normally: plastic bags, sand/stones, glass, paper etc.), the easier the treatment process (lower costs through lower effort) and higher quality in the end product. The range starts with basic open garden/community or industrialized windrow composting (to mainly produce compost), and goes through relatively advanced systems like anaerobic digestion plants (to produce the add-on biogas) up to high-end systems like mechanical and biological

[9] Extract: More than a hundred people killed in Koshe landfill slide in Addis Ababa in July 2019 (https://unhabitat.org/after-the-tragic-landslide-that-killed-116-koshe-landfill-in-addis-ababa-is-safer), around fifteen people killed in Maputo 2018 (https://www.theguardian.com/global-development/2018/feb/26/explosion-fatal-rubbish-landslide-mozambique-hulene-dump)

[10] United Nations Framework Convention on Climate Change, 26th Conference of the Parties – COP26, Glasgow, Scotland, 2021 (https://ukcop26.org/)

treatment plants that integrate different technologies and derive various output (compost, biogas, recyclables, RDF).

For a mixture of wastes, it must always be assumed that there are far greater risks and potential hazards, and thus higher requirements for treatment and safe disposal, than is generally the case with homogeneous and relatively uniform waste quantities. Consequently, waste collection should, if possible, also be oriented towards forming such homogeneous and relatively similar waste streams and not mixing them unnecessarily.

Considering this principle is of farreaching significance: In addition to reduced needs and lower costs for subsequent treatment, efficient recycling and circular economy also take their starting point here. It is therefore the optimal scenario when waste materials of the same kind are kept separate at the point of generation as 'source-separated' waste. Due to its high share in the waste and its high negative impacts when dumped the separate collection of organic waste has the highest priority. Nonetheless there are limits for separate collection, leaving a stream of 'mixed' waste.

Chapter 4 Collection and logistics concepts explains the ways how waste streams can be collected and logistically managed, including esp. the separate collection of organic wastes.

For these two main waste streams, mixed waste and separate collected organic waste, this guideline will present the different handling and treatment options. The graphic (Figure 11) below illustrates the very basic available and robust treatment concepts, their end products as well as other characteristics. This graphic shall give a first overview. A detailed description is given in chapter 5 Treatment.

- In best case, biodegradable waste is separately collected and finally used as clean compost in agriculture, thus supporting resource efficiency and climate protection. The minimum task is to decompose the organic fraction of mixed waste in a short time (of less than half a year) under controlled conditions, so that it has lost at least 90 % of its methane and leachate producing potential and can then be landfilled almost without later emissions. An ecological "add-on" in both basic ways is to recover the biogenic energy by the production of biogas or extraction of refuse derived fuels (RDF). By these treatments some additional value will be gained for society: More jobs and better health conditions.

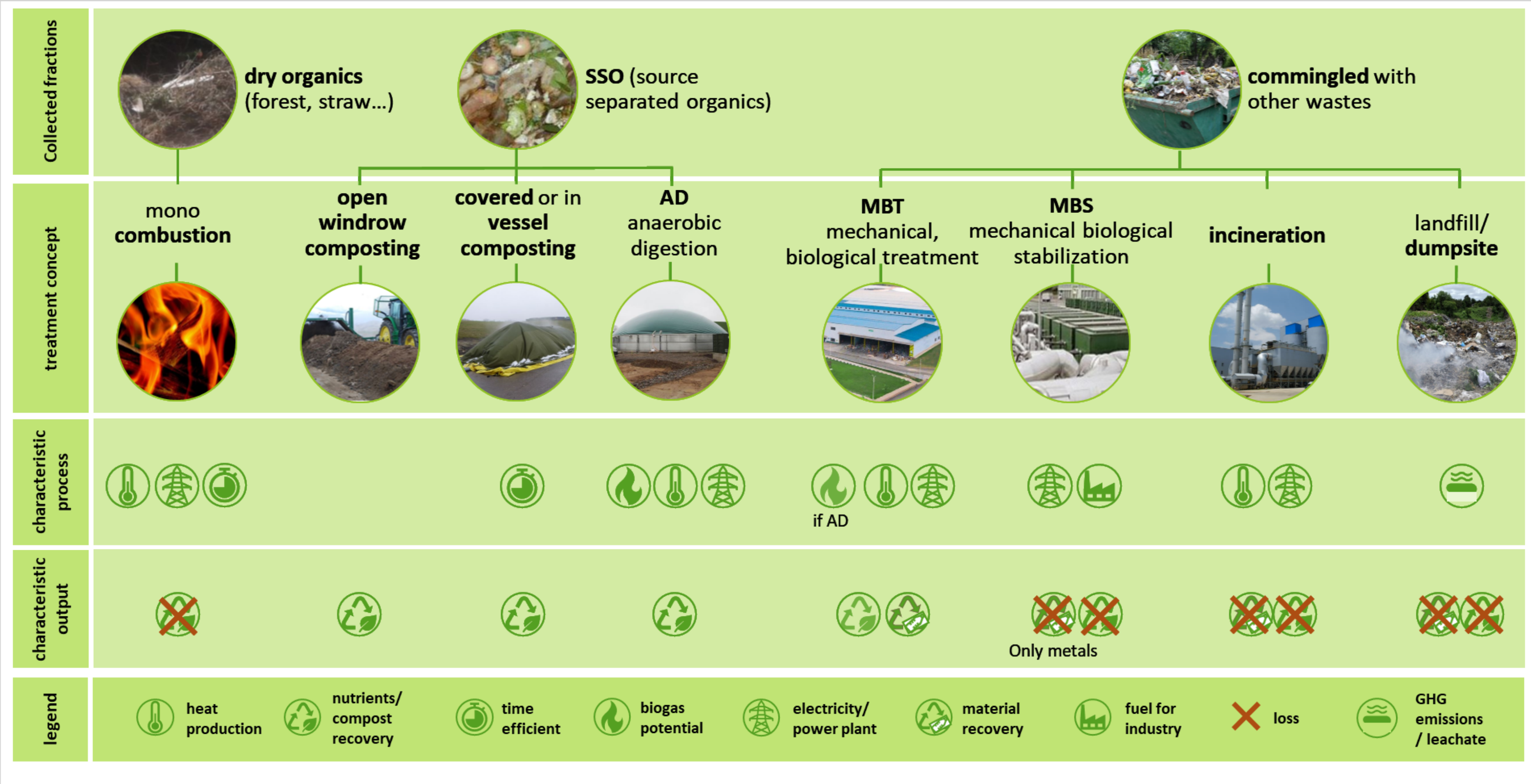

Figure 10: Overview waste treatment technologies - visualizing process- and output characteristics (ICU)

4 Collection and logistics concepts

Although waste collection rates occur to be quite high in Ethiopia (which is an appreciable factor), the downside praxis of landfilling almost all collected wastes has to be improved. New approaches of waste handling will demand adapted logistics concepts – primarily to separately manage biodegradable waste fractions.

The objective of this chapter is to give decision makers in eastern Africa a guideline on the design and implementation of collection systems for biodegradable waste material as part of the household waste – source separated and mixed. The different components for a collection system and their respective characteristics will be illustrated and underlined with considerations regarding their specific suitability, requirements, and other considerations.

After a short **status-quo** summary the following sections will present basic **preliminary considerations** as well as a number of **key principles** for the planning of collection systems (sections 4.1 and 4.2). – focusing on biodegradable or mixed wastes. A comprehensive overview of the **decision areas** for the **design** of such systems is presented in section 4.3 followed by an instruction section, on how to **design and dimension** a collection system (demand side calculations).

In section 4.6 a range of examples and **recommendations** for collection systems for **different types of settlement structures** (metropolitan, semi urban to urban and rural) is presented as an adaptation of the before presented considerations, principles and decision areas.

Minimum requirements and general cost considerations of the required investment and operational costs are given, as well as a methodology for the estimation of the service costs of a logistical concept. The methodology is then adapted on two settlement structures.

Box 1 - 5:

The whole chapter 4 includes practical experiences from planners and operators of collection systems (Africa and structurally similar regions) - presented in these green boxes.

4.1 Status quo – collection rates, masses and actors

In Sub Saharan Africa overall waste collection rates are about 44 %, however the rate is much higher in urban areas than in rural areas, where waste collection services are minimal (average 9 %). (Kaza et al. 2018, p. 79).

In Ethiopia waste is collected only partially, mainly in urban regions. The collection of waste is often non-existent or sporadic, especially in economically underdeveloped regions (Teshome 2021). As an example, for Ethiopia's largest city, Addis Ababa, the collection rate is 70 % (Kaza et al. 2018). With a population of around 3,350,000, this corresponds to a daily uncollected amount of waste of around 500 t.

Door to door service is the most common collection system in East Africa cities (Kabera et al. 2019). To overcome access difficulties, often the secondary transport is arranged by carts, wheelbarrows or small vehicles. The waste collected is then temporary accumulated in transfer stations. The improper management and design of waste transfer stations is a further problem of the collection/transport system in East Africa cities. Waste transfer stations are designed to give flexibility to the primary collection, increasing its efficiency and reducing related costs. Nevertheless, for East African cities, transfer points are most of the times simply unprotected open spaces or open containers: when pick up is delayed they can become a serious nuisance for the city, causing odours, compromising the neighbourhood aesthetically and above all seriously affecting environment and public health.

The input of the following sections is developed by the **Rodiek & Co. GmbH** from extensive project insights (1988-2022) if not stated otherwise.

4.2 Basic preliminary considerations

As waste management systems need to be tailored to specific local conditions, a key factor for an efficient solution is the collection of accurate data on the status quo of the existing waste management system. Initially, the various stakeholders should agree on a model region in which the collection and treatment of biogenic fractions will be carried out and collect data for this area. This is helpful to gain experience and create a positive example for a later nationwide expansion. At all stages during the planning and development phase local stakeholders should be included, in order to identify the specific need and requirements as well as to assess whether a potential solution really meets the requirements.

The planning and design of waste logistics systems typically needs real **data** on the status quo in the following areas:

Waste quantities and qualities

- Waste generation & composition
- Population density
- Determine fractions & quantities collected

Collection system

- Determination of general status quo with special regards to the need and expectations of the population and the informal sector
- Determine reasonable distances - size of collection area
- Determination of collection mode & frequency
- Determination of suitable containers / vehicles
- Percentage informal/formal collectors

Treatment capacities
- Determination of available treatment capacities
- Determination of suitable treatment processes

Transport capacities
- Analysis of transport capacities in the existing waste management system
- Determination of the number of required vehicles

Personnel
- Qualitative personnel requirements
- Quantitative personnel requirements

When designing logistics concepts for the collection of waste, a multitude of decisions have to be made, that each have significant influence on the final configuration of the system.

However as discussed in the previous sections, there are certain **key principles**, that all waste management solutions have in common:

- The selected technologies must work reliably under the local conditions
- Transport cost typically make up for the largest part of the overall cost and therefore should be minimized
- The characteristics of the logistics system should meet the needs and expectations of the local waste generators.
- The overall cost has to be recovered either through a waste fee and/or the sale of treatment products.
- There is a trade-off between minimal transport cost and maximum quality of treatment products, which needs to be solved for the individual context.

Decisionmakers should have sufficient knowledge of the available technology options and the design processes, as well as a broad idea of what waste logistics in their area of authority should look like. The further development and refinement of the concepts can be supported by **specialized consultants** with experience in planning and implementation of waste logistics systems in African countries.

4.3 Decision areas

A concept for the collection of waste can only be successful in the long term if it is technically as well as economically feasible and if it meets the expectations of the people, it services. Additionally, any system that is designed should respect the ecological demands given.

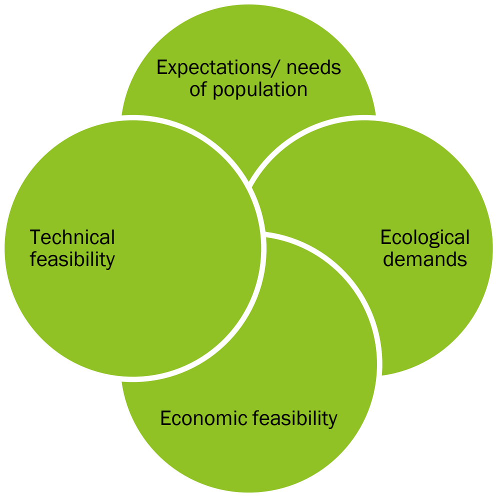

Figure 11: Success factors for waste logistics systems (Rodiek 1988-2022)

Transferring the criteria shown in Figure 11 to the context of waste collection and logistics, the following **decision areas** can be derived:

1) Collection mode
2) Timing of collection (collection times and frequency)
3) Point of collection
4) Vehicle types
5) Container types
6) Transport stages
7) Storage
8) Transfer
9) Treatment
10) Digitalization

These decision areas will be further elaborated in the paragraphs below by providing a short overview of the main characteristics and some leading questions to be used to describe the local situation for which the collection system shall be designed. Also, some general recommendations will be made from experience in the African context.

4.4 Collection mode

Mixed or separate collection

In order ensure the highest quality of treatment products, waste collection should aim at forming homogeneous waste streams, keep different waste streams separated from each other and to avoid mixing waste streams with different compositions. In an ideal scenario the waste would be separated at source and fed into separate treatment processes, optimized for the characteristics of each waste stream.

Typically, source-separation of biogenic waste streams bear the following benefits:

- allow more specific treatment processes and therefore greater efficiency
- less effort for preparation of the material for treatment
- lower treatment costs
- less residual waste to be disposed at landfill, thereby reducing ecological damages and disposal cost
- generate compost of high value and applicability

Some waste sources usually generate homogeneous streams of biogenic waste material, which require little to no effort to collect them separately and keep them separate throughout the value chain.

Typically, these sources are:

- Municipal garden maintenance
- Markets
- Food wholesalers and retailers
- Food processing industry
- Restaurants / Hotels
- Specific agriculture residues, if not recycled directly

On the other hand, source-separation of household waste streams does require more effort and involvement of the waste generators as well as greater effort to keep the waste streams separated through the logistics system. A separate collection of organics implies a separate collection of residual waste as well. The same applies to recyclables, which can achieve a much greater quality if collected separately and not mixed with residual or organic waste.

Under certain conditions the additional costs associated with the introduction of the additional collection and container system for biogenic waste for a municipality might be offset by cost reductions from the collection and disposal of a reduced volume of residual waste (Rodiek 1988-2022).

Figure 12: Mutual interactions and correlations between collection mode and treatment technologies (Rodiek 1988-2022)

4.4.1 Timing of collection

Timing of collection refers to the frequency of the collection, the time of day, and the days of the week.

Frequency of the collection
Considering the climate conditions in East Africa it is recommended to ensure that the collection intervals are never more than 3 days to minimize formation of odors and vermin (Coffey and Coad 2010).

Time of day
Time of day refers to whether the collection is conducted during the day or at night. While the individual collection times might vary for each customer, and even from collection to collection, the decision whether collection should be carried out during the day or at night can have great influence on the type of collection system.

Collection during the night typically has the advantage of less traffic, which means that the collection can be done in a much more time efficient manner and without causing much traffic disturbance. An added benefit is that the collection crews are not subject to the health effects of heat and sun radiation. However, collection at night might not be in favor of the collection crews, who might prefer common daily work hours. Working at night could also have implications on work safety, the cleanliness of the collection points as well as security of the workforce, depending on the crime prevalence (Coffey and Coad 2010).

In a two-stage transport system it is a viable option to conduct the primary stage within the residential areas during the day, and then conduct the secondary stage, with larger vehicles along the busier highways during the night.

Days of week
The number of workdays is required to determine the size of the workforce as well as the required waste storage on days without collection.

Table 2: Leading questions regarding Timing of collection

Decision area	Leading questions
Frequency of the collection	• How much storage space do the customers have available to store waste between collections?
	• Are there cultural dispositions towards waste that require people to dispose of their waste at certain times?
	• How long may waste be stored under local climate conditions?
Time of day	• Is there a preferred time for the population to have the waste removed from the households? E.g., conveniently on the way to work in the morning or in the evening, after the last meal, to have the house clean for the night.
	• Are there significant differences in traffic speed during the day? e.g., is there a rush hour and otherwise flowing traffic? Does waste have to be picked up at night, due to congestion during the day?

Days of the week	• Are there any days of the week with specific cultural significance? (e.g., Sundays in Christian countries, Fridays in Muslim countries)
	• How many days per week are workdays?

4.4.2 Point of collection

Point of collection refers to the point at which the responsibility for the waste material is transferred from the customer to the service provider. Unlike in western countries, where typically a clear distinction between collection system and delivery systems can be observed, in lower income countries, waste handover can take place through a variety of different systems. There is also a variety of potential points of collection: in the street, at the property boundary or inside the property (Coffey and Coad 2010).

Figure 13: Points of collection (Coffey and Coad 2010)

Leading questions regarding the point of collection are (Rodiek 1988-2022):

- Are the customers willing to carry their waste over some distance to community containers or collection vehicles in the street?
- How far are customers willing to carry their waste?
- Are the customers flexible enough to carry out their waste the moment the collection vehicle arrives?
- How is the overall waste management system positioned towards waste picking - do waste pickers need access to the waste containers prior to collection?
- How is the attitude of the customers towards strangers entering their property to take out the waste?

Collection in the street does require a certain amount of cooperation from the customers. They either must carry their waste to communal containers or bring out the waste at the time the collection vehicle arrives. In general distances below 200m to the communal containers are recommended. The effort of the customers on this first mile could lead to reductions of the collection cost (Coffey and Coad 2010).

Collection from inside the property requires much time and personnel when it is done at a household level. For collection from commercial sources, it might be a suitable option, as it does not require workers to pause their main activities to take out the waste containers.

Box 1: Door-to-door collection as a communication-tool for environmental awareness and better qualities.

A WWF pilot project in the Mekong Delta, Vietnam has made good experiences with door-to-door collection through a sorting-cart model.

Here the waste is collected by workers, equipped with a hand cart, in which the bags with waste are opened and checked whether the material is sufficiently segregated.

In addition to ensuring high quality segregated material, the interaction at the point of handover functions as a communication tool, where the households can be educated and supported in their environmental awareness (Pfaff-Simoneit 2012)

This labour intense procedure also reduces the necessary investment costs to a minimum, while creating a large amount of jobs. Depending on the local market for high quality compost, the resulting labour cost can be recovered or have to be subsidized through a fee system.

4.4.3 Container types

As with the selection of vehicles, care must be taken to ensure that the vehicle type and container type are compatible. Containers are either emptied on site and returned to their place (i.e., emptying containers), or removed entirely and replaced with empty containers (i.e., exchange containers).

The material of the containers can play a significant role in the overall cost of the system, as cheaper low-grade steel containers tend to have a much shorter operational life than low-corrosion steel grades.

Wheelie bins from plastic are typically a low-cost, highly efficient, and hygienic option. However not suitable wherever solid fuels are used, as they are easily destroyed by fire from hot ashes.

Waste bags are a common low-cost option. They have the advantage that they do not need any specialized loading equipment or designated storage space. Through color-coding a separate collection can be introduced without much investment into multiple container systems.

Transparent bags even allow the collection crews to check for impurities without having to open the bag. The bags can be sold to the customers at the price of the service fee and thereby providing a reliable system for fee collection. The downside to waste bags is that they can tear, if filled with heavy materials and are easily ripped open by animals.

4.4.4 Vehicle types

There exists a vast variety of vehicles that can be used for transport and collection of waste. Each with different characteristics that make them useful in very specific situations. Some vehicles, such as tricycles are small and agile enough to enter the narrow alleys in informal settlements, while others, for example semi-trailers are especially useful for transporting large waste quantities over longer distances. Here are some examples for vehicle types to be used for waste collection:

- Compaction truck
- Skip loader
- Roll-off tipper
- Micro truck
- Flatbed truck
- Tricycle
- Hand cart

The decision for certain vehicle types resp. their local combinations should be based on the following criteria:

- Availability of experienced mechanics for repair and maintenance
- Compatibility with waste container
- Availability of spare parts and consumables
- amount and bulk density of the waste material
- settlement structure and traffic conditions
- Required capital cost
- Operational cost

4.4.5 Transport stages

As mentioned above different types of vehicles have benefits in specific situations. Therefore, it might make economic sense to transfer waste from one vehicle to another, to achieve the best performance for the whole system.

Direct collection
In direct collection, the waste is taken directly from the point of collection to the final destination. This is typically the case with roll-off containers or with compaction trucks, where bins are emptied into the truck, until it is full. Then the truck directly takes the material to the final destination.

Multistage collection
In multistage collection, the waste is typically picked up by a smaller vehicle, e.g., a tricycle. These vehicles have the advantage of increased maneuverability in narrow and densely populated areas. However, their capacity is low. Therefore, to minimize transport cost, the material can be loaded into a vehicle with a much larger capacity. Once this vehicle is completely full, it can then transport the waste over a much greater distance, thereby minimizing the transport time and cost per unit of material. As mentioned in section 4.4.1 the stages might also be split between daytime and nighttime collection to avoid the most severe traffic congestions.

4.4.6 Storage

Waste typically needs to be stored for a period of time until the collection vehicle arrives. Storage can be done in waste bags or smaller containers at the household level, or in larger containers at a block or community level.

The requirements for storage are to minimize leakage into the environment during storage, limit access of animals and vermin and to facilitate quick and easy loading for the material for pick-up.

4.4.7 Transfer

If a multistage transport system is used, the waste needs to be transferred from one mode of transport to the other. Transfer systems should be designed in a way that:

- Minimizes required loading times
- Allows flexibility for the vehicles of the different stages (no waiting for each other)
- Reduces manual handling of the waste for improved hygiene
- Is easy to clean at the end of the day.
- Minimizes the contamination of the environment with waste, through paved floor, roofing, enclosure, etc.

Options range from simply dumping material from the first stage vehicles onto the ground and loading it into the second stage vehicles by help of wheel loaders (rendezvous transfer or wheel loader transfer), dropping the material from a ramp into containers located below (split-level transfer) to mechanized designs with elevators or compactors (Coffey and Coad 2010).

It is also possible to include a small sorting belt at a transfer station or give informal waste collectors access to the material in order to remove some of the recyclable material before it is transferred and potentially contaminated with the other waste streams.

4.4.8 Treatment site location

Depending on the local needs and expectations, it is possible to implement one central treatment site, or multiple decentral treatment sites.

A central treatment site makes especially sense, when the facility requires high capital investments, that could be spread over large throughput quantities to minimize the specific operational cost. Also, the travel distances should not be too long, and traffic conditions should allow reasonable travel times.

Decentral treatment sites have the advantage that the travel distances can be kept short. However, depending on the treatment processes, the same equipment and machinery must be purchased multiple times. Therefore, decentral treatment sites are particularly suitable, if distances and travel times are particularly long and processes are selected, that require lower capital investments.

In all cases it is advisable to locate treatment sites next to final disposal sites, so that arising residues can be disposed at minimal transport cost.

4.4.9 Digitalization

Digitalization also plays a significant role in waste logistics systems in low- and middle-income countries. The following applications for digital technologies may provide additional value to a logistics concept:

- Route planning and optimization
- Monitoring of fill level
- Location tracking of containers and vehicles
- Reporting of problems with containers
- Tracking of material in- and outflows
- Tracking of payments
- Confirmations of pick-ups
- Mapping of communal containers

4.5 Designing and dimensioning of collection systems

Dimensioning of a collection system for biogenic waste for a certain collection area requires data on the expected waste amounts. These should be reliable, as a multitude of economic decisions will be based on them.

Based on the expected waste amounts the overall volume of waste over a period of time is calculated. This is then used together with the required collection frequency to determine the minimum storage volume, from which the number of individual containers can be derived. The volume of waste along with the travel times of vehicles is used to calculate the required number of vehicles. The required workforce can be derived from the number of collection tours, the effort of collection as well as the number of workdays.

4.5.1 Required storage/number of containers

The overall storage volume within a collection area must be sufficient for storing all the waste accumulated during the longest interval between collections as well as allow a margin of safety to accommodate the occasional peak in waste generation.

While meeting these minimum requirements, it also must be considered, that the bulk density and -derived from this- the volume of waste depends on the type of container. In larger containers, the weight of the upper layers of waste press down on the lower layers, effectively compacting them. This effect is much less in smaller containers. Therefore, the types of containers are a key factor in the dimensioning process.

The process for determining the required number of containers is described in the following table:

Table 3: Process for determining the required number of containers (Rodiek 1988-2022; Coffey and Coad 2010).

Step	Description	Example
1.	Determine the number of collections per week	$2\ collections\ per\ week$
2.	Determine the longest interval between collections	$\frac{7\ days}{2\ collections} = \sim 4\ days$
3.	Determine the number of inhabitants and households within the collection area	$\frac{10.134\ cap}{4{,}3\ cap\ /\ hh} = 2357\ hh$
4.	Determine waste weight per household after longest interval	$r = 0{,}5\ \frac{kg}{cap * d} = 2{,}15\ \frac{kg}{hh * d}$ $m = 8{,}6\ \frac{kg}{hh} after\ longest\ interval$
5.	Determine type of container, level of compaction and bulk weight in container - refer to Table 3[11]	MGB 1100L containers – medium compaction = 300 kg/m³
6.	Determine peak factor and calculate volume requirements per household	$\alpha = 0{,}3$ $V = 1{,}3 * 0{,}0286\ \frac{m^3}{hh} = 37{,}3\ \frac{L}{hh}$
7.	Determine number of households to be connected to container	$n_{hh} = \frac{1100\ L}{37{,}3\ L} = \sim 30\ hh$
8.	Determine required number of containers	$n_{containers} = \frac{2357\ hh}{30\ hh} = \sim 79\ containers$

Table 4: bulk weight in relation to level of compaction of different waste types (Rodiek 1988-2022)

Waste type	Low compaction	Medium compaction	High compaction
Food waste	300 kg/m³	500 kg/m³	1000 kg/m³
Biowaste	250 kg/m³	400 kg/m³	600 kg/m³
Mixed waste	180 kg/m³	300 kg/m³	450 kg/m³

This process can be applied to communal containers as well as individual containers for each dwelling (for example compounds or high-rises). Step 6 can also be used to determine the appropriate waste storage volume for each dwelling.

When dimensioning a collection system that uses communal or shared containers, another factor to consider is the distance from each household to the container site. The further the distance between a household and the communal containers, the greater the probability that some waste is dumped along the way instead of brought to the container. In general, the maximum acceptable distance is less than 200 m (Coffey and Coad 2010).

[11] The bulk weight depends on the actual material. It is recommended to experimentally determine the actual values.

4.5.2 Required number of vehicles

Once the type of vehicle has been decided, the required number of vehicles must be determined. The number of vehicles should be sufficient to carry out all required transport tasks in the required time. It is important to note that the vehicles are not available 100% of the time due to repair and maintenance, accidents, and other reasons. Typically, vehicles with a higher degree of automatization and technology, have a lower availability due to the fact the repair might be more time consuming, specialized staff is needed and spare parts are difficult to obtain.

Key factor for determining the number of vehicles is the load capacity of the vehicles as well as the number of trips they can make during a shift.

The process for determining the required number of vehicles is described in the following table:

Table 5: Process for determining the required number of vehicles (Coffey and Coad 2010)

Step	Description	Example
1.	Determine waste amount to be collected per workday	$daily\ amount: m = 0{,}5 \frac{kg}{cap * d} * 10.134\ cap = 5.067\ \frac{kg}{d}$ $Amount\ per\ work\ day: 5.067\ \frac{kg}{d} * \frac{7d}{2\ collections} = 17{,}7t$
2.	Determine no. of trips within one shift	$work\ hours\ per\ shift: s = 8h$ $Degree\ of\ utilization: u = 95\%$ $Time\ for\ collection: t_c = 90\ min$ $Time\ for\ travelling: t_t = 120\ min$ $Time\ for\ unloading: t_L = 10\ min$ $number\ of\ trips\ per\ shift: n = \frac{8h * 60 \frac{min}{h} * 0{,}95}{220\ min} = \sim 2$
3.	Determine the load capacity of the vehicle	$load\ capacity = TPW - net\ weight$ $\text{Load capacity}\ compactor\ truck: 18t - 10t = 8t$
4.	Determine number of vehicles in daily use	$n = \frac{17{,}7t}{8t * 2\ \ trips} = 1{,}1\ vehicles \sim 2$

5.	Determine availability of vehicles and total number of required vehicles	Availability Compactor truck = 75% $Total\ number\ of\ vehicles: n_{total} = 2 * (1 + (1 - 75\%)) = \sim 3$

The total number represents the number of a specific type of vehicles, that is needed to carry out the daily transport tasks for this specific vehicle, while considering that some vehicles undergo maintenance or are not available for other reasons.

Table 6: Vehicle types and technical specifications (Rodiek 1988-2022)

Vehicle type	Total permissible weight (TPW)	Net weight	Load capacity	daytime travel speed within settlement area	nighttime travel speed within settlement area	daytime travel speed outside settlement area	nighttime travel speed outside settlement area
Compaction truck 2-Axles	16t	10,26t	5,74t	15 km/h	25 km/h	35 km/h	60 km/h
Compaction truck 2-Axles	26t	17,7t	8,3t	15 km/h	25 km/h	35 km/h	60 km/h
Skip loader 2-Axles	18t	10t	8t	15 km/h	25 km/h	35 km/h	60 km/h
Skip loader 3-Axles	26t	13t	13t	15 km/h	25 km/h	35 km/h	60 km/h
Roll-off dump truck 3-Axles	26t	12t	14t	15 km/h	25 km/h	35 km/h	60 km/h
Roll-off dump truck 2-Axles	18t	11,6t	5,9t	15 km/h	25 km/h	35 km/h	60 km/h
Mikro-truck	5,5t	3,1t	2,4t	20 km/h	25 km/h	35 km/h	60 km/h
Pick-up	7,5t	4,1t	3,4t	20 km/h	25 km/h	35 km/h	60 km/h
Tricycle (Suizhou ShenWei Mining Machinery Co.,Ltd.)				30 km/h	40 km/h	40 km/h	40 km/h

Time for collection refers to the actual collection of waste. e.g., door-to-door collection for compaction truck, collection of single skip container for skip loader.

Time for travelling refers to the time spent travelling from the vehicle depot to the collection area and then to the unloading site. This might be round trips if the unloading site and the vehicle depot are identical. Travelling times might differ according to the time of day as well as the settlement structure. Travelling speed should best be determined experimentally on site.

The process for determining the required number of vehicles can be applied to both primary and secondary collection and transport. For every type of vehicle, the process starts with determining the waste amount per workday to be collected with this specific type of vehicle.

4.5.3 Required workforce

The required size of the workforce depends on a wide range of factors including the following:

- Workdays per week and number of shifts per day
- Number of vehicles in daily use
- Amount of manual labor required for collection, loading, and transfer
- Amount of repair required
- Amount of supervision required

4.5.4 Requirements for managed container sites (Example)

Location factors
For the selection of sites for placement of communal containers, transfer stations and even treatment facilities, the following location factors should be considered:

- Number of waste pickers active in the collection area
- Amount of material available
- Accessibility by trucks
- Transport cost
- Proximity to treatment facility
- Proximity to other collection sites (for optimized routing)
- Secure storage facilities
- Relationship with community representatives
- Support from community representatives
- Population density / no. of inhabitants / area size
- Environmental awareness
- Attitude towards waste related activities
- Average income situation
- Crime prevalence
- Local competition
- Local regulation regarding location of waste activities (e.g. distance to residential housing)
- Availability and characteristics of land within the community

The suitability of a container site can be determined by conducting a utility analysis in which relevance of each factor and the respective performance are evaluated.

Space requirements
The required space for container sites, is derived from the floor space of the used containers. In addition to that, traffic areas are required to give access to the population for delivery of materials, for maneuvering the collection vehicles and for any necessary operational buildings such as administration buildings, staff rooms, workshops, etc.

The length of the container space must be at least the length of the vehicle plus the drop-off length and the length of the container.

The width of the container space corresponds to the width of the containers plus an additional 0.8 - 1.0 m to allow safe and ergonomic filling of the containers and to ensure that the containers can easily be lifted and lowered from the vehicle.

To ensure a smooth exchange of the containers an additional container space should be left empty.

Besides the space required to place the containers, container sites also need space for maneuvering the vehicles. This depends on the number and size of the containers set up, as well as the size of the vehicles used for collection and their turning circle as well as their trailing curve. On a sufficiently sized maneuvering area, vehicles can freely maneuver, with a minimal number of back-and-forth movements, which helps reduce lading times and fuel consumption. CAD based tools can be used to simulate trailing curves for a wide range of vehicles to verify the space is sufficient. A separate entrance and exit can help minimize necessary maneuvering.

For example, for 7 m³ skip containers, a free maneuvering area of 20.00 x 4.00 m is required per container parking space.

The following figure roughly outlines a blueprint setup for managed container sites according to the EcoPontes Model by Rodiek & Co. GmbH:

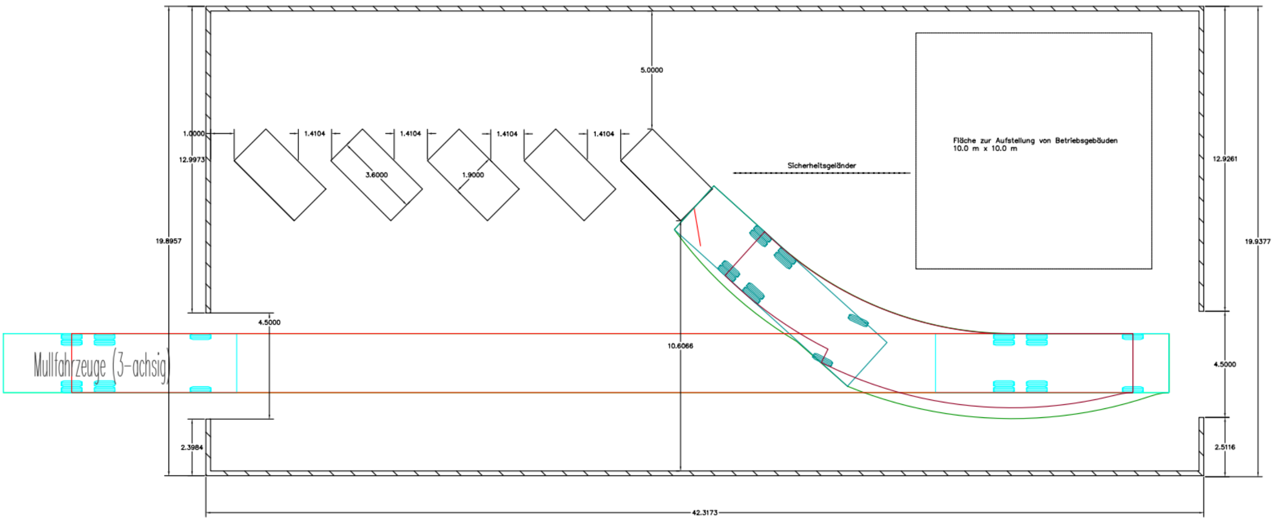

Figure 14: Blueprint setup for managed container sites according to the EcoPontes Model (Rodiek 1988-2022)

4.5.5 Additional planning considerations

Traffic within container sites

Ideally, delivery and collection areas should be kept separate from each other to ensure safe operation. If necessary, the separation should be implemented through suitable measures, such as. barriers and signage.

Waiting areas could be located outside the property to ensure trouble free maneuvering within the container sites.

Enclosure of the plot
The plot must be equipped with a suitable fencing to ensure the restriction of access, the security of stored materials and equipment, and to protect stored materials from wind, or animals from getting onto the plot.

The fencing should have a minimum height of 2.20 m. The fencing requires lockable gates to restrict access. Sliding gates (electrically operated if necessary) are recommended, as minimal movement areas for the gates are required.

Access to the site
Minimum passage width: approx. 3.5 m. Trucks have a larger turning circle and shear. Turning in at right angles is therefore not possible. For tipping trucks with 3 axles, the driveway should have a minimum width of 5.10 m to allow turning in from acute angles.

Minimum roof clearance: approx. 4.00 m.

Roofing
The delivery area and container stands may have a roof to protect them from sunlight and rainfall. The roof may be of locally customary construction. For unhindered lowering or rolling off the containers, the minimum lowering height should be observed (for skip loaders 4.40 m, for roll-off tippers 7.50 m).

Load-bearing floor
The floor should have sufficient load-bearing capacity to allow trucks to drive over it safely. The load-bearing capacity of the floor depends on the axle load of the vehicles. Approximately 6 kN/m^2 can be assumed as a guide value.

A concrete, asphalt or paved surface ensures safe driving even during precipitation, e.g., in the rainy season. A slope of 2 - 2.5 % for sealed surfaces is required to ensure reliable drainage of precipitation water.

Water drainage
A facility for property drainage should be connected at the lowest point of the slope. If available, a connection to the public sewer system or to open drainage channels is suitable for this purpose. Local infiltration via a sufficiently dimensioned soil filter/infiltration area or storage in a rainwater cistern is also suitable.

A design rainfall rate for a rainfall event of a statistical frequency of 5 years and a rainfall duration of 5 minutes (r (5;5)) should be used as the basis for dimensioning the drainage systems.

4.6 Recommendations for logistical concepts in different settlement structures

As shown in the previous section, development of suitable logistics concepts for biodegradable waste is a multi-dimensional, non-quantifiable complex problem: A variety of decision areas for the development of a logistics concept exists, with an even greater variety of different characteristics. All of which need to be combined to meet ecological, technical and economic targets as well as satisfy customer needs and expectations.

Morphological analysis is a useful tool to systematically explore possible combinations of characteristics that can lead to solutions that provide the best results regarding technical and economic feasibility as well as meeting customer expectations.

Figure 15: Systematic development of possible characteristics of logistic systems through morphological analysis

The different solutions should be examined regarding their implications, their ecological benefit and demands for the envisioned treatment processes. The scenarios identified through this methodology should then be financially evaluated. Local stakeholders should be involved at all stages in the development and evaluation process to include specific local knowledge and to make sure the solution does in fact meet local needs and expectations.

This methodology has been applied for exemplarily designing concepts for collection and logistics of biogenic waste material for three different types of settlement structure. The following chapters describe the model solutions and highlight why they are suitable for the respective context.

The Table 7 shows the possible design parameters for waste logistics concepts and their different characteristics. The lines follow the typical order within the design process, but each line of potential alternative solutions is to be viewed independently and not connected to the line above or below:

Table 7: Design parameters for waste logistics concepts and their different characteristics (Rodiek 1988-2022)

<table>
<tr><th>Criteria</th><th colspan="12">Potential alternative solutions</th></tr>
<tr><td>Collection Mode</td><td colspan="4">separation at household level</td><td colspan="4">mixed collection, sorting at final destination</td><td colspan="4">mixed collection, sorting at transfer stations</td></tr>
<tr><td>separate collection of commercial sources</td><td colspan="6">Yes</td><td colspan="6">No</td></tr>
<tr><td>Frequency of Collection</td><td colspan="3">daily</td><td colspan="3">every other day</td><td colspan="3">once a week</td><td colspan="3">bi-weekly</td></tr>
</table>

Point of collection	community containers	collection within street with vehicle signaling	kerbside collection	back door collection	
responsible for handover	waste delivered to community containers	waste picked-up by collection crews	waste picked up by small service providers (e.g., Informal sector) and brought to community containers		
transport stages	direct collection	two stage collection	three stage collection		
1st stage time of day	day	night			
1st stage container	pre-paid plastic bags, transparent	wheel bins	wheel containers	skip containers	roll-off containers
1st stage vehicle	Hand cart	Tricycle	Compaction trucks	Skip loader	Roll-off tipper
1st stage transfer	none	ramp transfer	wheel loader transfer from ground	mechanized transfer station	
2nd stage time of day	day	night			
2nd stage container	plastic bags	wheelie bins	wheel containers	skip containers	roll-off containers
2nd stage vehicle	Flatbed truck	Compaction trucks	Skip loader	Roll-off dump truck	none
2nd stage transfer	none	ramp transfer	wheel loader transfer from ground	mechanized transfer station	
Treatment sites	central treatment site	multiple smaller decentral treatment sites			
co-financing through treatment products	yes	no			
financing of operative cost	pay as you throw	wheelie bins on subscription	Public waste fee	through treatment products only	

The following logistics concepts for each type of settlement structure were developed by identifying the most suitable combination of characteristics for each parameter. Each combination is illustrated by a colored path along the table of characteristics. Each concept is then further elaborated with short comments on the chosen characteristics:

4.6.1 Metropolitan areas

Especially in large metropolitan areas, the settlement structures might vary from one neighborhood to the other. There might be neighborhoods with many high-rise-buildings, informal settlements, and suburbs with single-family dwellings. In order to achieve an optimal solution, it is recommended to adjust the first stage logistics according to the needs and requirements of the respective area but ensure that they still fit into the logistics concept of the overall city.

Table 8: Logistical concept for biogenic waste in **metropolitan areas**

Criteria	Potential alternative solutions				
collection mode	**separation at household level**	mixed collection, sorting at final destination	mixed collection, sorting at transfer stations		
separate collection of commercial sources	**yes**	no			
Frequency of Collection	daily	**every other day**	once a week	bi-weekly	
Point of collection	community containers	collection within street with vehicle signaling	**kerbside collection**	back door collection	
responsible for handover	waste delivered to community containers	waste picked-up by collection crews	**waste picked up by small service providers (e.g., Informal sector) and brought to community containers**		
transport stages	direct collection	**two stage collection**	three stage collection		
1st stage time of day	**day**	night			
1st stage container	**pre-paid plastic bags, transparent**	wheelie bins	wheel containers	skip containers	roll-off containers
1st stage vehicle	Hand cart	**Tricycle**	Compaction trucks	Skip loader	Roll-off tipper
1st stage transfer	none	**ramp transfer**	**wheel loader transfer from ground**	mechanized transfer station	
2nd stage time of day	day	**night**			
2nd stage container	plastic bags	wheelie bins	wheel containers	skip containers	**roll-off containers**
2nd stage vehicle	Flatbed truck	Compaction trucks	Skip loader	**Roll-off tipper**	none
2nd stage transfer	**none**	ramp transfer	wheel loader transfer from ground	mechanized transfer station	
Treatment sites	central treatment site	**multiple smaller decentral treatment sites**			
co-financing through treatment products	**yes**	no			
financing of operative cost	pay as you throw	wheelie bins on subscription	**Public waste fee**	through treatment products only	

The selected characteristics are elaborated in Table 9

Table 9: Discussion of the characteristics of a waste logistics system for **metropolitan areas**

Characteristics	Comments
Separation at household level	Households should be encouraged to participate in sustainable management of their waste through awareness campaigns as well as quality checks and communication at the point of collection.
Separate collection from commercial sources	In metropolitan areas the number of commercial sources with fairly homogeneous biogenic waste material is large enough to create separate waste streams.
Collection every other day	Especially in densely populated areas, the intervals between collections should be kept short. This is to prevent unhygienic conditions, odor pollution and discontent of the population with the waste collection service.
Kerbside collection	Collection in front of the houses give an opportunity for communication with the collection crews which can be a strong incentive to participate source-separation.
Waste picked up by small service providers (e.g., Informal sector) and brought to community containers	In Addis Ababa, currently over 600 micro enterprises are responsible for the first stage waste collection. These provide work to over 6,400 people, who can be trained, qualified, and provided with awareness materials, to support the households to separate their biogenic waste material.
Two stage collection	As is currently the case in Addis Ababa, a second stage transport is required to load the material from the small vehicles of the cleaning service associations onto larger vehicles for transport over longer distances
1st Stage collection during the day	In order to carry out the awareness and quality control aspects of the collection, the primary collection crews should be able to interact with the households at reasonable hours.
Waste storage in pre-paid plastic bags, transparent	Transparent plastic bags allow the collection crews to perform quality checks in a more hygienic manner. Bags with a prepaid service fee ensure the actual service costs are recovered.
1st stage collection via tricycle	The micro enterprises should use small vehicles with good maneuverability and minimal capital cost. Tricycles with a tipper should be the preferred option for ease of unloading. It is advisable to implement different collection days for biogenic waste and residual waste
Transfer to 2nd stage via ramp transfer	Ramp transfer into large roll-off containers reduces the required handling and minimizes capital investments into transfer infrastructures.
2nd stage transport during the night	For increased transport efficiency, the 2nd-stage transport can be carried out at night to avoid heavy traffic
Transfer into roll-off containers	Roll-off containers provide enough storage space for large amounts of biogenic waste
2nd stage transport via roll-off tipper	Biogenic waste material, which already has a relatively high bulk density, usually does not achieve high compaction rates in a compactor truck. Therefore, the immense investments and operational cost of a compactor truck are typically not justifiable for this type of material. Roll-off tippers on the other hand provide large transport capacity at a more reasonable price.

Treatment in multiple smaller decentral treatment sites	Several strategically located treatment sites minimize logistic costs through short transport distances and travel times. Depending on the waste sources in the catchment area as well as the demand for products from biogenic waste material, specific treatment technologies can be implemented.
Co-financing through treatment products	Co-financing through the treatment products can be a way of subsidizing collection services for disadvantaged groups within a metropolis. Prerequisite for maximum revenues is the quality of the input material. The logistic system has been designed to ensure sufficient qualities and minimize logistic cost in order to generate as much surplus as possible.
Financing of operative cost through public waste fee	Operative cost of the system needs to be financed through a public waste fee. As mentioned above this fee can be collected through prepaid- Waste Bags.

4.6.2 Semi-urban to urban areas

Table 10: Logistical concept for biogenic waste in **semi-urban to urban areas**

<table>
<tr><th>Criteria</th><th colspan="10">Potential alternative solutions</th></tr>
<tr><td>collection mode</td><td colspan="3">separation at household level</td><td colspan="4">mixed collection, sorting at final destination</td><td colspan="3">mixed collection, sorting at transfer stations</td></tr>
<tr><td>separate collection of commercial sources</td><td colspan="5">yes</td><td colspan="5">no</td></tr>
<tr><td>Frequency of Collection</td><td colspan="2">daily</td><td colspan="3">every other day</td><td colspan="3">once a week</td><td colspan="2">bi-weekly</td></tr>
<tr><td>Point of collection</td><td colspan="2">community containers</td><td colspan="3">collection within street with vehicle signaling</td><td colspan="3">kerbside collection</td><td colspan="2">back door collection</td></tr>
<tr><td>responsible for handover</td><td colspan="3">waste delivered to community containers</td><td colspan="4">waste picked-up by collection crews</td><td colspan="3">waste picked up by small service providers (e.g., Informal sector) and brought to community containers</td></tr>
<tr><td>transport stages</td><td colspan="3">direct collection</td><td colspan="4">two stage collection</td><td colspan="3">three stage collection</td></tr>
<tr><td>1st stage time of day</td><td colspan="5">day</td><td colspan="5">night</td></tr>
<tr><td>1st stage container</td><td>pre-paid plastic bags, transparent</td><td colspan="3">wheelie bins</td><td colspan="2">wheel containers</td><td colspan="3">skip containers</td><td>roll-off containers</td></tr>
<tr><td>1st stage vehicle</td><td>Hand cart</td><td colspan="3">Tricycle</td><td colspan="2">Compaction trucks</td><td colspan="3">Skip loader</td><td>Roll-off tipper</td></tr>
<tr><td>1st stage transfer</td><td colspan="2">none</td><td colspan="3">ramp transfer</td><td colspan="3">wheel loader transfer from ground</td><td colspan="2">mechanized transfer station</td></tr>
<tr><td>Treatment sites</td><td colspan="5">central treatment site</td><td colspan="5">multiple smaller decentral treatment sites</td></tr>
<tr><td>co-financing through treatment products</td><td colspan="5">yes</td><td colspan="5">no</td></tr>
<tr><td>financing of operative cost</td><td colspan="2">pay as you throw</td><td colspan="3">wheelie bins on subscription</td><td colspan="3">Public waste fee</td><td colspan="2">through treatment products only</td></tr>
</table>

In Table 11 the selected characteristics will be further discussed:

Table 11: Discussion of the characteristics of a waste logistics system for **semi-urban to urban areas**

Characteristics	Comments
Mixed collection, sorting at transfer stations	It is the task of the households to decide whether they separate within their homes or at the handover point
Separate collection from commercial sources	Biogenic waste material from commercial sources is collected separately
On-demand collection of containers according to fill-level	At managed container sites, the collection of full containers can be carried out on demand. For this purpose, a daily fill-level notification is sent so that the dispatchers can plan collections accordingly.
Community containers	The community containers are placed at managed container sites, where the population can not only deliver their biogenic waste material, but also residual waste, recyclables, and other waste types. The staff of the container site will provide assistance and awareness.
Households deliver waste to community containers	Households deliver their waste material to the managed container sites.
Direct collection	The material is picked-up on demand and directly transported to the treatment facility
Collection during the night	
Waste storage in skip containers	Depending on the population within the catchment area of a container site, either 7 m³ skip containers can be used or 30m³ roll-off containers.
Transport via skip loader	In order to minimize investments and operational cost, skip loaders and roll-off dump trucks should be preferred over compaction trucks
Central treatment site	A central treatment site with sufficient capacity is suitable in semi-urban to urban areas due to shorter transport distances
Co-financing through treatment products	If co-financing through the treatment products is expected, the quality requirements for the input material should be met.
pay as you throw	The managed container sites are a fairly effective tool to implement a pay as you throw system. Each bag brought to the facility can be counted and billed to the specific customer.

4.6.3 Rural areas

Table 12: Logistical concept for biogenic waste in **rural areas**

<table>
<tr><th>Criteria</th><th colspan="6">Potential alternative solutions</th></tr>
<tr><td>collection mode</td><td colspan="2">separation at household level</td><td colspan="2">mixed collection, sorting at final destination</td><td colspan="2">mixed collection, sorting at transfer stations</td></tr>
<tr><td>separate collection of commercial sources</td><td colspan="3">yes</td><td colspan="3">no</td></tr>
<tr><td>Frequency of Collection</td><td>daily</td><td colspan="2">every other day</td><td colspan="2">once a week</td><td>bi-weekly</td></tr>
</table>

Point of collection	community containers	collection within street with vehicle signalling	kerbside collection	Direct delivery to treatment facility
responsible for handover	waste delivered by households	waste picked-up by collection crews	waste picked up by small service providers (e.g., Informal sector) and brought to community containers	
transport stages	direct collection	two stage collection	three stage collection	
1st stage time of day	day	night		
Treatment sites	central treatment site	multiple smaller decentral treatment sites		
co-financing through treatment products	yes	no		
financing of operative cost	pay as you throw	wheelie bins on subscription	Public waste fee	through treatment products only

Table 13 discusses the selected characteristics:

Table 13: Discussion of the characteristics of a waste logistics system **for rural areas**

Potential alternative solutions	
Mixed collection, sorting at final destination	In rural areas the household waste typically has a much higher content of biogenic waste material. Therefore, it can be appropriate to implement a mixed collection with subsequent sorting to remove any recyclables or impurities.
No separate collection from commercial sources	Due to much lower population densities, longer travel distances and a lower number of commercial sources, separate collection from commercial sources might not be economical. Instead, it is recommended to establish decentral treatment sites either very close to the commercial sources or within. They should be designed in a way to also treat the waste from the surrounding neighborhoods.
Direct delivery to treatment facility	
Communal treatment (composting facilities)	Small composting facilities on a neighborhood level allows household to deliver their biogenic waste material directly, thus avoiding further logistics cost. Commercial sources of larger amounts of biogenic waste material, e.g., markets, restaurants, agriculture, food processing could establish their own decentralized treatment facility which are designed to co-process the waste of the surrounding population.
Co-financing of logistic cost not required	Co-financing of the logistics through treatment products might not always be possible depending on the type of treatment process, the local demand for the respective products and the input material.
Pay as you throw system for informal logistics	Household not able or willing to deliver the material to the treatment sites could use logistics provided by the informal sector on the basis of a pay as you throw system

4.7 Cost consideration of logistical concepts

Financial comparison of waste management systems is a quite complex task, that requires in depth consideration of the individual situation, components, and goals to be achieved. However, a rough comparison based on the cost per ton throughput over a certain period of time could give a first indication whether a concept should be preferred over another.

The following section will give an overview of different aspects that should be respected for the cost determination of logistical systems as well as present a methodology to estimate service costs and adapt the methodology on a semi urban to urban and metropolitan settlement structure.

4.7.1 Cost types

The costs of the implementation and maintenance of logistical concepts of waste management can generally be ordered by cost types. The following table offers a list of different cost types and examples for the better understanding:

Table 14: Capital related cost of waste logistics concepts

	Cost type	Examples
Capital expenditures (CAPEX) of waste logistics concepts	Collection vehicles	(e.g. truck, tricycles, etc.)
	Containers and bins	
	Other collection equipment	(e.g., handcarts gloves, boots, etc.)
	Mobile equipment	(e.g., wheel loaders, shredders, forklifts, tractors, etc.)
	Facilities for collection and transfer	(e.g., collection points, managed container sites, buy-back centres, transfer stations etc.)
	Treatment facilities:	• Land • Construction • Budlings • machinery (e.g., sorting, composting, biogas digestion, MBT, Incineration, etc.)
	IT- and telecommunication equipment	
Other capital related Cost	Interest on externally financed investments	
	Depreciation cost of buildings, facilities and machinery	

Table 15: Operational expenditures (OPEX) of logistics concepts

	Cost type	Examples
Operational expenditures (OPEX) of logistics concepts	Labour cost	(incl. social insurances, taxes, overtime compensation, bonuses and vacation, etc.) • Collection and transport staff (drivers, loaders, other - e.g., bins distribution, washing…) • Dispatchers and supervisors • Repair and maintenance staff • Staff in facilities and installations • General administration staff and management • PR and awareness raising / waste advisers

		• Fee collection
	Contractors	• Collection and transport services • Operational services • Rental of machines and equipment
	Consumables and energy	• Fuel • Waste bags • Electricity • Water supply • Telecommunication and internet cost • Other consumables (e.g., stationary, working clothes, shoes, gloves, helmets…) • PR-materials, promotional items, advertising etc.
	Maintenance and repairs	• Tyres • Spare parts • Motor oil, hydraulic oil, break fluids, grease, etc. • Services • Taxes and insurances • Registration and licences • Advisory cost, audits, certifications, consultants
	Rental and leasing cost	
	Services	
	Taxes and insurances	
	Registration and licences	
	Advisory cost, audits, certifications, consultants	

4.7.2 Price estimation methodology on service costs

The following table illustrates the guiding principles for price determination based on service cost, adapted to the typical cost positions of waste management systems.

Table 16: Simple calculation of specific logistics cost (Rodiek 1988-2022)

	Price estimation based on service cost types		
	Service period		*[months]*
	Material quantity per period		*[t]*
	Cost type	**Total**	**Note**
	Direct material cost		*quantity of input materials [t] x cost [$/t]*
+	Primary transport cost		*specific transport cost [$/km or $/t] x quantity [km or t]*
+	Disposal cost		*quantity of input material [t] x waste [%] x specific disposal cost [$/t] +transport cost to landfill $/to*

+	Material overheads		*cost of collection supervisors, documentation tools, etc. x degree of utilization in $/period*
=	**Cost of materials**		**$**
+	Secondary transport cost		*specific transport cost [$/km or $/t] x quantity [km or t] per period*
+	Treatment labour cost		*hours x labour cost $/h or quantity x labour cost $/t*
+	Treatment additives & consumables		*Quantity of additives x additive cost $/t (e.g., binding wire, packaging, etc.)*
+	Disposal treatment residues		*input quantity x %waste x specific disposal cost*
+	Utilities		*quantity of water, electricity, diesel, etc. [n] x cost [$/n] per treated input quantity*
+	Machinery and equipment cost		*total cost (depreciation) per period / total capacity per period x (quantity in period / capacity per period)*
+	Repair and maintenance		*hours [h] x cost [$/h]*
+	Treatment overheads		*supplies, rent, leasing, supervisors, insurance etc.*
+	Special direct cost of treatment		
=	**Cost of treatment**		**$**
+	Sales/Distribution overheads surcharge		*distribution staff, equipment, others per period*
+	Special direct cost of sales/distribution		*e.g., special provisions per quantity*
+	Administrative overheads surcharge		*admin staff, office cost, licenses, fees, marketing,*
=	**Cost of goods sold**		**$**
=	**Cost per ton**		**Cost of goods sold [$] / Material quantity per period [t]**

In order to evaluate the economic feasibility of a waste management system it is not sufficient to consider the cost of logistics and treatment separately. The system as a whole has to be considered.

The resulting overall cost should be recovered through a combination of a waste fee and the revenue from selling the treatment products (Lohri et al. 2014). With better quality of the treatment products a higher sales price can be realized, which in turn help to cross-finance and reduce the waste fee to be paid by the population (Rodiek 1988-2022).

4.7.3 Cost calculations for semi-urban to urban and metropolitan areas

The following tables are example cost calculations for the logistics systems for semi-urban to urban areas and metropolitan areas, as proposed in 4.6.1 and 4.6.2, respectively. The results are annual logistics cost, specific logistics cost per ton of waste material and specific logistic cost per capita. In order to determine the overall system cost, the cost for treatment of the organic fractions, and disposal of the residual fractions have to be added. In case a revenue is generated through the treatment, this revenue can be used to offset part of the resulting cost. Any remaining cost need to be covered through a waste management fee.

For illustration purposes the example cost calculations are simplified in the following ways:

- Full coverage of the respective collection areas is assumed.
- The focus lies on collection of waste from households.
- Collection from commercial sources is neglected, as the cost for transport and disposal should be covered by the individual waste generators.
- Typical overhead surcharges such as sales, distribution, and administration are neglected.

Table 17: Example calculation of logistics cost for semi-urban to urban areas.

Example calculation		Semi-Urban to urban areas
Population	cap	500.000,00
Annual waste generation	t/a	100.000,00
daily waste generation	t/d	273,97
% organic content	%	70,00

		7m³ skip containers	Skip loaders 2-axles	Small managed container site	TOTAL
Quantity		314	76	79	
Cost per Unit	$	$ 1.850,00	$ 75.000,00	$ 10.000,00	
Investment	$	$ 580.900,00	$ 5.700.000,00	$ 785.000,00	$ -7.065.900,00
Depreciation period	a	5	7	10	
Depreciation amount	$	$ 116.180,00	$ 814.285,71	$ 78.500,00	$ -1.008.965,71
Fixed cost per year	$	$ 116.180,00	$ 814.285,71	$ 78.500,00	$ -1.008.965,71
Raw materials, consumables and supplies per year	$		$ 81.428,57		$ -81.428,57
Repair and maintenance cost per year	$	$ 29.045,00	$ 570.000,00	$ 78.500,00	$ -677.545,00
Fuel consumption	L/h		30,00		
Fuel consumption per year	L/a		6.240,00		
Fuel cost	$/L		$ 0,705		
Fuel cost per year	$/a		$ 4.399,20		$ -4.399,20
Water consumption per year	m³/a			2.449,20	
Water cost	$/m³			$ 0,74	
Water cost per year	$/a			$ 1.802,61	$ -1.802,61
Number of workers per unit			1	4	
Total number of workers			76	314	
avg. Annual wages	$		$ 3.000,00	$ 2.500,00	
ancilliary cost in % of ann.wage	%		50,0	50,0	
Labour cost per year	$		$ 228.000,00	$ 785.000,00	$ -1.013.000,00
Variable cost per year	$/a	$ 29.045,00	$ 883.827,77	$ 865.302,61	$ 1.778.175,38
Fixed cost per year	$/a	$ 116.180,00	$ 814.285,71	$ 78.500,00	$ -1.008.965,71
Variable cost per year	$/a	$ 29.045,00	$ 883.827,77	$ 865.302,61	$ -1.778.175,38
Total logistics cost per year	$/a	$ 145.225,00	$ 1.698.113,49	$ 943.802,61	$ -2.787.141,10
Specific logistics cost	$/t				$ -27,87
logistics cost per capita	$/cap.				$ -5,57

Table 18: Example calculation of logistics cost for metropolitan areas.

Example calculation		Metropolitan areas
Population	cap	3.500.000,00
Annual waste generation	t/a	613.200,00
daily waste generation	t/d	1.680,00
% organic content	%	50,00

		Tricycle	Roll-off containers	Roll-off tipper	Ramp transfer stations	TOTAL
Quantity		1.470	285	72	143	
Cost per Unit	$	$ 5.000,00	$ 5.600,00	$ 85.000,00	$ 7.500,00	
Investment	$	$ 7.350.000,00	$ 1.596.000,00	$ 6.120.000,00	$ 1.072.500,00	$ -16.138.500,00
Depreciation period	a	2	5	7	5	
Depreciation amount	$	$ 3.675.000,00	$ 319.200,00	$ 874.285,71	$ 214.500,00	$ -5.082.985,71
Fixed cost per year	$	$ 3.675.000,00	$ 319.200,00	$ 874.285,71	$ 214.500,00	$ -5.082.985,71
Raw mat., consum. & supplies p.a.	$/a			$ 87.428,57	$ 21.450,00	$ -108.878,57
Repair and maintenance cost p.a.	$/a	$ 735.000,00	$ 79.800,00	$ 612.000,00	$ 53.625,00	$ -1.480.425,00
Fuel consumption	L/h	5		30,00		
Fuel consumption per year	L/a	47.040,00		27.360,00		
Fuel cost	$/L	$ 0,705		$ 0,705		
Fuel cost per year	$/a	$ 33.163,20		$ 19.288,80		$ -52.452,00
Water consumption per year	m³/a					
Water cost	$/m³					
Water cost per year	$/a					- €
Number of workers per unit		2		1	1	
Total number of workers		2.940		72	143	3.155
avg. Annual wages	$	$ 2.500,00		$ 3.000,00	$ 2.000,00	
ancilliary cost	%	50,0		50,0	50,0	
Labour cost per year	$	$ 7.350.000,00		$ 216.000,00	$ 286.000,00	$ -7.852.000,00
Variable cost per year	$/a	$ 8.118.163,20	$ 79.800,00	$ 934.717,37	$ 361.075,00	$ -9.493.755,57
Fixed cost per year	$/a	$ 3.675.000,00	$ 319.200,00	$ 874.285,71	$ 214.500,00	$ -5.082.985,71
Variable cost per year	$/a	$ 8.118.163,20	$ 79.800,00	$ 934.717,37	$ 361.075,00	$ -9.493.755,57
Total logistics cost per year	$/a	$ 11.793.163,20	$ 399.000,00	$ 1.809.003,09	$ 575.575,00	$ -14.576.741,29
Specific logistics cost	$/t					$ -23,77
logistics cost per capita	$/cap.					$ -4,16

5 Treatment concepts

As outlined in chapter 3 the main objective is to eliminate the high negative impacts of organic waste when landfilled, dumped or open burned. The best way is to extract this waste from the mixed waste as **source separated organic** (SSO), to produce "clean" compost. As a result of various initiatives and partially triggered by investment aid, some initial treatment trials and few larger-scale plant developments or pilot projects which also target SSO waste have recently been and are being carried out in selected African countries. These include in Ethiopia primarily programs for biogas production from residual material fermentation via small-scale projects e.g. National Biogas Program (NBPE) and composting initiatives via special producer cooperatives and community projects. To strengthen these SSO-initiatives is urgently needed and recommended. Such projects can already utilize a relevant share of organic waste (see mass balance in chapter 6) and can be realized with a relative low budget (see chapter 9).

Even with a high degree of separate collection, there will always be a high, **relevant share of organic waste in the remaining mixed waste**, which therefore is to be treated before landfilled, either by incineration or by biological processes.

Concerning this treatment of mixed waste, Ethiopia became the first country on the African continent with a mass-burn waste incinerator in operation, in Addis Ababa. Other projects of similar scale with focus on mechanical-biological treatment or sorting have meanwhile been realized in Ghana and other African countries. Because of their relative novelty, it is too early to judge whether these projects can operate self-sufficient over the long-term.

This chapter provides details of these characteristics, focussing mainly on **biological treatment** options and their specific effects in terms of energy and material recovery. Their two main subsystems are composting and anaerobic digestions – they are both applicable for SSO and mixed waste. Both systems will be described by their basic characteristics and examples of local application will be given. Aside of this, an own chapter handles the main combustion systems. (INTECUS 1991-2022, 2022)

Both composting and anaerobic digestion make use of natural processes in the form of a technical application. Organic waste serves as nutrition for countless microorganisms so that they can degrade and decompose it. This is possible both in the absence of air and in the presence of atmospheric oxygen. whereby reactions and products differ a lot between composting and anaerobic digestion. Controlled waste treatment builds directly on these special features and takes them as an advantage and by the way eliminating the negative effects of these natural processes through technical application (Table 19).

However, since anaerobic digestion is a naturally occurring process, it takes place in improper waste management as well, especially when organic waste is dumped on inadequate landfills. The produced methane and other gases are hereby discharged uncontrollably into the atmosphere. Methane with a 25-fold higher greenhouse potential of CO_2 has in this case a very high negative impact in terms of climate change, but can also locally lead to fires and explosions. Moreover, liquid products are formed which penetrate into the soil and groundwater where these may have toxic effects or other negative implications.

Table 19: Principal features and differences of the basic processes used for treating biogenic waste

Process features	Aerobic decomposition	Anaerobic decomposition
Access of air/oxygen	required	excluded
Reaction environment	penetrable, max 65 % moisture	highly humid, up to 95 % moisture
Microorganic sensitivity	rather low	high (pH, temperature)
Energy transformation	heat development + evaporation	through biogas formation
Gas formation/release	H_2O vapour + CO_2	methane (60 %) + CO_2 (40 %)
Recoverable energy	none	appr. 600 kWh/t biogenic input via biogas
Further outputs	low-reactive (stabilized) and humus-like solids (compost)	digested residual matter (digestate) and polluted effluent requiring treatment or nutrient-rich liquid (fertilizer)
Final dewatering and stabilisation	not needed, due to self-running evaporation	needed, by way of different means (e.g. mechanical press/centrifuge)
Overall process complexity	rather low	higher

The need to treat biogenic waste components arises therefore primarily to eliminate negative impacts when dumped or landfilled. Strategies for proper organic waste management therefore foresee to: segregate biodegradable material from other waste streams and landfills (waste segregation); decomposition and transform organic material into less reactive and less climate critical substances (waste reduction); recover materials from waste in general that can be fed back into material cycles and substitute raw materials or energy (resource recovery); reduce the general burdens and costs that society hast to bear to maintain human safety and environmental funtions (sustainability).

The main goals and strategies of biogenic waste treatment can be summarized as follows:

- *Waste segregation*
- Waste reduction
- Resource Recovery
- Sustainability

The processes that can be employed for treatment address above-mentioned strategies and objectives with a varying priority and intensity, and thereby built on the material-chemical characteristics of biogenic waste in different ways. However, the conclusion that can be generalised is that even the simplest treatment of biogenic waste is far better than to put it unprocessed on landfills.

The following chapters describe the biological and **basic technical characteristics** for:

- Composting
- Anaerobic digestion
- Mechanical biological treatment
- Combustion of biomass

The description of each of these concepts includes the technical alternatives mass balances, application fields, realized examples and coarse estimated costs for investment and operation.

5.1 Composting

Composting describes a process of **biological decomposition of organic matter under aerobic conditions**, means the permanent access of air.

A compostable raw material has

- a water content (wet share) of 55-65 %,
- the dry share holds roughly two thirds of organic dry substance (ODS) and one third of inorganics.

During the composting process,

- the organic dry substance (ODS) is decomposed by 60%, releasing biological energy, which evaporates water.
- The energy from one kilogram of decomposed ODS evaporates 5-8 kg of the material's moisture, thus bringing the water content down to less than 25 % within a shorter period (usually 2-3 weeks).

In such conditions the biological activity ceases, leaving the material in a state of "dry stabilisation".

For a continued decomposition of the ODS a moisture level of at least 40% is needed and therefore:

- water must be added to the material, resulting in a summed-up water demand in the range of 250-350 ltr/t of biogenic input.
- Turning and mixing of the material during the composting process provides for new biologically accessible surfaces, aeration and the possibility to moistening, and to maintain the ideal conditions for complete material hygienisation. The turning itself has only a short effect on oxygen supply, however. The biological oxygen demand in the pile is on a level, that latest after one day after turning more oxygen is needed.

In its technical meaning, composting hence is to be referred to a series of treatment steps beginning from the acceptance of the input material up until the generation of the **compost product** itself in a controlled manner. This operative control mainly involves steering the aeration intensity and duration of treatment in order to ensure that the material decomposes up to a state that is sufficiently stable for nuisance-free storage and handling as well as satisfactorily **matured and clean for safe use in agriculture**. The latter can essentially only be achieved by focusing exclusively on biogenic waste material (or SSO) as an input into the composting process (see 5.1.2).

Project reference box 1: Organic vs. Mixed waste *"composting"*

In relation to the aforementioned it has to be noted that, in some countries, including in Africa, there exist waste treatment facilities which under the label of 'composting plants' process a mixed waste input or a previously diverted portion of biogenic components from this waste in aerated conditions to so-called compost products. To remain clear in the definitions and distinction between the different treatment options as described in this document their operation may be classified as a mechanical-biological treatment-(MBT) in the first place (see 5.3).

It should nevertheless be recognised that even with this approach, treatment results for the biogenic portion of the plant input can certainly come close to the desired quality for a compost or meet local requirements for agricultural use entirely. Only a continuous and permanent batch-wise testing and approval can however ensure that the treatment in these cases is actually equivalent to a sole biogenic material composting. It is generally more objective and transparent for the end user therefore if a material treated in this way is regarded as **compost-like output (CLO)** with possibly certain restrictions on use. Occasionally, the terms mixed waste composting and organic composting are used to express this difference in the practice. (Donovan et al. 2010)

Generally, though, a five- to tenfold higher concentration of heavy metals is observed in a composting output from mixed household waste, compared to compost from pure biogenic material [European Leonardo-da-Vinci 'WASTE TRAIN'-project, 2007 (ICU Berlin 2022)]. Even with mechanically highly upgraded technologies it is not possible to separate the biogenic components from a mixed waste so precisely, that the produced compost shows the quality of compost from pure, source separated organics. In long terms, an accumulation of heavy metals and higher loads of visual and long-lasting impurities in soil is to be expected by using mixed waste composting outputs.

As far as the treatment-induced reduction of the GHG formation potential is concerned, there is no significant difference between the composting of source-separated and mixed waste, i.e. the relief resulting to landfills is nearly comparable.

Principal objective of the composting process is the **conversion of biogenic material into a humus-like product** suitable as soil improver and for agricultural purposes. A desired side effect is that an initially highly reactive portion of the waste is turned into a material which is showing earth-like behaviour and that those waste amounts still requiring other forms of disposal can be tremendously reduced where such practice is adopted.

The nutrient recycling taking place this way is particularly focussed on nitrogen (N) and phosphate (P) as these components can mainly replace chemical fertilisers and thus **minimises the need for relying on fossil P and mineral N-fertilisers** which become increasingly expensive and scarce. Unlike fresh plant residues or animal manure, composted or digested biogenic matter diminishes slowly in the soil because of the decomposition it has already undergone during treatment, concentrating the more lasting components. Beside ecological effects there can also significant financial benefits be attained from composting, including saved disposal costs (see Table 20).

Table 20: Key nutrient values of compost from biogenic waste and exemplary calculation for the derivable monetary benefit (adapted from ECN 2020 and Wrap 2016)

	Nitrogen (N)	Phosphate (P2O5)	Potash (K2O)	Total
Assumed market price of fertilisers [$/kg]	1.00	0.80	0.60	
Compost from a mix of biogenic waste material (garden and kitchen waste)				
Mean available nutrient content [kg/t compost]	10	4	6	
Monetary value of nutrient content [$/t compost]	10	3.20	3.60	16.80
Biodigestate (liquid fertiliser)				
Mean available nutrient content [kg/t digestate]	5.30	0.25	1.50	
Monetary value of nutrient content [$/t digestate]	5.30	0.20	0.90	6.40

Further to compost quality, sufficient attention should be paid on soil application rates and/or the recommendations given in that context[12]. Mineral nitrogen, phosphate and further mineralisation products may result in emissions of N and P to ground and surface water where these nutrients are present in excess of soil holding capacity and cannot be used by plants.

5.1.1 Main technical variants

The technical concepts for composting are generally distinguished according to following main criteria:

- **Arrangement of piling up the input material for treatment** (i.e. design of composting pile)
  Windrow (either of triangular or trapezoid resp. tabular shape) or tunnel;
- **Material encapsulation during the principal treatment stage**
  open-air, semipermeable cover (membrane or roofed shelter) or fully enclosed (tunnel or box);
- **Aeration procedure used in the principal treatment stage**
  passive (chimney-effect and turning) or active (pressure ventilation).

This results in the following variant combinations and technical designs commonly applied for composting in the waste treatment practice:

- ➢ *Passively aerated open air windrow composting,*
- ➢ *Passively or actively aerated windrow or bay composting with cover,*
- ➢ *Actively aerated tunnel or in-vessel composting.*

[12] Certain countries have already regulations on the properties that compost products have to meet, and on limits for their application proposed or in place. Such should be checked with competent local bodies or the national authorities.

Essential technical components

The processes for input preparation and for conditioning the compost product are basically the same in all technical variants, thus requiring a common set of mechanized equipment. Removing disturbing and/or unwanted items (impurities) manually from the process input and outputs might work in some cases. Principal differences in the technical components arise from the encapsulation method and aeration technique applied on the material (Table 21).

Table 21: Essential technical components in the different composting variants

Component	Open air windrow composting	Bay composting with cover	Tunnel or in-vessel composting
Devices for material preparation and conditioning	Shredder, Drum screen, Magnet separator		
Feeding equipment	Front loader tractor resp. wheel loader, Belt conveyor		
Composting area	Floor slab	Sheltered floor or concrete bay	Tunnel or drum
Aeration equipment	Turner device *(which may also involve using solely wheel loaders or shovel tractors for this)*	Air blower or Turner device *(which may also involve using wheel loaders or shovel tractors for this)*	Air blower
Control equipment	Temperature sensor	Semipermeable membrane, Temperature sensor	Temperature & oxygen sensor

Commonalities of all technical variants

The composting of biogenic matter begins whenever there are sufficient oxygen, water and ambient temperatures present. It is essential therefore ensuring that air can sufficiently well circulate through the composting input, that the material is moist enough and cannot cool down too much. Particularly influential on the composting process are the input material's

- particle size
- porosity
- moisture and
- carbon/nitrogen (C/N)-ratio.

Particle size of the material describes the available surface area for microbial activity whereas porosity affects the airflow and is a measure of the pore spaces left from the particles in a composting pile.

The optimum particle size is dependent upon the raw material. A smaller particle size will increase the rate of aerobic decomposition since the available surface area is increased. Depending on the composition of the waste, size reduction can be achieved by manual and mechanical methods such as chopping, shredding and passing the input through a screen. Typical particle sizes should be approx. 1-3 cm for actively aerated composting and 5-10 cm for passive aeration and windrow composting.

Bulking agents (such can be wood chips, corncobs, crop residues or the screen overflow from compost sieving for example) can be added to the input material if it lacks the structure to maintain adequate porosity. Naturally porous and lighter materials, such as leaves, can be built into larger piles whereas for more dense materials, such as manure, smaller designs have to be used to minimize anaerobic zones.

Moisture content also varies with the particle size and physical characteristics of the input material. A moisture content too low, usually below 40 %, will slow the composting process whereas a moisture content above 65% will restrict the air movement through the pore spaces and result in anaerobic conditions. Excess leachate may also be produced if the moisture content is too high. To activate aerobic bacteria, the moisture content of the feedstock should be kept above 40 %, preferably between 50-60 % and the pH approx. 7. Manure and food waste both have a high moisture content of around 70-80 %. To maintain aerobic conditions, it is necessary to reduce the moisture content by adding drier organic materials such as sawdust or rice husk to the input. Dry leaves and tree trimmings can also be used to adjust moisture content.

A C/N ratio ranging from 25/1 to 30/1 is described as the optimum for a fast composting, but higher ratios up to 40/1 may be possible. Overloads of nitrogen in the input material must be avoided since almost the entire nitrogen fixed in the organic material is going to be released as ammonium thru micro-biological activities. High concentrations of ammonium at a pH>7 can cause the emission of ammonia. The optimum C/N ratio again can be attained by combining various materials in the input.

The conditions on site eventually determine how the material is arranged for composting. The material must be piled up in a way (i.e. windrows of certain shape or bays/boxes) that a complete cool down is prevented and the available space and technical equipment can be used effectively. Once the appropriate material setup is done, the composting is taking place in several phases.

The **four principal phases of the composting respectively treatment process** comprise:

- **Starting phase** (mesophilic temperature range, approx. 45 °C);
- **Intensive rotting phase** (thermophilic temperature range, 45-70 °C, process temperature of above 55 °C must be achieved for germ reduction, total pathogen elimination and destruction of weed seeds above of 65 °C);
- **Decaying or conversion phase** (continuous cooling down, increase of mesophilic organisms, mass occurrence of actinomycetes);
- **Maturation.**

Hereby, a balance needs to be achieved between **proper aeration** and **temperature** requirements. The consumption of oxygen is greatest during the early stages and gradually decreases as the process continues to maturity. With proper temperature monitoring the need of additional air supply can be determined and, depending on the technical variant and applied method of aeration, any necessary actions initiated.

Insufficient aeration and lacking oxygen slow down the composting process, creating anaerobic conditions and higher odour emissions. Different anaerobic reactions by microorganisms form intermediate decomposition compounds such as methane, hydrogen sulfide, and organic acids. Physically turning the compost or providing forced aeration maintains the aerobic conditions and limits odours.

A complete hygienisation and safe compost product requires that within the composting process the input material is exposed to a temperature of:

- 55 °C as a minimum for at least two weeks; or
- 65 °C as a minimum for at least one week (60 °C in case of in-vessel composting).

The energy which leads to such temperature developments is normally created by the process itself. Depending on the technical variant applied, this treatment state can be reached within a shorter or longer period of time, which also results in a correspondingly shorter or longer overall treatment time.

Usual time spans in industrial composting are in the range of **10-14 weeks for the overall treatment**. This duration increases the simpler and less intensively mechanized and controlled the technical processes are designed and can then take several additional weeks and even up to 6 months in total.

As indicators for a matured and stable compost should be taken:

- material does not re-heat over 25 °C upon standing and has an earth-like smell,
- material shows a C/N ratio of less than 22, making it safe for agricultural use,
- material feels crumbly, when squeezed in a closed fist no free water comes out and it does not fall apart after opening the hand.

The finished compost eventually undergoes a fine sorting, for example via a screen and classifier, in order to ultimately remove impurities and return incompletely decomposed, oversized components into the rotting process.

5.1.2 Input material and general mass balance

The separation of the biodegradable waste at source is an important prerequisite because it reduces the non-organic content in the waste entering a composting process. The initial inclusion of non-organic components such as plastic and glass in the process input determines the impurity content at the end of the composting. Moreover, any non-biodegradable and hazardous component is a potential contaminant which can have a negative effect on the final quality of compost (see Project reference box 1 above).

Plastic components in the waste and remaining later on in the compost will decompose into smaller pieces under the influence of sunlight but eventually stay in the soil as microplastics for centuries. Where the biodegradable waste is separated well at source and municipalities successfully collect it as an input to composting, it will not also be necessary to apply a series of additional mechanized processes to separate and remove contaminants.

The following generalized mass flow balance can be derived for industrial composting processes applied on biogenic waste material (see Figure 16).

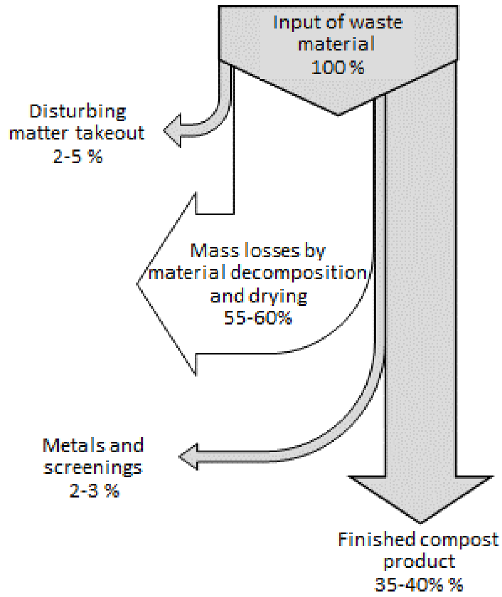

Figure 16: Mass flow balance (averaged and generalised) for biogenic waste material

5.1.3 Technical variants primarily considered for local application

Selecting a composting system design usually involves optimization between transportation efforts, land availability, labour and capital expenses, feedstock supply, and markets (see also Table 22). There hardly exists one “right answer” but rather several possible options. For example, combinations of home- and community composting schemes and large-scale industrial composting facilities should be encouraged to reduce municipal costs.

Table 22: Consolidated overview of the technical variants considered for composting-related waste treatment concepts

	Open air windrow composting	Bay composting with cover	Tunnel or in-vessel composting	Home resp. community composting	Worm composting	Use of black soldier fly
Common application range	medium to large volume flows	medium to large volume flows	large volume flows	small individual volumes only	rather small volumes	rather small to medium volumes
Manageable material range	rather wide less food scrap	wide, incl. food scrap	wide, incl. food scrap	limited, rather no food scrap	limited but incl. food scrap	Limited, espec. food scrap
Space consumption	generally high	moderate	moderate	rather low	generally low	generally low
Technical complexity	moderate	moderate to high	generally high	low	low	moderate
Financial intensity	moderate	moderate to high	moderate to high	rather low	low to rather moderate	moderate to rather high
Robustness in changing climates	moderate	rather high	rather high	limited	limited	low
Ease of public acceptance and urban integration	limited	moderate	rather high	rather high	moderate	moderate

5.1.4 Home and local community composting

Home and local community composting involves diverse forms of setting up simple composting units directly on private premises within the residential environment or at more centralized locations in village-like structures. Private initiative can work as a trigger but adoption of the concept can also be stimulated by financial incentives and the provision of necessary tools and/or materials for the composting units.

In principle these **simple composting units can be constructed from locally available materials** such as wood planks, bamboo, wire mesh, pallets, bricks, etc., or just take the shape of purposefully layered and controlled piles of biogenic waste materials (Figure 17).

Figure 17: Examples of simple composting units for individual home composting and set up as a village-composting facility (Picture sources: INTECUS / LIPOR/Community of Porto, 2021)

The design and operation of these composting units should not attract rodents or scavenging animals, though shaded places the drying out of the material can be avoided and manual turning is normally sufficient for aeration and to supress odour development effectively. The processes and principles are basically the same as in the technical variants for industrial composting.

Home composting is usually a part, often though even the nucellus of this concept, and can be applied as a simple way to manage the individual biogenic waste generated in kitchens, the garden or from private livestock. It effectively reduces waste quantities for collection, thereby improving efficiency and reducing operating costs. Implemented in the form of a decentralized composting at neighbourhood or community scale it can provide larger community groups a way to compost at very low cost. (Rothenberger et al. 2006)

This decentralized concept is therefore of high value to achieve

- an **extended awareness of waste responsibility**; here to make use of the biogenic material as the major waste component,
- an **easy, fast and cheap individual waste treatment** without waiting for a superior order or initiative, and
- **triple positive impacts**: (i) reducing negative dumpsite impacts, (ii) production of usable compost, (iii) prospectively increasing the sorting efficiency of recyclables from the remaining waste.

Households, commercial establishments (e.g., small markets or shops), and institutions (e.g., government buildings, schools) in an area can compost on vacant land, beside community gardens, or in public parks. Local governments can support such initiatives through public education, providing land for the composting site, assisting with start-up costs, transporting and disposing of rejects to local landfills, and using the final compost in public parks.

Public health officials may discourage home composting because of perceived health risks; however, local governments and community leaders can overcome this concern through proper training, awareness creation, and by promoting education on compost processes, e.g., how to minimize the presence of rodents and flies. The concept is particularly worth to be promoted when a significant number of homes have their individual or collective yards or gardens, there is a sufficient availability of space and well-organized supervision can be ensured.

As far as the concept exceeds the home composting on private premises and covers the collection and composting of biogenic waste from markets, groceries, canteens and communal greenery, the concerned community should take care of

- proper site selection and operational conditions for the composting place,
- an attended and reliable operation mode for a sustainably functioning composting,
- sufficient application areas and ensured distribution ways for the produced compost.

- ➢ *The home and local community composting approach belongs to the treatment options in the cost range below 10 $ per ton treated*[13] *and is rather workable as long as the aggregate amount in the area of a settlement remains in the range of less than 5 t per day.*
- ➢ *To treat bigger waste quantities within a formalised framework and waste management system, more centralised facilities using one of the following large-scale technical variants must be employed.*

5.1.5 Open air windrow composting

Open air windrow composting can probably be labelled as the technically simplest option for composting at larger scale and as the variant that follows next to home and community-composting practices when shifting to an industrial-like implementation.

This technical variant can score with the advantage of **requiring less stationary infrastructure**, and thus being less investment expensive while generally more flexibly and easy to operate than other industrial variants of composting. The biggest disadvantages arise from the **considerable higher space demand** and the risks associated with the exposure to weather (which may affect process speed and efficiency) and possibly occurring emissions such as dusts and odours (causing nuisances).

As in any composting facility, there must be a zoning of the operation area to provide space for waste unloading and preparation works upfront of the composting and for sieving and bagging of the compost afterwards, including some storage buffer at both ends of these operations.

By far the most additional space is needed for those structures where the material undergoes the several composting phases and the maturing in the windrows (Figure 18). Since **open air windrow composting is**

[13] OPEX of approx. 6 EUR/t*a [according to model calcs in 'Decentralised Composting for Cities of Low- and Middle-Income Countries. A Users' Manual, 2006]

taking the longest time here, it is the variant with the highest requirements in space per ton of waste treated. Since treatment quantity and space requirements correlate strongly, this variant is usually only considered for composting plants with a capacity below 10,000 t/a.

Figure 18: Open air windrow composting in practice (Picture source: INTECUS)

The area where the material is piled up in windrow lanes during these phases is preferably laid out as a continuous concrete slab, slightly sloped (1 %) towards one side to allow excessive water to flow into a drain. The shape, dimensions and setup (positioning) of the windrows can be variable, depending on the material characteristics, floor space dimensions, structural conditions and the equipment used for material intake and discharge and, in particular, for aeration.

In big open windrows without forced aeration the inside temperature can go up to 70 °C and higher, which might be wrongly interpreted as an indicator for high biological activity. In fact, a dried outer 20 cm-layer of compost material has -due to its inner porosity- a energy transmission resistance of 4 cm of styrofoam; thereby only a minimum of biological activity in the heap’s core is already sufficient here to hold the undesired high temperature level.

Sufficient oxygen supply is automatically provided when sufficient aeration for cooling is given. At windrows, the depth of natural oxygen supply normally ceases at 1m from surface and a chimney effect for self-aeration over the entire pile can be consistently maintained only with smaller windrow heights, up to approx. 1.8 m in the maximum. As a general rule, therefore, static windrows should not be higher than 2 m to minimize anaerobic inner parts and prevent overheating.

An active (forced) aeration on the other hand reaches the whole composting mass and helps adjusting the airflow to stabilize temperature in an optimum range. Thus, in order to be able to deal with higher waste quantities and ensure fully controlled material aeration, special turning devices are commonly employed for this composting variant. Through their use, it is possible to work with larger windrow profiles whereby width and height of the windrows are usually adapted to the cross-section of the machine passage. For its turning operations, the machine moves along the windrow basis (or bay walls) while a rotary shaft equipped with paddle plates mixes and loosens the material in beneath.

Figure 19: Examples of turner devices of varying size and capacity used for open windrow composting (Picture sources: INTECUS)

As far as the segment of compost turning units currently found on the market is concerned, a range between 1.5 and 3 m for the windrow height and between 2.5 and 10 m for the windrow's base width can be considered. High performance commercial turners do have a turning capacity in the range of 500 - 7,000 m^3/h. However, this equipment component proves to be available in incredible variety; in addition to self-propelled turners, numerous trailer variants and self-designs are also common, with each design having its own performance parameters and operational peculiarities (Figure 19). Available wheel loaders or shovel tractors can provide an alternative equipment for turning where investment funds are limited.

The frequency of aerating the windrows depends on the progress of the material decomposition, determined by monitoring the windrow internal temperatures and possibly the dissolved oxygen. The applied turning regimes show rather wide variations and change throughout the treatment process. Frequencies between once every two weeks and 3 times per each week are being observed during the intensive rotting phase. This goes down to a frequency below 1 time per week or only once during the decay and maturing stage. The need for a rather frequent material turning, especially in the case of windrow composting, entails certain manpower effort and thus creates higher employment opportunities.

With a treatment period of 12 weeks and more needed for windrow composting, a **space requirement in the range of 0.8 - 1 m^2 per m^3 input material** can be assumed as a rough orientation. Approximately 75 % of the consumed space relates to material storage in the windrows, although a good 40 % of this is required for machine movements.

The specific total energy consumption for operating an open-air windrow composting plant with heavy mechanized equipment can be calculated with 18 kWh/t on average. Almost 90 % of the energy consumption is hereby accounted for by the consumption of machine fuels.

- *For this technical variant the assumed range of total costs is 10-25 $/t including the CAPEX share.*

Especially **in regions marked by rainy seasons** and wind blow, bringing parts of the composting installation **under a roof or shelter** can be indispensable (Figure 20). Protecting the material from excessive weather impacts is particularly recommendable in the initial rotting and storage sections, to keep the produced compost dry Although the investment in a shelter can be significant, processing a disproportionate amount of leachate or diminishing the quality of the compost in storage are always more expensive in the long run. Another point to mention is that a roof or shelter is an excellent place to install a photovoltaic system and let the sun help to generate the required energy and pay back the investment.

Project reference box 2: Windrow composting pilots in Ethiopia

The cities Bishoftu, Adama, Bahir Dar, Dire Dawa, Mekelle and Hawassa received modern composting machineries and equipment through the Ministry of Urban Development and Construction (MUDC) in September 2020 under the Ethiopian NAMA COMPOST Project. Amongst others this involved 12 tractor-pulled trailers for separate transportation of organic waste, 6 tractors along with semi-automatic tractor-pulled compost turners, 60 compost fleece, and 12 digital thermometers for six composting pilot sites.

From originally planned six only three composting sheds were eventually realized. From the compost sheds planned, drainage work, fencing and vehicle access required more work for Hawassa compost shed while Bahir Dar compost shed also needed completing vehicle access. In Dire Dawa, the compost sheds needed additional work and compost production outside of the sheds was taking place. Overall, the total annual compost production capacity has reached more than 45,000 tons per each city. A total of 109,220 tons of compost were produced from 363,704 tons of organic waste in the project period. (UNDP Ethiopia 2022)

Figure 20: Compost shelter for windrow composting pilot in Bishoftu, Ethiopia [Picture and further reading source: (UNDP 2017)

5.1.6 Composting in windrows or bays with cover

Covering windrows or bays **reduces the risks of uncontrolled emissions and weather impacts** while enabling optimized decomposition processes and shorter treatment times. This means a higher material throughput or lower space requirements for this technical variant.

The main technical difference to open air windrow composting is the use of a special cover fabric or tarpaulin placed above the composting material, especially during the intensive rotting phase. Data from corresponding field tests show a three to four times higher throughput capacity; instead of approx. 2 t in the open air windrow variant, between 6-9 t could be treated per square meter of treatment area and year with optimal coverage (W. L. Gore & Associates 2012; W. L. Gore & Associates GmbH 2022; UTV AG 2015). The additional technical investment remains hereby reasonable. Constructing bays into which the composting input is placed can further enhance the holding capacity and encapsulation of the material while at the same time reducing the consumption of the cover fabric.

Air-impermeable covers are completely unsuitable for the industrial composting processes, however. For this reason, semi-permeable cover materials are used, where a distinction is made between two types of cover material; fleece cover and cover membrane (tarpaulin). With a fleece cover, the protection and drainage effect of rainwater and suppression of odour can only be attained to limited extent.

A cover with a membrane is much more effective here but it is important to note that such can only work in conjunction with an active material aeration. Various ways of realizing this have established in the practice. Both flexible ventilation hoses introduced in the windrows or bays and the use of turning machines are options. The use of turning machines in this case is coupled with solutions that ensure that the cover membrane is lifted for a short time and put back again in the course of the turning process. This effectively limits the release of emissions and particulate matter. Another alternative is the forced aeration via a ventilation system directly integrated into the bays by way of channels and aeration plates in the floor area. With that the treatment runs almost continuously under the protection of the membrane cover (Figure 21).

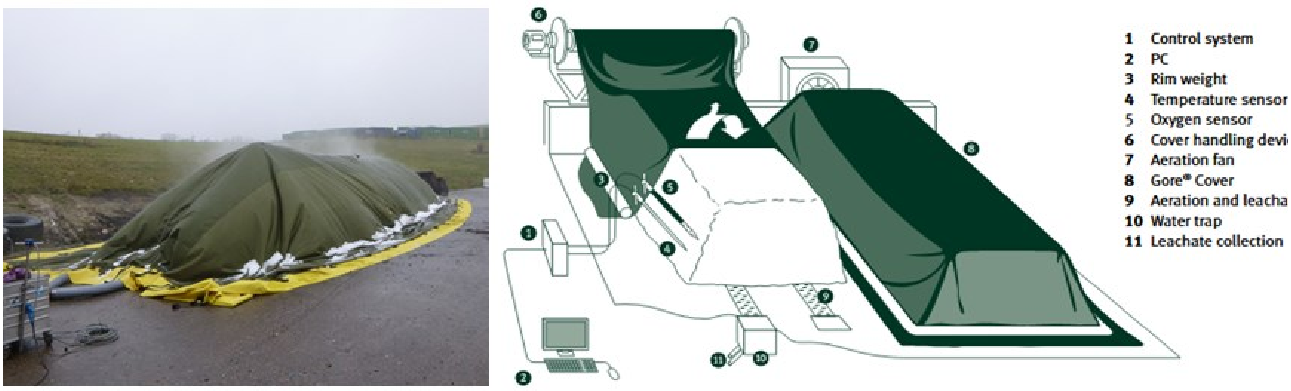

Figure 21: Windrow composting with GORE® cover membrane; practical example and schematic drawing (Picture sources: courtesy of UTV AG + W.L. GORE)

The function and operation mode of the semipermeable membrane is to create an ideal microclimate for composting largely unaffected by external weather conditions while retaining the required moisture and odours. Micropores in the special membrane allow water vapour to escape from the rotting material and at the same time protect it from rainwater penetration. Condensation effects on the underside of the membrane simultaneously ensure a favourable temperature profile, a certain degree of rewetting and the binding or dissolution of odour carries (Figure 21, left).

Overall, this means that the composting process can be carried out more quickly and with less impact to the surrounding environment. Composting facilities of the corresponding type are therefore generally better accepted, which broadens the spectrum of possible locations. Even those authorising bodies generally known as the strictest in Europe and North America accept membrane covered treatment with technically proven fabric, like for example the GORE® Cover, as compliant to the standard of best available technology for encapsulated composting.

Furthermore, steps like turning for aeration can be spared, if a forced permanent ventilation is installed. The treatment duration is therefore shortened, especially in the rotting phases, thus making **total treatment durations of 12 weeks or less possible.** The tarpaulins full functionality typically last 7-8 years in moderate climatic conditions, although the later usage on sections to cover against rain in storage is also common after that.

Since this variant is in principle independent of fixed structures, there is less criticality with regard to lower and upper throughput limits, although the minimum supply with mechanized equipment, i.e. shredder and screen, must also be taken into account here. This leads to the application for installations normally bigger than 5,000 t/a.

The specific total energy consumption of the like composting facilities may assume a greater range, depending on the aeration technique, the level of mechanization and structural design eventually applied. Values in a range from <5 kWh/t composting input up to 52 kWh/t on average for technically sophisticated installations are quoted.

- *Including the CAPEX share, a 20-45 $/t range of total costs is usually assumed for this technology variant.*

5.1.7 Tunnel or in-vessel composting

Tunnel or in-vessel composting practically resembles the transposition of composting under a semi-permeable membrane (Figure 22, left) into a technically more sophisticated, structurally completely closed or encapsulated system with forced aeration (Figure 22, right).

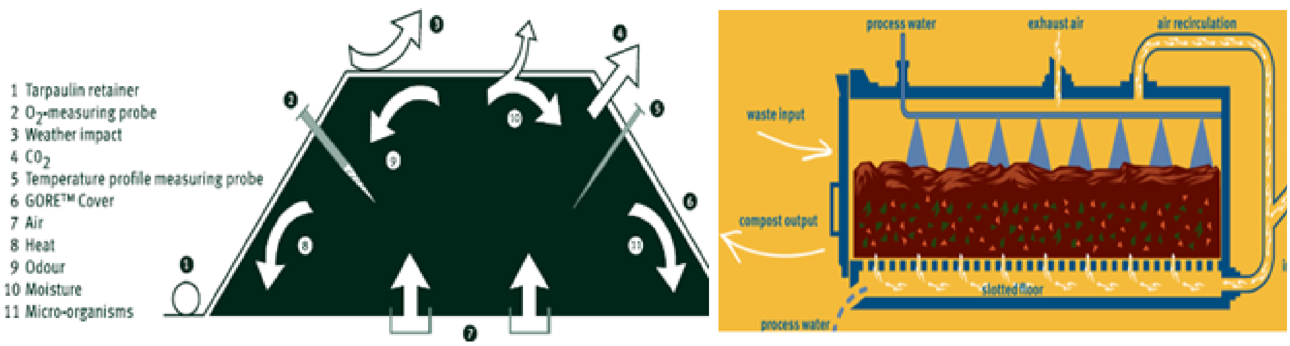

Figure 22: Working principle of GORE® cover membrane vs. design and working mode of a fully enclosed tunnel composting system (Picture sources: courtesy of W.L. GORE+UTV AG / INTECUS with permission by former Linde KCA)

Principal motives for this variant are the **acceleration of the treatment process**, thus higher throughput quantities with lower space consumption, along with the higher independence from external influences and better protection of the environment resulting in a rising acceptance.

The intensive rotting, which is transferred into a fully encapsulated and controllable system and thus shortened, is usually followed by the maturation of the compost which can be in windrows again. An intensive, automatically controlled forced ventilation by and large replaces the use of turners for aeration, exhaust air streams can be specifically routed via filter systems.

To pass the exhaust airflows from waste treatment processes through filter systems is a standard in many countries and often also a legal requirement where strict emission control acts are in place. For composting facilities, simple air filtration units, such as so-called natural biofilter systems, can already suffice considering the rather harmless composition of the process gases generated and that odours are to be coped with primarily. Various materials such as woodchips, sawdust or straw can suit here as natural biofilter, including the not yet fully decomposed but already stabilized screen overflow from fine sorting the composting output.

The encapsulated construction for composting with its monitoring and control technology entails a considerable additional technical and financial investment, however.

- *As a result, the concept proves to be economically feasible especially for higher throughput quantities from 10,000 - 40,000 t/a, including the CAPEX share costs >50 $/t have to be assumed.*

The critical throughput threshold usually increases if a fully stationary plant is preferred over a modular container box solution (Figure 23). With its optimised space requirement and protection of the neighbourhood from dust and odour emissions, this technical variant simultaneously exhibits **improved integration possibilities in a populated environment**, which means increased suitability for use in urban conurbations.

Figure 23: Different type tunnel composting installations (Eggersmann)

5.1.8 Further treatment options attributed to this technology segment

There also exist some other treatment processes that are very similar to composting or are even referred to as such. These should not go unmentioned because of their potential adoptability in the target region. It must be noted though that these have not yet become solutions of large-scale technical nature or in worldwide distribution. Instead, they have so far proved effective in certain niche markets, under specific regulatory circumstances and as concepts that can be applied on waste flows of smaller volume in particular. First practical applications of these additional treatment options can already be found in Africa. These include the so-called

- **worm composting** and the
- use of the **black soldier fly** for the metabolization (recycling) of biogenic waste.

In worm composting, large numbers of special compost worms accelerate the natural oxidative, i.e. aerobic decomposition and transformation process of composting. These worms break down and digest the biogenic waste components and, through their excretions, contribute to a **high compost quality and nutrient accessibility** for the plants fertilised with it. For this, they need conditions that suit optimally their living and reproductive environment. The African climate and deliberate human intervention provide helpful prerequisites here.

Nearly a concept of the same sort is the use of the black soldier fly for biogenic waste treatment. Basis of this process is to breed black soldier fly larvae in a waste biomass. The larval growth requires a nutritious, especially protein-rich substrate that especially food waste can provide. Warmth is essential in the whole development and processing cycle, and a naturally higher temperature level and possibility to tap outside heat provide therefore preferable conditions. The waste biomass gives the larvae both "home" and food in one, with the result that most of the **waste is converted into new, animal biomass and excreta**. All this basically occurs in anaerobic conditions. The newly produced biomass is of marketable value and particularly demanded as a fodder material by farmers and the animal rearing industry. Resulting residues are taken to conventional aerobic treatment by way of composting and can then be used in agriculture.

Experience with the production of protein feed from biogenic waste using the black soldier fly is available on larger scale from South Africa[14]. Applications of this concept are also known from other places, including Canada and Bogor/Indonesia[15]. A reference guide for this technology was written at Eawag, the Swiss Federal Institute of Aquatic Science and Technology, Dübendorf[16].

5.2 Anaerobic digestion

The process of anaerobic digestion (AD) involves the gradual bacterial decomposition of the biogenic waste in the (relative) absence of oxygen into methane, carbon dioxide and water. This is in contrast with the aerobic biodegradation or so-called composting process.

Under AD-conditions the organic substance is first split in acetic acid (within a rather short period of time), and this organic acid is then feeding methane producing microorganisms. These methane-generating organisms have on one hand a slow reproduction rate (compared to the aerobic ones), on the other hand they are very sensitive against changes in process temperature and especially of pH-value. Therefore, the process needs -compared to composting- special care in feeding, very tight temperature/pH control and sufficient internal/external inoculation to hold a sufficient population of these methane-organisms in the digested material.

Principal objectives of the treatment by an AD process are the **energetic utilization of the waste through the production of biogas** with a simultaneous reduction of the mass, the biological activity and thus the reaction potential of the treatment residues.

Anaerobic digestion in general produces 80-140 Nm^3 biogas per ton of processed waste input from municipal sources. The biogas yield may increase the more energy rich organic waste substrates, for example waste from industrial food processing or from grease traps is being fed into the process. Beside

[14] see for example the commercial ventures of Proticycle, Inseco or NAMBU
[15] https://circulars.iclei.org/wp-content/uploads/2021/03/Bogor_ICLEI-Circulars-case-study_Final-2.pdf
[16] available under the literature citation Dortmans B.M.A., Diener S., Verstappen B.M., Zurbrügg C. (2017): Black Soldier Fly Biowaste Processing - A Step-by-Step Guide.

the varying amounts of biogas generated, there will be considerable differences with regards to the quality of the process output and its mass proportion relative to the input stream depending on the process intake and specific design of the applied technological solution.

5.2.1 Main technical variants

AD technical concepts are generally distinguished according to the following main criteria:

- Moisture content of the material at the time of entry into the digestion process and ambient environment in which this process is eventually taking place:
  dry or wet

- Differences in material feed and biogas extraction procedure at the individual treatment units:
  continuous or discontinuous

This results in the following AD variant combinations and technical designs commonly applied in the waste treatment practice:

- *Wet digestion (only available as continuous) process design,*
- *Dry fermentation,*
  → *plug-flow* (=continuous) or
  batch (=discontinuous) process *design.*

The mentioned technical designs comprise or may typically require the following hardware as a minimum:

Table 23: Essential technical components in the different variants of AD

Component	Wet digestion	Dry fermentation	
		plug flow	batch design
Receiving facility	tank/silos	flat bunker	flat bunker
Devices for input preparation	dissolver	screen/magnet/homogenizer	-
Feeding equipment/installations	pumps & pipes	(screw) conveyor	wheel loader
Digester units with process water inlet	tanks with stirrer	containers with rotating paddles	container/boxes
Digester heating	required	optional	optional
Biogas storage	any type of tanks		
Biogas processing unit	electricity generator or combined heat and power (CHP) unit		
Equipment to handle digestate	dewatering unit	drying unit	-

Commonalities of all technical variants

Digester units are constructed as sealed structures (dry process: fermenter boxes/wet process: tanks) which retain any liquid content and can be technically hold gas-tight for as long as the process for biogas generation is continued. As the production of biogas begins to develop optimally in a mesophilic temperature range (38-40 °C), these structures are often equipped with a heating system integrated into the wall and/or floor areas.

Further mechanical components attached to these structures provide for a stirring (wet process) and mixing of the material input as well as its movement through the process (dry fermentation plug-flow design). No such component is needed for dry fermentation in the batch design. However, all variants work with specific equipment and installations for material feeding and handling, and require the inoculation of the fresh input material to set the AD process in motion. The procedures applied for that may vary but normally rely on adding material portions or process water tapped from the fermentation process already in progress. The quantities of material used or returned for inoculation can be quite significant (up to 45 % of the mass in ongoing treatment).

The input material is retained for biogas production in the fermentation/digester units for a period ranging between **3-4 weeks**. The average retention time in the wet process is hereby generally shorter with about 20 days than that of the dry process with an average of 25 days (FNR, Fachagentur Nachwachsende Rohstoffe e.V. 2004).

Biogas yields also can be assumed to be higher for the wet process as compared to the dry processes, although this difference mainly has to be attributed to the different energy content of the materials fed into these processes. The generated biogas is extracted via valves from the system. A piping system enables that process water can be added or returned to the process as necessary in all technical variants.

The **residues from AD** processes are commonly referred to as the **'digestate'**. Digestate can be used as a subsidy for industrial fertilizers. The digestate shows varying characteristics in dependence from the input material and operating conditions. In general, these characteristics comprise:

- a high content of water (especially for wet processes the digester output typically has a dry matter ratio of only 1-8 %, for dry fermentation that is in the range of 30-40 %);
- the presence of odorous compounds (hydrogen sulfide, ammonia, amines, volatile organic acids, reduced sulfur compounds);
- the presence of concentrations of inorganic nutrients (Ammonium-N and P), and
- that potentially toxic elements (for example heavy metals) can be included.

Because of the above characteristics an appropriate form of **post-treatment**, for example by **composting**, must be undertaken on the digestate before the material can be further utilized or finally disposed of (Thamer 2014). Since AD processes are typically characterized by surplus amounts of water, this usually involves dewatering and/or the drying respectively stabilization or hygienisation of the digestate, accompanied by an appropriate effluent (i.e. wastewater) treatment. Dewatering also ensures that no high loads of moisture are transferred to landfills or introduced to subsequent processing.

Dewatering technologies for digestate include mechanical but also thermal processes. Most commonly used devices for this in the wet process design are gravity belt thickener, various types squeezer (e.g. screw press, belt filter press), centrifuges and dryer systems (e.g. belt dryer, paddle dryer, drum dryer).

Due to the generally lower proportion of free liquids in the digestate coming from dry fermentation processes, there is lesser need to avail of this kind applications here. Using excess heat or taking the digestate directly into composting is often sufficient to achieve the necessary final stabilization and hygenisation of the process residues. Where a pure biogenic waste has delivered the material input to AD, utilization of the liquid process output as a liquid fertilizer can be a possible alternative.

5.2.2 Input material and general mass balance

As there are considerable differences in the ability of the respective processes to deal with different input materials and thus achieve the treatment objectives efficiently, it is imperative to consider the waste stream to be treated when selecting the appropriate AD concept.

Any of the technical variants can be applied on biogenic waste materials which have been source separated or split up in a pre-treatment operation such as MBT (see 5.3).

Wet digestion is preferably applied on an input of biogenic waste material with a DS content below 15%. The process suits in particular for largely liquid or particularly moist biogenic waste streams, such as manure, organic sludges or those generated during food processing or in canteens and the catering sector. Where the required moisture level is not practically guaranteed, the material must either be slurried or a liquid organic concentrate obtained from it. Percolation is one of the techniques applied here to the waste in order to achieve this.

To be suitable for **dry fermentation** the input material, on contrary, must be showing a dry substance content ranging from 20 % up to 50 % in the maximum. Dry fermentation using the plug-flow design requires material of higher moisture which is why 15 – 30 % DS content in the input is generally considered appropriate here.

Both, the wet digestion process and dry fermentation using plug-flow design do not qualify for an untreated input of mixed waste, however. The conditions for using these treatment variants must be created by **separating or extracting the biogenic components** upfront of AD from the mixed waste. Most common is to send the waste for this purpose via a screen and then apply the AD processes on the particle fraction <80mm, in which biogenic components accumulate and disturbing objects are largely eliminated.

Dry fermentation in batch design can score here as a technically less demanding and **more robust concept** that, in principle, can be applied also to mixed waste or a biogenic input that is more heavily interspersed with inorganic and other foreign matter. Despite the lower pre-processing requirement, it remains essential that the content of biogenic components in the waste material is sufficiently high and that anything which significantly impedes the AD process and subsequent processing of the digestate (such as extremely dangerous and bulky items, bagged goods, etc.) is removed.

Processes fed with largely pure biogenic waste material may allow the output of semi-solid residues to amount to only 150-300 kg dry matter per ton of input, meaning a quantitative reduction of the process intake by 70-85 %. These residues require further treatment to become eventually a stabilized material. By and large they suit for producing a marketable end-product for agricultural and landscaping use by way of composting.

Processes fed with an organic-rich mixed waste do also lead to a significantly reduced biological reactivity and lower output amount in comparison to the input quantity although that happens at lesser scale.

Generally, it can be expected that the solid output is in the range of 550-650 kg per ton of material input, meaning the **total waste mass shrinks by about 35 to 45 %** during the process.

The process residues need to undergo further treatment to be eventually ready for landfill disposal or other uses. Applying an additional rotting on these residues reduces further mass and reactivity of the remaining waste. The same principles as in composting do apply for the final utilization of the treated output. The use cases of the final product are highly determined by the purity of the input material. Compost from pure biogenic waste input can be safely used in agriculture, whereas compost from mixed waste input is restricted to appropriate applications, i.e. landfill coverage.

From the above, the following generalized mass flow can be derived for AD processes (Figure 24):

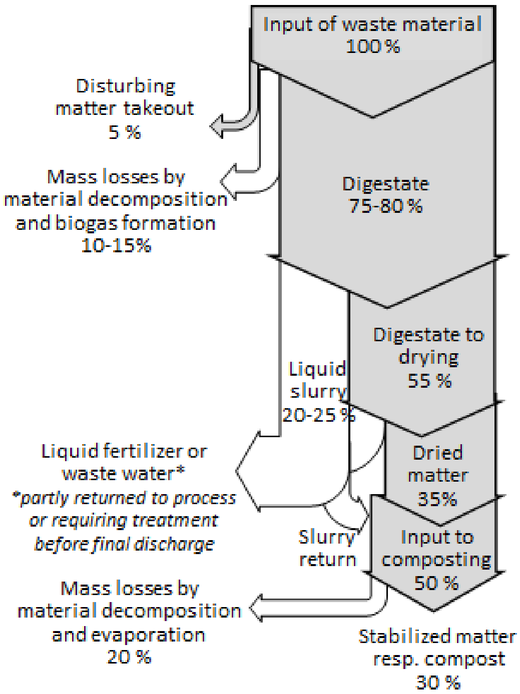

Figure 24: Mass flow balance (averaged and generalised) for AD processes with biogenic waste material input

Biogas utilisation

Roughly 100 m³ of biogas are produced per ton of biogenic waste, holding 60 % of methane and providing 6 kWh heating value per m³ respectively 600 kWh per ton input to AD.

The biogas can be utilized in a number of ways. It can be used as a natural gas substitute in form of biomethane, to fuel boilers to produce heat, or to fuel generators to generate electricity, ideally in combination with heat use (CHP). In a CHP roughly 30 % of the biogas energy are converted to electricity, 50 – 60 % into heat.

Biogas electricity production per ton of waste input to AD can range from 75 up to 225 kWh, varying according to the feedstock composition, biogas production rates and efficiency of the electrical generation equipment.

Some of the electricity generated (10-15 %) is consumed directly by the treatment facility. The same applies to the excess heat which, depending on the total amount produced and further circumstances (e.g. local climate conditions), at least is partly needed to operate the fermenter units at optimum temperature. A certain portion of the heat might also be used for drying the digestate before it is transferred to subsequent processes. This in total can sum up to a self-consumption of 60 % heat by the plant, a further portion comprises loses to the atmosphere.

The majority of the excess electricity produced can be sold and exported via the electricity distribution network. Generating electricity from biogas is generally considered 'renewable energy' and meanwhile benefits from support under Renewables Acts and 'Green energy'-programs in numerous countries. Excess heat can also be fed into a local district heating scheme or go via steam chillers into cooling applications, should there be available users.

Alternatively to power generation, the produced **biogas can be also processed into biomethane.** This can then be fed into the natural gas grid or used as vehicle fuel (e.g. compressed natural gas-CNG). In that way, the generated energy can be stored and used in a wider market. However, for such high specification applications, or when using more sophisticated electricity generation equipment (e.g. gas turbines), biogas from AD will require more pre-treatment to upgrade its quality. This includes the removal of hydrogen sulphide as a corrosive gas, moisture removal, pressurisation to boost gas pressure, and mostly methane up-concentration above 90 % by the removal of carbon dioxide to increase the calorific value of the biogas. The cost of the equipment required to upgrade biogas can be significant.

5.2.3 Technical variants primarily considered for local application

5.2.4 The AD wet process

Unlike the concept of dry fermentation, the wet process is already **practicable even in relatively small installations** directly connected with the household. This is favoured by the fact that liquid biogenic waste material accumulates directly at the individual premises in the form of faeces, kitchen residues and, in rural areas, also through livestock manure, for example. Often then these materials can directly flow into a digester unit without that major additional technical installations or preparatory measures become necessary. Micro-digester of this kind therefore can be realised in relatively simple constructional designs and thus at very reasonable cost, and therewith have a relevant significance and justification in the individual waste disposal practice, especially in areas that are difficult to supply with regular disposal services.

Project reference box 3: Small, decentralized micro-digester (wet process) applications in rural Africa

In a number of African countries, biogas is traditionally used in small and very small installations for providing household energy and for supplying social institutions with gas as fuel for cooking, heating and lighting. With the help of IDA funds (e.g. CARMATEC, ABPP by SVN) several thousand small and medium-size digester and also larger-sized installations with a digester capacity over 100m³ have been erected. The National Biogas Program – Ethiopia (NBPE) took off in 2009 with the objective of developing a commercially viable domestic biogas sector. Until the year 2019, when it officially ended, four regions in Ethiopia (Oromiya, Amhara, Tigray and South Nations Nationalities and People's Region) particularly benefitted from the program. Under this support scheme, more than 13,000 digester installations for rural households were successfully realized against an initial target of about 25,000 such installations. During the construction phase it was found that the Fixed Dome model is the most preferred plant model in Ethiopia, other designs introduced included the Interlocking Stabilized Soil Blocks (ISSB) and Solid State Digester (SSD), though these turned out to be less popular. The large majority of projects made use of manure, other agricultural and faecal waste to fed the digesters and in more than 90 % of these fertiliser was produced as a by-product. Through that, improved agricultural production and incomes, including from the sale of excess bio-slurry to other farmers, were seen.

Further potentials for industrial biogas and electricity generation in Africa remain(ed) largely untapped, however. Municipal solid waste, sisal and coffee production are the most promising sectors with the greatest potential. However, specific electricity production costs for small plants (50kWel) range between 0.11 and 0.29 US$/kWh [GTZ-commissioned DBFZ-study on 'Agro industrial Biogas in Kenya'].

Source: The Africa Biogas Partnership Programme (ABPP 2019)

Wet digestion in **small, decentralized micro-digester units** is hence furthermore considered one component in a conceptual approach for the future management of biogenic waste streams in Eastern Africa, even though a further in-depth explanation and technical details on this will be dispensed here.

On the other hand, large-scale plants applying the AD wet process (Figure 25) are suitable for large biogenic waste streams accumulated in one area at commercial sources. This, for example, is the case where dairies, factory farms and the food industry do have their production units located.

Project reference box 4: Decentralized AD wet process application for wet markets & catering stalls

Such a system, known as Bio-Regen Food waste processing machines and working with microbes in a closed systems to produce liquid bio fertiliser, was taken up by the local council at George Town, capital of Penang/Malaysia to treat the organic waste from 'wet' markets in the frame of a pilot. The project proved successful and factories and schools now also use the machinery. The pilot has prompted a Request for Proposals by the Penang Island City Council to divert 100 tonnes of food waste per day at source. Moreover, the Batu Maung Waste Transfer Station on Penang Island now includes chipper machines to deal with green waste from gardens, parks and roadside trimmings as a suitable AD input material.

a) Bio-Regen Food waste processing machine supplied by Bio-regen Photonics

b) A market worker prepares food scraps to be fed into the food processing machine

c) Fermentation tanks get filled with processed food waste to which market grey water and the inoculant (bokashi) are added

Source: Report on The Pilot Project for the Separation and Treatment of Food Waste for Georgetown Heritage Area and Buffer Zone, Penang, Malaysia (CCAC 2017; ABPP 2019)

Not least **the expected benefits, e.g. in terms of energy self-supply, are a good incentive** for industrial waste producers to invest in such AD variants. The effect of these incentives is even greater if backed by a regulatory framework with appropriate waste disposal fees. This should give commercial entities a sufficient interest in setting up such type of facilities themselves. AD wet processes can make an important contribution to the reduction of waste and to the self-sufficient production of renewable energy, especially at commercial sites or in agricultural areas. However, the recommendations within this guide are more directed towards the establishment of the gradual introduction of separate waste collection and the treatment of SSO and mixed waste within the responsibility of municipalities (see chapter 7).

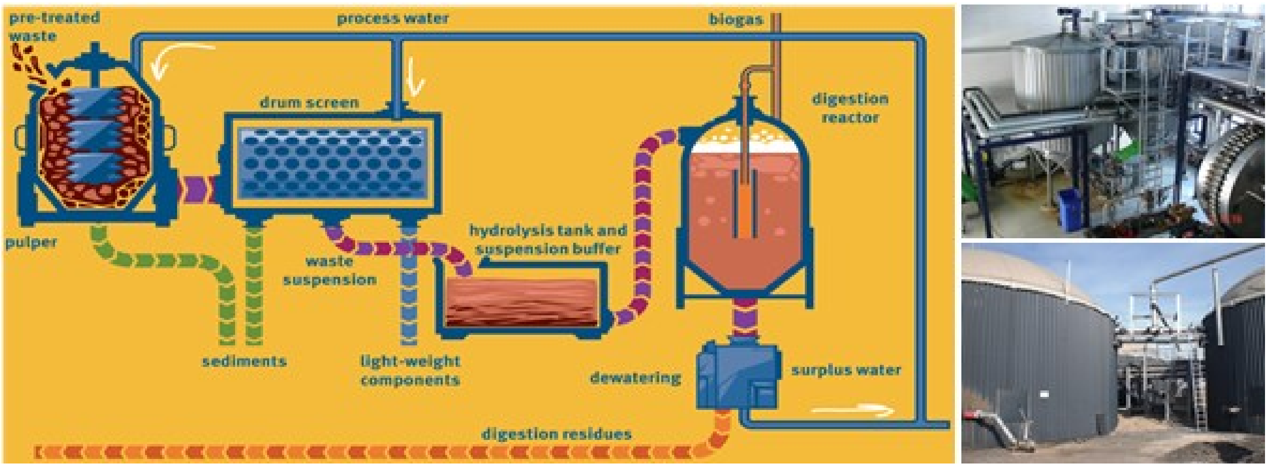

Figure 25: Process flow and main components (schematic and real-life) of an industrial-scale AD wet process installation (Picture sources: INTECUS with permission by former Linde KCA)

Following benchmark values* for the application of this treatment technology *(wet digestion process)* can be taken from literature as an orientation (Data source: BPMWM citing UBA Texte 43/2010):

- Space demand: 0.15-0.25 m²/t, i.e. 4,500-5,000 m² for 20,000 t/a; 6,000-8,000 m² for 40,000 t/a installed capacity
- CAPEX for an installed capacity of 20,000 t/a: 250 – 500 EUR/t yearly capacity
- OPEX for an installed capacity of 20,000 t/a: 20–50 EUR/t processed (plus share of CAPEX per year)

**Pls. note that scaling effects apply and that other factors, such as local component purchase and labour costs, can change the figures*

5.2.5 Dry fermentation

The dry fermentation process has proven itself for commercial as well as municipal waste treatment in as a supplement or alternative to the AD wet process primarily due to following characteristics:

- good applicability to a wider range of waste materials, including both purely biogenic materials and pre-separated organic rich fractions from mixed waste;
- comparatively low requirements for prior input preparation and post-treatment of the process output (digestate and waste water);
- overall significantly lower dependencies on additional water supply and waste water disposal
- rather low process management and control requirements with simultaneously higher tolerance and control options with regard to the process input;
- less prone to wear and malfunctions, thus less complicated and low-risk operation management.

Dry fermentation processes can be operated in both the mesophilic (38-40°C) and thermophilic (50-55°C) temperature range. The advantages of working in a thermophilic temperature range derive for the most part from microorganisms characterised by a higher metabolism. This can increase the biogas yield by up to 20% and allows for a shorter retention time of the waste in the fermenter, thus leading to a higher throughput. Moreover, thermophilic treatment achieves that the waste input is better sanitized so that subsequent processing steps applied on the digestate to obtain a fully stabilized material or compost can be simpler in design and less costly.

Dry box fermentation in batch operations design constitute a single-step fermentation process whereby single-step means that the various degradation reactions (hydrolysis, acidification and methanisation) occur in one process step.

The installation design and management of batch operations are relatively simple with a modular expandable series of garage-shaped fermenters providing the principal technical component (Figure 26). This design feature results in a recurring regime of separate material feeding, temporary static retention and discharge of the input and thus to discontinuous treatment at each individual fermenter unit. The staggered implementation in several units at plant-scale leads to a constant flow of operation, however.

The process input is fed for treatment into these fermenters where also the inoculation takes place by mixing the new input with material that already has been fermented. A mechanical pre-treatment might be necessary for bulky material or waste bags in order to ensure the degradation process by increasing the surface area of the material and tearing open and removing bags. Wheel loaders or belt conveyors are used for feeding the input material into the fermenter/pre-treatment.

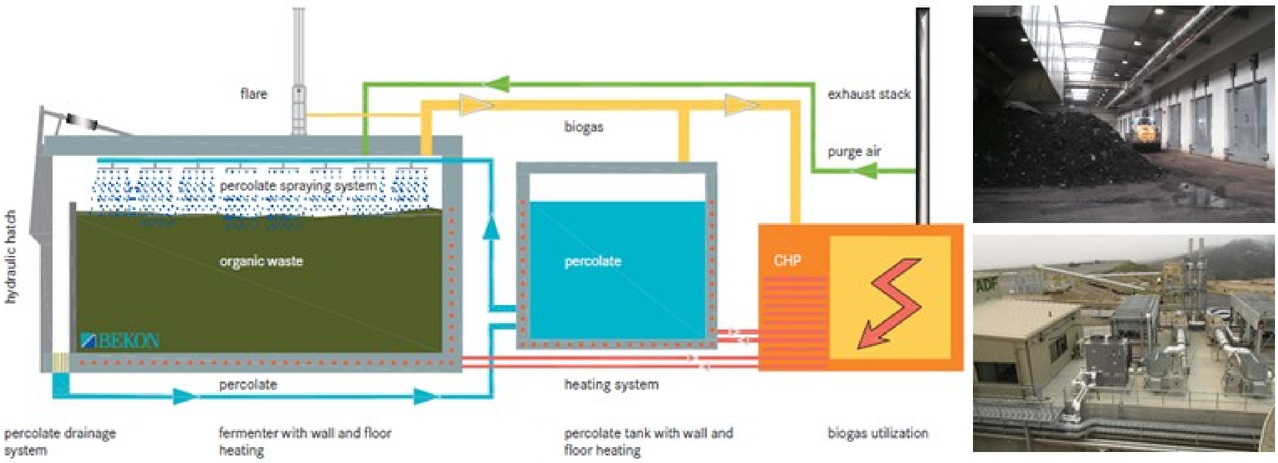

Figure 26: Process flow and main components (schematic & real-life) of a batch design industrial-scale dry fermentation installation, featuring BEKON technology (Eggersmann-BEKON / INTECUS with permission by Eggersmann)

Once the garage type fermenter is closed off by a hydraulic hatch, the biological waste begins to digest immediately, resulting in the production of biogas. Excess liquid that accumulates during the fermentation process as percolate is caught via a drainage and returned to the fermenting material in a cycle to keep it moist. Wall and floor heating allow to adjust temperatures to an optimum level for microbiological activity and biogas production (Figure 26).

The duration to retain the material in a fermenter is basically determined by the intensity in which biogas flows from the input can still be observed. **Retention times up to 35 days** are noted in batch design operations.

A continuous biogas yield is ensured by filling and operating a series of fermenters at staggered time intervals with always a number being simultaneously in the phase of biogas production. Gas tanks work in addition as a buffer storage so that stable flows of biogas can be maintained to whatever subsequent processes or power units. The process of operating the fermenter boxes staggered in time, also makes it easier to temporarily takeout individual fermenter units whilst the overall treatment continuous running.

This in turn allows for necessary revisions, adjustments or repairs without jeopardizing or even stopping the treatment and disposal job as a whole.

Adopting the batch design thus leads in principle to advantages in terms of robustness and flexibility in operating dry fermentation facilities. Among others, there is greater flexibility with regard to the fermenter box design, which makes it easier to adapt to the available space and properties of the input material or also with regard to other machinery and equipment. The market offers here even pre-fabricated modules that can be directly shipped to the site and quickly coupled together to form fully operational installations[17].

Equipment wear, replacements and repair requirements stay likewise at comparatively low level, considering that hardly any equipment must be installed that exerts a mechanical effect on the waste and is permanently in contact with it. This aspect also contributes significantly to the fact that the technology of dry fermentation in batch design in principle can also be applied to a mixed waste stream and that, in addition, only very few or no steps at all are necessary to prepare the waste upfront of such treatment process.

Following benchmark values for the application of this treatment technology (dry fermentation batch process) can be taken from literature as an orientation (Data source: BPMWM citing* UBA Texte 43/2010 (INTECUS 2018)*):*

- *Space demand: 0.125-0.2 m²/t; i.e. 2,500-3,000 m² for 20,000 t/a; 5,000m² for 40,000 t/a installed capacity*
- *CAPEX for an installed capacity of 20,000 t/a: 150 – 310 EUR/t yearly capacity*
- *OPEX for an installed capacity of 20,000 t/a: 15 – 30 EUR/t processed (plus share of CAPEX per year)*

**Pls. note that scaling effects apply and that other factors, such as local component purchase and labour costs, can change the figures*

Dry fermentation in batch design appears an option across different urban structure settings in Africa since handling the waste input and digestate goes for the most part with robust wheel loaders and enables using a more inhomogeneous waste input, including mixed material streams.

The construction of the basic installations (boxes) can largely be done **with locally available materials** (concrete/steel), the modular structure also allows to avail of ready-made fermentation containers and/or to directly import such. Moreover, all this is providing for a great flexibility with regard to the capacity of the installations and requirements in space and on emission protection in the light of the available land and the surroundings at the respective site of location. The technical potential to achieve self-sufficiency in the necessary electrical energy and heat also increases independence from external supply infrastructures and thus the range of possible locations.

Dry fermentation plug-flow design consists of treatment units whose design ensures that the material moves dynamically through the fermenter. This allows a permanent material input and output and thus leads to an uninterrupted, continuously running treatment in each individual unit. The mixing and steady flow of the process input through the horizontal vessel is achieved with several transversal agitators. This

[17] For example, the German supplier Eggersmann, as well as other suppliers, builds plants in batch construction from a processing capacity of approx. 5,000 t/a and usually with 3-4 coupled garage fermenters as a minimum.

arrangement prevents scum layers and sediments to form and guarantees an optimum microbiological decomposition and release of gas bubbles. The input material is conveyed into the treatment unit by a compact feeding unit (Figure 27).

Each agitator drive only operates intermittently, which results in reasonable energy consumption. However, due to the use of these moving parts that are constantly exposed to waste, the risks of component wear and hence the **requirements for the input quality are comparatively higher**. Generally, the input must be freed from mechanically disturbing items and more fluid in its consistency. An adjustment of the water content must therefore be undertaken, if necessary. The fermentation residue is eventually discharged by means of vacuum discharge from the system. Overall, retention times of the material in the treatment unit of about **20 days** are noted in plug-flow operations (FNR, Fachagentur Nachwachsende Rohstoffe e.V. 2004).

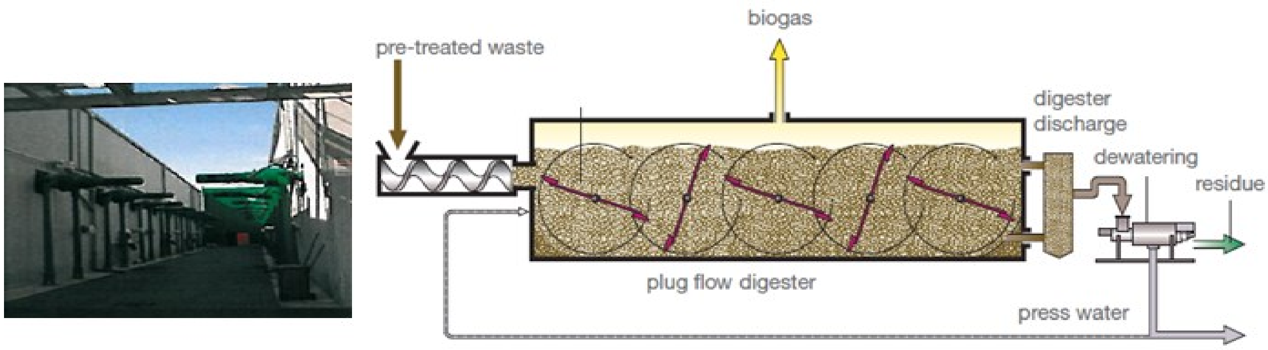

Figure 27: Process flow and main components (schematic & real-life) of a pug-flow industrial-scale dry fermentation installation, featuring STRABAG LARAN® technology (INTECUS with permission by STRABAG Umwelttechnik GmbH)

Following benchmark values for the application of this treatment technology (dry fermentation plug-flow design) can be taken from literature as an orientation (Data source: BPMWM citing UBA Texte 43/2010 (INTECUS 2018)):*

- *Space demand: 0.13-0.275 m^2/t; i.e. 4,000-5,500 m^2 for 20,000 t/a; 5,000-6,000 m^2 for 40,000 t/a installed capacity*
- *CAPEX for an installed capacity of 20,000 t/a: 250 – 480 EUR/t yearly capacity*
- *OPEX for an installed capacity of 20,000 t/a: 18 – 38 EUR/t processed (plus share of CAPEX per year)*

**Pls. note that scaling effects apply and that other factors, such as local component purchase and labour costs, can change the figures*

5.3 Mechanical biological treatment

A mechanical biological treatment is designed to process **mixed waste streams** with higher organic loads collected from households as well as commercial and industrial sources. It combines in one facility the mechanical processing of waste with biological steps such as anaerobic digestion and/or composting applied on the biogenic waste components. "MBT" is originally meant as the **general alternative to incineration.**

MBT represents neither a single technology nor a standardized technical solution, since it combines a wide range of techniques and processing operations (mechanical and biological) that are purposefully coupled so as to ensure that the specific needs and requirements on the treatment products in the respective legal environments and markets will be met.

The principal objectives for employing MBT might therefore vary and even change over time, although the basic concepts aim at:

- reducing the overall volume and mass,
- reducing the biochemical reactivity of the biogenic components in the waste going to landfills,

combined with certain circular economy objectives in regards to

- material recycling and/or
- the recovery of energy from waste.

Essential technical components

Due to the high variability with regard to possible process combinations, their coupling and respective treatment objectives, hardly a generalisation or summarized overview for standard equipment of MBT plants can be given. At least for the part of mechanical processing, however, following hardware spectrum that is largely transferable to all installations of the more advanced type is characteristic:

Table 24: Essential technical components in MBT installations

MBT components - mechanical part	Functions
Wheel loader/General purpose gripper	material feeding, handling and pre-sorting
Belt conveyor (horizontal/ascending)	material feeding and transport
Comminutor/Shredder(s)	bag opener, particle size reduction
Screen(s)	size classification, material flow splitting (by size, also taking advantage of the fact that biogenic waste components accumulate in the fine fraction
Separator(s) -*most commonly included*	- magnetic: separation of ferrous metal components - eddy current: separation of non-ferrous metal components - ballistic/air flow: separation of heavy and light-weight items
Separator(s) -*optionally included*	- screen: size classification, separation of flat and voluminous items - ballistic/air flow: separation of heavy and light-weight items - optical: separation by other material characteristics - swim/sink: separation by densities (floatable, absorbent)
Sorting belt/cabin - *optionally included*	to conduct manual material separation or sorting

5.3.1 Main technical variants

The further description concerns two main concepts of the basic alternatives to incineration:

MBS – Mechanical-biological stabilization: is basically geared to reduce the moisture content of the waste by quick aerated rotting (biological step). This increases the calorific-value of the process input material and a large share of it can be converted into a marketable fuel, after a mechanical cleaning (removal of unwanted items) and conditioning. The system thus uses the biological reactivity to dry the waste and then extracts a larger share of combustible materials, intended for industrial use. Thereby the final elimination of biogenic reactivity takes place *outside the facility*, in the following combustion. Plastics and paper in the waste aren't recovered for material recycling, they are part of the refused-derived fuel (RDF).

MBT – Splitting concept: undertakes the diversion of non-biodegradable and biodegradable components through mechanical splitting/sorting of the waste input into materials for recycling and/or energy recovery and fractions that can be landfilled right away or past a further treatment. The biological treatment is hereby applied on the fraction of biodegradable components with the aim to achieve a stabilisation into a compost-like output (CLO) for certain usage on land and, optionally, to also generate biogas for energy recovery.

The splitting concept MBT is technically derived from just those waste treatment installations that where installed in Europe decades ago for composting mixed waste with the aim to produce compost and thereby save landfill capacities. The project in Ghana (see Project Reference Box 5) follows similar intentions. Following hereafter, the term "MBT" is generically used when referring to the "MBT-splitting-concept".

The **main process features** of **MBT** are as follows:

1) UPFRONT-preparation: The mixed waste input is – mainly by screening – separated in
   - an *undersize fraction*, making up 50-70 % of the input and holding most of the biogenic components,
   - an *oversize fraction*, holding most of the bigger, recoverable recyclables, which can be picked from a sorting belt by hand. Either the sorting residues or the oversize fraction in total can be used for combustion and energy recovery, due to a higher heating value.

2) The *undersize fraction* is biologically (aerobic and/or anaerobic) treated until its biological activity has nearly completely faded. In the best case, this CLO output can be used for non-agricultural purposes e.g. landfill covering, regularly it is the material left for landfill disposal, there showing almost no more gas and leachate emissions.

Integrating an anaerobic digestion process in the MBT does have two funtions, elimination of pathogens and recovey of energy from the biogenic waste components are achieved at the same time. This, however, goes hand in hand with a much higher complexity and more technical challenges in the respective plant designs and operations.

Subject to its quality, the usage of CLO in the restoration, reclamation or improvement of barren and previously developed land (e.g. brownfields, abandoned tailings) can be possible. Not generally advisable is the usage of CLO produced from mixed MSW on agricultural land due to concerns on harmful content such as varying heavy metal concentrations, microplastics or other water and soil polluting substances (e.g. PFC, POPs; see also the corresponding notes in chapter 3.2). Where output quality is insufficient or no any other permitted outlets are available, the CLO may have to be disposed to landfills.

Project Reference Box 5: - MBT applications in Africa

An MBT project (KCARP) has been launched in the city of Kumasi, Ghana in 2018 where the classical splitting approach (separation of recyclables and classification by size) of the input of mixed waste has been combined with a composting of the separated fraction of fines (<80mm). Whilst technically the plant absolutely meets the standards of European countries, it needs to be highlighted that it unlikely achieves to deliver a compost output with consistently sound parameters for impurities and soil safety and would thus fail to receive the European label of certified compost quality. It is already enough as critical or exclusion criterion that mixed waste gives the plant input from which the feedstock for the composting process is derived. It must therefore be stressed once again that for the production of safe and permanently marketable composts only source-separated biogenic waste can be considered and should be used.
The KCARP in Kumasi features a technically advanced and optimized design of another MBT facility (ACARP) in Adjen Kotoku, Ghana which, however, had to undergo several retrofits already. Both facilities started with a daily input capacity of 600 tons, for the ACARP facility is foreseen the upgrading to 800 t/d (ACARP 2022) whereas the KCARP is said to manage 1,200 t/d already today (KCARP 2022). The number of workforce employed for operating the two plants is in the range of 350 to 400 per each facility inclusive transportation services.

Source: Recycling magazine - International Edition, Winter 2022 p.22-23

The typical mechanical biological stabilization - MBS differs from the MBT concept in that:

- The upfront preparation is reduced to pure coarse grinding with optional a ferrous metal extraction, the shredded and still mixed waste is given to aerobic operated boxes or bays,
- Composting alike biological processes raise the temperature in the material to a level that water is evaporated. As soon as the moisture content goes below 20% the biological process stops.

Two principal options apply now for the still mixed but dried process output:

I. **Untreated use**: Taking it as it is to a waste incineration plant for combustion, so as to feed it to the furnace instead of raw waste with a too low heating value to burn without additional energy support (gas, oil, coal). If so, the MBS can be understood just as a conditioning facility for the incineration.

II. **Rear-end preparation**: The dry mixed output is mostly shredded again and separated by screens in various fractions (3-4). These individual fractions are further separated by either ballistic separators or wind shifter in a light fraction (paper, plastics, textiles and dry organics) and an inert, heavy fraction (glass, stones, ceramics, sand). Metals are separated as well. This complex rear-end preparation (RDF conditioning) is often needed to meet cement kilns or power plants' fuel needs (Table 25). In the best case, only the inert materials remain to be landfilled. (INTECUS 2021)

The **reactivity of the biogenic components is not substantially reduced** within the MBS process. These biogenic components are finally combusted, by whichever finally chosen combustion system. The availability of combustion capacities is hence a mandatory pre-requisite for adopting such an approach.

Commonalities of all technical variants

The meaning of “stabilization” is different in the two concepts. At MBT the output to landfill is ‘stable’, since the reactive organic share is completely biologically “burned”. At MBS “stabilization” means that the reactivity of the biogenic material hasn’t yet gone but is blocked by the drying process, until the output is eventually combusted.

In their own way, both technical variants make important contributions to relieving the pressure on landfill capacities and reducing GHG emissions there, and this in spite of partly very different process configurations and output streams.

5.3.2 Input material and general mass balance

Mechanical-biological treatment can diminish the need for segregating different waste materials at source and for collecting recyclables separately. Therefore, it is mostly adopted from municipalities facing huge difficulties in implementing source separation or financial hurdles of separate collection are too high. These systems are typically interlinked with curb side collection of mixed waste and give local decision-makers the chance to reduce the logistic challenges and costs.

The relief for landfills resulting from MBS or MBT is roughly on par for both technical variants. While in the MBT splitting concept the biogenic waste components are subject of targeted biological degradation processes with the aim to achieve the best technically possible volume reduction and complete elimination of their gas-forming potential in the landfill body. In MBS these biogenic waste components are largely converted into an industrially usable fuel and thus diverted from the landfill.

In terms of each specific climate balance however, the MBS process has an advantage compared to MBT due to its substitution potential for fossil fuels. This can be at least partially compensated for the MBT splitting concept by including AD as a biological treatment stage and using the biogas it generates.

The following mass balances relate to the treatment of waste in central Europe with a higher share of materials with higher heating value (paper, plastic, textiles,) than mostly seen in Africa. In African countries these shares are mostly below 20% and the dominant fraction are biogenic compounds with a high water content, that will be evaporated in both variants. This influences the mass balance in terms of higher proportions of evaporated water and lower extraction rates for recyclables respectively RDF (Figure 28).

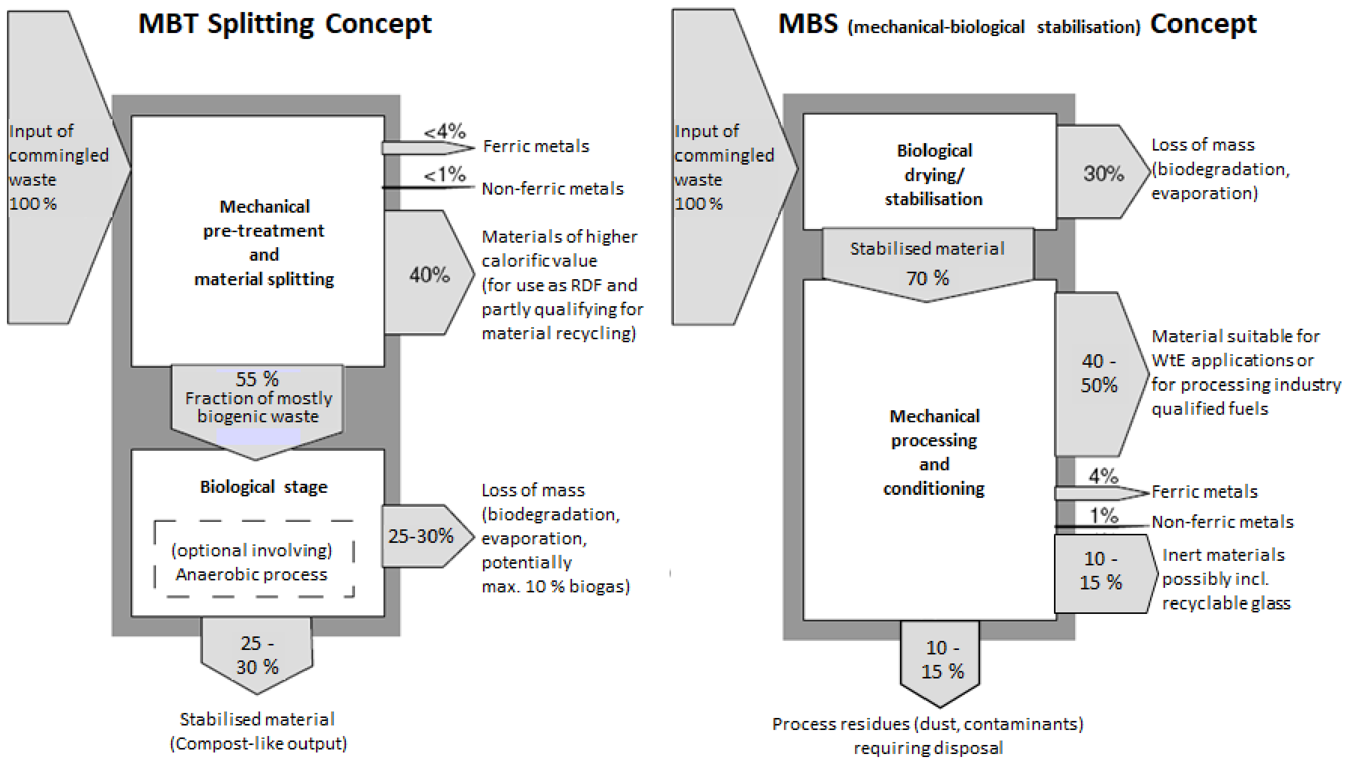

Figure 28: Mass balance and differences of the principal MBT concepts

5.3.3 Technical variants primarily considered for local application

Splitting concept MBT and MBS are both suitable for Eastern Africa. With each of these two variants readily combustible fractions of varying quality and quantity can be extracted (for the most part) from municipal and commercial unseparated waste. Options for using these fractions as alternative fuels can already be assumed in the existing industrial structures. A particularly well conceivable option for the target region appears to exist with the application of *simplified MBS schemes* for the purpose of converting MSW into an industrial fuel or material with better combustible properties as without treatment.

In addition, the MBT splitting concept offers various possibilities for recovering waste components for material recycling. Especially in metropolitan centres, changing consumption patterns lead to over-proportionally growing shares of recyclable and valuable discards (e.g. packaging) vis á vis biogenic waste components, which increases not only the need but also the economic feasibility for their recovery. In addition, landfill space is scarce, especially in urban areas, and all reserves must be exploited to free further capacities here.

5.3.4 Membrane-covered mechanical biological stabilization

The MBS concept's primary aim is to reduce the amount of waste that must ultimately go to landfills and at the same time to produce a material with a good suitability to recover energy in industrial processes.

Aside from rather sophisticated installations technically more simple methods can be employed to realize MBS in few steps as well, **resulting in low-complex and relatively low-cost waste treatment.**

One such variant to which this applies is the implementation of MBS by means of the treatment in membrane-covered bays or windrows (as described for composting), but here applied on the mixed waste or entire MSW stream. This variant, offered for example under the international market labels Convaero Bio Dry™ or GORE® Cover **process takes not more than 4-8 weeks** in the maximum, and comprises of three phases. (CONVAERO GmbH 2016)

Project Reference Box 5: Membrane-covered applications of MBS and for composting

The simple membrane-covered variant for the dry stabilization of mixed waste and for the composting of source separated biogenic waste has been already applied in the form of pilot demonstrations and with small and larger-scale installations in many regions, including countries in the Middle East Syria (e.g. Northern Iraq, Syria, Saudi-Arabia) and Northern Africa (e.g. Tunisia). The firms interviewed for the WasteGui-project reported successful operations of installations with membrane cover for example from Suleymaniyah /Northern Iraq, Tanger/Morocco, the Nile Delta/Egypt and Cilacap/Indonesia (all Eggersmann), Al-Salamiyah /Central Syria (INTECUS) and Tabarka/Tunisia (UTVAG).

a) 
b) 
c) 

Membrane-covered MBS in a) pilot-scale in Central Syria, b) a medium-scale facility in Central Java and c) large-scale plant in Northern Iraq

Source: WasteGui-integrated survey among technology planers and supplier firms (Photos: left: INTECUS, middle, right. courtesy of Eggersmann (Eggersmann Group 2020; Al Saedi et al. 2021)

The mechanical processing takes out large disturbing non-crushable items followed by a pre-shredding of the process input material and optional screening of the treated output. The central component is the cover laminate which is used to fully encapsulate the input material piled up in windrows or bays. Here the biological process of composting sets in and leads to the quick drying of the encapsulated material thanks to the specific properties of the laminate cover, which still allow to ventilate the material with air. Since it is not compost but a dry stabilized waste that gets produced here, the process in principle can be terminated after the phase of intensive rotting.

The **stabilized output with enriched calorific value** delivers a dry material mixture from which a fraction with fuel properties (RDF) can be diverted with reasonable effort. Employing metal separators and a screen for the takeout of fines might suffice for that. Depending on individual industry's specifications (see Table 25), a further processing of the fuel material may however be required.

Table 25: Orientation values for processed MSW in the light of general fuel suitability for industrial processes (based on various sources, incl. MUNLV-NRW 2005 and EN 15359: 2011)

PARAMETER	Dry stabilized MSW	High-calorific MSW fraction	General fuel fraction (RDF)	Industry preferred range
Heating value [MJ/kg]	15	17	14.5	10 - 25
Water content [%]	30	9	30	15 - 30
Ash content [%]		14	9	< 25
Chlorine [%]	0.5	0.8	0.3	< 1.5
Sulphur [%]		0.1	0.1	< 3
Mercury [mg/kg]	0.3	0.28	0.1	< 0.3
Lead [mg/kg]	148	132	25	< 100
Grain size		1 - 50	1 - 50	10 - 30

This **alternative fuel,** which can be handed to local industrial plants and used by them in energy generating (incineration) processes means an added value. Without it, the eco-efficiency of MBT in a system solely reliant on landfill disposal is to be questioned. Local industries therefore must be early involved and consulted in the system design for waste treatment, among others to ask for the specifications of the fuels and other materials which they may take over from waste processors.

Ethiopia's capital Addis Ababa, for example, is charakterized by an industrial environment which offers great potentials for the use of RDFs due to the high presence of clinker and cement producing facilities. In the country operate about 18 such facilities with a total production of 11 mega tons overall. Three of those plants located close to the national capital together cover more than half the total installed capacity of cement production in Ethiopia[18]. The share of alternative fuels from waste used within the total thermal energy input in cement production in 2014 has been 16 % on average globally and 41 % in cement plants run in the EU. Some countries, like Austria and Germany, exceeded a level of 60 % with few individual plants covering even 100 % of their fuel needs this way. Marocco and Tunisia both came to 6% in their cement industry whilst Egypt showed to have reached 9 % already (GCCA, 2016). The vision to gradually

[18] The Dangote cement plant, producing 2.5 mega tons of cement per year is less than 90km away from Addis Ababa (Dangote cement plc 2022). Just 65 km outside of Addis Ababa operates the Derba Midroc cement plant with another 2.5 Mt of cement annual capacity (Derba Midroc Cement 2022). Habesha operates a 1.4Mt per year cement plant 35 km north-west of Addis Ababa (Waltainfo 2017)

switch from fossil to waste fuels in the near future is also described in the environmental agenda of selected Ethiopian plants.

The capital region of Ethiopia moreover faces currently a situation in the waste management system where the benefits of the specified MBS concept become even more evident. Few years ago, the Reppie waste incinerator has been inaugurated in Addis Ababa as the first ever mass-burn waste incinerator on the African continent.

This plant[19] was expected to convert up to 70 % of the daily collected waste to energy. For this, the $120 million facility operates two MARTIN cooled reverse grate systems with a capacity of 2 x 700 t/d, representing an annual waste-disposal capacity of 420,000 t, designed for the combustion of waste in a calorific value range of 5.5 - 9.5 MJ/kg. Since entering into operation in April 2019, the facility is said to be using only about half of its initially installed capacity[20], whereby it can be assumed that the high biogenic content and moisture it adds to the input material is a likely part of the problem of operating the incinerator at near to full capacity. It stands to reason that by means of an upstream membrane-covered MBS process the waste input could be sufficiently quick conditioned to match better the requirements for combustion in the Reppie plant. With the nearly 35 hectares area of an old landfill there could even be enough space available for such a drying installation directly beside the plant.

5.3.5 Combustion of biomass

Using harvested agricultural and forest biomass as a renewable fuel source is a very common and well-known practice for electricity generation. Drying the material is often indispensable here to obtain a suitable calorific value exceeding 10 MJ/kg. Above described concepts for alternative fuel production from waste with biogenic components or its direct incineration with energy recovery stand somehow in one row with the approach to combust biomass for power generation.

The utilization and inertisation of biogenic carbon by thermal oxidation (oxidative combustion) or non-oxidative alternative processes (including pyrolysis, hydrothermal carbonization, gasification) is equivalent to a treatment of biogenic material or waste. Using biomass harvested as a fuel or burning it in the form of waste biomass for the dual purpose of treatment and energy generation is not tremendously different in the end.

Principal objectives

A biomass power technology or ‘thermal treatment’ of that sort can be employed to generate electricity on demand at any time, as long as a sufficient supply of suitable biomass stocks is assured. Agricultural and forest product residues, food processing waste (e.g. peel remnants, mill residues) and other waste biomass do qualify as feedstock for energy conversion without increasing the land requirements for natural biomass production.

The waste in this case works as a fuel and the biogenic carbon is hereby oxidized in a temperature spectrum above 600 °C therewith losing its reactivity and becoming an inert material (ash). Hot steam

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[19] engineered by Ramboll Group and today owned by Ethiopian Electric Power (EEP) (Cambridge Industries 2016)

[20] Press statement of the plant’s director in the Addis Standard, October 16, 2020, cited with *“Currently the plant it taking only 47 percent for different reasons”*.

of about 200 - 400 °C is produced in special boiler systems and superheaters, and can eventually expand in a turbine propelling an electricity generator.

Main technical variants

Which kind of facilities and technical configurations are to be employed for the incineration depends largely on the quality of available waste biomass and what principal purposes the process shall serve.

Basically, a distinction must be made between two technical variants or plant types for the incineration of waste biomass, these are:

- *mass-burn combustion or general waste incineration, and*
- *mono-incinerators.*

Mass-burn combustion or general waste incineration

Mass-burn combustion or general waste incineration are basically applied to dispose different mixtures of waste, thus including the biogenic components, as an alternative to landfilling. Thermal oxidation and high temperatures above 900 °C ensure an almost complete inertisation of the waste input. This leads to an enormously higher mass and volume reduction and a generally safer manageable output than dumping untreated waste on a landfill. Recovering energy from this process is not the primary goal but is a common additional benefit and almost taken for granted today for both ecological and economic reasons.

Mass-burn waste incinerators have to comply with very strict requirements for cleaning the flue gases in order to avoid emissions of various harmful substances or keep them within specified limits. To this end, different kinds of filter units and other technical installations (e.g. flue gas scrubbers) are to be integrated in these incineration plants, thereby contributing to considerable **high capital and operation expenses** for this technology. These plants are furthermore designed in such a way that mainly **relatively low-calorific waste mixtures** (usual range of 5 - 9 MJ/kg heating value) can be incinerated, which means however, that back-up firing systems with fossil fuels often have to be employed as well. This diminishes further the energy efficiency of these systems, which is not very high anyway. The preparation of waste for mass-incineration is usually limited to a certain degree of mixing to achieve a uniform calorific value; furthermore, oversized and thus process-disturbing components must be removed or pre-shredded.

Mono-incinerators

in contrary, are tailor-made systems to burn **very specific fuel materials** for heat and power generation with high energy efficiency. Biomass power plants are one type of this special installations. Their material feeding and firing systems are extremely adapted to the kind of fuel material used (Figure 29). In case of waste biomass, these are mono-fractions either out of source-separated materials (e.g. chopped straw or wood waste) or specially generated mixtures of biomass waste (e.g. biomass pellets or briquettes).

Due to the very defined material compositions and combustion properties, the technical requirements and installations for flue gas cleaning and emission control are often significantly lower. The accepted intake of waste biomass is primarily considered a fuel product for power production and co-generation (CHP) and not as a material requiring safe disposal.

Preparing the biomass for mono-incineration involves all necessary steps for material conditioning or processing until it is becoming a fuel product with defined properties (e.g. size, heating value, moisture, ash content, content of critical substances). To generate upfront of the incineration a RDF or combustible dry stabilate from biogenic waste components, for example by dry stabilization MBS, can also be counted hereunder.

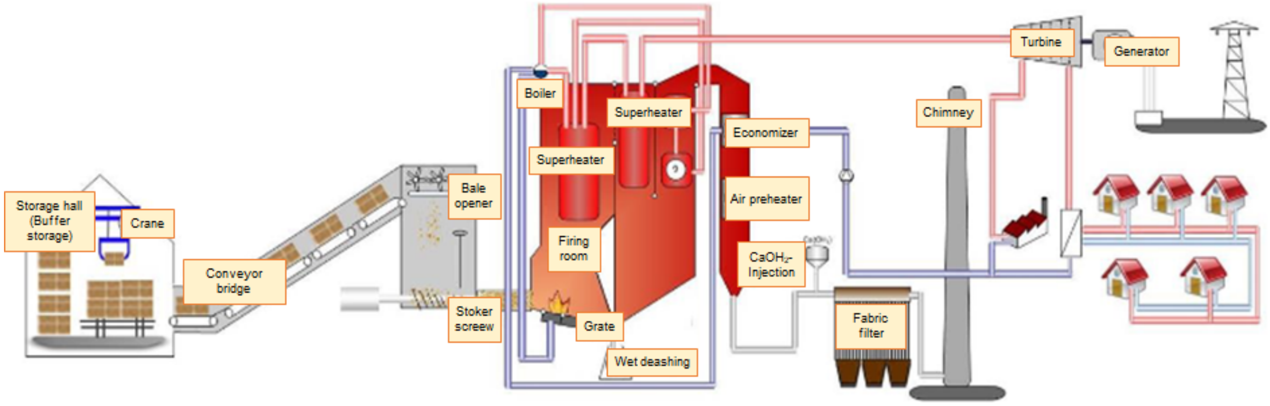


Figure 29: Main components of a straw-fired biomass mono-incineration plant, featuring the BEKW power plant design (INTECUS with permission by Bioenergiekraftwerk Emsland GmbH & Co. KG))

Project reference box 6: Projects for biomass power plants in Africa

Ex#1: Côte d'Ivoire; A 46 MW biomass power plant is to be built in the Aboisso Department in south-eastern Côte d'Ivoire with an investment of EUR 156 million. It will be fuelled by some 450,000 tons of palm waste with about 30 % of this biomass coming from Palmci's palm oil plantations, with the remaining 70 % being collected from small-scale growers in the region. Over a period of 25 years, the company Biovéa Énergie will be responsible for designing, building, operating and transferring the plant which is scheduled to open in September 2024 (Agence Française de Développement (AFD) Group).

Ex#2: South Africa - KwaZulu-Natal; The Mkuze Biomass Power Plant is a 17.5MW biopower project and is expected to enter into commercial operation in 2024. The project consists of one unit of a full condensing turbine and is expected to generate 132,000MWh electricity and supply enough clean energy to power 40,000 households. Project cost of around $100 million are expected. Agricultural by-products and wood by-products will be used as a feedstock to power the project. (GlobalData's Power Intelligence Center).

Ex#3: South Africa; Two earlier attempts to develop South Africa's biomass energy potential - the Howick 5MW biomass electricity plant, and the Tstsikamma biomass electricity plant of 6MW (meant to supply a sawmill and neighbouring communities with steam and electricity) did apparently fail. Allegedly, this was mostly due to local market conditions and not as a result of insuperable technological difficulties, however (iied briefing 2013).

Sources: see indicated inside the text for each project

Limitations affecting a wider application of biomass combustion in Africa

A mass-burn waste incineration is already realized within the Reppie plant in Ethiopia, but the project has yet to pass the test of sustained continuous operations and sufficient capacity utilization as well as coping with the delivered waste composition. Such evidence provides an essential basis for replicating this technology approach elsewhere in the country and in other East African countries. Testing this facility should also clarify if the introduction of a pre-treatment concept might be beneficial.

Moreover, an economic perspective for this treatment option only opens up in the case of permanently high and concentrated waste volumes. In Africa, urban agglomerations and large cities with population concentrations between 300,000 and 500,000 inhabitants are such likely locations, which in turn means for Ethiopia that hardly any other sites or projects are likely to come into view for this.

A **higher application potential** may be assumed for Africa as far as the **mono-incineration** in biomass-to-power projects are concerned, in particular where direct connections can be established with industries and commercial units that produce suitable amounts of waste biomass and at the same time may act as users of the generated power. That Ethiopia has to deal with significant quantities of certain biomass, biogenic wastes and residues, like miscanthus reed, coffee bean husks and straw, all materials which have a proven suitability as fuels in biomass-to-power mono-incineration plants already, appears to add a supportive fact here.

However, **other frameworks must also be considered**, and there are numerous that do not support to see biomass-to-power mono-incineration projects as a preferred solution for biomass waste management in East Africa. One subject to consider is that the per capita consumption of electricity in sub-Saharan Africa is still rather low. A decade ago, it averaged barely at more than 450 KWh annually, with the average falling below 130 KWh when South Africa was excluded from the statistic (World Bank 2014).

- **The lack of access to electricity** is the greatest in the marginalized urban districts and rural areas, where also an estimated 80 % of the households are yet dependent on forest biomass and mainly agricultural waste as their primary source of energy (Damm and Triebel 2008). Moreover, remote areas in Africa still pose a challenge for conventional grid connection in general. Biomass-to-power through incineration is not quite a flexible technical solution (rarely modular but stationary installation) and can thus hardly help overcoming these problems in rural regions although most of the potential fuel sources would probably be found there.

More difficulties arise from following issues:

- **Land and supply conflicts:** If biomass is burned that does not consist of waste or unwanted residues, the production area competes with the land demand for food and fodder production. Certain groups of the population may perhaps also be deprived of existential supply goods, such as residues or wood needed for firing, directly. Especially in low-income countries, biomass production for energy generation can become a price driver for food and a potential source of social conflict.
- **Requirement to run at full load:** Biomass-fired power plants cannot be operated economically if their capacities can only be utilized partially. They must run at full load. However, even in well-

designed biomass power plants, about two-thirds of the primary energy is lost as excess heat if no heat extraction is established. A pure biomass power plant that only generates electricity is therefore not very efficient, so that only the combined use of heat and electricity makes such plant economically viable. Operating it at full load comes with the need that electricity and heat must find continuous consumers. However, in Africa there is a rather low demand for heat supply over the entire year. Therefore, biomass power plants can only work economically where excess heat is constantly used, e.g. by industrial consumers.

- **High space demand:** A rather big land area is needed to store those amounts of biomass required to ensure continuous incineration. Thus, biomass-fired power plants are not quite suitable in metropolitan areas with high land pressure, but rather in rural areas. Here, however, higher heat losses do occur due to the transportation over longer pipelines, so that the plants fail to achieve the efficiencies that are theoretically possible. Also, for plants in which biomass is converted to biogas before combustion, longer distances to more densely populated areas are advisable, since there may be stronger odour emissions. The longer distance for heat transport also leads to lower efficiencies here. This type of biomass-to-power installations, on the other hand, has a predominantly internal heat utilization and more possibilities for modular size adjustment and for reduced or even temporarily suspended operation (e.g. dry-fermentation batch design).

5.4 Technology assessment for Eastern Africa

The previous chapters gave an overview of different treatment options for organic waste and their technological variants including technical descriptions. Project reference boxes and explanations on boundary conditions for individual feasibility and effectiveness provided first indications regarding regional suitability.

It should be emphasised that a **differentiated assessment and more intensive screening** needs to be carried out to properly rate local suitability and make final decisions on the actual adoption of certain treatment options. The last described example of biomass-to-power through incineration and various limiting aspects mentioned there may just serve as an example for this. These considerations shall be supplemented and deepened hereafter by referring to steps and methodical concepts that can help to perform such thorough review and enable reasoned decisions for introducing a specific technological concept.

5.4.1 Methodical basis and approach

One possible method to support the decision-making on locally appropriate treatment concepts is **SWOT** analysis. This strategic planning tool is used to evaluate the **S**trengths, **W**eaknesses, **O**pportunities, and the **T**hreats involved in a project or business venture. It involves specifying the objective of the business venture or project and identifying the internal and external factors that are favourable and unfavourable to achieving that objective. These factors are hardly ever static but constantly changing, and directly or indirectly impact on implementation success (

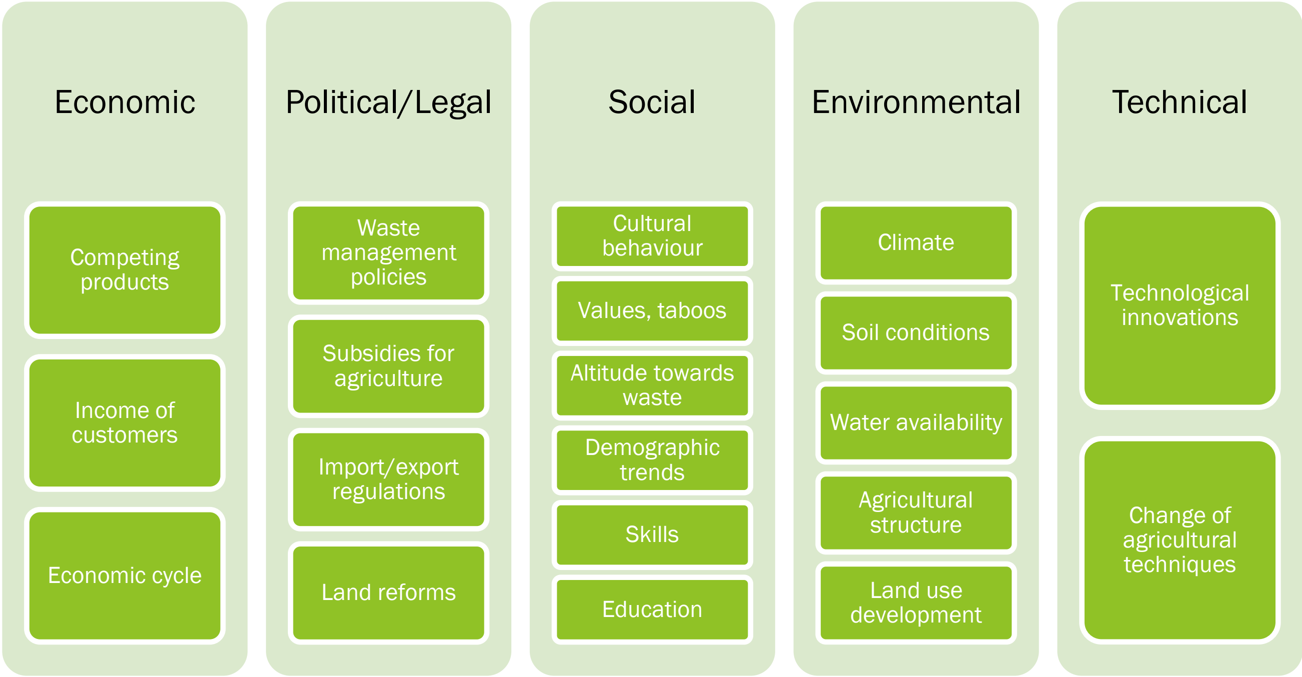


Figure 30). Treating biogenic waste by means of a specific technology constitutes a project or entrepreneurial venture of significant importance for many places in Africa.

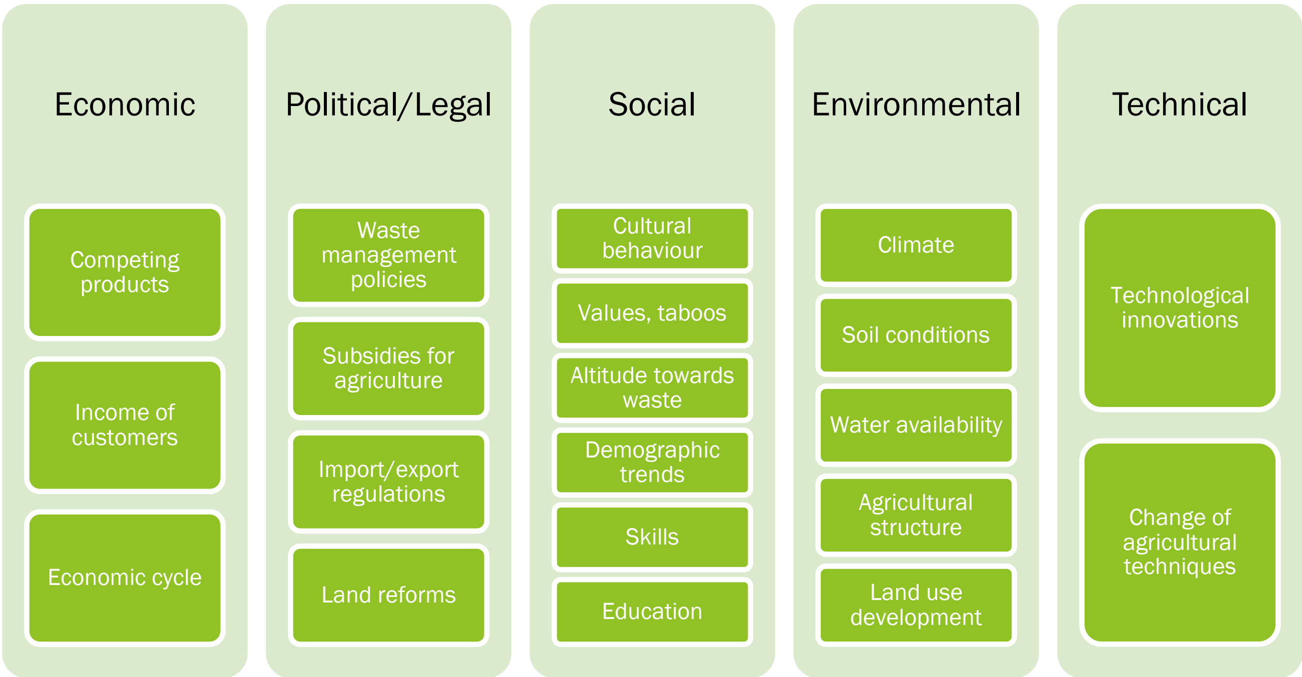


Figure 30: Exemplary overview of factors influencing a business environment (DBFZ adapted from Decentralised Composting for Cities of Low- and Middle-Income Countries. Manual published by Waste Concern and Eawag, 2006)

The following exemplary assessment is based on the premise; **'reducing amount and reactivity of biogenic waste requiring disposal and deriving as much as possible additional benefit** (through material loops and energy recovery)'. The SWOT analysis is looking at possible applications of the different technical variants independently from (or across) different territorial and urban structures in the target region East Africa.

The evaluation of the SWOT analysis delivers by no means a final or binding assessment but rather a single evaluation example, drawn up from the longstanding insights the authors gained during the introduction of waste treatment concepts and technical solutions in their home country (Germany) and abroad, and considering additional opinions from consulted experts and technology representatives[21].

A SWOT evaluation can constitute an important element in the decision-making process on the investment(s) to be made and, possibly, for (pre-)selecting the most prospective technology option(s). There is, however, no fixed list of criteria and weightings to be adopted for this evaluation, especially since technical experts, investors, banks, politicians and the public, i.e. the various stakeholders of such a project, each take and represent a different perspective on it (e.g. "not everything that is technically possible is also financially feasible, not everything that is financially feasible is also socially acceptable", etc.).

Aspects that can be assigned well to the individual SWOT categories were selected (Table 26) and given a score in the range from 0 to 5. In the categories 'Strengths' and 'Opportunities', the highest value of 5 represents the most positive and the value of 0 the least positive disposition/impact. Conversely, the highest value of 5 in the categories 'Weaknesses' and 'Threats' represents the worst and the value of 0 the least negative disposition/impact.

[21] see the acknowledgement in this document

Table 26: Criteria used for the assessment of treatment technologies based on SWOT analysis

Strengths	Opportunities
• Environmental relief compared to untreated disposal • Scalability (modular design and expandability options) • Readily existing demand/usage potential for process outputs (market orientation) • General availability of sinks and offtakers for treated outputs incl. residues	• Job creation potential • Wider demand and marketability potential for process outputs • Immediate usability of locally existing knowledge and/or experiences • Possibilities to work with direct local refinancing/refinance mechanisms
Weaknesses	**Threats**
• Intensity of area occupancy • Overall cost intensity • External dependency for technical equipment/components • Potential limitations to acquire suitable input volumes • Potential limitations to acquire input of suitable quality • Potential acceptance problems or persuasion requirements with public • Further disposal and caretaking requirements for process outputs incl. residues • Requirements for qualified personnel and/or qualification of staff	• Complexity of technology and operational management • Dependence on critical infrastructure (grid/permanent water supply) • Difficulties and/or effort to ensure sufficient input volumes • Limitations to adjust to changing input flows (adaptive capacity) • Immediate negative consequences in case of breakdown or operation failures • Requirements on permanent surveillance/monitoring

In the overall assessment, the technology variant that achieves the highest total score for 'Strengths' and 'Opportunities' and the lowest total score for 'Weaknesses' and 'Threats' therefore performs best. For this purpose, the score's sum values are once more converted into points that correspond to the rankings 1 - 3 [rank value] and are additionally visually highlighted by means of a traffic light system [green scores best] (Table 27).

Each treatment option was evaluated on the basis of the material stream for which the previous descriptions highlighted a particular suitability of the technology, e.g. source-separated biogenic waste in the evaluation of composting. It was likewise attempted to consider the information available on the initial waste management situation in the target region (see document sections on 'Status Quo') during the yet largely subjective evaluation.

In addition to the evaluation and ranking scores which can be seen in the table view, special chart graphics provide a more visually pleasing comparison of the technical variants in terms of their performance in the different SWOT categories (Figure 31 - Figure 34).

Table 27: Results of the SWOT assessment for the different technology options for biogenic waste treatment in Africa

Assessment categories / criteria	**Rating:**	**5 - extremely high → 0 - not at all**					
Material focus	*source-sep.*	*commingled*	*commingled*	*commingled*	*source-sep.*	*source-sep.*	*commingled*
Strengths	**Composting**	**MBS (dry stabilisation)**	**MBT (splitting concept)**	**Dry fermentation**	**Wet digestion**	**Mono-combustion**	**Mixed-combustion**
Environmental relief compared to untreated disposal	4	4	3	3	4	4	3
Scalability (modular design and expandability options)	5	4	3	3	4	1	1
Readily existing demand/usage potential for process outputs (market orientation)	4	2	1	3	4	2	1
General availability of sinks and offtakers for treated outputs incl. residues	4	3	2	3	3	4	2
Total score for assessment category	*17*	*13*	*9*	*12*	*15*	*11*	*7*
Rank value (highest total score wins)	*3*	*1*			*2*		
Weaknesses							
Intensity of area occupancy	2	3	4	3	2	4	4
Overall cost intensity	1	2	4	3	3	4	5
External dependency for technical equipment/components	1	2	3	4	3	5	5
Potential limitations to acquire suitable input volumes	2	1	0	2	1	5	4
Potential limitations to acquire input of suitable quality	2	1	1	2	2	3	3
Potential acceptance problems or persuasion requirements with public	2	2	3	3	3	2	4
Further disposal and caretaking requirements for process outputs incl. residues	1	3	4	3	3	3	4
Requirements for qualified personnel and/or qualification of staff	2	2	3	3	3	4	5
Total score for assessment category	*13*	*16*	*22*	*23*	*20*	*30*	*34*
Rank value (lowest total score wins)	*3*	*2*			*1*		
Opportunities							
Job creation potential	3	3	3	3	2	1	2
Wider demand and marketability potential for process outputs	3	2	1	2	4	2	1
Immediate usability of locally existing knowledge and/or experiences	4	3	2	2	4	0	1
Possibilities to work with direct local refinancing/refinance mechanisms	4	2	1	3	2	2	2
Total score for assessment category	*14*	*10*	*7*	*10*	*12*	*5*	*6*
Rank value (highest total score wins)	*3*	*1*		*1*	*2*		
Threats							
Complexity of technology and operational management	2	2	3	3	4	4	5
Dependence on critical infrastructure (grid/permanent water supply)	1	2	2	3	4	5	4
Difficulties and/or effort to ensure sufficient input volumes	4	1	1	2	3	5	3
Limitations to adjust to changing input flows (adaptive capacity)	2	1	1	2	3	5	4
Immediate negative consequences in case of breakdown or operation failures	1	3	2	3	3	4	4
Requirements on permanent surveillance/monitoring	2	2	1	3	4	4	5
Total score for assessment category	*12*	*11*	*10*	*16*	*21*	*27*	*25*
Rank value (lowest total score wins)	*1*	*2*	*3*				
Total aggregate rank	**10**	**6**	**3**	**1**	**5**	**0**	**0**

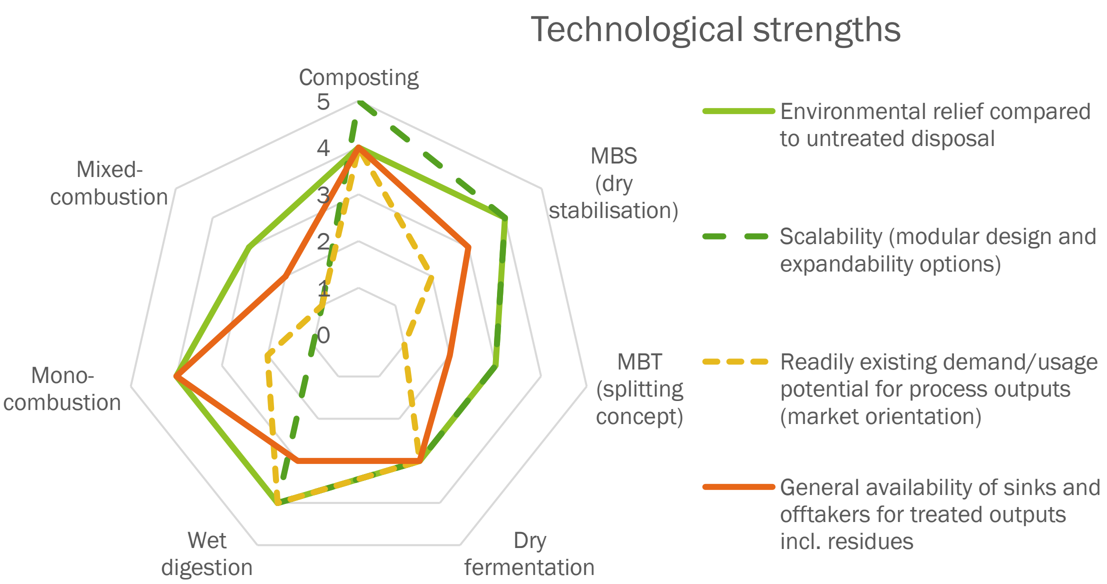


Figure 31: Results of SWOT evaluation for the considered treatment options (Graphic: INTECUS, Analysis made in the frame of the WasteGui-project)

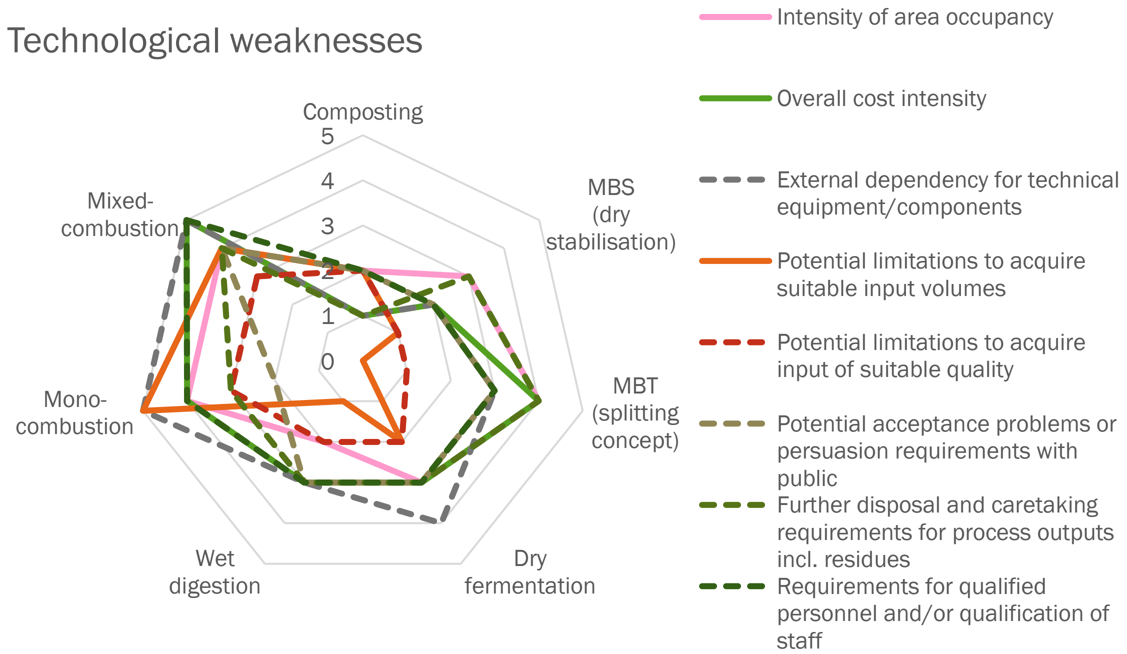


Figure 32: Results of SWOT evaluation for the considered treatment options (Graphic: INTECUS, Analysis made in the frame of the WasteGui-project)

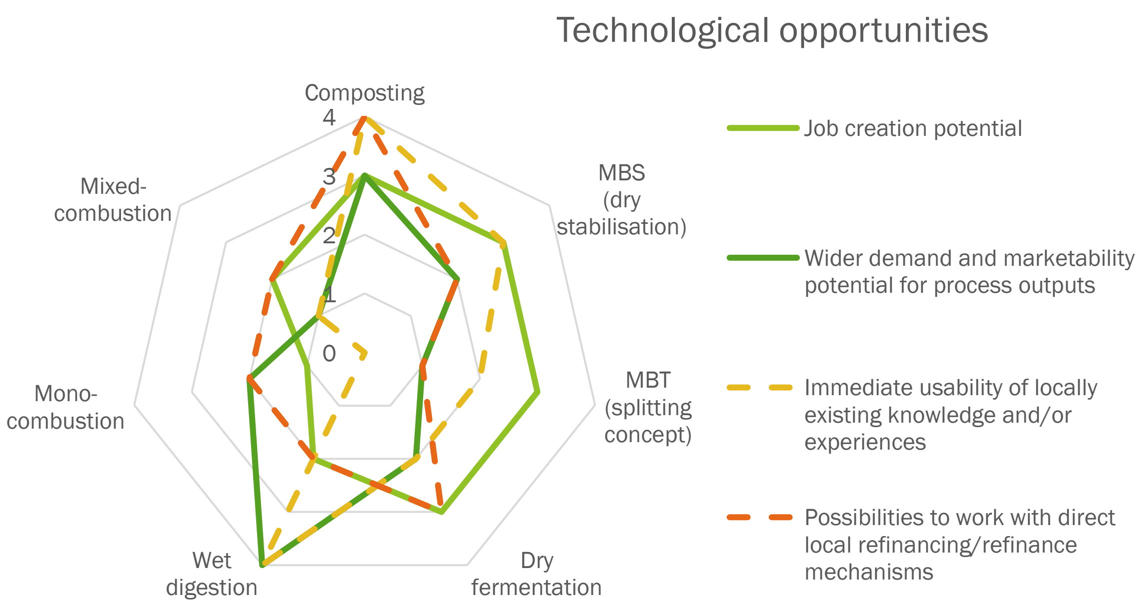


Figure 33: Results of SWOT evaluation for the considered treatment options (Graphic: INTECUS, Analysis made in the frame of the WasteGui-project)

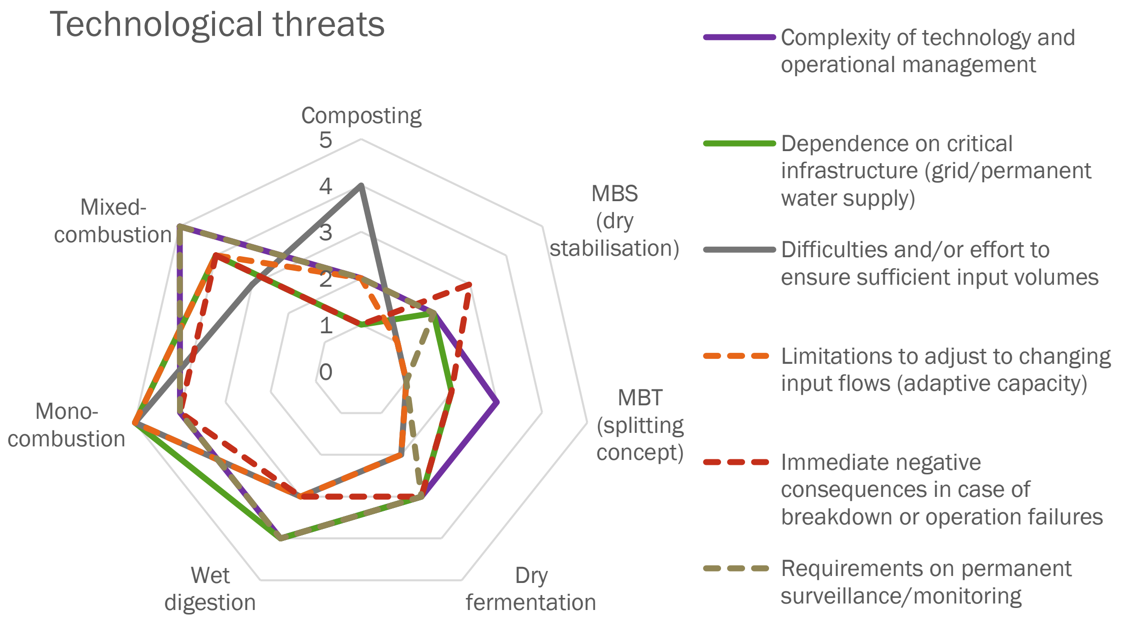


Figure 34: Results of SWOT evaluation for the considered treatment options (Graphic: INTECUS, Analysis made in the frame of the WasteGui-project)

5.4.2 Preliminary conclusions from the SWOT exercise

The SWOT method shows that the different technology options have different advantages in each evaluated category and that their suitability can vary greatly depending on the set priorities, treatment objectives as well as the local conditions and frameworks.

In the overall evaluation, however, the composting clearly stands out with its advantages as a simple, cost-effective treatment option that can be quickly established in the different types of areas through various modifications and design sizes. Dry stabilisation with the integration of composting-alike process steps can score with similar advantages and is therefore plausibly ranked just behind composting in this evaluation.

As already outlined above, the subsequent utilisation of the MBS process output as fuel for energy production must be taken into account in this treatment option. Due to a strong presence of the cement-producing industry and the large-scale waste incineration plant Reppie, the conditions for this seem to be given at least in the greater area of the capital Addis Ababa.

In other parts of Ethiopia, on the other hand, AD processes implemented through decentral small-scale wet digestion facilities (home digester) and large-scale installations in the agriculture and food industry segment or dry fermentation plants for the organic-rich mixed waste in medium-sized cities (25,000 - 100,000 inhab.) are likely to have suitability advantages and should be therefore of particular interest there.

5.5 Assessment of technology costs

Most often in decision-making particular attention is paid on the economic and financial viability of the treatment concepts, not at last to raise the necessary funds for investment and not to overburden state budgets and/or the public who is paying for the waste services. The amount of investment is only one side of the coin; often the **subsequent expenditure** for the **ongoing operation** of the technical facilities is no less enormous and a more difficult burden on which treatment projects also tend to fail. The whole subject is particularly critical for countries with less strongly developed economies and a high proportion of the population having minimal monetary income and who may not pay or be able to afford to pay for waste management.

These aspects must hence be thoroughly investigated and become subject of upfront assessments too, so as it is also done in the above exemplary SWOT analysis and by way of another evaluation method respectively assessment exercise presented in Figure 35.

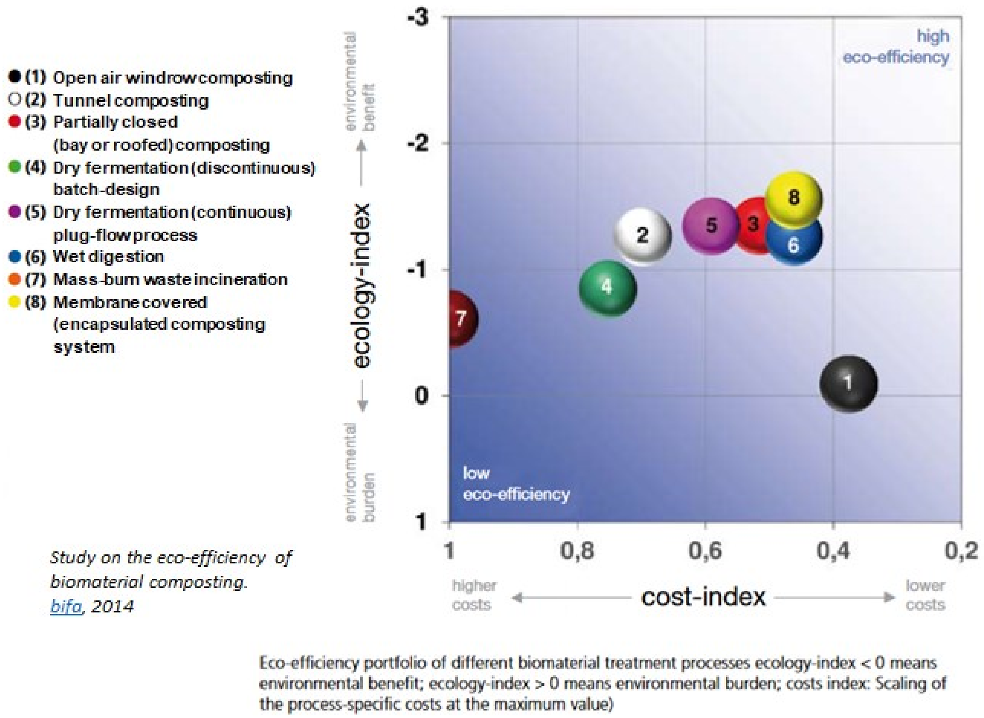


Figure 35: Result of an assessment on the eco-efficiency of treatment options for biogenic waste in specific settings of Germany (Picture sources: : UTV AG 2015)

The whole can be backed by reference values for plant investments and operating expenses or through information indicating their relations. The following depict selected examples for this kind information (see Table 28 and Project reference box for a composting investment in Tunisia).

Table 28: Consolidated overview of the main project costs for constructing and operating a treatment installation for biogenic waste (example: windrow composting)

Cost positions	Cost type	Principal cost components
0. Planning	non-recurring	
I. Site	*varying*	
I.1 Acquisition of land area	non-recurring (or recurring)	purchase price (or leasing rate)
I.2 Land clearing/preparation	non-recurring	machine & operator's costs, soil excavation and disposal
I.3 Infrastructural development	non-recurring	machine & operator's costs, material costs (roads, power lines, piping system)
II. Plant installation	*varying*	
II.1 Building construction	non-recurring	machine and operator's costs, material costs
II.2 Stationary and mobile equipment	recurring (within depreciation cycles)	purchase price
II.2a Wheel loaders/shovel tractors		depreciation rate & repairs
II.2b Shredder		depreciation rate & repairs
II.2c Screen(s)		depreciation rate & repairs
II.2d Turning/ventilation device(s)		depreciation rate & repairs
II.2e Filter system(s)		depreciation rate & repairs
II.2f Bagging machine		depreciation rate & repairs
II.2g Sensors/control instruments		depreciation rate & repairs
II.2h Steering device(s), e.g. PC hardware		depreciation rate & repairs
II.2i Basic lab equipment		depreciation rate & repairs
III. Operations management	recurring	
III.1 Supervising staff		saleries & social security contributions
III.2 Admin and lab staff		saleries & social security contributions
III.3 Equipment operating staff		saleries & social security contributions
IV. Material supplies and disposal	recurring	
IV.1 Machine fuels and lubricants		purchase of diesel and lubricants
IV.2 Electric power		purchase of electricity
IV.3 Fresh water		purchase of water
IV.4 Filtration agents		purchase of filter materials
IV.5 Waste water		disposal and/or treatment costs
IV.6 Process and other residues		disposal and/or treatment costs
V. Other	recurring	
V.1 Insurances		insurance rates
V.2 Capital services		redemption and interest rates
V.3 Certifications & services		royalties & service fees
V.4 Marketing		payments for advertising
V.5 Taxes		tax rates
Project default values		
Land requirement	*[ha/t input]*	0,0002
Fuel demand	*[ltr diesel/t input]*	2,5
Electricity demand	*[kWh/t input]*	4
Water demand	*[ltr/t input]*	250
Capital cost contingency	*[% of Capex]*	10
Maintenance cost	*[% of Capex]*	2
Insurance cost	*[% of total Capex excl. taxes]*	1
Outside services & supplies	*[% of O&M before contingency]*	2
O&M cost contingency	*[% of O&M]*	10

Project Reference Box 7: Exemplary cost projections for biogenic waste treatment plant in Tunisia

Table 8. Cost–benefit of establishing a composting plant in Tunisia.

Estimated Civil Engineering * Investment Cost (Part 1)			Investment Costs on Material and Equipment (Part 2) **			Investment Cost Management			Yearly Costs for Operation and Maintenance ***		Yearly Costs for Capital, Consumption, & Operation		Yearly Profit from the Sales of Compost at 30 €/ton	
Engineering a	3%	70,000	Turner machine	12%	250,000	State grants	30%	622,500	Personal cost	60,000	Capital related cost	43,575	Compost sales	210,000
Preparation of land and layout (10 donums)	24%	500,000	Front loader	6%	120,000	Own contribution	0%	0.00	Fuel & energy consumption	45,000	Operation and maintenance related cost	158,500	Production cost	202,075
Outdoor facility	34%	700,000	Rotary drum screen)	10%	200,000	Additional investment required	70%	1,452,500	Water consumption	3500	Total yearly cost (€/year)	202,075	Net profit	7925
Sum of Part1	61%	1,270,000	Shredder	10%	200,000	** Machines and equipment needed: - front loader (1) - shredder (1) - drum screen (2) - temperature probe (2) - gas measurement (1) - Water tank (1) - Water pump (1)			Equipment's and others	10,000	*** Personnel: - Qualified supervisor (1) - Trained worker (4) - Worker (2) - Driver (1) *** On-site staff responsibilities include: - monitoring the biological process - turning of windrows - watering of windrows - quality control of finished compost.			
* Site preparation and design including: - accessibility and parking concepts - composting platform (asphalt/concrete) - drainage system for leachate, thereby protecting groundwater. - Water and electricity supply - Fencing			Workshop equipment's	1%	25,000				Building maintenance	5000				
			Office equipment	0.5%	10,000				Machine maintenance	30,000				
			Sum of Part 2	39%	805,000				Insurance	5000				
			Total setup costs	100%	2,075,000				Total operation & maintenance cost/a	158,500				

Table 9. Capital and operation costs of the biogas plant in Tunisia.

Capital Investment Costs (CAPEX) *		Operation Costs (OPEX)			
**Capital Cost Component ** **	**Percentage of the Cost (%) *** **	**Operation Components**	**Unit**	**Number**	**Operation Cost**
Construction and land arrangement	3.78%	Maintenance cost	€/kWh	-	0.015
Loading hall	9.28%	Maintenance cost for pumps and compressors	%	-	1.5
CHP facility	2.32%	Staff salaries ****	€/Mann	12	1000
Drilling cost	0.93%	Personal logistic	€/Mann	12	500
Mixing chamber	1.39%	Facility insurance	%	-	7
Sanitization	4.64%	Power consumption	%	-	10
Fermenter	2.32%	Load management	%	-	5
Storage	6.49%				
Control system	5.57%				
Social room	3.71%				
Gas track (pipes)	1.67%				
Emergency factors	1.39%				
Pumps & compressors	1.39%				
Heat exchangers	0.93%				
Pipes connections	4.64%				
Biofilter	7.42%				
Electrical installation	4.64%				
Planning and design steps	1.5%				
Networks	4.64%				
Others	2.13%				
Total setup costs	100%				

* CAPEX has been estimated at about 3.5 million US dollars; ** Capital cost of component was based on the prices of the equipment and instruments in Germany; *** Their contribution to total cost has been worldwide stated based on experience; **** Salaries were calculated based on the level of wages in the study area: Tunisia.

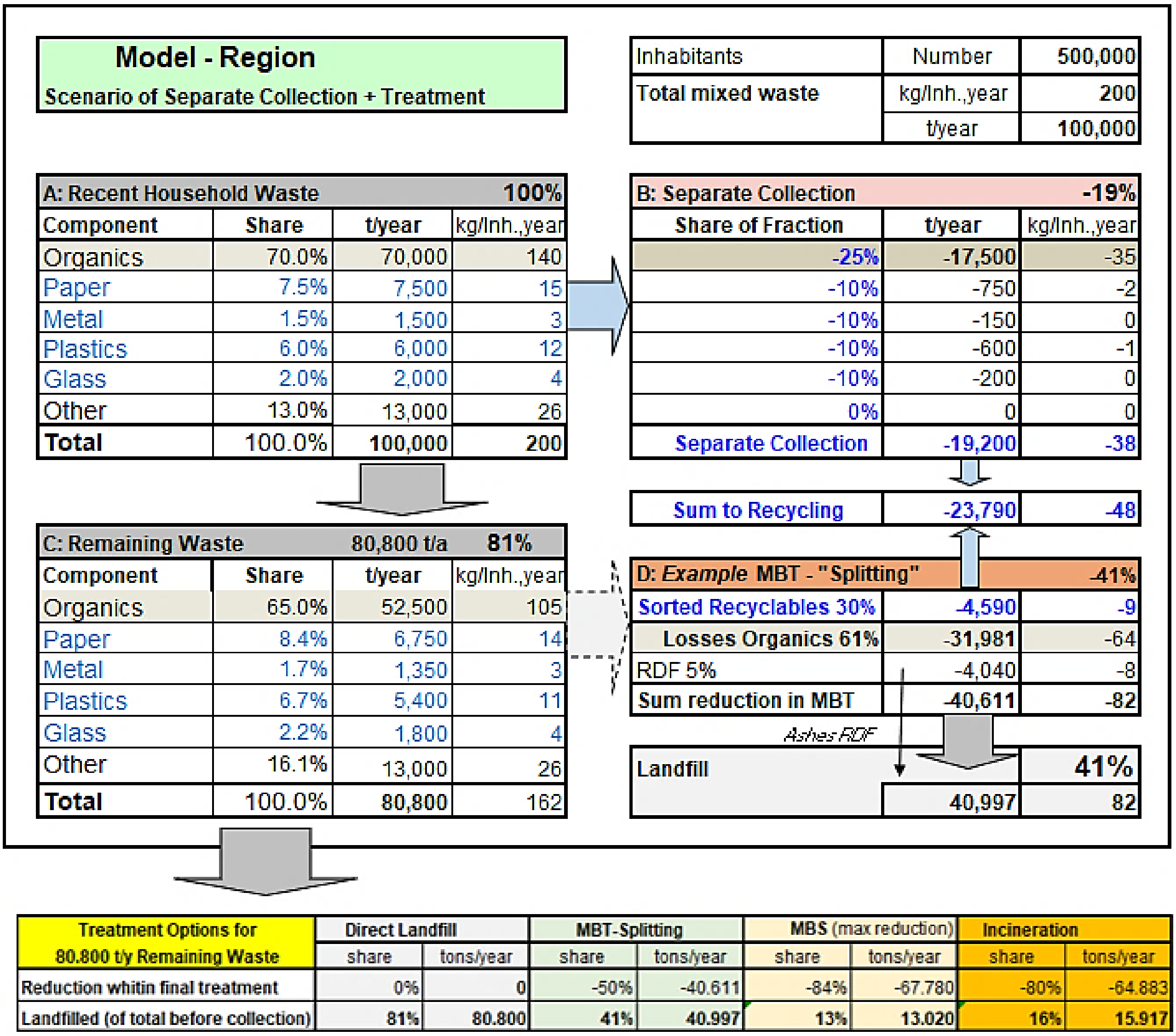
Source: (Chaher et al. 2020) in "Potential of Sustainable Concept for Handling Organic Waste in Tunisia"

6 Reduction effect of separate collection and treatment

As described, the reduction of organic material going unused and untreated to landfill is the most important goal.

For a closer understanding which effects can be achieved by a **combination of separate collection and treatment**, a model was developed and calculated in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

In the following example the model region has 500,000 inhabitants with 200 kg/capita/year of mixed household waste, resulting in around 100,000 tons per year.



Model - Region
Scenario of Separate Collection + Treatment

Inhabitants	Number	500,000
Total mixed waste	kg/Inh.,year	200
	t/year	100,000

A: Recent Household Waste			100%
Component	Share	t/year	kg/Inh.,year
Organics	70.0%	70,000	140
Paper	7.5%	7,500	15
Metal	1.5%	1,500	3
Plastics	6.0%	6,000	12
Glass	2.0%	2,000	4
Other	13.0%	13,000	26
Total	100.0%	**100,000**	**200**

B: Separate Collection		-19%
Share of Fraction	t/year	kg/Inh.,year
-25%	-17,500	-35
-10%	-750	-2
-10%	-150	0
-10%	-600	-1
-10%	-200	0
0%	0	0
Separate Collection	-19,200	-38
Sum to Recycling	-23,790	-48

C: Remaining Waste		80,800 t/a	81%
Component	Share	t/year	kg/Inh.,year
Organics	65.0%	52,500	105
Paper	8.4%	6,750	14
Metal	1.7%	1,350	3
Plastics	6.7%	5,400	11
Glass	2.2%	1,800	4
Other	16.1%	13,000	26
Total	100.0%	80,800	162

D: *Example* MBT - "Splitting"		-41%
Sorted Recyclables 30%	-4,590	-9
Losses Organics 61%	-31,981	-64
RDF 5%	-4,040	-8
Sum reduction in MBT	-40,611	-82
Ashes RDF		
Landfill		41%
	40,997	82

Treatment Options for 80.800 t/y Remaining Waste	Direct Landfill		MBT-Splitting		MBS (max reduction)		Incineration	
	share	tons/year	share	tons/year	share	tons/year	share	tons/year
Reduction whitin final treatment	0%	0	-50%	-40.611	-84%	-67.780	-80%	-64.883
Landfilled (of total before collection)	81%	80.800	41%	40.997	13%	13.020	16%	15.917

Figure 36: Model calculation for separate collection and treatment (table A to D)

In the integrated **table A** - a realistic composition of the household waste is set, dominated by 70 % of organic waste, while the dry recyclable wastes account only for 17 %. Based on these shares, the masses per year of the concerned fractions were calculated.

Assuming in **table B** that (only) 25 % of the organic waste is separately collected, the amount of 70,000 t/y of organics in the mixed waste is reduced by 17,500 t/y of SSO. Assuming that the dry recyclables are already separately collected in a broader extend (by given economic incentives for the households), their *additional* separation can be presumed lower, with 10 %. In total 19 % of the original waste is recovered for recycling, and more than 90 % of this amount account to the SSO – due to the high share in the original waste. Estimated collecting rates of the **dry recyclables** are more or less **without relevant effect**, since their mass potential is very low. A further increase of the SSO-collection rate from 25 % to 35 % would lead to a separate collected share of 26 % compared to the calculated 19 % - a significant improvement.

After subtraction the separated masses roughly 81,000 t/y of remaining mixed waste is the result, with fraction masses and consistencies shown in **table C**: After a separate collection of 25 % of the organic waste their *share* has lowered only from 70 % to 65 %. This due to the subtraction of the 19,000 tons from the *tota*l mass as well. Even with a 50 % collection rate of SSO, the organic share in the remaining would still be at 55 %.

It is shown that **separate collection of SSO reduces the remaining waste** to be treated in the **range of 20 %** - if established, open to more. On the other hand, the remaining waste has still a dominant share of organics, as a task for its further treatment to eliminate ecological damages, if it is landfilled.

The four basic options of final disposal are in a short form listed in Table 29. It shows the reductions of masses in the process and illustrates the remaining demand for landfilled masses (including in case of incineration the ashes of combustion of waste or RDF). These characteristics and the reduction potentials of greenhouse gases, compared with the common situation of landfilling. are further described below.

In **table D** the mass flows of the MBT treatment concept further broken down. The main mass reduction is here achieved by the mass loss of the organic fraction by 61 %. 30 % of the dry recyclables shall be sorted out and are added to the separate collected recyclables. The total share of material recycling thereby improves to 24 % of the total waste. Additionally, around 5 % of the MBT input is recovered as RDF for energetical use. In total, the mass reduction *within the MBT* is at roughly 50 %. Combined with the separate collected fractions the total waste reduction is almost 60 %, only 41 % of the original waste *mass* is landfilled. Since these residues are of high density, the **landfilled *volume* is assumed to be reduced by around 25 %** compared to the volume of the unseparated and untreated waste.

Clearly to recognize: The absolute **dominant share of the total mass reduction** of 59 % is contributed by the **reduction of the organic waste**, with 17.5 % by separate collection and 32.0 % by losses in the MBT.

Since the MBT is only *one* option to treat the remaining waste after separate collection, in Table 29 the four alternatives are listed. In the upper part of this table, the mass distributions within the concepts are shown, here as well related to the 80,800 tons to be treated finally. A complete landfilling of the waste (left column) has no extraction. As far as the waste is incinerated (right column), except of the metals (90 % of them are extracted) all is burned, leaving a share of ashes in the range of 20 % (this share of ashes is as well set for RDF by MBT).

The mass distribution within the MBT was described above, the figures are taken from there. The amount of later landfilled ashes is low, since only few RDF is extracted.

The MBS extracts roughly the same masses from the organics as the MBT, more of evaporated water, less by only low degradation of the organic dry mass. 50 % of total input are won as RDF (aimed to be combusted in industry), added by small shares of metals. The extracted, later landfilled inert material share in the MBS of 13 % is far lower than at the MBT. But the later burned RDF leaves 20 % of ashes, which prospectively are landfilled too, if not completely given to the cement industry (where it is part of the produced cement).

Influenced by the ash masses, the final landfill demand of MBS is in the range of 20 % of the input of the treatment, thereby at less than half of the MBT residues.

Table 29: Treatment options for remaining waste (landfill, MBT, MBS, Incineration)

Treatment Options for 80,800 t/y Remaining Waste	**Direct Landfill**		**MBT-Splitting**		**MBS (max)**		**Incineration**	
	share	tons/year	share *)	tons/year	share	tons/year	share	tons/year
Reduction of Organics by MBx	0%	0	-40%	-31,981	-37%	-30,205	0%	0
Sorted Recyclables	0%	0	-6%	-4,590	-1.5%	-1,215	-1.5%	-1,215
RDF / Incinerated	0%	0	-5%	-4,040	-50%	-40,400	-98%	-79,585
Sum reduction by treatment	**0%**	**0**	**-50%**	**-40,611**	**-89%**	**-71,820**	**-100%**	**-80,800**
Residues treatment to landfill	100%	80,800	50%	40,189	11%	8,980	0%	0
Ashes of Incin./RDFuse	0%	0	1%	808	5%	4,040 **)	20%	15,917
Landfilled total	**100%**	**80,800**	**51%**	**40,997**	**16%**	**13,020**	**20%**	**15,917**
GHG-Emission specific Mg CO_2/Mg		*0.65*	*-90%*	*0.07*	*-90%*	*0.07*	*-97%*	*0.02*
GHG-Emission Mg CO_2/year***)		52,520		2,665		846		310
Reduction GHG-Emission	0%	0	**-95%**	-49,855	**-98%**	-51,674	**-99%**	-52,210

*) all shares are related to input of *treatment (=100%),* not to the amount before separate collection

**) RDF assumed 50% to cement (no ashes), 50% to powerplant (20% ashes to landfill)

***) All values concern the remaining emissions only of the *landfilled material, other benefits of energetic use neglected*

GHG-Reduction by treatment

The bottom part of this table concerns the reduction potential of GHG, compared to the pure landfilling. For the landfill, an emission rate of 1 Mg CO_2e per ton of organics is estimated. The organics have a share of 65 %, thus the mixed waste emits 0.65 Mg CO_2e per ton.

Due to the biological degradation, the specific gas forming potential of the landfilled MBT-Output is reduced to about 10 % of the value of untreated waste. The same remaining gas value is assumed for the landfilled residues of the MBS. Understood that the ashes of the incineration are again lower, here set on 3 % of the untreated.

These specific values are now multiplied with the very masses going finally to the landfill in the concepts. Finally, there is a **reduction rate in GHG-production above 90 % in all concepts.** This calculation includes only the reduction of the *landfill's* emissions by the treatment, other GHG-reduction net effects by e.g. produced biogas or energy use of RDF/incineration are still not included, nor the positive net effects of the separate collection.

There might be some inaccuracies in this model calculation, but it leads to the secured basic conclusions:

- *Measures to high effective recovery shares, reduction of volume use and emissions of landfills must be addressed to the biodegradable fraction.*
- *Separate collection of organic waste has an immediate reduction effect und should be initiated as fast as possible, starting with the "easy to get" – organic waste streams (municipal green, market wastes)*
- *Separate collection of organics, how intensive ever, will always leave a high remaining share of organics in the remaining waste, thus a further treatment of this waste is necessary.*
- *All the described technical options to treat the remaining waste (MBT, MBS, incineration) have a similar high reduction potential of GHG-emissions compared to landfilling. The small GHG-differences between these treatment systems should not be used as an evaluation criterion. Other local, operative and economic criteria determine the realization.*

As described, as far as the masses of daily waste do not justify a mass-burn incineration, the remaining concept alternatives, MBT (Splitting) or MBS, provide solutions for various daily masses. Decision criteria between these options are described in section 7.2.

7 Conclusions for locally specific implementation

The conclusions and recommendations in this section focus on the "separate collection" of organic waste, specifically structured for three dwelling structures. It furthermore elucidates on the establishment of different suitable treatment options and on corresponding cost frames. In addition, this section offers suggestions to address public sensibilisation and acceptance in and for the implementation process. The following tasks and actions are recommended by the authors:

First task

- *Establish waste collection - complete collection and removal of all wastes as regularly and promptly as possible from the (human) environment is the central objective of waste management.*

Second tasks

- *Minimize risks - the ecological damages at final disposal are to be minimized - or at least to be reduced as far as possible.*

The following two key fields of action - that have a positive effect on each other - are proposed as follow up strategies in addition to the aforementioned two priority tasks:

- Separate waste collection at source.
- Treatment of the remaining mixed waste.

All the measures needed for this must concern the main frame conditions and strategies:

- Overall costs must be related to economic power (household income resp. GDP).
- Raise awareness (citizens, politics, stakeholders).
- Follow evolution steps (start simple, collect experience, expand).

7.1 Establishment of separate waste collection systems

The key advantage of **source separation** lies in the following: the mutual impurity and contamination that different waste fractions have on each other will be minimized. This applies mostly to the water containing **biodegradable fraction** on the one side and the relatively dry recyclables on the other.

The source separation of dry recyclables is already fostered to a certain extend by commercial incentives, since these materials have a monetary value. This is at no doubt debatable, but – as shown in chapter 6 – the mass reducing effect will stay comparably low due to the low collectable potential (max. 20 %) in the waste. But, more important, the damaging effects of the landfilled remaining wastes are almost the same, since they still comprise the organics.

In comparison, as described in chapter 6, the separate collection of the biogenic fraction achieves a multiple times higher mass reduction. It furthermore immediately and effectively reduces the landfill emissions – even at smaller collection rates. Beyond that, a good applicable compost is produced.

➢ *The primary measures of separate collection should focus on the organic fraction.*

In order to establish a separate collection system in general, it is necessary to analyze the status quo of the solid waste management (SWM) system that falls under one´s area of responsibility. At best, this can be based on data in the following five areas of action (UNEP 2009):

- **Policies:** Analyzing the availability, enforcement and impact of regulations and economic tools.
- **Institutions:** Assessing the institutional framework, resources, and jurisdictions for current institutions.
- **Financing Mechanisms:** Evaluating information on relevant economic instruments as financial disincentives and economic incentives addressing solid waste management.
- **Collection & Treatment:** Analyzing the efficiency and effectiveness of collection, treatment and disposal system including technologies.
- **Stakeholder Participation:** Understanding the role of different stakeholders at different levels of the solid waste management chain.

In the preparatory phase of concepts for separate collection systems for the respective settlement areas, recommendations are made for the five fields of action. The interactions of these different fields of action are shown in figure 37.

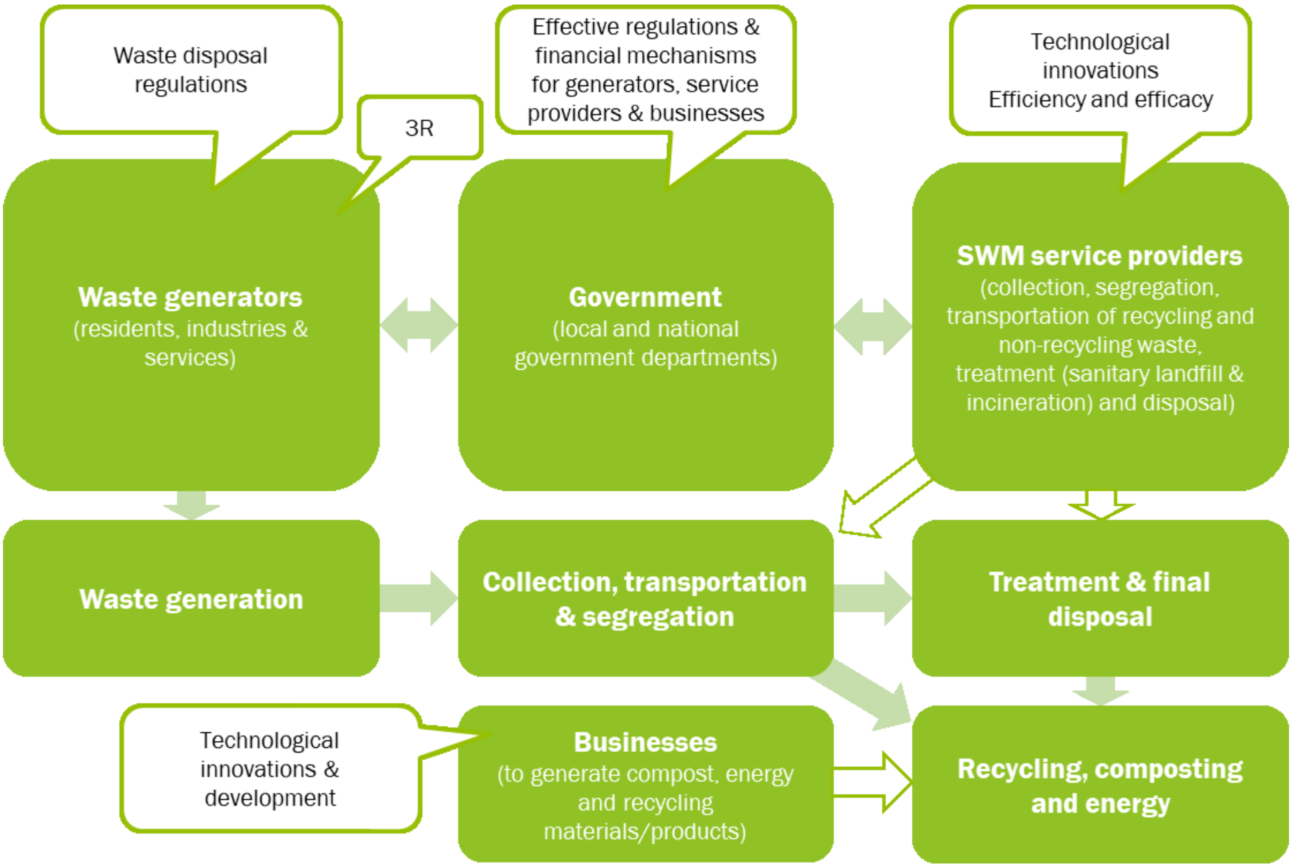


Figure 37: Stakeholders and areas of action in Integrated Solid Waste Management (DBFZ adapted from UNEP 2009)

Since the actual waste generators, governments/municipalities and SWM Service Providers in the local value chain vary greatly in terms of cultural aspects, previous involvement with the topic of waste, or have different technological requirements, it is important to establish pilot projects. It is recommended to select model regions at different levels of urbanization in different geographical and cultural areas in the country: metropolis (Addis Ababa), semi-urban to urban areas (20,000 – 500,000 inhabitants), rural areas (less than 20,000 Inhabitants) with municipalities that show a strong political will to improve the collection of biogenic waste.

In the following, the different options in the design of the framework conditions are presented, as well as scenarios in the practical implementation of separate biogenic waste collection systems. It should be noted though, that a certain amount of mixed waste remains in the separate biogenic waste stream. The amount of this share depends on various factors, first and foremost on the participation of the population.

The separation of biogenic waste may entail several advantages. It reduces the amount of residual waste and enables yield assurance through the selling of composts and fermentation residues in agriculture. Biogas can also be produced from biogenic waste to generate electricity and heat, reducing the need for fossil fuels such as coal and oil. Thus, landfills are relieved and a positive contribution to the climate and soil is made.

The main implementing stakeholders of municipal solid waste policies are local authorities which need to effectively organize and implement biogenic waste management activities. The aim has to be to protect the environment and raise awareness among citizens, as well as to reduce management costs to the benefit of the public. The difficulty is that not existing municipal solid waste segregation systems must be adapted stepwise. It is a decision of the municipalities to in which way to introduce waste collection, e.g., as a collection or delivery system, to use biowaste garbage bins or bags. In any case the system design should be based on the disposal needs of the citizens and coordinated with the separate collection system for green waste. Separation at source programs for household waste streams are especially challenging since they highly depend on the behavior of the waste generators. Therefore, capacity-building programs to raise public awareness are a prerequisite for the development of a sustainable SWM system.

The purpose of this chapter is to present concepts for separate collection systems with their specific advantages and disadvantages for different context areas (metropolis / urban and semi urban/ rural).

7.1.1 Metropolitan areas

In a metropolis like Addis Ababa the waste management infrastructure is best developed as compared to the other settlement area types. The collection of waste is well established and carried out by more than 600 private companies. Separate collection of recyclables at household level already exists, which makes a separate collection of biogenic waste quicker to implement. Also, a certain level of awareness in the population is preexisting. Therefore, theoretically sufficient quantity is available for different treatment processes. In order to increase the quality of biogenic waste material, the separation of waste can be enhanced through several measures in the various field of action:

Policies

Further development of the existing legal regulations as:

- Solid Waste Management proclamation, Article 11.1: Households have to make sure that the recyclable materials are segregated from other waste destined for disposal site → Inclusion of biogenic waste as recyclable,
- Solid Waste Management Proclamation No. 513/2007: This policy mainly covers the general obligations of urban administration, solid waste management planning, the inter-regional movement of solid waste, the management of household solid waste, waste collection and storage, transportation, recycling, incineration, disposal, and auditing of solid waste disposal sites. It also addresses the significance of community participation in its mission → Integration of supporting guidelines for solid waste management strategies, such as waste prevention and reduction, solid waste segregation at source, and waste collection fee systems.

Institutions

- Definition of responsibilities.
- Establishment of supervisory and executive authorities.
- Recording of waste composition and generation.
- Tracking of all waste streams (municipal, industrial, commercial) and monetary flows.

Financing Mechanisms

- Establishment of different incentives for private waste management companies for collection of biogenic and green waste and transport to treatment site.
- Volume-based user fees for commercial and industrial sector on a volume-base.
- Green/Climate bonds.
- Penalty, fine and levy: Contamination with other waste, such as plastic, should be kept as low as possible; the environmentally damaging disposal of waste through illegal dumping and incineration must be countered by user-friendly waste collection and a ban on incineration.

Collection & Treatment

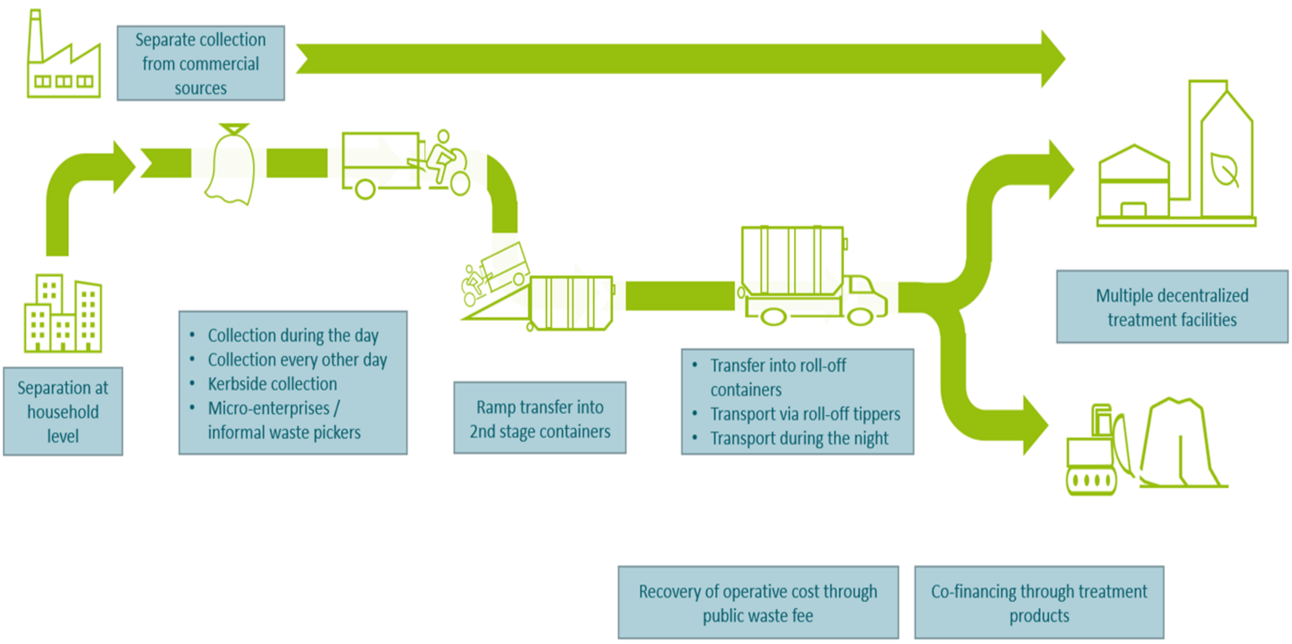


Figure 38: Concept for separate biogenic waste collection and treatment technologies for metropolitan area (Rodiek 1988-2022)

Stakeholder Participation

- Municipalities define the framework conditions for the collection of sufficient quantities of biogenic waste.
- Collection through licensed private micro-enterprises and larger waste management companies.

Table 30: Advantages and disadvantages of the proposed waste logistics concept for metropolitan areas (Rodiek 1988-2022)

Advantages ++	Disadvantages - -
Aggregation of larger quantities throughout different districts of the metropolis	great competition between waste management companies for separated good quality material
Greater choice in treatment procedures	
Co-operation between public and private organizations	
Direct communication with households and awareness raising through door-to-door collection	

7.1.2 Semi-urban areas

In semi-urban areas, more emphasize has to be put on creating framework conditions by the municipalities.

Policies

- See chapter 7.1.1.
- Ensuring the production of high-quality compost and the utilization of the compost.

Institutions

- See chapter 7.1.1.

Financing Mechanisms

- Levying of fees with simultaneous compulsory connection for households.
- Increasing local taxes.
- Increasing the share of general municipal income that is allocated to solid waste management.

Collection & Treatment

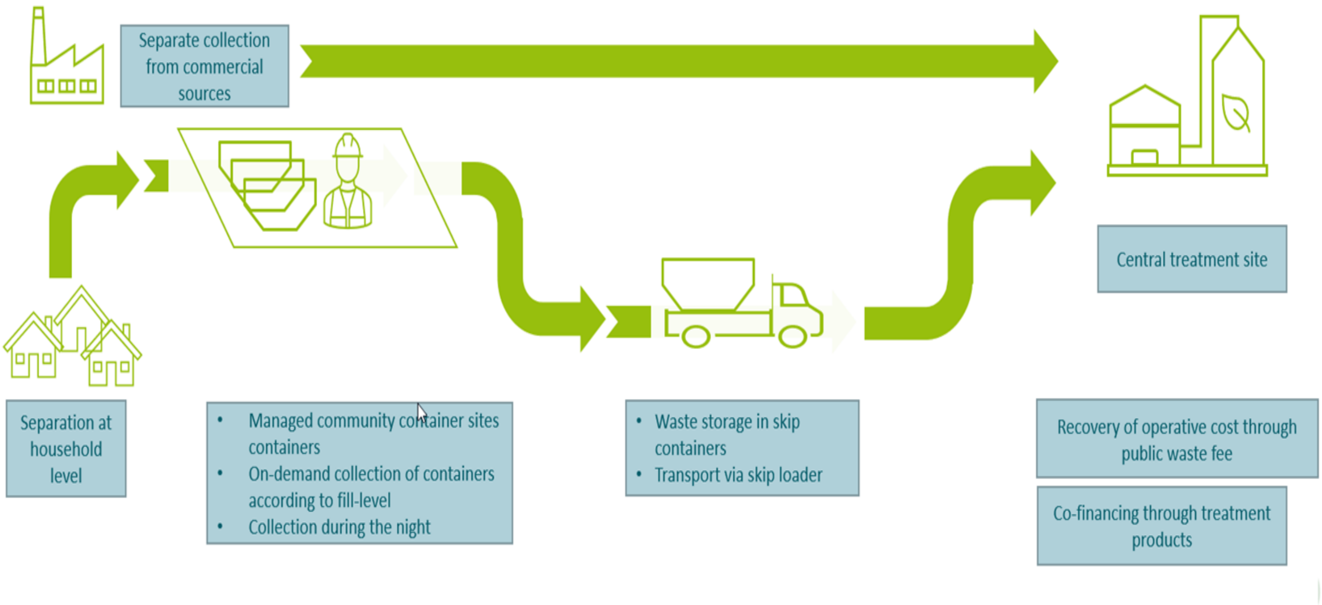


Figure 39: Concept for separate biogenic waste collection and treatment technologies for semi-urban areas (Rodiek 1988-2022)

Stakeholder Participation

- Municipal collection and compost in municipal hands.
- Close collaboration between municipalities and local / regional treatment facilities (e.g. request information about compost quality).

Table 31: Advantages and disadvantages of the proposed waste logistics concept for semi-urban to urban areas (Rodiek 1988-2022)

Advantages ++	Disadvantages - -
Managed container sites ensure good quality of segregation levels and function as communication mechanism and promote environmental awareness	Potentially longer transport distances could lead to higher logistics cost (should be part of financial assessment)
	Delivery system of waste might lead to illegal dumping of waste if container sites are not located conveniently

7.1.3 Rural areas

Policies

- See chapter 7.1.1.

Institutions

- Strong involvement of the public in strategy development and emphasize advantages of producing own compost.

Financing Mechanisms

- No formal financing system.
- Logistics and treatment cost are covered through own work contributions.
- The feasibility of the suggested system is mainly due to its low initial investment, simple technology, and routine monitoring.

Collection & Treatment

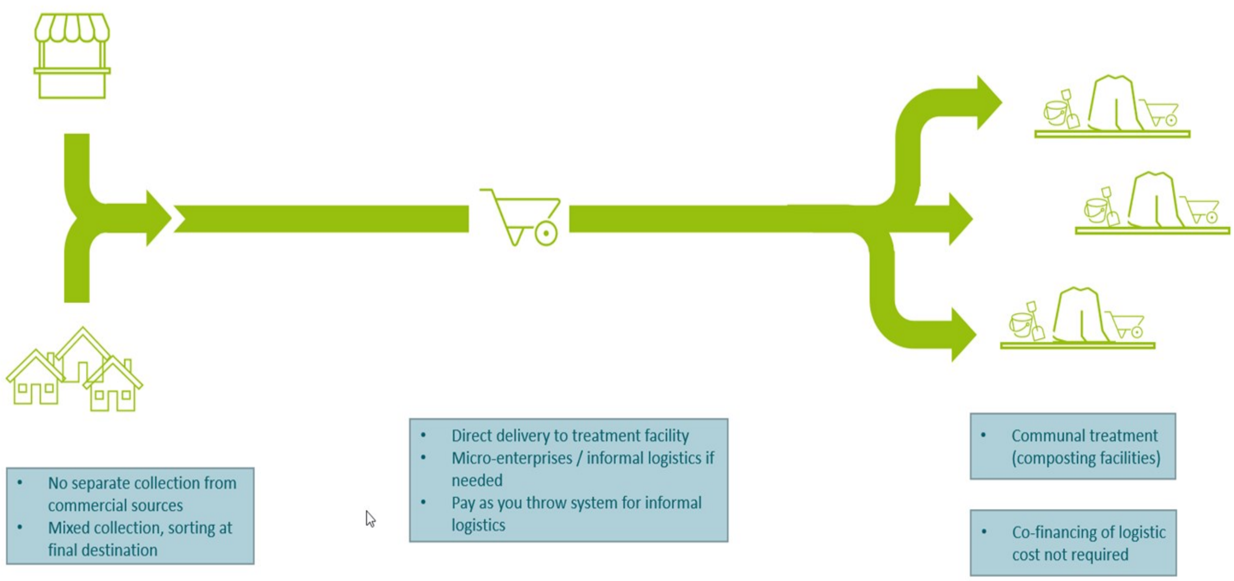


Figure 40: Concept for separate biogenic waste collection and treatment technologies for rural areas (Rodiek 1988-2022)

Stakeholder Participation

- Municipalities and communities organize centralized composting sites.
- Households, farmers set up private composting and use the compost for own cultivation of vegetables and fruits.

Table 32: Advantages and disadvantages of the proposed waste logistics concept for rural areas (Rodiek 1988-2022)

Advantages ++	Disadvantages - -
Minimization of all logistics cost	Demand for final compost products close to the composting site might be low. This could lead to low revenues or could make transport to sites of higher demand necessary
Participation of community poses benefits for the society as well as promotes environmental awareness.	
Low initial investment	

7.2 Establishment of treatment systems

The main two ***treatment demands*** concern the separate collected organics (lower shares) and the remaining waste (higher share).

The capacities to treat these two streams are determined a) by the foreseeable waste amounts after measures of separate collection in the region and b) the expected masses of SSO.

As can already be derived from the descriptions, the technical options are not only geared towards varying treatment objectives. Also, differences in their effectiveness and benefits need to be seen in relation to the different waste streams, as there are interrelationships of those aspects. Such interrelationships also exist between the techniques themselves, in that they can be used in combination or complementary to each other, resulting in treatment cascades, for example. An attempt to illustrate this schematically is provided in figure 41.

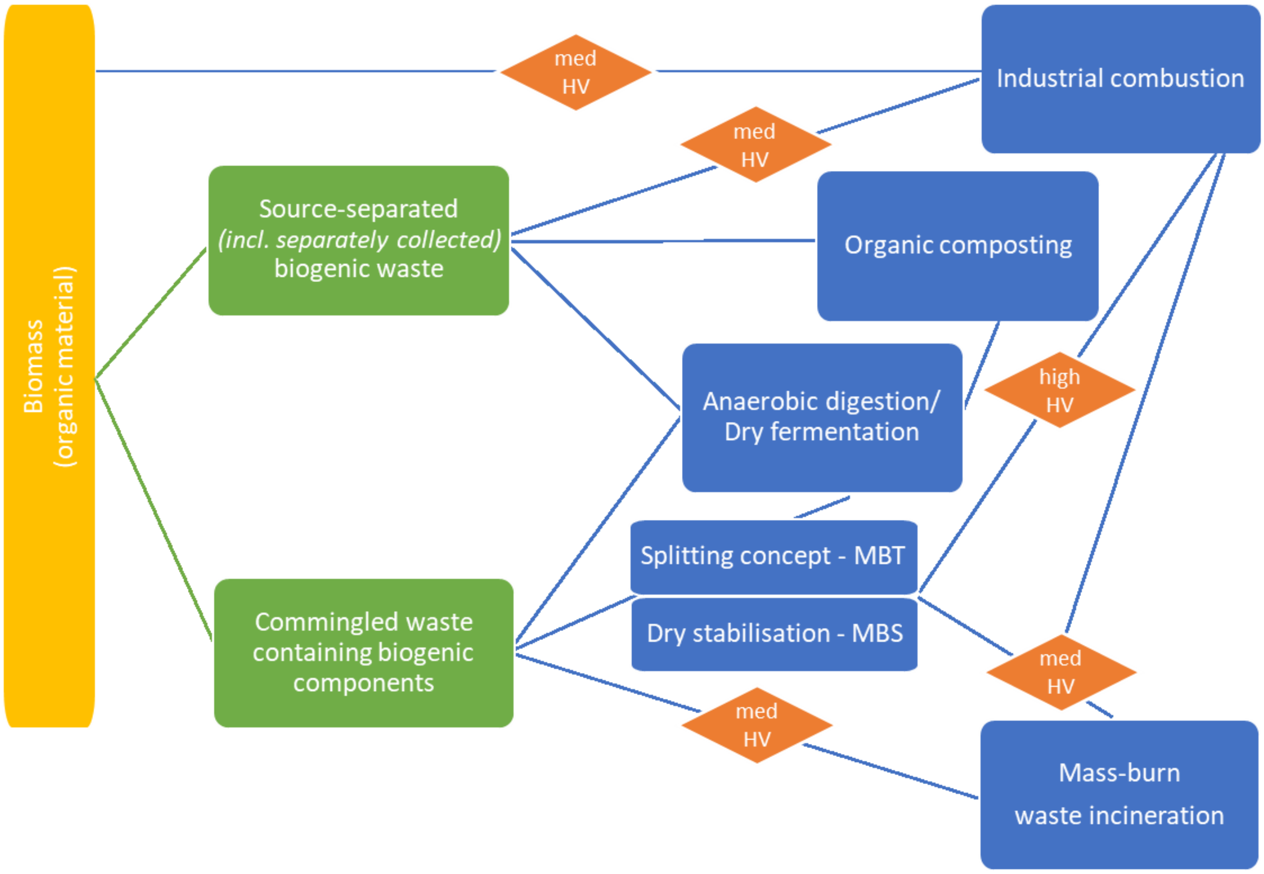


Figure 41: Treatment techniques and their possible interrelations with each other and the to be treated waste (fractions) (INTECUS)

The deliverable waste and the possibilities of further utilization or safe storage of the treatment outputs are thus limiting which of the technical options can be actually considered. In addition, there are numerous other influencing factors. Consequently, there are no generally applicable solutions which can ensure a successful and sustainable waste treatment, as those must always be selected (and developed) to suit local circumstances and conditions.

The mere look at economic viability thresholds and suitability parameters for waste flows of certain types and sizes, including their main places of generation, roughly suggests following scheme of territorial priorities for the previously described technology and process portfolio (Figure 42).

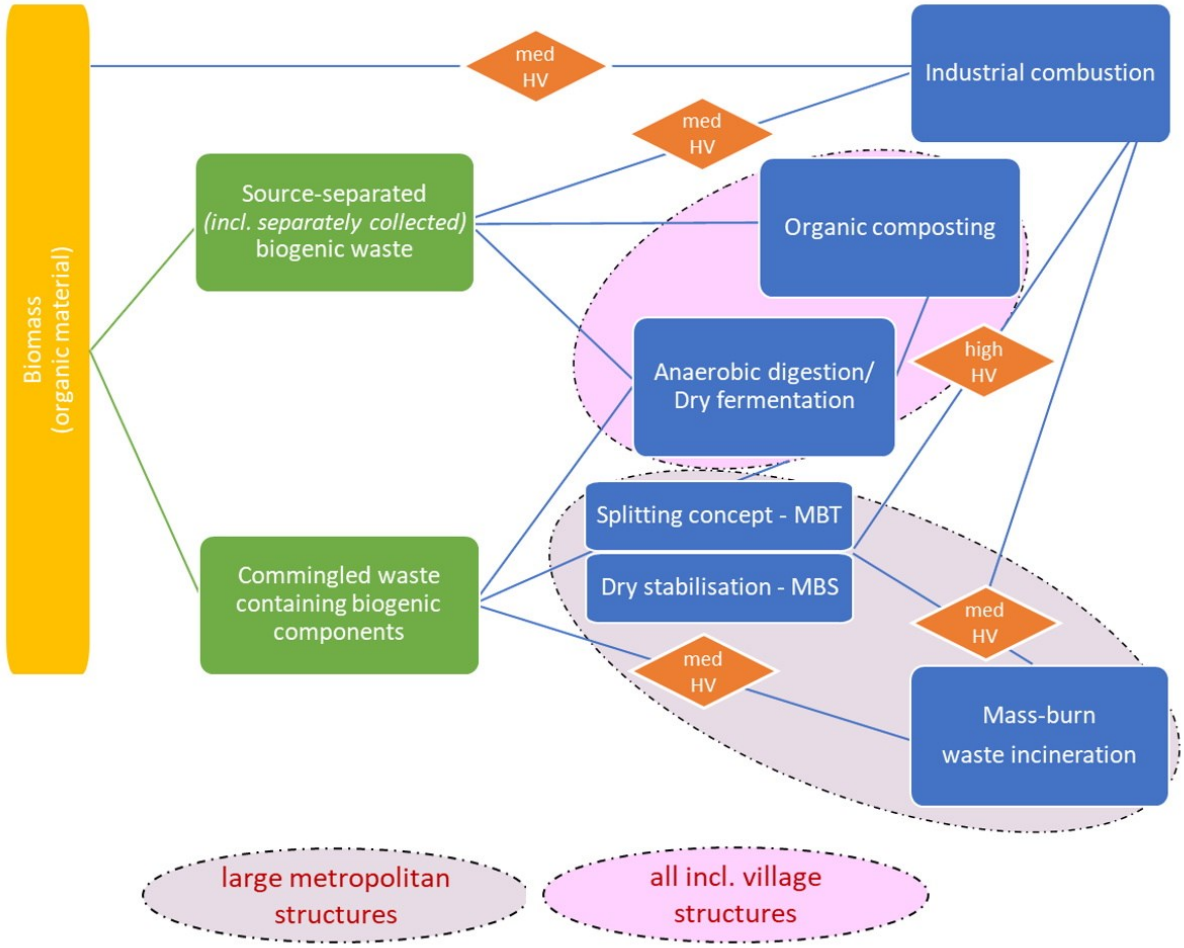


Figure 42: Coarse territorial allocation of the different treatment techniques for biogenic waste (Graphic: INTECUS using on own expertise)

The AD technique, in particular dry fermentation in batch design, is widely applicable regardless of whether the biogenic waste is present as source-separated material or as a component of mixed waste. This applies analogously to composting, whereby the focus here should lie on source-separated material.

This yet very general territorial allocation scheme cannot be projected equally well to every location and must be re-evaluated or further specified by considering numerous additional details about the very situation and target visions for local waste management. A large variety of factors play a role in this. Beside technical, infrastructural and climatological aspects, there are also economic and social issues that do have considerable impact on the appropriate decisions

Focussing on the treatment of the (remaining) **mixed waste:**

For a thermal utilisation of mixed waste in a **mass-burn waste incineration** with energy recovery a high waste mass of above 100,000 t/y is needed, and that heat and generated electricity can be fed into the (existing) grid. This is a realistic scenario for large metropolitan areas in Africa only.

Incineration concepts do not only demand high yearly masses, but also a sufficient heating value of the waste itself – in order to avoid co-firing with gas, oil or coal. The minimum heating value of about 8 MJ/kg is often a crucial point due to the high share of wet organics (with a heating value in the range of 3 - 4 MJ/kg). To increase the heating value especially a biological drying of at least of a share of the waste in a separate MBS-facility should be assessed.

For **lower regional masses** of waste per year two main mechanical-biological systems can be applied:

MBT "Splitting", realizable in lower capacities, can start in a simple form at a size of 20,000 t/y, including extracted smaller amounts of dry recyclables and higher caloric RDF (as screen residues) 50 % of the input mass, resp. max. 25 % of its volume are left as an almost biologically "burned out" material, which is to be landfilled (if not be used as a low quality "compost" for special *non-agricultural* application).

Dry stabilisation MBS, especially in the membrane-covered variant, also has a quite universal applicability due to the possibility of realising it in a very variable technical configuration and scale. There is, except metals, no recyclable output, about half of the input remains as raw RDF. The minimum capacity and the needed equipment follow the regional possible use of RDF - as described below.

Table 33: Characteristics of MBT and MBS

Criteria	MBT	MBS
Minimum size for economic viability t/y	20,000 (simple aerobic) 30,000 (AD)	20,000 (if RDF to mass incineration) 80,000 (when RDF refined for industrial use)
Space demand facility	higher	lower
Volume reduction landfill	75 % direct (almost no ashes)	Ca. 90 % direct without indirect ashes
GHG-Reduction landfill	90-95 %	95-98 %
Potential for material recovery (metal, plastic, paper, textiles)	exists (but low share of input)	rather excluded (except metals)
Potential for energy recovery	RDF: from mechanically extracted high-calorific material components, (~ 5% input) plus Aerobic: none from biological processes, AD: ≥ 50m³ biogas per t biogenic input	Higher than MBT: 80 % of dry mass of organics plus paper/plastics/textiles are energetically used.
Dependencies for output	Landfill capacity for max 25 % of volume input plus offtakers for max 10% of input (as sum of recyclables and RDF)	Landfill max 10 % of volume input plus offtakers **for 50 % of input as RDF +** meeting the industry's fuel specifications
Technical complexity	Aerobic: low AD: middle	RDF to mass incineration: low RDF to industry: medium to high
Flexibility towards use for mixed waste and SSO treatment	Possible (in batch and windrow systems)	No, separate solution for each input stream needed

As an extract of a complete SWOT-analysis with much more evaluation parameters, certain central appearing characteristics of these two options are juxtaposed in the Table 33 above, including the concerned basic mass proportions described in Chapter 5.3.1 and 6.

Undoubtedly, there are obvious advantages of the MBS over MBT in terms of in lower space demand, lower demand on landfill volume and *additional* GHG reduction. But, if the dried raw output is *not* given directly to a waste incineration, all this depends on the **guarantee of the industrial partners (cement kilns, power plants) to take the produced RDF.** These operators have their own fuel requirements, such as higher heating value, particle texture and size, ash content, ash melting point, presence of heavy metals, chlorine and sulfur. **Thus, these quality standards of the RDF and the related contract conditions must be clarified in advance.** If the quality demands reveal to be higher (by reasons of e.g. cement quality, process conditions and emission limits, like in the EU), these needs can only be met by a mechanically high elaborate treatment of the raw RDF from the pure drying system, which then economically requires the MBS equipped in this way to be in the order of more than 80,000 t/y.

The MBT is far less affected by these RDF conditions, since it produces significantly fewer amounts of it, as well as out sorted recyclables. The corresponding externally needed **guarantee for MBT**: more and sufficient landfill volume for the treated residues, compared to the extracted inert material of the MBS (in case of preparing industrial used RDF).

Another aspect should be mentioned: between the options MBT/MBS and incineration to treat mixed waste, the concept MBT is the only flexible one concerning the (future targeted) separate collection of organic waste (SSO). The technical equipment of the MBT can process both waste streams equally well. When the biogenic fraction in the mixed waste goes down (by separately collecting this fraction), the freed capacity for conducting the biological treatment stage can be used for handling instantly the source separated biogenic material (e.g. conversion into a compost or biogas-producing facility).

8 Economic feasibility – the COST frame

In the concerned chapters above the options of collection and treatment are described to achieve the desired ecological goals. This chapter focuses on the **local economic situation** – this defines the local budget to implement the optional components

This aspect is described in the following sections, followed by recommendations “what to do first”.

The realization of any approaches to improve the waste management depends on the availability of financial means. **Extent and quality of all measures in waste management are determined by the achievable budget for it.** The size of this budget necessarily follows the economic power of the concerned state/region and the available income of the households. (Worldbank 2018) states here:

"Internationally, 1-1.5 % of average spendable household income is considered an acceptable threshold payment…"[22]

For a coarse orientation the following affordable and acceptable shares can be applied:

- *For the household waste: 1 % of the available income of the households*
- *For <u>all</u> produced wastes: 0.5 % of the <u>local</u> Gross Domestic Product (GDP)*

Since both, the household and the GDP income, differ extremely between the different states and as well as between the regions of one state (e.g. city higher than rural), this realistic yearly budget for waste management must be determined <u>per region.</u>

The way to identify this budget is shown in Figure 43 - first for the waste from **households** as the main action field of the local municipality (with added virtual figures to make the way of calculation clearer).

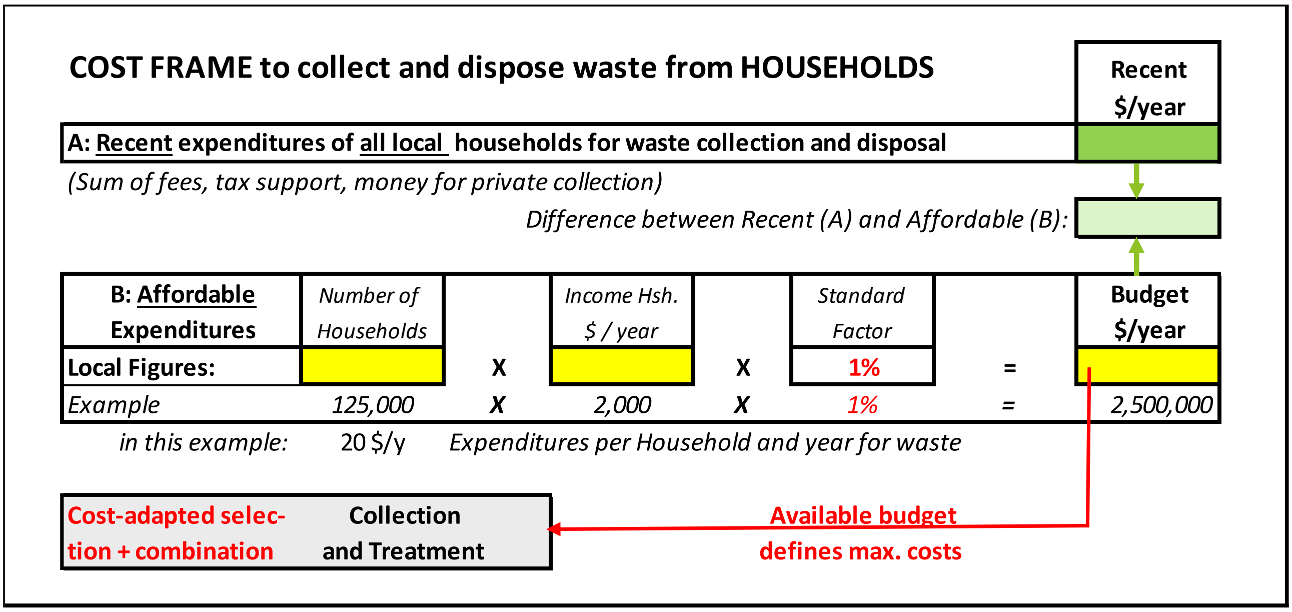


Figure 43: Cost frame to collect and dispose waste from households

In the first **Part A** should be placed how much all the households in the region pay for their waste – this should include direct fees to the municipality, the additional amounts by tax shares and the sum of money given to private/informal collection. At last, the research for this leads to a better insight into the *recent* cost status and its distribution.

In **Part B** - by using existing statistics respectively estimations - the number of local households should be determined, and the *average* income. From the product of it, 1 % of it is taken to get the *justified* yearly budget to handle the household waste. This figure can then first be compared with the yearly amounts of

[22] https://openknowledge.worldbank.org/bitstream/handle/10986/30434/130055-WP-P162603-WasteManagement-PUBLIC.pdf?sequence=1&isAllowed=y

recent payments from Part A, answering the question: How much more can *justified* be spent *more* than now?

> ➢ *Knowing the quantified and justified budget is extremely important to adapt the kind and extent of collection and treatment concepts as well as their combination*

Again, this yearly budget is not necessarily alone for the municipality's action, it must also include potential payments for private and even informal activities: They should be further considered in the fields, where these actors can perform a higher financial and operative efficiency, e.g. in the control function of separate collection.

Aside, at least 10 % of this budget should not be used for the immediate expenditures, this share will be needed for (future) sanitation of the existing dumpsites (Closing cost of a landfill with final profiling, gas collection, sealing, water drainage, recultivation in Germany around 60 $/m², for Africa estimated 20 - 30 $/m².)

Less important, but to complete these considerations for household waste, Figure 44 shows the relation to the GDP and the justified cost for **all** waste in the region.

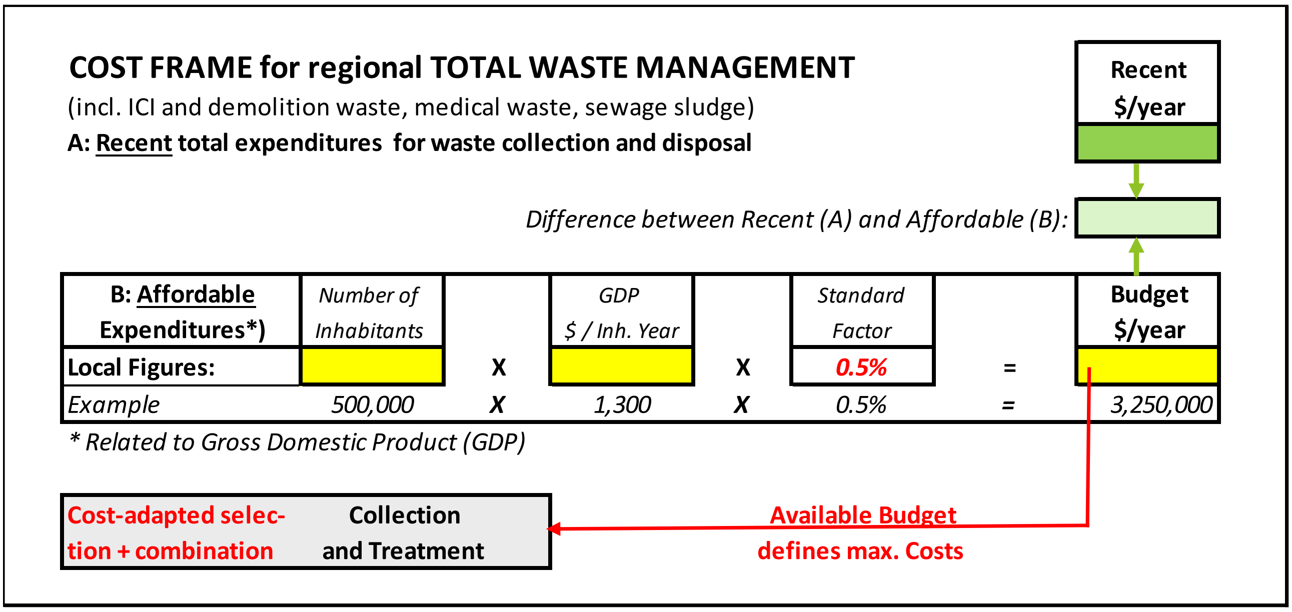


Figure 44: Cost frame to collect and dispose all waste of a region, related to GDP

Basically, it is the same proceeding as with household waste, but the *recent* expenditures for waste outside of the municipality are difficult to determine. Thus, the yearly *recent* expenditures will stay quite unclear. But the regional GDP should be known or can at least be estimated (here by multiplication of GDP per inhabitant and their number). This multiplied by 0.5 % leads to the justified yearly budget to treat all regional waste – of course higher than the budget for the household waste. The minimum recognition of this GDP-related calculation: This budget minus the one for household waste leads to the coarse amount, how much all the commercial actors *outside the households* can and should spend in total for transportation and treatment of their waste.

iIf these commercial waste masses are co-collected and treated by the equipment of the communities, of course the producer must pay the concerned prices. This provides a relevant additional budget, but as well as a corresponding increase especially of the treatment capacities.

Coarse comparison: AFFORDABLE versus NEEDED
Having filled it with the local data, Figure 43 will give the municipality a specific amount for affordable yearly waste expenditures per household, in relation to the local yearly income. Let us assume for a first comparison, 20 $ per year and household are affordable for waste related payments.

Coming from the detailed data of chapter 4 and 5 (Collection and Treatment) we can combine them to a coarse estimation (Table 34) for a *complete* collection and proper treatment of waste. This cost estimation is for 500,000 inhabitants resp. 125,000 households with 200 kg/capita/year leading to around 100,000 t/y of waste.

Table 34: Estimated costs to collect and dispose waste of households in full extend

Scenario Costs for 500.000 inhabitants = 125.000 households, 200 kg/Inh, year		waste mass ton/year	costs per ton	costs per house-hold and year	total costs
Collection costs	*total waste*	100,000	**25 $**	**20 $**	**2,500,000 $**
Treatment costs SSO, simple composting		19,200	18 $	14 $	336,000 $
Treatment costs remaining mixed waste		80,800	**60 $**	48 $	4,848,000 $
Treatment costs	*total waste*	100,000	**52 $**	**41 $**	**5,184,000 $**
Total Costs	***total waste***	**100,000**	**77 $**	**61 $**	**7,684,000 $**

This calculation refers to the mass balance in **chapter 6** assuming that 19,200 t/year esp. of organic waste are separately collected and treated with open composting at low costs of 18 $/ton. Costs for collection are set at 25 $/ton. The most cost influencing factor is the specific amount for the treatment of mixed waste, here assumed with 60 $/ton for a "state of the art" MBT or MBS.

Coming from these first settings we recognize total costs of 77 $/ton resp. 61 $/y related to the household. Even if we say that 20 % of the total costs are covered by external (industrial/commercial) producers, the remaining 49 $/y cannot be covered by the average household income in African countries, thereby only about half of all desired measures could be realized by *own* local financial fundings.

This shows first the importance to know *in advance* the achievable *own local financial resources*.

9 Think big, but start small: Model Projects

Based on the local conditions and the given planning aspects for collection and treatment the local municipality should and will work out a waste management concept for the complete region, including activities for separate collection and estimated costs – these might pile up to some million $ per year. This high amount leads – understandable – to the question: **Does this work as forecasted, especially the efficiency of separate collection?**

This question was set wherever an extended separate collection was projected, especially for SSO. Since the specific complications, the degree of participation, the masses of separated SSO and its quality are not predictable, some central rules can be given:

Step 1: Installation of a composting site

1. Set up a first **lower scaled, open windrow composting** site and start it with the "easy to get" organic fractions: Municipal green waste, followed by organic market waste, "clean" commercial/industrial organic residues etc.
2. **Ensure** the quality-adapted **utilization of the produced compost.** In this context it is advisable to not focus on financial revenues but on positive experiences of the off takers (schools, hotels, municipal parks, small agricultural enterprises, private house garden farmers etc.) and decision makers (municipality, politics, administration). Awareness raising and engagement of both off-takers and decision-makers is of great importance for the success of waste management projects, so that stakeholders commit to the respective project in terms of content and funding. A helping factor to generate future demand and to reduce risk of quality dissatisfaction is to give away the compost on a free basis in the first year of production.

Recommendations/Requirements for the Composting site:

- First size around **3,000 m²** (more local space advantageous for later extension)
- **25 %** of it should be **roofed** to protect matured compost against rain
- **Water** supply for remoistening (best: rain collection from roofed areas)
- **Wheel loader** (Option: rented 1 day per week to turn the piles)
- Advantageous: Tractor-driven small **pile turning machine**
- Mobile (small) **shredder** to grind branches either directly at source or at the composting site – this provides needed structure material
- (Drum) **Screen** 20 mm to refine the raw compost

Some of the mechanical equipment will first work below their potential capacity – this is unavoidable but does not matter: Prospectively the masses will increase to use the capacities.

Having established the full working first composting site and performing it for about one year with "easy to get"-material, the first step is done, with the following important effects:

- The **municipality shows their engaged attitude** within their own possibilities to step forward in the recycling of organic waste
- The conversion of "ugly" organics to "fine" compost can be **presented in in a realized, good working way** - important to raise awareness and motivation for it.
- The operator has **gained experience** with the composting in several operative and technical aspects
- During the first operation phase, the long-term **reliable application of the produced compost is secured.** This security is of **dominant importance to win citizens for separate collection** of organic waste. Neglecting this made already several projects of separate collection fail.

Step 2: Introduction of separate collection of organics by the citizens

After the "easy to get" organic masses the next step is to win separate collected organic waste from households, with a much higher collectable potential, but as well with a much higher demand of convincing the citizens to participate.

Again, here two basic rules, followed by all communities in Germany/Middle Europe that established the system of SSO completely:

- *Not implementing a concept of separate collection of SSO that seems be fitting and workable throughout the whole region.*
- *First of all, gaining experience on a small scale, with only some thousand inhabitants.*

The aim of these smaller collection models was and is *not a scientific one*. The aim is to prove acceptance and high function in a "lighthouse project", to be published and copied. Thereby:

Model projects are to be arranged in a way that they *are* **successful** in terms of participation, separated mass and quality of SSO.

This means for the **selection and conduction of a model area for the SSO project**:

The **citizens** of the model area should have

- low existential sorrows distracting them from the project's goal,
- higher social stability,
- own responsibility per household for the waste,
- house to house collection.

This leads mainly to areas with higher education degree, higher income and single houses with gardens. The thereby co-collected garden waste pushes the SSO mass coming to a higher separation rate – welcome to demonstrate the reduction effect. Local politicians, representatives of NGOs or other influencers living in the model area are a positive factor for success.

Aspects on the **operative and administrative** side:

If a **bag system** is used (very common): Different colored *transparent* bags, e.g. green for organics, grey for remaining waste. The transparency gives the needed possibility to check the quality of SSO. During the pilot phase, a sufficient number of bags must be provided by the municipality and are distributed to the households on demand at collection, for free (SSO-bags are emptied at the composting site and recycled[23],).

Important: To get the **mass shares of separate collection** the incoming waste streams SSO *and* mixed waste from the model area must be **weighed**, if possible, continuously during the project time of one year, at least completely in one week every three months. In parallel, counting the bags of SSO and mixed

[23] To use plastic bags for SSO is here only a short term solution for the model project. In long terms, bags for collection should and will be replaced by bins. Biodegradable bags might appear as an alternative, but have a longer degradation time which is not finished within the composting process. Thereby at least they will disturb the optical impression of the compost.

waste bags is added. It must be secured that all wastes of this weighing and counting balance come *exclusively from the model area* and not from other sources.

The **actors in collection** must **be reliable and interested in the success of the project.** Their main tasks:

- Control the quality of SSO at the collection point,
- Related immediate feedback to the household, elimination of misunderstandings,
- Collection of complains and ideas, forwarding them to the monitoring center of the project.

Components of Public Work:

- **Paper flyers** with the project description/ participation request to all households,
- **Project publication** in e.g. newspapers and placing in **social media**
- **Telephone-Hotline** for question and complains
- Immediate **elimination of occurring obstacles**

Related costs for the model project
As said, the central aim of the model project is to **demonstrate a good function of separate collection of organic waste** including the proper treatment. When the project fails, by which reason ever, the approach is locally irreversibly "burned" for the next five to ten years: **There is no alternative to success.** Therefore, the **financial support** of this model area must be **much higher** in preparation and during the test period than it will be possible in a complete regional scale in the future. Nevertheless, the costs for this model project should only represent a small amount of a municipality's current waste management budget due to the comparatively small size of the project.

Results of the model project (composting site plus separate collection)**:**

- A complete working composting site will be established with the needed experience in operation and use of the compost
- The separate collection and use of organic waste will be successfully demonstrated, as a model to be copied by others.
- The involved stakeholders collect experience in collection and treatment – important to extend the concept successfully.
- By taking responsibility, the municipality acts as a role model for citizens and thereby demonstrates the importance organic waste management.

10 Conclusion

The recent waste management in Ethiopia and East African States produces strong negative environmental effects, endangers the health of population and fails to recover material and energy. When landfilled, the untreated waste produces heavily contaminated leachate, strong emissions of methane as a greenhouse gas, this added by occasional explosions, landslips and a permanent infection risk for people working on or close to the landfill.

Almost all these negative impacts are caused by the biogenic components in the waste, holding a very high share of around 70 % - quite similar in all East African States.

Therefor the untreated biogenic waste must no longer be landfilled. The ways to achieve this:

- Complete regular collection of all waste to direct it in controlled disposal ways
- Source separate collection of organic waste – this can reduce the remaining waste and let produce applicable compost with almost no contaminations
- Treatment of the remaining waste to eliminate the biological reactivity before it goes to the landfill

This guide provides in this respect examples, detailed data, information, realization options and regional recommendations for the different systems of

- Collection, with logistic aspects, needed equipment and planning hints for the local configuration
- Treatment, for both separate collected organics and mixed waste, here with biologically concepts in the focus, since they are powerful and easier to realize especially for lower capacities.

Criteria for concept decisions are provided in both fields, helping at the final selection following the local conditions. An own chapter handles the framing conditions to realize the improved waste management, with integrated hints increase both:

a) local financial budget, esp. determined by an affordable share of the household income. This shows that the budget will allow to realize the first, most important steps of a later full-scale implementation.

b) public and political awareness, which is recently low for the subject “waste”, but very important to win for the needed willingness to participate.

Waste management is an evolutionary process following the economic power of the concerned state or region. Aside of the upcoming long-term planning and realization of the complete system, finally recommendations are given for the first steps of well payable model projects to collect experience in treatment and separate collection of organic waste.

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Stakeholder feedback

An important part of the project *Guideline for organic waste treatment in East Africa* was the engagement of stakeholders from all areas of waste management - politics, administration, science and private sector. The aim was to gain and transfer knowledge about current practices in organic waste management and how to improve and adapt them locally in order to raise awareness of the importance of proper organic waste handling and treatment.

In addition to face-to-face dialogue with stakeholders, contributions to specialised journals, conference participation and involvement in various networks, two workshops were held as part of this project. In the course of these two workshops the results of the present report as well as the outcomes of our status-quo survey (Lenhart et al. 2022) were made available to a wide audience. During the events, there were lively discussions which opened up further questions and gave insights into the practical experiences of the participants.

In the first workshop[24], the “circular solutions festival” organized by the “PREVENT waste alliance” as a hybrid conference, the audience mainly consisted of NGOs and private companies. An important comment from the plenary was that composting, as one of the key recommendations within this guideline, in particular is already established worldwide. However, the understanding and the technologies used differ enormously from country to country. Due to false expectations or inappropriate technical solutions, trust in the technology was partially damaged. However, adapted technologies and knowledge about process control and parameters are urgently needed for successful implementation. We hope that the explanations in chapter 5 of this guideline can offer some help in this regard.

Furthermore, technical details for specific logistics concepts and possibilities for community/village composting were discussed. The challenges Ethiopia and other East African countries face at the moment were highlighted, especially in valorisation of organic waste. Organic waste is often not associated with any monetary value, although East African countries import large amounts of industrial fertiliser, where compost and digestate could be a major substitute. Giving organic waste a value is highly important.

As for the second workshop, organized by “CIFA Onlus” as a hybrid conference in Addis Ababa, the attendants mainly came from public authorities and private companies from Ethiopia as well as from NGOs being active in East Africa. Participants particularly pointed out the problems they face in their daily work, but also problems in initiating projects to create new treatment and logistics capacities. These include:

- high dependency on imported technologies and locally available trained personnel - accompanied by difficulties in process management
- a lack of reliability on legal framework conditions and the wish for more political support
- establishment of a market for the sale of composts and biofertilizers as well as other financing options in general
- creation of uniform quality criteria for better comparability of the products

[24] Available online to watch at: YouTube

- networking of actors in the organic waste sector in Ethiopia to monitor current trends and establish synergies.

Another important point within the discussion was the discrepancy between the available literature values on waste generation or composition and the collected data of authorised institutions in Ethiopia. These differences are a result of the shortage of uniform methods for waste characterisation and the statistically insufficient scope of sampling in large parts. A gradual introduction of affordable methods for characterisation in cooperation with the responsible municipalities would significantly improve the quality and availability of data, which can provide local businesses and municipalities with better planning security and opportunities for process optimisation.

In summary, the two workshops and contact with stakeholders in Ethiopia led to fruitful discussions and practical insights to everyday and systematic challenges of local actors and decision-makers. During the event following areas of action in particular were identified, which go beyond the scope of this guideline and demand action in the future:

- Improve data availability and quality
- network and develop a municipal, country or national strategy
- develop appropriate technical and trained human resources
- raise awareness to gain policy support
- give organic waste a value

This guide does not claim to be universally applicable, as individual challenges of municipalities and companies require detailed assessment. However, we think that this project provides a sound basis for creating a common strategy and implementing concrete projects in organic waste management. We hope that it will help in your daily work and this will be just the start!

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