Challenges and Potential of Anaerobic Digestion from Municipal and Agricultural Organic Waste in Ethiopia

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ABSTRACT

Poor solid waste management is a global issue that causes vast environmental, social, and financial costs to societies. Considering waste as a potential resource, both materially and energetically, will contribute towards reducing residual waste and represent direct support to developing a circular economy. The challenges and potentials of organic waste in Ethiopia and other East African countries have been examined in the "Guideline for organic waste treatment in East Africa" project by the German Biomass Research Center (DBFZ). With a waste generation of 6.63 million tons per year, of which 55-80 percent is organic waste, Ethiopia has excellent potential for valorizing organic waste. Anaerobic digestion can be one integral part of this systematic approach. This paper aims to overview the challenges and potentials of using anaerobic digestion for treating MSW and agricultural residues from a macro-perspective. The methodology is based on a systematic literature review, meta-analysis, and expert interviews. MSW has a potential of 161 to 385 million m3 year-1 of methane. As one example for the agricultural sector, coffee byproducts have a potential of 68 million m3 year-1. Technical and economic restrictions in logistics and processing technologies pose the most significant challenges in utilizing this potential.

Keywords: Agricultural Byproducts; Anerobic Digestion; Biogas; Ethiopia; Municipal Organic Waste

INTRODUCTION

The following paper describes the outcomes of a research project that intends to develop a comprehensive guideline for organic waste management directed to decision-makers and planners from municipalities, science, and private companies in Ethiopia and other East African countries. The outcomes of a baseline study regarding the challenges and potentials of organic waste and pathways for the technical implementation of anaerobic treatment facilities within a holistic waste management system will be described.

All outcomes were elaborated in the context of the pilot project "Guideline for organic waste treatment in East Africa" as part of a call for solutions by the PREVENT Waste Alliance, an initiative by the German Federal Ministry for Economic Cooperation and Development (BMZ). The project aimed to develop a legal, technical, and economic guideline for dealing with organic waste as a primary strategy for politics, administration, research, and the private sector for East African countries using the example of Ethiopia.
The guideline should be a profound basis to apprise decision-makers of efficient and well-proven technical solutions in organic waste handling and give planners and builders a good starting point for future planning (Wiegel et al., 2022). The status-quo report provides a general overview of organic waste management in East African countries, explicitly using Ethiopia as an example (Lenhart et al., 2022). All investigations were carried out assuming that successful technical implementation can only be achieved by considering the entire logistics and treatment value chain and the legal framework conditions.

Municipal solid organic waste

The total solid waste generated in East African countries in 2016 was estimated to be 52.6 million metric tons annually. The global average was calculated to be 0.74 kg day^{-1} $capita^{-1}$. Therefore, the average per capita waste generation is significantly higher in EAC than 0.46 kg day^{-1} $capita^{-1}$ in Sub-Saharan countries, an increase of 22 percent (Kaza et al., 2018). Considerable spatial differences in the amount of waste generated can be observed, 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 Seychelles or 1 kg per day for Mauritius (Figure 1). High per capita waste generation rates reported for small-island States are typical, often due to high levels of tourism and better waste accounting (UNEP, 2018).

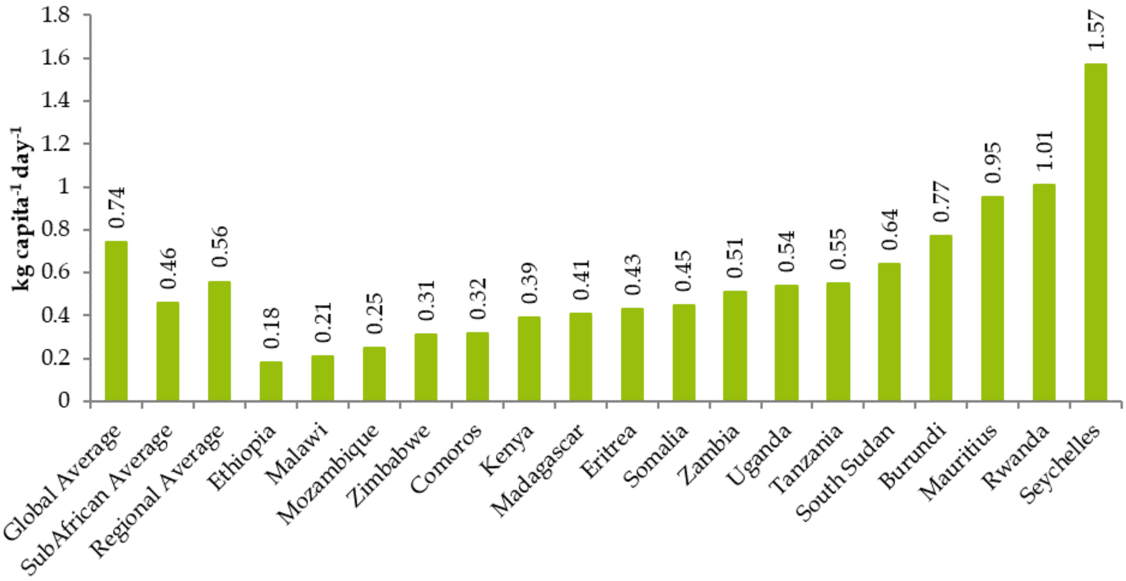

Figure 1. Waste generation per day and per capita in East African (Lenhart et al., 2022) countries data explored from (Kaza et al., 2018)

The per capita waste generation in Ethiopia is the lowest in East Africa. This is due to a high percentage of people living in rural areas, with 80 % reported in 2016. According to the used dataset, this lowers the average per capita production rate significantly since the rural population is considered to have half the waste generation rate than the urban population. Other studies also confirm this. The average capita-specific waste generation in Ethiopia and other EAC is reported to be extremely low compared to developed countries, below 0.5 kg day-1 capita-1, with a waste density between 330 and 370 kg m^{-3} (Birhanu, 2015; Gelan, 2021; Teshome, 2021).

Considering the population of each country and the total amount of waste produced per year, the situation is reversed: small-island States produce small quantities of solid waste. In contrast, four of the

17 analyzed countries produce more than 50 % of the waste generated in Eastern Africa, Ethiopia being the third major producer with 6.53 million tons per year (World Bank 2020).

One of the most significant challenges in the economic development of low-income countries, in general, is the correlated growth of waste volume with rising income, which is often not considered within the planning process of waste management structures (Teshome, 2021), e.g., in Addis Ababa, waste volumes are increasing. However, waste management efficiency is decreasing (Gelan, 2021). The same problem exists in other developing countries and is common in Africa. To estimate the trend of waste generation in East Africa, generation rate projections are taken from "More growth, less garbage," while population projections are from UN Population Projections, Medium Variant, 2019 Revision. Considering both the population growth and the variation in waste generated per day per capita, in 2050, total waste produced in Eastern Africa is expected to reach 192 million metric tons per year - an increment of three times from 2020.

Waste composition categorizes types of materials in municipal solid waste (Kaza et al., 2018). For EAC, very few data are available on the composition of municipal solid waste, which is generally obtained from major cities. A study on waste composition in African countries has been compiled by the African Clean Cities Platform (ACCP 2019). The study has collected data from the 41 cities of 29 African countries participating in the program. These data have been integrated with the waste composition reported by UNEP for 12 African cities (UNEP, 2018). What a Waste 2.0 and ACCP 2019 use different methodological approaches, which is why the data generated can only be compared to a limited extent. A coarse comparison has been visualized in **Error! Reference source not found.**

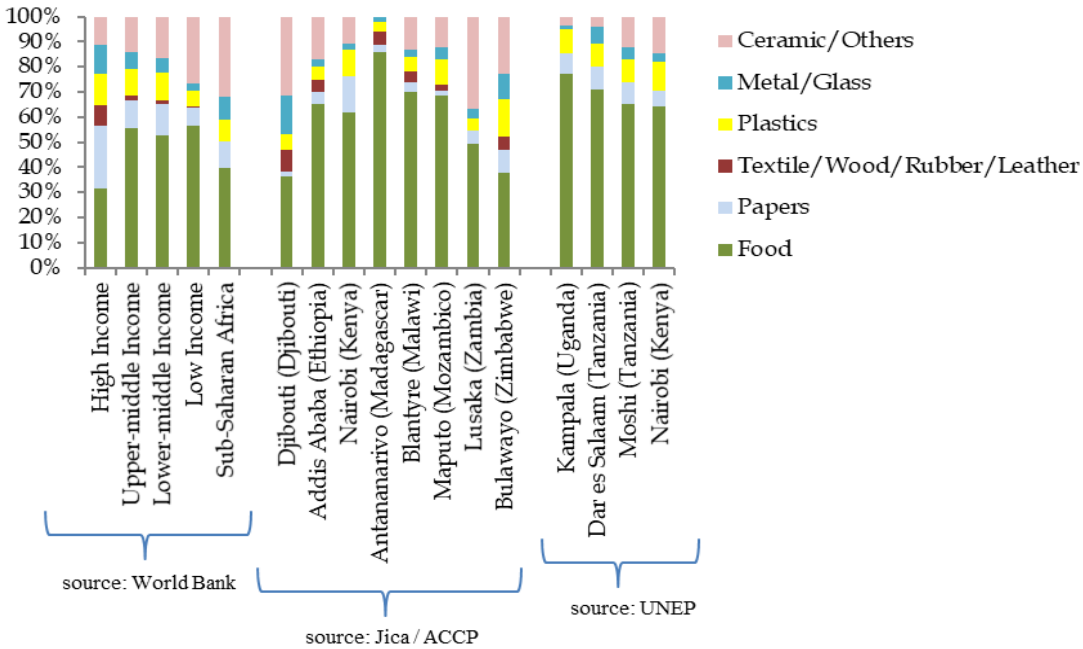

Figure 2. The waste composition according to income level and selected examples from cities of EAC (Lenhart et al., 2022)

Generally, the composition of waste varies according to the income level. With the increasing income level, the percentage of organic waste tends to decrease while the quantity of plastic and paper waste increases. The dominant fraction within the waste composition of East African cities is represented by organic waste. Besides the total quantities and composition of waste streams, knowledge of the current state of already existing treatment facilities, logistics, and regulatory framework is also essential to recommend practical implementation. Since the status quo of these areas also varies significantly among regions of individual countries, and comprehensive data on EAC are not available, case studies can approximate the current state. For this reason, three different case studies for varying settlement structures were prepared within the project presented here. The infrastructural conditions of cities and municipalities are decisive for selecting adapted technical solutions for the treatment and logistics of waste. Therefore, the three case studies, Addis Ababa, Hawassa, and Gidole, are discussed within the study (Lenhart et al., 2022). Subsequently, the case of Addis Ababa will be highlighted.

The case of Addis Ababa

Addis Ababa, the capital city of Ethiopia, is a megacity in rapid development that counts approximately 5 million inhabitants (Lenhart et al., 2022). MSWM in the city was structured recently and is still subjected to various changes that aim at adapting the system to the needs and capabilities of the specific context. Since January 2010 till now, responsibility for solid waste management has been assigned to Addis Ababa City Solid Waste Management Agency (AACSWMA).

Since 2004, as per its development plan, Addis Ababa started encouraging private companies and Micro and Small Enterprise (MSE) Unions to participate in MSWM. As a result, in 2017, there were six private companies and 521 MSEs, with more than 10,000 operators collecting from households, institutions, and commercial areas (Mohammed & Elias, 2017). In 2018, the MSEs involved in collecting municipal solid waste were grouped into cooperatives, called collectors' associations; each newly formed collectors' association was appointed to provide collection service exclusively to one or two Woredas, depending on their geographical extension. Each association of collectors takes care of the door-to-door waste collection for families residing in the area of competence and usually provides service to each family unit twice a week. The associations are under the supervision of the Woreda Solid Waste Management office (Lenhart et al., 2022).

In Addis Ababa, waste is collected through a multi-stage system. The structure is based on the administrative districts of the city. The Addis Ababa Solid Waste Management Agency organizes the entire waste collection and promotes the integration of the private sector, which collects waste from institutions. In 2020 119 municipal collection vehicles and 161 private vehicles from 53 private companies are engaged in waste transport to the city-owned Reppi landfill (Gelan, 2021). Manual waste collection is often necessary because residential areas are densely built, roads and paths are unpaved and unsuitable for heavy equipment. This also results in a high laborer requirement of 7 to 14 people 1000 t^{-1} $year^{-1}$(Pfaff-Simoneit, 2012). Decentralized collection points for pre-treatment or waste separation are used. Each Solid Waste Collectors association utilizes several collection points to store their daily waste collected from the nearby neighborhood. The waste is brought to the collection points using small-scale transport vehicles. The municipality is then in charge of transporting to the landfill by compactor trucks. These trucks are scheduled to pass each collection point at least once or twice per day, but the schedule often needs to be respected due to the scarcity of trucks and the high frequency of stops (Lenhart et al., 2022).

The compensation system adopted by AACSWMA for waste collection is based on the quantity of waste delivered to the landfill. This approach ensures that most of the waste will be transported to the Reppi landfill and is thought to reduce illegal dumping practices. On the other hand, this system discourages practices aimed at reducing waste entering landfills, such as recycling practices (Lenhart et al., 2022).

A lack of recycling practices and improper landfill design without sealing and coverage lead to uncontrolled methane emissions. Between 2012 and 2017, 4,848,147 tCO_{2e} methane was emitted, positively correlating with the increment of solid waste disposal in Adds Ababa and its surroundings. The study indicates as a cause of the massive amount of emissions a low level of 3Rs strategy implementation in the Solid Waste sector that restricts resource recovery and contributes to GHG emission in the study area (Ali & Tarekegn, 2018).

To overcome this problem, the municipality of Addis Ababa decided to promote the creation of compost producers' MSEs and to link them with the cooperatives in charge of urban greenery as a first market outlet. In 2022, 76 composting MSEs were active (more or less one per Woreda), involving around 772 members. At their creation, the compost producers' associations were provided with small land (300 m^2 on average) and primary business and technical training. The municipality further promoted this business, guaranteeing a monetary incentive for each kg of compost sold to Urban Greenery cooperatives (Lenhart et al., 2022).

The use of anaerobic digestion (AD) as a treatment option for organic waste has yet to be implemented on the municipal level. Small-scale composting sites so far have been proven to be effective, low-cost solutions on the Woreda level. So far, no logistical concept exists to provide source-separated organics (SSO). Having an organic fraction separated at the source would benefit AD in producing high-quality digestates for using agricultural land besides biogas. Nevertheless, is the organic fraction within Addis Ababa a suitable substrate for AD and the most significant opportunity to reduce the city's overall waste volume when collected separately? The overall waste volume of Addis Ababa could be reduced by up to 48 %, only focusing on household organic waste based on composition and sources (AACSWMA 2019; GES 2020).

Agricultural and other relevant organic residues

Ethiopia's most important economic sector is still the agricultural sector. The top 3 exported goods are coffee, spices, vegetables, and oil seeds (OEC 2019). With the production and processing of agricultural products comes organic waste. Though, agricultural waste is often not felt as a threat to the environment and public health or even as a nuisance since it is traditionally disposed of through direct use - direct animal feeding, direct application to fields, or direct combustion. Nevertheless, it is important to consider that agriculture and livestock production practices are rapidly changing in Ethiopia, as seen in the example of floriculture production (Gelaye, 2023). The amount and type of residues generated could become a problem soon.

Unlike agricultural waste, invasive species such as water hyacinth already pose a problem - directly and indirectly affecting fish, crops, livestock production, electric power generation, irrigation, waterway transportation, tourism, and human health. Nevertheless, the biomasses mentioned above not only create problems but also a significant untapped potential and this is largely without any competition for utilization. These relatively homogenous waste streams are highly suitable for utilization in AD due to less need for pre-treatment compared to mixed municipal waste and typically less effort in logistics compared to door-to-door collection. Taking coffee byproducts as an example, Ethiopia is the major exporter of coffee among all the African countries (Figure 3). The amount of coffee exported in 2019/2020 from Ethiopia was 271,111 metric tons; Ethiopian coffee production varied from around 370,000 tons to 470,000 tons in the last decade (Degaga, 2020).

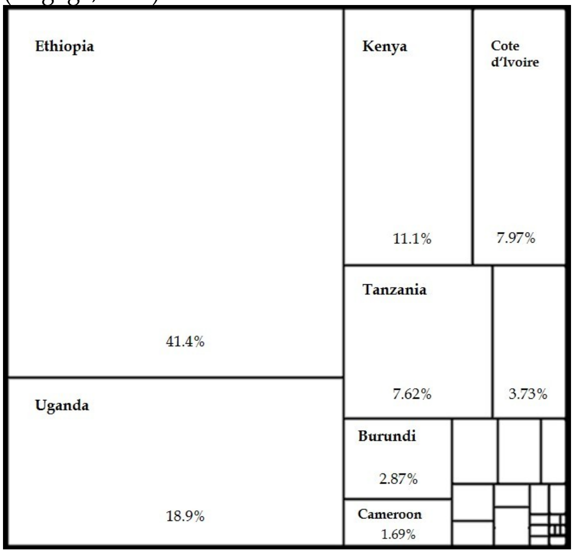

Figure 3. Value of coffee export in 2019 among African countries (OEC 2019)

Given the enormous amount of bio-product generated by the coffee process sector and the high potential environmental problems caused by coffee processing residues, there is a great interest in converting coffee bio-products from a threat to a resource, as evidenced by numerous studies on this topic available in the literature.

Biogas in Ethiopia

Biogas or AD has been well-known in Ethiopia and EAC since 1957 and recent activities since the early 2000s. The dissemination of small-scale domestic biogas plants throughout East Africa has been successful. Mid-scale biogas plants within the private sector are starting to grow. Large-scale plants on an industrial level, found throughout Germany for the treatment of agricultural, industrial, or municipal waste streams, have yet to be introduced. Especially two projects have recently been crucial for disseminating domestic digesters.

The Africa Biogas Partnership Program (ABPP) is a partnership between Hivos and SNV to support national programs on domestic biogas in five African countries. The program aimed at constructing 100,000 biogas plants in Ethiopia, Kenya, Tanzania, Uganda, and Burkina Faso, providing about half a million people access to a sustainable energy source by 2017 (Lenhart et al., 2022).

The overall objective of the ABPP was to contribute to achieving the Millennium Development Goals through the sustained construction of domestic biogas plants as a local, sustainable energy source. This was intended to be fulfilled by developing a commercially viable and market-oriented biogas sector. Until its project ended in 2019, the ABPP constructed over 18,500 biogas plants (Lenhart et al., 2022).

The Biogas Dissemination Scale-Up Program (NBPE+) is a public-private partnership at the federal, regional, and district levels funded by the European Union and the Government of Ethiopia. SNV manages this program and also provides technical assistance in the implementation. The Ministry of Water, Irrigation, and Electricity executes the program on behalf of the Government of Ethiopia (Lenhart et al., 2022).

The program was launched in May 2017 with an implementation period of over five years. The Biogas Dissemination Scale-Up Program builds on the achievements of the National Biogas Program of Ethiopia (NBPE), which has been implemented since 2009 in four regions funded by the governments of the Netherlands and Ethiopia. NBPE is part of the ABPP, with Hivos as a fund manager and SNV providing technical assistance. By the end of 2016, NBPE had supported the installation of over 15,000 biodigesters in Ethiopia, mostly fixed-dome digesters. Within NBPE+, a further 36,000 biodigesters will be constructed (Lenhart et al., 2022; SNV, 2022). The domestic digesters from NBPE+ use only cattle manure, human excreta, and water for AD. Therefore, despite the success and widespread dissemination of SNV's project, other relevant waste streams presented still offer great unused potential, especially for mid- to large-scale applications.

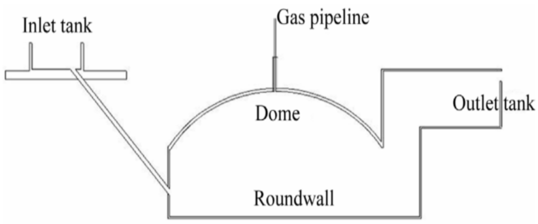

Figure 4. GGC 2047 fixed dome digester (Mulinda et al., 2013)

The predominantly used biogas models in domestic use are the Sinidu and the Sinidu 2008 model. The technical design of both models is based on the GGC 2047 fixed dome model from Nepal. Both models function completely without mechanical components and are optimized for using liquid substrates in the form of manure and water. The reactor volumes vary between 4-10 m³ (SNV 2019). The Sinidu models have an overflow with one or more subsequent slurry pits for subsequent stabilization through atomization. The Sinidu 2008 model is a further development to reduce the required water input, optimize the design and adapt to different types of ground.

MATERIALS AND METHODS

The methodology is based on a systematic literature review, meta-analysis, and expert interviews. Thirtyseven scientific articles, 56 reports, and 50 other literature sources were reviewed for this purpose. The complete list of references can be obtained from DBFZ reports 45 and 47 (Lenhart et al., 2022; Wiegel et al., 2022). Data on waste generation, waste composition, recycling rates, and organic waste management of East African countries have been obtained using secondary sources. Regarding essential data on municipal waste generation, the study uses mainly the dataset "What a Waste 2.0," published in 2018; what a Waste 2.0 document reports data predominantly from 2011–17, although comprehensive data spans about two decades. Notes on the data acquisition methodology of What a Waste 2.0 means can be found in its introduction chapter (Kaza et al., 2018).

Regarding treatment technologies currently implemented in Eastern Africa and relevant projects on organic waste management, primary information has been gathered by research on the web. For three case study areas, Addis Ababa, Hawassa, and Gidole, interviews have been conducted with experts: AACSWMA, Programme Coordinator for the WASH program, NAMA project (Lenhart et al., 2022). Production rates and export volume were selected for relevant agricultural waste streams. Other biomasses were selected by environmental impact. Data were obtained from multiple secondary sources.

There still need to be consistent standards for the collection of waste management statistics in Ethiopia. Due to the low collection rate and the large proportion of unformalized waste collectors, the statistics presented cannot be regarded as reliable for the whole country. Nevertheless, the data presented provide a good basis for an initial assessment of expected potential. However, a standardization for collecting waste management data based on LAGA PN 98 from Germany or other international standards is still recommended. In contrast, agricultural production and sales figures, in combination with specific residue shares, provide a reliable database for estimating residue potentials in the agricultural sector. However, further field studies are mandatory for each case's technical planning. Implementation strategies were developed in cooperation with science and the private sector based on the historical development of the German organic waste management system. Practical experiences from German and Ethiopian experts in the waste management sector have also been implemented.

RESULTS AND DISCUSSION

Based on the status quo report results, some residual material potentials are examined for their suitability for AD. In addition, assessments for practical implementation are presented based on the developed guideline.

Potential and challenges of municipal solid organic waste for anaerobic digestion

Ethiopia has a waste generation of 6.53 million tons annually (World Bank, 2020), of which 55-80 percent is organic waste, depending on the region. However, due to high population growth and improving income levels, this amount is expected to triple by 2050 (Lenhart et al., 2022). An average biogas potential of 75-123 m^3 for the organic fraction of household waste and average methane content of 60% (Döhler, 2013) results in an annual potential of 161 to 385 million m^3 methane today – or 483 to 1,155 million m^3 in 2050. Realistically, 60 to 97 % waste capture rates can be achieved in the long run, but the process towards this goal is very challenging in the short to medium term.

AD is a viable option on the institutional scale to eliminate the biological reactivity of organic waste and reduce the overall waste volume while producing biogas as a renewable energy source and digestates as fertilizer. The best way to produce high-quality fertilizer is to utilize SSO. This can be achieved quite easily on a small scale, as shown within the project NBPE+. On a large scale, a holistic logistics concept is needed to separate organics at source from households. Therefore, a long-term strategic orientation from the municipalities is required. The introduction of such a collection system that allows the gaining of SSO has to be a stepwise and evolutionary process and cannot be introduced overnight. However, AD can play an important role even in the short-term within MSWM while focusing on "low-hanging fruits." Homogenous waste streams from garden maintenance and pruning, food processing industries, restaurants, and markets can be used immediately for biogas and fertilizer production. The efforts for logistics and pre-treatment are much less compared to household organic waste.

Organic waste from households typically has higher dry matter contents and a broader particle size distribution than a mixture of manure and water. Due to the broader particle size distribution and the influence of impurities, AD applications for MSW usually require various treatment steps, such as size reduction, impurity separation, screening, and mixing or inoculation (Kaltschmitt et al., 2016). The small-scale fixed-dome digester currently predominantly used is technically inappropriate for this purpose. Dry fermentation processes in batch (discontinuous) or plug flow (continuous) design with adequate mechanized or manual treatment processes is more appropriate for fermentation domestic organic waste with a high dry matter content of 15-50 % in high volumes.

The choice of a continuous or discontinuous process must be discussed for each case. What they have in common, however, is that due to the higher degree of mechanization compared to the Sinidu fermenters, a larger substrate requirement and, thus, a significantly larger reactor volume are needed for profitable operation. This means that waste management biogas plants are mainly suitable for institutional applications, such as municipal waste management, in which an entire city or at least a district provides organic waste.

The residues from AD processes (digestate) can be used as a subsidy for industrial fertilizers. Digestate shows varying characteristics in dependence on the input material and operating conditions. Usually, the water content is still relatively high at 60-99 %, and it contains odor-forming substances and inorganic nutrients. Therefore, after-treatment, e.g., composting, is mandatory (Wiegel et al., 2022).

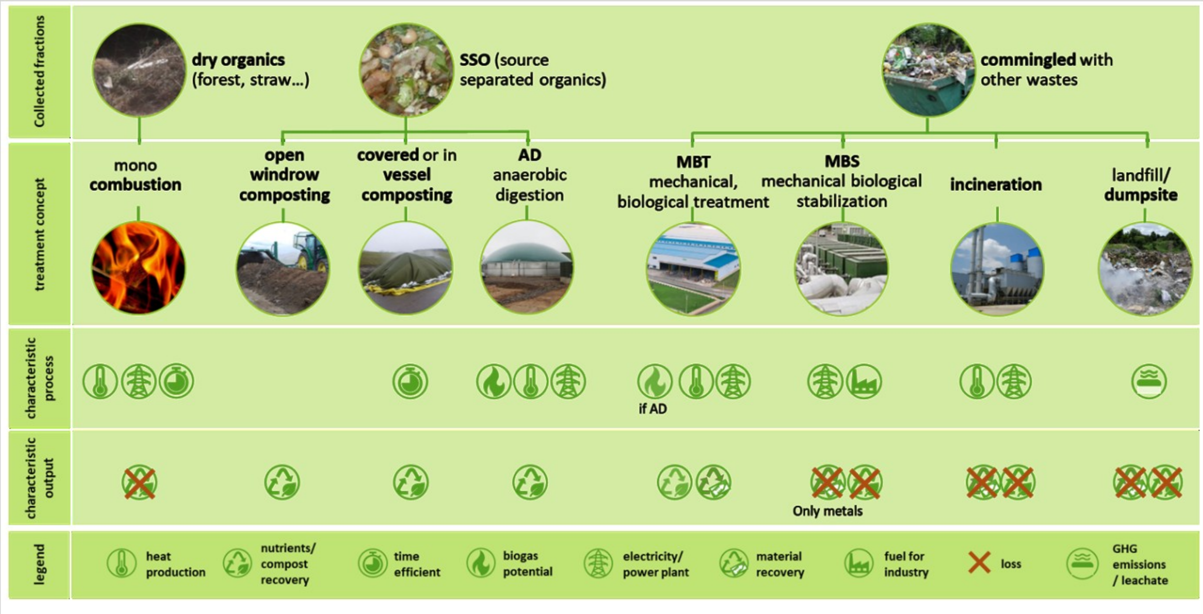

Figure 5. Overview waste treatment technologies - visualizing process- and output characteristics (© 2022 ICU) (Wiegel et al., 2022)

For commingled waste streams, like municipal household waste, other treatment options like mechanical biological treatment (MBT), mechanical biological stabilization (MBS), or incineration should be introduced (see Figure 5). While AD of SSO should be part of a long-term strategy to produce high-quality products, all other options can eliminate biological reactivity and reduce the waste volume significantly. MBT can also have an AD stage for biogas production within the processing chain to utilize the energetic potential. Controlled incineration should only be the last resort in terms of circular economy, as valuable nutrients are lost in this way, but anything else done with organic waste is far better than land-filling or open (uncontrolled) burning – in all considerable aspects.

The recommendations developed within the guideline consider composting the first important step in treating MSWM due to its low technological complexity and the possibility of creating local value chains involving communities. Accordingly, the recommendations for starting a comprehensive MSWM strategy are (Wiegel et al. ,2022):

Step 1: Installation of a composting site

Set up a first lower-scaled, open windrow composting site and start it with easily collectible organic fractions. Ensure the quality-adapted utilization of the produced compost.

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

Focus on something other than large-scale solutions. First, gaining experience on a small scale, with only some thousand inhabitants.

The potential of agricultural residues and other relevant biomasses for anaerobic digestion

Other biomasses without competing use cases beyond household waste also show great potentials for anaerobic digestion, such as residues from coffee processing, water hyacinths, animal manure from livestock, or abattoir waste, to name a few. Focussing on these homogenous waste streams or "low-hanging fruits" is beneficial for keeping logistic and pre-treatment costs low while producing high-quality products similar to AD for SSO in MSWM practices. In addition, some of these organic residues, such as coffee husks, cause visible problems for the population. Solving these problems can lead to increased acceptance and thus promote the spread of biogas technologies.

A look at the German biogas sector also shows that the focus on agricultural and industrial residues is promising for the expansion of AD. In Germany, more than 9,000 biogas plants are in operation (Stefan Majer et al., 2019), with a total installed capacity of 5,600 MW (BMEL 2022). Of these, 8470 are agricultural plants alone, including small-scale liquid manure plants (800) following §27b EEG 2012/ §46 EEG 2014/ §44 EEG 2017 and biomethane upgrading plants (203).

Ethiopia's agricultural sector offers many opportunities for the implementation of AD. One example is the production of coffee. Ethiopia, the major coffee exporter on the African continent, has large quantities of processing residues, causing potential environmental problems. According to a study on the bio-gas potential of coffee processing waste in Ethiopia, coffee byproducts exhibit promising bio-methane potential, comparable to common agro-industrial residues and some energy crops. The study estimated that anaerobic fermentation of coffee processing byproducts generated by the Ethiopian coffee sector has a significant potential to generate methane as high as 68 million m^3 $year^{-1}$, which can produce 238,000 MWh_{el} (0.85 PJ $year^{-1}$) of electricity and 272,586 MWh_{th} (0.98 PJ $year^{-1}$) thermal energy (Chala et al., 2018).

The widespread small-scale digesters in Ethiopia are well-proven in domestic use cases in rural areas for subsistence farmers. An introduction of new digester types is no viable option. Further optimization is already foreseen in programs such as the NBPE+. However, larger farms or aggro-industrial parks can benefit from other technological approaches on the middle to large scale. New substrate materials for AD processes in Ethiopia other than dung and water, such as coffee byproducts, crop harvesting residues, Etc., need different technical pre-treatment and processing. Dry fermentation processes analog to MSW can be viable for residues with high dry matter content and less water availability. However, wet fermentation with higher volumes can also be viable for substrate mixtures with high water content. Wet fermentation with mechanical steering and electrification is the dominant plant design in Germany.

Newer plants are shifting from electrification to biomethane upgrading. Such designs can also be transferred to Ethiopia with different usage concepts, such as using cooking gas.

CONCLUSION

With its high share of organic waste, Ethiopia's waste composition characteristic demands particular attention. If unmanaged and not treated, the organic matter is accountable for numerous negative environmental, health, and social impacts. The uncontrolled disposal of waste, especially organic waste, in public spaces is dangerous and often a source of contamination. Organic waste is an attractor of pests and insects. In addition, high temperatures promote the development of pathogens that can lead to gastrointestinal tract diseases. Diseases such as hepatitis and cholera are also not uncommon in waste environments. Improper organic waste treatment can promote the production of landfill leachate, which in the worst case, can lead to groundwater and surface water contamination. In addition, uncontrolled methane and nitrous oxide emissions from open landfills promote the greenhouse effect and thus exacerbate the effects of global warming. Methane emissions come exclusively from the organic fractions of the waste. Accordingly, adequate waste management of organic waste greatly influences the reduction of greenhouse gases.

Especially waste from industry, agriculture, trade, and commerce is suitable for energy recovery with AD under certain conditions. In principle, municipal waste is also suitable for digestion, but it contains a high proportion of impurities, which makes it even more challenging to use fermentation residues as fertilizer. Focussing on homogenous waste streams and solving the problems of communities with nuisances and invasive plants can be a feasible way to introduce mid- to large-scale biodigester. MBT and AD of SSO can also be viable options for introduction in the MSWM. Both biogas production from municipal solid waste and agricultural residues can be a feasible business model for energy and fertilizer production while eliminating risks of uncontrolled emissions.

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