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The Energy Potential Assessment of Controlled Landfills in Morocco, by Dimensioning a Dry and Discontinuous Methanation Plant, Following the Household and Similar Waste Physicochemical Characterization Results

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Abstract

The study was made by district (industrial zone, popular area with average habitats, villa zone, and rural area). A manual and careful sorting (nine categories) is carried out for this study. Thus, the characterization results are (organic matter 54,94%, plastic 15,18%, paper and cardboard 9,72%, textile 7,46%, sanitary textile 5,82%, metals 2,20%, glass 1,89%, Wood 1,82% and Others 1,28%) revealed a dominance of organic matter and an increase in plastic rate that did not exceed 8% in the past. Added to this, the results of the analysis of physicochemical parameters (loss on ignition of the order of 60,26%, humidity rate quite high 59,05%, a total organic carbon (TOC) of 33,47%, and a Lower Heating Value (LHV) of 1840,3 kcal/kg). From these data, we were able to demonstrate the inefficiency of the direct burying solution. Also, we were able to choose the most appropriate anaerobic digestion technology for our HSW (dry discontinuous and mesophilic) and sized the anaerobic digestion unit to assess the electricity production capacity that can be produced in our landfills. Therefore, we have realized three scenarios one which is pessimistic, one optimistic, and the last real, with a load factor of 0.9, and electrical efficiency of 39%. The results of this study are respectively: 18, 29, and 24 concerning the number of digesters to be built, 1,325 kWh, 2,154 kWh, and 1,790 kWh for the electric power per hour, and 4,496,634 m^3/year, 7,307,010 m^3/year, and 6,070,464 m^3/year for the methane produced per year.

Keywords: Recovery matter, Organic matter, Biogas, Electrical efficiency, Discontinuous digesters

1 Introduction

Household and similar waste (HSW) management are one of the main challenges facing Morocco. The factors combination such as population growth, urban expansion, the development of socio-economic and production activities, as well as the changes in lifestyles and consumption patterns, generates a growing field of waste, either average 0,75 kg/day (1). HSW management remains problematic almost for all local authorities in Morocco. The large quantities of waste produced, the financial shortfall, the organizational, institutional, and managerial weaknesses, the shortage of qualified personnel, the insufficient infrastructure, and the low level of environmental education constitute the important elements of this problem.

Added to this, the inadequacy of Western solutions to local specificities following the report on Infrastructure Reform (Ministry of Energy Mines Water and Environment, 2013) (2). Otherwise, Landfills are the fastest alternative for governments to manage their HSW. Nevertheless, their operation leads to environmental impacts such as the demand for large areas of soil, the generation of large volumes of leachates, and the emission of gaseous pollutants such as methane. This activity contributes between 6 and 18% of methane emitted (3) which is the third source of emission of this gaseous pollutant. This gas has a climate-warming potential 21 times higher than that of carbon dioxide (4). However, all municipalities in Morocco must engage in new approaches adapted to our needs, and responding to the diversity of our waste, to achieve the strategic objectives of the national HSW program (NHWP) by 2022 (5). Thus, the application of the anaerobic digestion process is an alternative for the management of HSW since the degradation conditions of the organic matter can be controlled, which makes it possible to reduce the environmental impacts resulting from the methane emissions, and also produce energy that we can use. Moreover, the use of biomass as a source of renewable energy is essential for

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the development of a sustainable energy policy. To this end, this work is oriented towards the physicochemical characterization of HSW to justify the choice of the most appropriate anaerobic digestion technology to use to achieve integrated and sustainable management of our HSW and make our landfills autonomous and generating income. Thus, the objective is to carry out the sizing of the anaerobic digestion installation and to assess the energy potential of the landfill using a technology that exactly meets the results obtained from the physicochemical characterization. This study was carried out at the Mohammadia-Benslimane Technical Landfill Center (TLC) in collaboration with the ECOMED group specialized in solid waste management.

2 Materials and Methods

2.1 Study area

The city of Mohammedia is located on the Atlantic Ocean coast 65 km southwest of Rabat and 24 km northeast of Casablanca. It is bounded to the north by the Atlantic Ocean, to the east and south by the Province of Benslimane, and to the west by the prefecture of Casablanca (see fig. 1). It covers an area of 180 km^2, the urban perimeter of the city extends over 34 km^2, between 7 ° 30 'West longitudes and 33 ° 44' and 33 ° 38 'North latitudes.

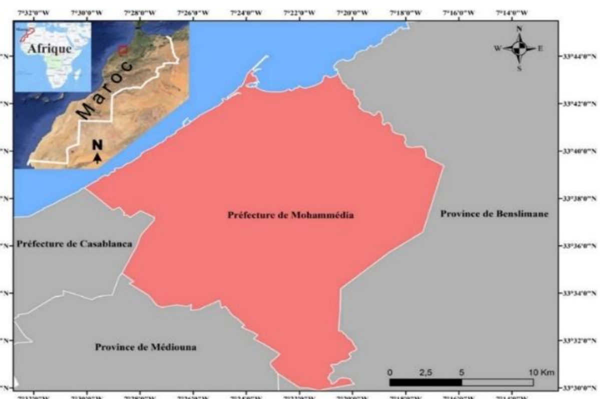

Figure. 1: The Geographical Location of Mohammedia (Google Earth)

The Mohammedia-Benslimane Interprovincial Controlled Landfill was inaugurated on February 27, 2012. The TLC only receives HSW from the Mohammedia prefecture, the province of Benslimane, and local companies (ordinary industrial waste). It occupies an area of 47 ha. It is located about 8 km east of the center of Beni Ykhlef in a very sparsely populated area, 17 km east of the center of Mohammedia and 24 km southwest of the center of Benslimane (see fig. 2).

Figure. 2: The Geographical location of the Mohammedia-Benslimane TLC (Google Earth)

The TLC receives an average of 500 tonnes of HSW per day, generated by a total population of 518,840 inhabitants **(**6), belonging to nine rural and urban communes (Table 1).

Table 1: Mohammedia and Benslimane communes Population

Municipalities	Population 2014
Urban municipality MOHAMMEDIA	208 612
Urban municipality AIN HARROUDA	62 420
Rural commune BENI YAKHLEF	48 338
Rural commune SIDI MOUSSA ALMAJDOUB	20 330
Rural commune SIDI MOUSSA BEN ALI	11 445
Rural commune ECH-CHALLALATE	53 503
Urban municipality BENSLIMANE	57 101
Urban municipality MANSOURIA	19 853
Urban municipality BOUZNIKA	37 238
Total population of the 9 municipalities	518 840

Only HSW, inert waste, and non-hazardous waste are admitted to the landfill. Nevertheless, waste not eligible for landfill corresponds to special waste (hazardous products including hospital waste), industrial waste, and other suspect waste not authorized by the delegator. Table 2 give the distribution and quantity of waste received by type:

Table 2: Quantity of waste received by type (ECOMED)

Type of waste	Tonnage (T)	%
Household waste	117679,96	65,01
Mixture of HW, soil & rubble	27016,63	14,92
Sweeping waste	10,27	0,01
Green waste	2761,21	1,53
Ordinary industrial waste	20132,08	11,12
Rubble	13423,53	7,42
Total	181023,67	100,00

This presentation of the study area made it possible to determine the characteristics of the study region. It is characterized by a high demographic density and developed industrial and domestic activities. This is accompanied by a significant production of solid waste, requiring efficient management to preserve the environment and the region's water resources. The two prefectures have chosen to put their waste in a controlled landfill. However, given the gradual increase in the quantity of waste from one year to the next and consequently a proliferation of management costs, recovery remains inevitable. Also, the choice of the most appropriate valuation method to the local context requires knowledge of the HSW characteristics in the studied area.

2.2 The selected sampling sectors

Since the characteristics of waste differ from one zone to another depending on the level of socio-economic and industrial development, there is a difference between the HSW from rural or urban municipalities. Therefore, samples were selected from three sectors of the urban commune of Mohammedia prefecture, in addition to a sample from the rural commune of Sidi Moussa Ben Ali. The choice of the municipality of Mohammedia is based on the quantity of HSW received at the TLC which represents

54,2% of the total tonnage per year. To reduce the variability in the composition of the waste and to achieve acceptable results, our sampling approach is based on the level of socio-economic and industrial development. Following this, these four sectors were chosen:
Sector I: Mohammedia Industrial Zone.
Sector II: Neighborhoods Ennasr & Errachidia (popular area with average habitats).
Sector III: Neighborhoods of the Sun & La Siesta (villa zone).
Sector IV: Rural commune Sidi Moussa Ben Ali (rural area).

For meaningful characterization, the sample must be representative. For this reason, measures had to be taken during the sampling procedures to reduce the margin of error. Once the garbage truck arrives at the landfill, the collected waste is weighed on a weighbridge and unloaded in form of a heap on a sorting platform. Then, they are homogenized by a bucket loader. Next, the quartering of the waste heap, and finally from each division, we take 25% of the total tonnage to constitute the final sample. The minimum quantity of samples deemed representative for this approach is superior to 500 kg (7), (Table 3).

Table 3: Masses of samples sorted by sector

Sectors	Sector I	Sector II	Sector III	Sector IV
Weight (kg)	2315	519	1012	503

2.3 Chemical analysis methods for HSW

The characterization can be supplemented by laboratory analyzes (Table 4). These analyzes can be relevant to complete compositional results from sorting.

Table 4: Physicochemical methods of analysis used

	Formula used
Density (T/m^3) [1]	$\rho = m/v$ (8)
Humidity (%) [2]	$H = [(m_0 - m_1)/m_0] \times 100$ (9)
Organic Matter (%) [3]	$MO = [(m_1 - m_2)/m1] \times 100$ (10)
Ash rate (%)	Ashes = 100 – MO% (10)
pH	pH meter with glass electrode in a suspension 1/10 (11)
TOC (%)	MO = TOC% x 1,8 (12)
LHV [4]	LHV = 40(P + T + B + F) + 90R - 46W (13)

[1]m = Sample mass; v = Truck or locker volume
[2]m_0 = Initial mass before drying; m_1 = Final mass after drying.
[3]m_1 = Initial mass before calcination; m_2 = Final mass after calcination.
[4]P = Paper and cardboard; T= total textiles; B= wood; F= fermentable; R= plastics; W= average waste humidity.

2.4 Anaerobic digestion processes analysis

As explained above, our goal is to improve the lifespan of the landfill and make it income-generating. To achieve this goal, we will focus on anaerobic digestion to produce biogas, and transform it into electricity. Anaerobic digestion is the most appropriate process for the treatment of HSW. The mechanisms and conditions of the anaerobic digestion inhibit the activity of pathogens present in this waste, which reduces the risk of contamination of the solid by-product such as digestate (14). There are parameters that influence anaerobic digestion, which gives rise to several possible configurations in which the anaerobic digestion process can develop. However, two criteria are the most important on which the classification of the anaerobic digestion process is based: the dry matter content and the operation mode of the digester.

Classification by dry matter content: Anaerobic digestion systems are cataloged based on the dry matter present in the organic matter used as a substrate. These systems can be humid or dry.

- Humid systems

They are systems that use substrates with a dry matter content between 2 and 12% (14), which gives them a liquid and homogeneous consistency. It is possible to use biomass with a content of 15% or more (15), but it would require the addition of water to adjust this content to the conditions for the digester operation.

- Dry systems

The biomass used in this type of system has a dry matter content between 15% and 40%, in some cases, this content can be 50% (16). The size of the digesters used in these systems is smaller than that used for humid systems due to a smaller volume of the substrate. The anaerobic digestion process in this type of system requires less thermal energy consumption because there is less presence of water in the substrate (17).

Classification according to the digester operation: The systems can be classified according to the movement of the substrate during the anaerobic digestion process, in other words, how the organic matter is introduced to the digester; They are continuous or discontinuous systems.

- Continuous systems

In this type of system, the matter is introduced continuously. thus, for each quantity of incoming matter, a fraction with the same volume leaves the digester.

- Discontinuous systems

They are also called batch systems. Their principle of operation seems like that of a (16). Nevertheless, in batch systems, the conditions of the anaerobic digestion process are controlled, which allows a better performance of biogas production. In these systems, the digester is fed with a fixed volume of the substrate and then sealed. Inside there are no moving parts and the substrate remains stationary while the mechanization stages follow one another in different periods.

A comparison of these technologies makes it possible to achieve an objective analysis of the advantages and disadvantages of their application for the management and energy recovery of HSW. Table 5 summarizes the main advantages and disadvantages of these systems' operation, which gives a general notion of their feasibility for application on an industrial scale.
Table 5: Advantages and disadvantages of anaerobic digestion systems (16).

Exclusive technology for anaerobic digestion cannot exist due to the multiple factors that intervene during the anaerobic digestion process, which leaves us the freedom to choose the technology that best adapts and responds perfectly to the nature of our waste in Morocco.

3 Results and Discussions

The HSW physicochemical characterization has allowed us to set up the necessary reference data that can be used to set up a sorting, processing, and recovery center for the management and treatment of waste in the controlled landfill.

3.1 Average physical composition of Mohammedia's HSW

Waste sorting showed the presence of different categories of waste from household garbage and ordinary industrial waste assimilated to household waste. In the four sectors, the garbage presents a great heterogeneity with a predominance of the fermentable fraction of animal and vegetable origin. We also note that the composition of this waste can vary according to the sectors. The results of sorting the different sectors are shown in table 6.

Systems	Advantages	Disadvantages
Humid, Continued	Good yield of biogas production per tonne of waste. The smoother flow of the substrate. Better dilution of nutrients in the substrate.	Water consumption. Strict substrate pretreatment. high thermal requirements during anaerobic digestion. Large volume reactor.
Sec, Continued	Reduced surface for the installation of the reactor. Little use of water to adjust the fresh matter. Constant production of biogas. A minimum level of improper in organic matter. Low thermal demand.	High investment cost. Risk of clogging if the substrate is not pretreated. High power consumption for pumping equipment. Need for post-treatment equipment for the digestate.
Sec, discontinued	Use of biomass with high dry matter content. Does not require very strict maintenance. Possibility of increasing its capacity with the coupling of new reactors. Low energy consumption. The digestate produced requires minimal post-treatment.	Lower biogas production efficiency compared to continuous systems. Requires more surface for its installation.

The average sorting results obtained across the four sectors show that the fermentable matter generated during the sorting period is 54,94%, followed by plastic and rubber 15,18% then paper and paperboard 9,72% (Table 6). The comparison of the results obtained with those of the national scale shows a similarity in all the components of the sample (Table 7). With a percentage increase in plastic, mainly due to the high use of plastic bags. Manual sorting of this waste indicates that recyclable matters constitute a considerable part of the total mass. According to the results, the recovery rate varies from one sector to another. The rate of paper and cardboard varies between 7.60 and 12.17%, plastic is between 12.88 and 18.67%, the rate of textiles varies between 4.68 and 14.44%. Glass, metals, and wood are presented in considerable quantities and their percentages differ slightly from one area to another. The variation in the proportions of recoverable matters depending on the sector is illustrated in figure 3. From figure 3, we can see that the rate of recyclable materials (plastic, paper, and cardboard) is practically important in all sectors. The histograms in Figure 4 show the average percentages of recyclable waste in Mohammedia city. The average recovery of recoverable waste entering the TLC is 38.27% of the total quantity of sorted waste, which represents more than a third of the total mass of the deposit.

3.2 Physicochemical analysis of HSW

The results of the physicochemical characterization of HSW were obtained on a representative sample, taken at random, which contains all the waste fractions (vegetable and fruit peelings, various complex compositions, broken glass, plastic, paper, etc.) determined when sorting.

Density: It is one of the important parameters both in the choice and design of the means of transporting HSW and in the stabilization of waste in landfills. It depends on the composition of the waste, especially the organic fraction with high humidity.

Table 6: Results of sorting Mohammedia's HSW

Categories	Sector I	Sector II	Sector III	Sector IV	Average
Fermentable waste	42,75%	60,51%	52,30%	64,20%	54,94%
Plastics and rubber	18,67%	13,74%	15,43%	12,88%	15,18%
Paper and cardboard	12,17%	8,25%	10,86%	7,60%	9,72%
Textiles	14,44%	5,24%	5,48%	4,68%	7,46%
Sanitary textiles	3,16%	7,52%	4,73%	7,87%	5,82%
Glass	2,23%	1,72%	2,79%	0,84%	1,89%
Metals	2,80%	1,58%	2,88%	1,54%	2,20%
Wood	2,13%	0,55%	4,20%	0,40%	1,82%
Other	1,90%	0,67%	1,95%	0,60%	1,28%

Table 7: Comparison of Mohammedia's HSW Composition with Morocco (Department of Commerce, Industry, and Department of the Environment, 2002)

Component	Mohammedia's HSW	Morocco's HSW
Fermentable waste	54,94%	50 à 70 %
Plastics and rubber	15,18%	6 à 8 %
Paper and cardboard	9,72%	5 à 10 %
Metals	2,20%	1 à 4 %
Glass-debris of ceramics	1,89%	1 à 2 %
Various (wood, others, …)	16,38%	16 %

Table 8: Density of incoming waste by type of truck (t/m^3)

Truck type	Min density	Max density	Average	Number of measurements	Observations
Open skips	0,34	0,88	0,61	2	Light compaction
Satellite skips	0,24	0,44	0,33	4	Zero compaction
Compactor	0,30	0,98	0,66	37	Heavy compaction

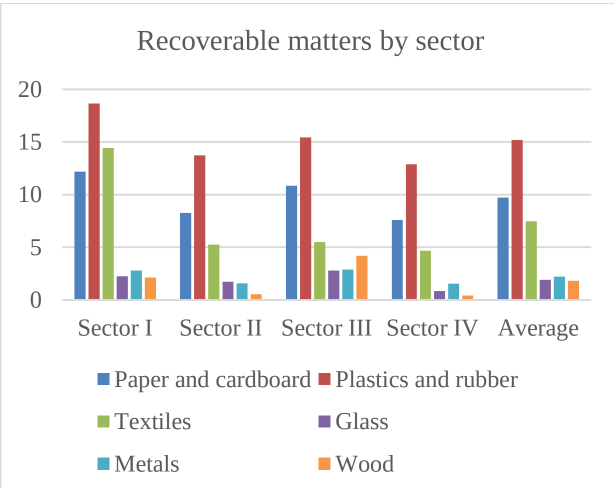

Figure 3: Proportion of recoverable matters for each sector

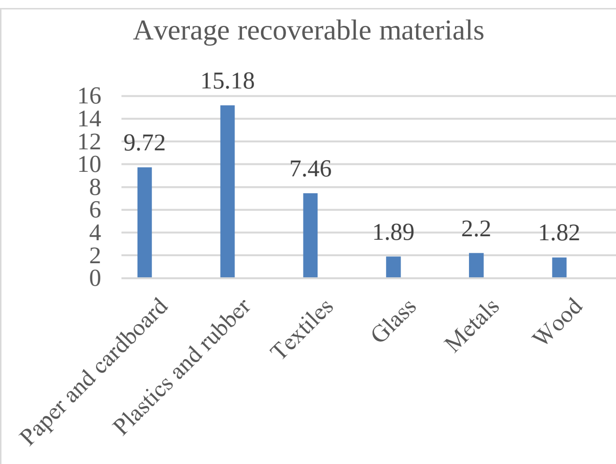

Figure 4: Average rate of each recyclable fraction of HSW in the city of Mohammedia

The volume was determined either by the type of truck or by measuring the dimensions of the dumpsters. Several tests have been carried out. Table 8 shows the results of measurements made in the landfill during this period. Density values vary depending on the type of truck entering the TLC. It can be noted that the density of incoming waste is generally high. On the average of 43 measurements taken during the observation period, we recorded an average density of 0.53. City trash density measurements range from 0.31 to 0.38, with an average of 0.34. Table 9 shows the results of the density measurements of waste in trash cans and in lockers after burial and compaction of the waste.

Table 9: Density of waste in trash cans and landfill lockers

	Min density	Max density	Average
garbage can (kg/l)	0,31	0,38	0,34
Landfill locker (t/m^3)	0,80	0,83	0,82

The average density in the landfill lockers is high, in the order of 0.82 t/m^3. This is due to the mechanical treatment by forced compaction applied by the operating department in addition to the high organic matter content.

Humidity: The humidity analysis was carried out on the waste by a fraction. Thus, an amount varying from 40 g to 1 kg depending on the category was dried at 105 ± 2 ° C for 24 hours. The humidity percentage is determined by the difference in weight of the sample before and after drying.

Table 10: Humidity of HSW by category

Categories	Humidity %	Weight ratio (dry/wet)
Fermentable waste	74,49	0,26
Paper and cardboard	43,57	0,56
Textiles	73,99	0,26
Sanitary Textiles	75,10	0,25
Plastics	38,06	0,62
Glasses	0,94	0,99
Metals	6,10	0,94
Wood	21,08	0,79
Average	59,05	0,41

The average humidity of household garbage in Mohammedia is high due to the high quantities of fermentable waste. The ratio (dry weight / wet weight) by category varies from 0.25 for sanitary textiles to 0.99 for glass as shown in Table 10. The high humidity of HSWs is at the origin of a significant production of leachate, which constitutes a disadvantage of treatment by landfill and for the exploitation of landfill centers, because the risk for the environment due to the biodegradation is relatively strong under these conditions.

pH: The results obtained on 10 g of dried, crushed and sieved fermentable waste gave a pH of 6.5, which shows that this waste is not very acidic, even neutral.

Organic matter or volatile solids: The calcination is carried out on a sample reconstituted from the fermentable fraction, dried, crushed, and calcined at 550 ° C. for 2 hours in the oven. The results obtained showed that the volatile solids represent 60.26% of the dry weight of the waste.

Total Organic Carbon (TOC): From the percentages of organic matter, we were able to determine the percentages of TOC, based on the fact that organic matter consists of almost 55.5% carbon. The calculation showed that the TOC represents 33.47% of the dry weight of the waste studied.

Ash rate: The ash is the residue from the calcination, it corresponds to the overall quantity of mineral matter contained in the sample. The results obtained showed that the ash represents 39.74% of the dry weight of the waste (Table 11).

Table 11: Organic matter content and ash of the studied TLC

Mass 1 (g)	Mass 2 (g)	OM (g)	LOI%	Ashes (%)
10,72	4,26	6,46	60,26	39,74

Lower calorific value (LCV): The LCV for Mohammedia's HSW was determined empirically, depending on the composition of the waste by category according to the formula described above. The results obtained (Table 12) show that the calculated LCV varies slightly from one sample to another, between 1775.2 and 1950 Kcal/kg. The highest value was found in sector I. it is around 1950 Kcal/kg. This can be explained by the high rate of plastic (18.67%) and paper-cardboard (12.17) fractions.

Table 12: LCV of Mohammedia's waste by sector studied

	Sector I	Sector II	Sector III	Sector IV	Average
LCV (Kcal/kg)	1950	1803,1	1775,2	1832,9	1840,3

The average LCV is 1840.3 kcal/kg, well above the average in developing countries, and is in the range of LCV of industrial countries (1500--2700 kcal/kg) (18). This high LCV is due to a relatively high rate of plastic (15.18%). This indicates that the waste studied can be treated by incineration with recovery and production of heat.

3.3 Sizing the anaerobic digestion unit

Research in the field of anaerobic digestion of waste has been in constant development since the 1980s **(**16). This has enabled the development of a variety of commercial-scale processes and technologies that are currently applied for the treatment of household organic waste. Table 13 summarizes some technologies that exist on an industrial scale.

Table 13: Main processes used in the world for anaerobic digestion of household waste (15)

Process	Dry matter content	Temperature range	Operation type
BEKON	Dry	Mesophilic	Discontinued
Waasa	Humid	Mesophilic or Thermophile	Continued
Valorga	Dry	Mesophilic or Thermophilic	Continued
Dranco	Dry	Thermophilic	Continued
Kompogas	Dry	Thermophilic	Continued
Citec	Humid	Thermophilic	Continued
Strabag	Humid	Mesophilic or Thermophilic	Continued
Schwarting–Uhde	Humid	Thermophilic	Continued
BTA	Humid	Mesophilic	Continued
ISKA	Humid	Mesophilic	Continued
Krüger	Humid	Mesophilic	Continued
Ros Roca	Humid	Mesophilic	Continued

Despite the variety of anaerobic digestion technologies, only some of them are more prevalent in industrial applications. Considering the two main criteria of the anaerobic digestion systems operation, which are dry matter content and biomass flux, it is possible to group the processes into three main categories as shown in Table 14, which will facilitate the analysis process envisaged.

Table 14: Processes grouped according to operating criteria

By dry matter content	By operation	Category	Process
Humid	Continued	Humid Continued	Wasaa
Dry	Continued	Dry Continued	Valorga Dranco Kompogas
	Discontinued	Dry discontinued	BEKON

As the choice of technology considers its application for the anaerobic digestion of the organic fraction of HSW. The option of selecting a humid system is excluded from the analysis because this type of technology only accepts biomass with a maximum dry matter content of 15% **(**16). The analysis will be based on three aspects: technical, economic, and environmental.

Technical analysis:

Energy production: One of the main goals of anaerobic systems is the production of energy from the resulting biogas. Thus, the criterion to be evaluated is the net quantity of electricity that is possible to obtain after the operation of the anaerobic digestion technology. This criterion is the most important in developing countries (16). The production of biogas per ton of waste is highest in continuous systems, compared to that produced by batch systems **(**16). However, since continuous systems use high power flow equipment, their operation requires high consumption of electricity, which is taken from that produced by cogeneration in the same installation. Even if the production efficiency of biogas is lower, the absence of pumps and moving parts in batch systems require less electricity consumption, which allows obtaining a quantity of net energy comparable to that obtained in continuous systems.

Operating mode: For continuous systems, depending on the technology, the particle size of the substrate should not exceed a maximum value to ensure their flow, which requires constant pretreatment. The system risks blockages during the flow of biomass if the pretreatment is not well done. In batch systems, the organic matter remains immobile inside the reactor, as a result, the particle size can be more heterogeneous, which requires a less demanding pretreatment consisting to remove larger particles by using a simple trommel. Usually, household organic waste has a 25% content of unsuitable matter **(**16). In continuous systems, this level can produce wear inside the reactor and parts of the pipeline during the flow of biomass. While for batch systems this risk is almost negligible due to the lack of movement of the biomass inside the reactor. Continuous systems are built so that anaerobic digestion occurs in a single reactor reducing the area required for the installation. However, in the event of a breakdown, there is always the risk of disrupting the anaerobic digestion process and stopping the production of biogas. If the failure is severe, it may require emptying the biomass from the reactor (19, 15). For batch systems, equipment maintenance is easier to manage. If one of the digesters needs repair, its operation is stopped, but the operation of the other reactors is adjusted and synchronized to maintain a constant production of the biogas.

Required surface: Batch systems require more surfaces for their installation. However, they can be adapted to already existing infrastructures or can be placed in closed landfill areas. Although continuous systems save space with the operation of a single digester, the digestate obtained still needs to be stabilized by composting processes, which requires surface area like batch systems. If considering an increase in the production of biogas, for batch systems it would just be necessary to add digesters to the installation and synchronize them with those already installed. As long as for a continuous system, it would require the installation of a complete reactor with a maximum size, which requires large investments.

Digestate: The digestate produced in continuous systems has a pasty consistency, indicating the presence of humidity which must be removed, either by heat treatments or by adding a lot of green waste. Before the biomass leaves the batch systems, the recirculation of the percolate is stopped to provide a digestate with less humidity, and which requires simpler post-treatment processes to transform this digestate into quality compost.

Economic analysis: The technologies used by the continuous systems are patented, this requires additional payment for the installation of this type of digesters. Consequently, the investment costs increase. Batch systems are simple processes that do not require the construction of very technical infrastructure, so their investment cost is more affordable. The selling price of electricity produced from biogas plants makes the payback time for a continuous type installation moderately long. For a batch-type installation, this payback time would be more affordable, since their investment amounts are lower than those for continuous systems.

Environmental analysis: Whatever the technical or economic differences between the different types of technologies, the application of an anaerobic digestion system always lead to several environmental benefits, especially in relation to waste treatment. Incorporating a digester into our current city management system will reduce the amount of organic waste going to landfills, as it accounts for over 54% of all landfilled waste. It is well known that methane has a warming power 21 times greater than that of carbon dioxide (4). Landfills are a major source of emissions of this type of gas, even if they are controlled. The implementation of anaerobic digestion completely prevents the emission of this greenhouse gas.

Choice of the anaerobic digestion technology adapted to our HSW: The methanization of HSW can produce between 100 and 150 m^3 of biogas per tonne of this type of substrate (16). As this process takes place in closed facilities, the methane does not escape to the atmosphere, which favors its capture and application for energy production. By the criterion of (Mata-Alvarez, 2003), discontinuous systems are the most appropriate for developing countries like Morocco. This criterion can be reinforced by the fact that the transport of biomass with the use of a wheel loader or the construction of an installation with the characteristics of discontinuous systems are not too technical processes, and which can be easily adapt to the national context. Considering the anaerobic digestion of all the organic fractions produced in a city would require a large investment in the short term, which is a limiting factor for a municipality in Morocco. Due to the modular operation of a discontinuous system, its initial installation capacity may be reduced and therefore its capital cost. The capacity of the installation can be gradually increased as the city's recycling system increases. Based on these analyzes, an anaerobic digestion system of the discontinuous type appears to be the most appropriate option for the energy recovery of household organic waste in our cities. Among the commercial technologies previously detailed, BEKON technology is that of the discontinuous type and on which the subsequent calculations are based.

Sizing the anaerobic digestion unit: The recovery of the organic fraction of HSW is evaluated with the anaerobic digestion process according to BEKON technology. Table 15 summarizes the basic data considering an organic matter content of 54%.

Table 15: Production of household waste in the city of Mohammadia

Waste generation		Value
Waste generation	Ton/year	181.024
Organic matter content	%	54
The organic fraction of HSW	Ton/year	97.753

To carry out a more objective analysis of the anaerobic digestion installation results with the batch process in the city, three scenarios are established, each of them valuing a part of organic matter fraction as shown in Table 16.

Table 16: Quantity of organic waste valued by each scenario

Scenarios	OM rate %	Quantity (ton/year)
Scenario 1, *pessimistic*	40	72.410
Scenario 2, *optimistic*	65	117.665
Scenario 3, *real*	54	97.753

The parameters for the waste methanization process must be in accordance with the technology selected. Table 17 shows the values for these parameters:

Table 17: Anaerobic Digestion Process Operating Parameter

Parameter	Value
Residence time	28 days
Drain time	1 day
Temperature range	mesophilic
Type of operation	discontinuous

Anaerobic digestion process: According to the BEKON process, a quantity of green waste must be added to the OFHW to obtain fresh mater. The additional quantity of this green mater corresponds to 15% of organic waste (20). Then, the fresh mater is inoculated with recirculated digestate of the same methanation process (see Fig. 5). The amount of the digestate added is equal to 40% of the substrate which is introduced into the digester (21).

Table 18: Quantity of matter for starting the anaerobic digestion process

	Scenario 1	Scenario 2	Scenario 3
OFHW (ton/year)	72.410	117.665	97.753
Add green waste (%)	15	15	15
Add green waste (ton/year)	10.861	17.650	14.663
Total fresh material (ton/year)	83.271	135.315	112.416
Recirculated digestate (%)	40	40	40
Recirculated digestate (ton/year)	55.514	90.210	74.944
Substrate (ton/year)	138.785	225.525	187.360

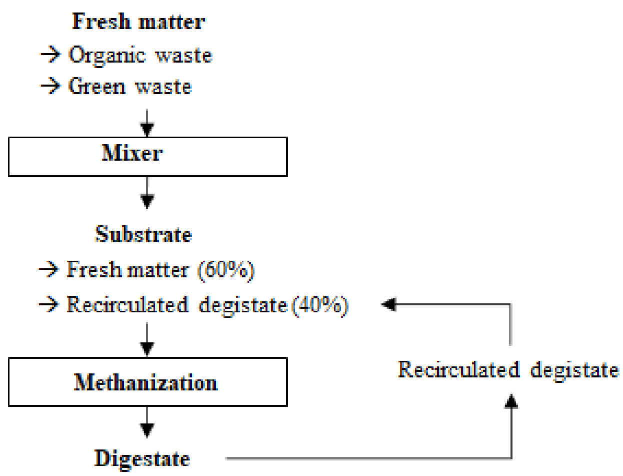

Figure 5: Schematic of starting the methanation process similar to that of BEKON technology

The calculation of the matter quantity used to start the anaerobic digestion process is shown in the following table. To calculate the number of digesters required for the anaerobic digestion of the substrate, we start from the dimensions of a BEKON process digester, which allows us to obtain its volume. We consider a filling rate of 80% which allows us to know the useful volume for the digester. The values given in the table below correspond to those reported in references to this technology **(**22).

Table 19: Dimensions of a similar digester of BEKON technology

Parameter	Value
Long (meters)	35
Width (meters)	7
High (meters)	5
Volume (m^3)	1 225
Filling rate (%)	80
Useful volume (m^3)	980

We take the value of 0.67 ton/m^3 as the minimum density of the substrate, to calculate its daily, which is added to the useful volume of the digester allows us to calculate the number of days for filling a single digester:

$$Filling\ time = \frac{\text{Digester useful volume}}{\text{Substrate volume per day}}$$

Table 20: Digester filling time per days

	Scenario 1	Scenario 2	Scenario 3
Useful volume of the digester (m^3)	980	980	980
Substrate quantity (ton/year)	138.785	225.525	187.360
Density (ton/m^3)	0,67	0,67	0,67
Substrate volume (m^3/year)	207.142	336.604	279.642
Substrate volume (m^3/day)	567	922	766
Digester filling time per day	2	2	2

The filling time of a digester calculated for each scenario added to this the residence time of 28 days, and 1 day for emptying the digester, gives the time of a digestion cycle for a digester. The number of cycles that a digester can perform during 1 year is calculated using the following formula:

$$\text{Cycle number for 1 year} = \frac{365\ \text{days}}{\text{Time of a digestive cycle}}$$

Table 21: Number of cycles per year performed for one digester

	Scenario 1	Scenario 2	Scenario 3
Filling time (days)	2	2	2
Residence time (days)	28	28	28
Drain time (days)	1	1	1
Temp of a digestion cycle (days)	31	31	31
Number of cycles of a single digester	12	12	12

Thus, to determine the number of digesters required, the total volume of the substrate for one year is divided by the useful volume of a digester and the number of cycles that can be carried out during the same period. The results in Table 22 show the number of digesters required for each scenario.

$$\text{Number of digesters} = \frac{\text{Substrate volume by one year}}{\text{Useful volume of digester x Number of digester cycles per year}}$$

Table 22: Calculating the number of digesters to treat 1 year of substrate

	Scenario 1	Scenario 2	Scenario 3
Substrate volume (m^3/year)	207.142	336.604	279.642
Useful volume of a digester (m^3)	980	980	980
Number of cycles per digester	12	12	12
Number of digesters	18	29	24

Biogas production: The biogas production yield can be calculated depending on the amount of substrate introduced into the digester. According to the commercial references of BEKON technology, the average value of this yield is 90 m^3 per tonne of a substrate **(**22). Research studies such as those carried out by (Banks et al., 2011) and (Wu, 2014) have calculated a methane content of about 60% in the biogas obtained from the anaerobic digestion of the organic fraction **(**23, 24). Thus, we take this value into account as a reference to estimate the quantity of methane that can be obtained by the process chosen as indicated in the following table:

Table 23: Estimated production of biogas and methane by anaerobic digestion for one year

		Scenario 1	Scenario 2	Scenario 3
Fresh matter	ton/year	83.271	135.315	112.416
Biogas production yield	m^3/ton	90	90	90
Biogas produced	m^3/year	7.494.390	12.178.350	10.117.440
Methane content	%	60	60	60
Methane produced	m^3/year	4.496.634	7.307.010	6.070.464

The energy recovery of biogas will be carried out by combustion in a cogeneration unit to obtain electrical and thermal energy, the efficiency is 39% and 40% respectively. Considering the LCV of methane at 5.96 KWh/m^3 (25), we can estimate the amount of energy contained in the biogas as indicated in the following table:

Table 24: Energy contained in the biogas produced

		Scenario 1	Scenario 2	Scenario 3
Energy contained in biogas				
Methane available	m^3/year	4.496.634	7.307.010	6.070.464
Methane LVC	KWh/m^3	5,96	5,96	5,96
Energy contained in biogas	KWh/year	26.799.938	43.549.779	36.179.965
Energy contained in biogas	MWh/year	26.800	43.550	36.180
Valuation by cogeneration				
Electrical efficiency	%	39	39	39
Electrical energy	MWh/year	10.452	16.984	14.110
Thermal efficiency	%	40	40	40
Thermal energy	MWh/year	10.720	17.420	14.472

We consider a load factor of 0.9 for the cogeneration engine. For the calculation of the cogeneration unit power, we use the energy contained in the biogas, the electrical efficiency of the cogeneration engine, and the number of operating hours according to the load factor of the unit from the following formula:

$$\text{Electrical power} = \frac{\text{Energy in produced biogas} \times \text{Electric motor efficiency}}{\text{Operating hours}}$$

Table 25: Electric power per hour according to each scenario

		Scenario 1	Scenario 2	Scenario 3
The energy contained in biogas	MW	26.800	43.550	36.180
Operating hours	Hours	7.884	7.884	7.884
Electrical efficiency	%	39	39	39
Electrical power	kWh	1.325	2.154	1.790

Mass balance of organic matter not sent to landfill: After calculating the amount of biogas produced, we can estimate the amount of organic matter that has turned into this gas, which is recovered and not sent to landfill. Also, as explained above, 40% of the digestate released from anaerobic digestion is always recirculated, an amount that is not negligible and which is never sent to landfill as shown in Table 26. Only with the pessimistic scenario, we will be able to produce 1.325 kWh of electricity, which represents 10.44 GW/year. In addition, we will be able to recover and recycle more than 54,306 tonnes/year of non-organic matter and transform more than 64,582 tonnes/year of organic matter into biogas.

4 Conclusion and perspective

The results show that our HSW contains real wealth. They prove that the direct burying solution is absolutely not the most optimal solution. Indeed, with the recovery and transformation of a rate of 54% of organic matter and 38% of recyclable matter, we largely exceed 80% of all waste received at the TLC. This implies the prolongation of the landfill lifespan (over three times in minimum), a very significant reduction in the production of leachates, and the possibility of having total energy and financial autonomy at the level of the landfill. In terms of profits, we can distinguish 5 categories including the sale of electricity, cogeneration and the use of thermal energy (combined cycle), the sale of compost (processed digestate), the savings generated by each ton of OFHW not sent to landfill, and the converted money from our participation to lower GHG rates. Thus, in a spirit of eco and social entrepreneurship, we are currently working on an autonomous household waste management model, which will contribute to the change of the municipality’s strategy, and move from delegated management to income-generating strategies in one of the most difficult areas to manage in developing countries. Total energy and financial autonomy are dedicated to our communes so that they can manage and not suffer from the parallel damage of a consumption evolution and the socio-economic level of the Moroccan citizen. The results show that our HSW contains real wealth. They prove that the direct burying solution is absolutely not the most optimal solution. Indeed, with the recovery and transformation of a rate of 54% of organic matter and 38% of recyclable matter, we largely exceed 80% of all waste received at the TLC. This implies the prolongation of the landfill lifespan (over three times in minimum), a very significant reduction in the production of leachates, and the possibility of having total energy and financial autonomy at the level of the landfill. In terms of profits, we can distinguish 5 categories including the sale of electricity, cogeneration and the use of thermal energy (combined cycle), the sale of compost (processed digestate), the savings generated by each ton of OFHW not sent to landfill, and the converted money from our participation to lower GHG rates. Thus, in a spirit of eco and social entrepreneurship, we are currently working on an autonomous household waste management model, which will contribute to the change of the municipality’s strategy, and move from delegated management to income-generating strategies in one of the most difficult areas to manage in developing countries. Total energy and financial autonomy are dedicated to our communes so that they can manage and not suffer from the parallel damage of a consumption evolution and the socio-economic level of the Moroccan citizen.

Table 26: Organic matter recovered by anaerobic digestion and not sent to landfill

		Scenario 1	Scenario 2	Scenario 3
Fresh matter	ton/year	83.271	135.315	112.416
Biogas production yield	m^3/ton	90	90	90
Biogas produced	m^3/year	7.494.390	12.178.350	10.117.440
Volumic mass of biogas	kg/m^3	1,21	1,21	1,21
Biogas produced	ton/year	9.068	14.735	12.242
Substrate in digesters	ton/year	138.785	225.525	187.360
Recirculated substrate rate	%	40	40	40
Recirculated digestate	ton/year	55.514	90.210	74.944
Total organic matter not sent to landfill	ton/year	64.582	104.945	87.186

Ethical issue

Authors are aware of and comply with, best practices in publication ethics specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language. Also, all procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All procedures performed in this study involving animals were following the ethical standards of the institution or practice at which the studies were conducted.

Competing interests

The authors declare that no conflict of interest would prejudice the impartiality of this scientific work.

Authors' contribution

All authors of this study have a complete contribution for data collection, data analyses, and manuscript writing.

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