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Study of the anaerobic digestion of household waste leachate from the Moulay Abdalah landfill in Morocco

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ABSTRACT

The Moulay Abdalah landfill in Morocco generates leachate, a pollutant that poses a significant environmental threat. This study focused on characterizing the biogas produced from the anaerobic digestion of leachate from this landfill and assessing its potential for energy recovery. The research involved collecting the leachate directly from the area of the landfill where household waste is compacted. This leachate was subjected to anaerobic digestion in two airtight digesters, each with a volume of 144 m^3. The resulting biogas was analyzed to determine its composition of methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S). The results revealed the presence of methanogenic and sulfate-reducing bacteria in the digested leachate, as evidenced by the methane and hydrogen sulfide content in the biogas, respectively. However, the composition of the biogas was found to be unsuitable for energy recovery. The methane content, the primary energy component of biogas, was less than 50%, while the standards for injection into the natural gas grid require a methane content between 55 and 75% (INERIS). The high concentration of hydrogen sulfide also hindered the energy recovery of the biogas. This study focused on a single site, and the results obtained may not be generalizable to other landfills. Additionally, the long-term impact of operating conditions on digester performance was not evaluated. The results of this study highlight the need for additional treatments to improve the quality of the biogas produced and make it suitable for energy recovery.

Keywords: anaerobic digestion, leachate, Moulay Abdalah landfill, biogas, sulfate-reducing bacteria, energy recovery.

INTRODUCTION

The Moulay Abdellah landfill, adjacent to the Oum er Rbia river, is a major environmental hazard in Morocco. It is contaminating water, harming public health, and damaging local ecosystems (Ouhakki et al., 2024). Landfill leachate is a contaminated effluent characterized by a high, relatively biodegradable organic load, with a biodegradability threshold BOD_5/COD greater than 0.3 (Freeman, 2016). These leachates can be rich in metals (up to 2 g/l) due to their relatively low pH (≤ 4) (Bakonyi et al., 2019). Valorizing these leachates can be an effective way to mitigate their negative environmental impact, which can arise from their organic load and heavy metal content (Rehman et al., 2023). The production of usable biogas is one method of valorizing leachates (Marticorena et al., 1993). Indeed, this biogas, derived from anaerobic stabilization and primarily composed of methane and carbon dioxide, can be used for electricity generation (Bharathiraja et al., 2018).

Anaerobic digestion is a natural process observed in the environments rich in organic matter but lacking oxygen (Botheju and Bakke, 2011). The absence of oxygen leads to the formation of biogas, which is primarily composed of methane (40–70%) and carbon dioxide (Koniuszewska et al., 2020). This process can be seen in landfills or marshes and is also known as methanogenic fermentation (Barlaz et al., 1990). Anaerobic digestion relies on a complex biological process involving a true microbial ecosystem, the balance of which is sometimes threatened by various disturbances caused by inhibitory substances (Stronach et al., 2012).

The Moulay Abdellah intercommunal landfill, receiving 68,728 tons of household waste annually from over 226,000 inhabitants, represents a major environmental challenge. Indeed, the decomposition of this waste generates leachate, pollutant-laden liquids that infiltrate the soil. Given the 28-hectare surface area of the landfill and its geographic location near El Jadida, it is likely that these leachates contaminate the region's groundwater, jeopardizing the quality of both surface and groundwater resources in the Oum Er-Rabia basin (Ouhakki et al., 2024). Moreover, the presence of toxic substances in these leachates can also pollute surrounding soils, impacting local ecosystems and reducing the quality of agricultural land (Hussein et al., 2021). In the long term, this pollution can have harmful consequences for biodiversity and public health, particularly due to the potential presence of carcinogenic or mutagenic substances in water and soil.

This study, conducted in February and March 2022, aimed to characterize the physicochemical composition of leachate from the Moulay Abdallah landfill and evaluate the energy potential of the biogas produced through its anaerobic digestion. It sought to determine the methane and hydrogen sulfide content of the biogas to assess its feasibility for electricity valorization. The objective was to provide new scientific results on the precise composition of the biogas, its electricity production potential, and the optimal conditions for anaerobic digestion of the leachate.

MATERIALS AND METHODS

To assess the energy recovery potential of leachate from the Moulay Abdallah landfill, an experimental study was conducted using a specially designed infrastructure. This infrastructure, schematically represented in Figure 1, consists of two anaerobic digesters in series, M_1 and M_2, connected by a piping system.

The digesters (Figure 2) are rectangular reinforced concrete tanks, each with a volume of 144 m³, designed to provide a 4-month retention time for the leachate. This relatively long retention time was chosen to promote the growth of microbial

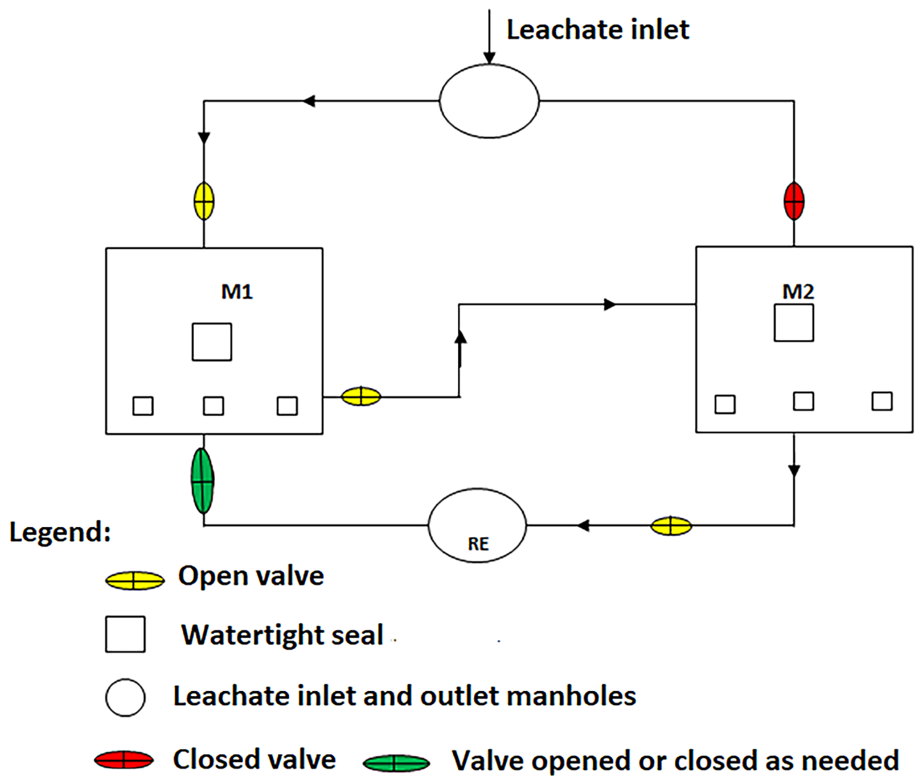

Figure 1. Designed infrastructure

Figure 2. The concrete tanks

communities responsible for organic matter degradation and biogas production. Each digester is equipped with a sealing system for measuring biogas quality and a safety flare designed to burn excess biogas (Figure 3). Raw leachate, collected at a flow rate of 25 m³/day, is introduced into the first digester, M_1 (Figure 4). This first stage of the system is responsible for hydrolysis and acidogenesis. During these phases, complex organic molecules are broken down into simpler molecules, notably volatile fatty acids (VFAs). These VFAs serve as the essential substrate for methane production in the second stage of the process.

Figure 3. Sealing system

After residing in digester M_1, the leachate is then transferred to digester M_2 (Figure 5). In this second stage, methanogenic bacteria convert VFAs into biogas, primarily composed of methane (CH_4) and carbon dioxide (CO_2), as well as other compounds such as hydrogen sulfide (H_2S). The quality of the biogas was monitored using a portable biogas analyzer, allowing for regular

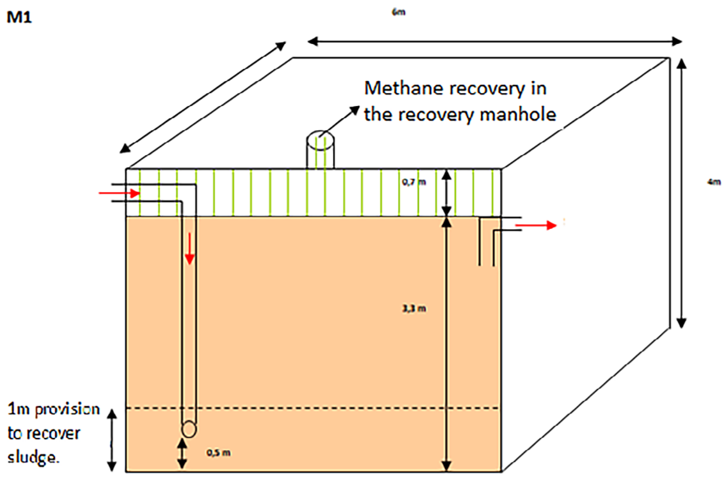

Figure 4. Design of methane production

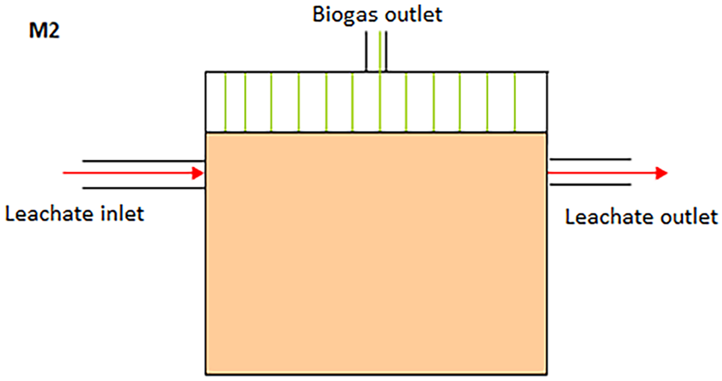

Figure 5. Design of biogas production

measurement of methane, carbon dioxide, oxygen, carbon monoxide, and hydrogen sulfide concentrations. In total, 26 measurements were taken for each digester at regular intervals to assess the evolution of biogas quality over time.

Methane was chosen as the primary indicator of biogas quality, because it is the main energy component of biogas and its concentration is directly linked to the energy potential of the biogas. A methane content exceeding 55% is generally considered indicative of high-quality biogas suitable for energy recovery. Conversely, the presence of hydrogen sulfide, even at low concentrations, can corrode equipment and reduce the efficiency of internal combustion engines used for electricity generation.

A preliminary assessment of the produced biogas quality was conducted 15 days after the system was fed with raw leachate. Measurements included temperature, methane percentage (CH_4), carbon dioxide percentage (CO_2), oxygen percentage (O_2), carbon monoxide concentration (CO in ppm), and hydrogen sulfide concentration (H_2S in ppm). In total, 26 measurements were taken for each unit, while keeping the system closed to ensure the sequential operation of the two digesters, M_1 and M_2.

The temperature in digesters M_1 and M_2 was maintained at 35 ± 1 °C and continuously recorded using calibrated digital temperature probes connected to a data acquisition system. The pH was measured twice weekly with a calibrated portable pH meter, while the oxidation-reduction potential (ORP) was monitored weekly using a calibrated portable ORP electrode. The leachate flow rate was controlled and measured daily with a volumetric flow meter. Biogas quality (CH_4, CO_2, O_2, CO, H_2S) was evaluated using a Gas Data GFM 406 portable biogas analyzer, with a total of 26 measurements taken for each digester over months 2 and 3 of 2022, with three repetitions per measurement.

RESULT AND DISCUSSION

Quality of the produced biogas

The results of the measurements taken for the entire study are summarized in Table 1, Table 2, and in the graphs of Figures 6 to 17. The analyses conducted after 15 days of digestion show that the produced biogas exhibits the following average characteristics (Table 1). After two months of anaerobic digestion of the leachates, we obtained values the averages (AVG), maximums (MAX), and minimums (MIN) of which are summarized in Table 2 below were obtained. The detailed measurements are shown in Figures 6 to 17.

Table 1. Quality of the biogas obtained after 15 days of leachate fermentation

Compants	M1	M2	RE
CH_4 (%)	10	10	9.8
CO_2 (%)	14	14.6	14.7
O_2 (%)	13	12.8	13
H_2S (ppm)	<<<500	<<<500	<<<500
CO (ppm)	3	3	90
T (°C)	23	23.6	24

Table 2. Quality of the biogas obtained after two months of Leachate fermentation

Compants	M1			M2			RE		
	MO	MAX	MIN	MO	MAX	MIN	MO	MAX	MIN
CH4 (%)	5.48	27.20	0.00	14.48	28.30	7.30	7.18	14.2	0.00
CO2 (%)	6.65	21.60	2.00	10.57	21.90	4.90	7.48	15.1	1.9
O2 (%)	13.23	17.30	3.40	9.08	12.80	3.50	12.22	17.6	8.1
H2S (ppm)	20.66	500.00	0.00	106.61	500.00	0.00	70.17	500	0
CO (ppm)	3.39	7.00	1.00	4.44	8.00	1.00	8.83	90	0
T (°C)	23.64	28.60	19.30	23.65	28.80	16.20	24.14	29.9	19.7

Evolution of CH_4, CO_2, and O_2

The CH_4 content shows the same trend in the three units M_1, M_2, and RE, as illustrated in Figures 6, 7, and 8. CH_4 is produced by methanogenic bacteria, which are strict anaerobes requiring a very low redox potential (below -300 mV) (Kurniawan et al., 2010). The maximum CH_4 content (28.30%) was recorded at the M_2 digester (Figure 7) at a temperature of 28.80 °C. Zero CH_4 content (0%) was recorded at the system's entrance at the M_1 digester (Figure 6) and at its exit at the RE viewing point, with temperatures ranging from 19.30 to 19.7 °C (Figure 8). In contrast, the M_2 digester never reached 0% CH_4 content (Figure 7). The CO_2 content shows the same trend across the three structures M_1, M_2, and RE (Figures 6 Figure 7, and Figure 8). The highest CO_2 content was recorded at the Methanizer M_2 (21.90%) at a temperature of 28.8 °C (Figure 7). The lowest content (1.9%) was recorded at the inspection chamber RE at a temperature of 19.7 °C (Figure 8).

The measured oxygen is part of the biogas generated within the system, since it has been completely isolated from the ambient air. The oxygen content shows the same trend across all three structures. The maximum content (17.6%) was recorded at the RE inspection chamber at a temperature of 29.9 °C (Figure 8). The minimum content (3.4%) was recorded at the M_1 digester at a temperature of 19.3 °C (Figure 6).

The correlation between variations in CH_4 and CO_2 suggests that these two gases are closely linked (Kurniawan et al., 2010). An increase in methane production is often associated with a decrease in CO_2 production, and vice versa. Indeed, the peaks in CO_2 and CH_4 concentrations always coincide with the drops in oxygen concentrations. This is because the same substrates (organic matter) can be used to produce either methane or CO_2, depending on environmental conditions and the microbial community (Megonigal et al., 2004). Examination of the results illustrated in Figure 6, 7, and 8 reveals the following:

When operating in series, the structures designed for the anaerobic digestion of leachates from household waste and waste similar to household waste, the concentrations of CH_4, CO_2, and O_2 in the produced biogas will evolve similarly in these structures.

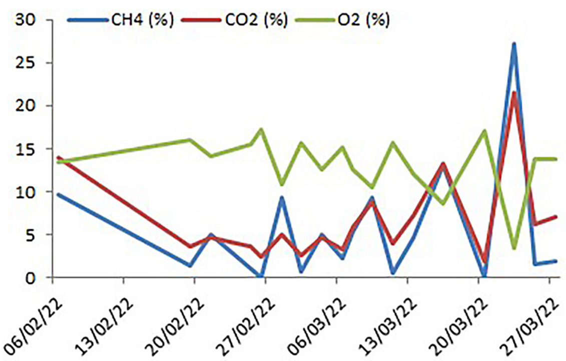

Figure 6. Temporal variation in the biogas content. derived from digested leachate in digester MI in CH_4, CO_2, and O_2

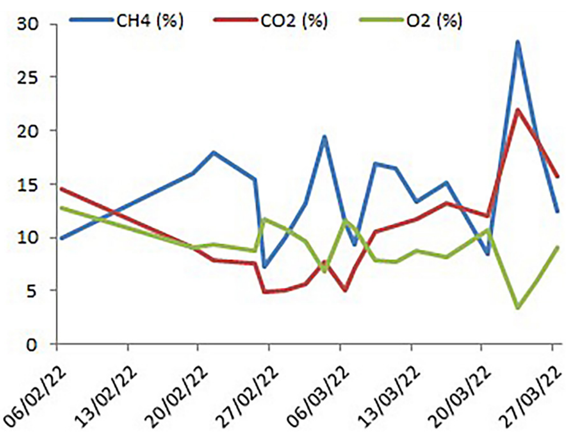

Figure 7. Temporal variation in the biogas content, derived from digested leachate in digester M2 in CH_4, CO_2, and O_2

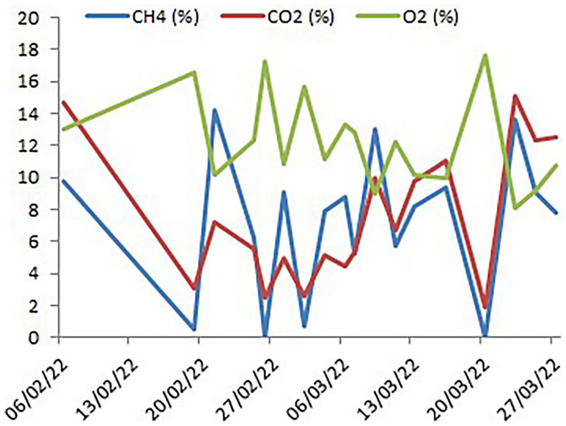

Figure 8. Temporal variation in the biogas content at the RE outlet in CH_4, CO_2, and O_2

Oxygen can be considered a limiting factor in the production of CH_4 and CO_2. This is because the microorganisms involved in the production of CH_4 and CO_2 have different metabolisms. Methanogenic bacteria are strict anaerobes, meaning they are poisoned by oxygen (Lu and Imlay, 2021). The presence of oxygen instead promotes the growth of aerobic bacteria that will consume organic matter and produce CO_2 instead of methane (Megonigal et al., 2004).

The biogas produced by the adopted process has a maximum CH_4 content of 28.3%. This percentage is relatively low for energy recovery, as a biogas is considered of good quality only if it contains at least 55% methane (Aromolaran, 2021).

Evolution of H_2S and CO

The concentration of H_2S in the produced biogas shows the same trend across the three structures, M_1, M_2, and RE, as illustrated in Figures 9, 10, and 11. H_2S is produced by sulfate-reducing bacteria, which are strict anaerobes that can use hydrogen, acetic acid, and volatile fatty acids to form carbon dioxide and hydrogen sulfide (Elferink, 1998; Hao et al., 1996; Mutegoa and Sahini, 2023).The highest concentration of this element was recorded at all the structures (Figure 9, Figure 10, and Figure 11). According to the biogas analyzer, it significantly exceeded 500 ppm. This concentration is the maximum detectable limit of the biogas analyzer used. To plot the curves, 500 ppm was used as the maximum value. The H_2S concentration was at its maximum value 15 days after the start of anaerobic digestion at all three structures (Figure 9, Figure 10, and Figure 11). The H_2S concentration decreased over a period of 7 days to reach its minimum value at all the structures. This decrease coincides with the peak in oxygen concentration at the same structures during the same period (7 days). The behavior

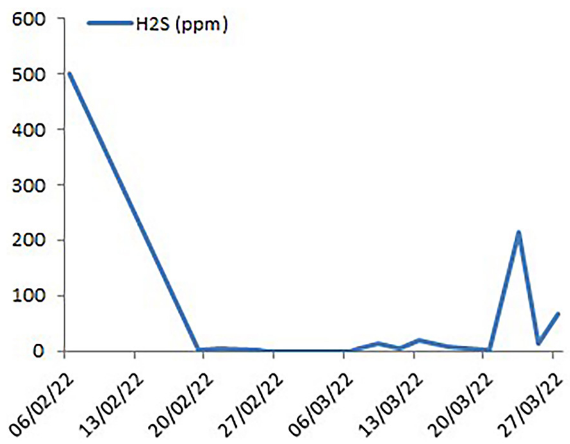

Figure 9. Temporal variation in the H_2S content of biogas derived from digested leachate in digester M1

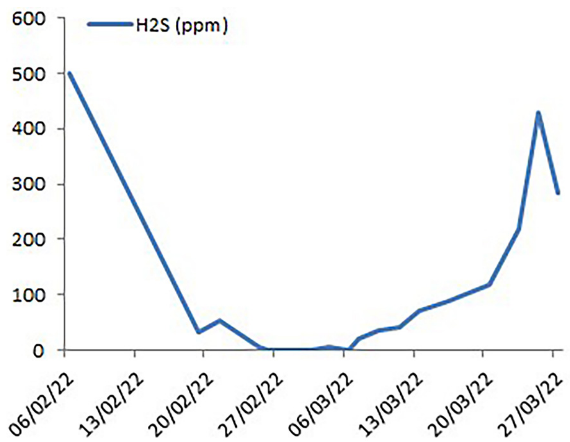

Figure 10. Temporal variation in the H_2S content of biogas derived from digested leachate in digester M2

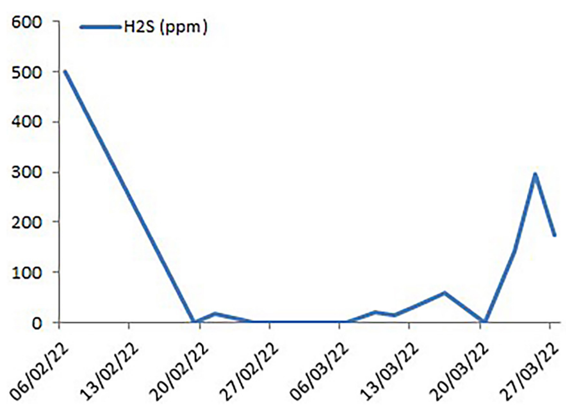

Figure 11. Temporal variation in the H_2S content of biogas at the RE outlet

of H_2S is similar to that of the other gases in the presence of oxygen (Figure 9, Figure 10, and Figure 11). A gradual increase in the H_2S concentration occurred 14 days after the initial decrease. The second peak was reached after 4 days. The recorded values were 215 ppm in M1 (Figure 9), 284 ppm in M2 (Figure 10), and 295 ppm at the RE (Figure 11).

The concentration of CO in the biogas produced from digested leachate within a specific digester 1 (Figure 12), exhibits significant variations over the study period. Very high peaks were observed, reaching nearly 7 ppm, alternating with periods of lower concentrations, around 3 ppm. There is no apparent linear trend in the CO concentration evolution. The variations seem rather random, suggesting that multiple factors may influence the CO production in this system. The CO concentration peaks could be linked to specific events in the anaerobic digestion process, such as changes in operating conditions (temperature, pH), the introduction of new feedstocks, or system disturbances (Kovalovszki et al., 2020; Wu et al., 2022). A high CO level can degrade biogas quality and reduce its calorific value, impacting its use as a fuel (Bharathiraja et al., 2018; Khan et al., 2017; Papadias et al., 2012). Understanding the factors causing these variations is crucial for optimizing the anaerobic digestion process and minimizing CO production. This could involve better control of operational parameters or the addition of specific compounds to inhibit CO formation.

Figure 13 illustrates the fluctuating variation in the CO concentration in biogas derived from the digested leachate within digester M_2 over a period from February 6th to March 27th, 2022. The CO levels oscillate significantly, reaching peaks near 8 ppm and troughs around 3 ppm, with no apparent linear trend. These variations can be attributed to various factors, such as digester operating conditions (temperature, pH), leachate composition, evolution of microbial communities, and disruptive events (Hussien and Kabbashi, 2022). These fluctuations highlight the complexity of the anaerobic digestion process and the importance of regularly monitoring digester parameters to optimize biogas production.

Figure 14 depicts the temporal profile of CO concentration in biogas generated from leachate within the RE system during the period from February 6th to March 27th, 2022. Commencing at an elevated level of approximately 90 ppm, the CO concentration exhibited a precipitous decline within the first 15 days, subsequently stabilizing at a significantly lower value. This trend, attributable to system acclimation and optimized operating parameters, underscores the efficacy of the

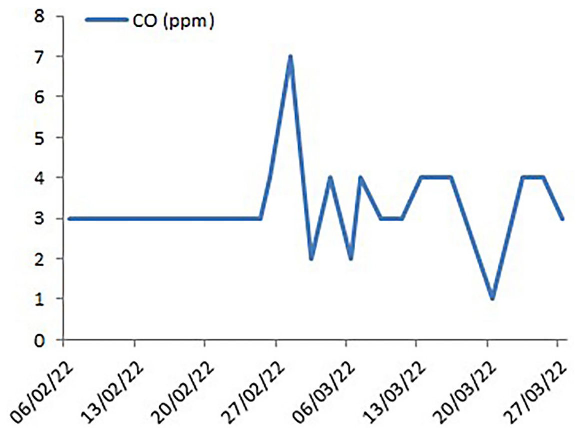

Figure 12. Temporal variation in the CO content of biogas derived from digested leachate in digester Ml

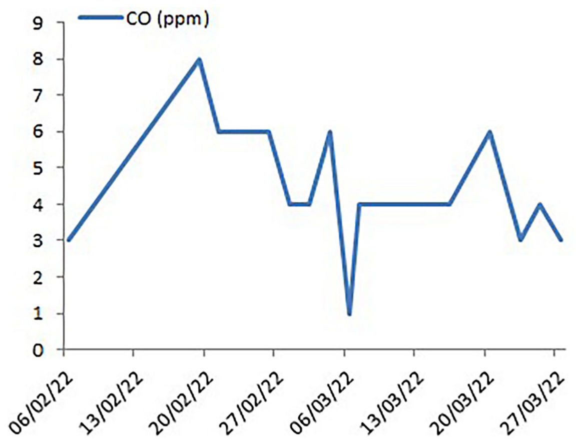

Figure 13. Temporal variation in the CO content of biogas derived from digested leachate in digester M_2

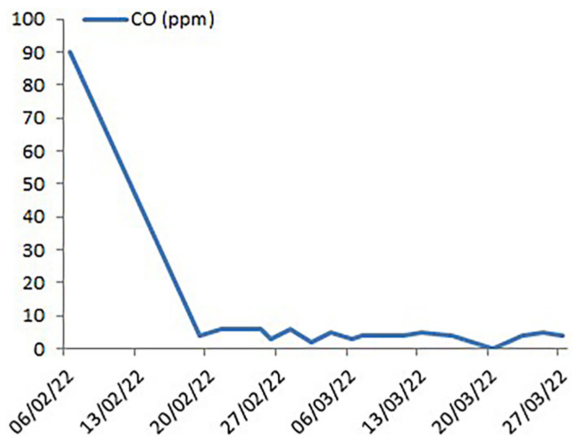

Figure 14. Temporal variation in the CO content of biogas derived from leachate at the RE outlet

RE system in mitigating CO production. Nevertheless, additional investigations are warranted to elucidate the fundamental mechanisms driving this reduction and to ascertain the factors governing the long-term constancy of CO concentration.

The examination of the results illustrated in Figures 9–14 reveals the following:

- during the serial operation of facilities designed for anaerobic digestion of leachates from municipal waste and waste similar to municipal waste, the concentrations of CO and H_2S in the produced biogas evolve in the same manner within these facilities.
- the biogas analyzer, a device intended to assess the quality of the biogas, detected H_2S concentrations (<<< 500 ppm) that significantly exceed its measurement range. This indicates that the produced biogas is of poor quality for potential valorization.
- the high concentration of H_2S may be indicative of intense activity by sulfate-reducing bacteria within the installed system.
- it can be deduced that the intensity of sulfate-reducing bacterial activity exceeds that of methanogenic bacteria.

Temperature evolution

Figures 15–17 illustrate the temporal evolution of temperature within three anaerobic digestion systems: digesters M_1 and M_2, as well as the RE system, over a period from February 6th to March 27th, 2022. The recorded temperature ranges from a maximum of 29.9 °C to a minimum of 16 °C. All three curves reveal a relative thermal stability, suggesting optimal operating conditions. However, minor variations are observed, particularly slightly larger fluctuations in digester M_2. The RE system is distinguished by a slightly lower average temperature and less pronounced variations, which could be attributed to specific operational characteristics or the nature of its substrate. These results highlight the importance of maintaining a stable temperature in digesters to optimize the methanation process. The examination of the results illustrated in Figures 15–17 reveals the following:

- the biogas production process is exothermic, leading to heat generation, which explains the maximum temperatures recorded in parallel with the maximum gas concentrations.
- temperature is a parameter the variation of which impacts the quality of the produced biogas. Indeed, an increase in temperature coincides with an increase in the production of CH_4, CO_2, CO, and H_2S. Conversely, a decrease in temperature is observed for O_2 production.

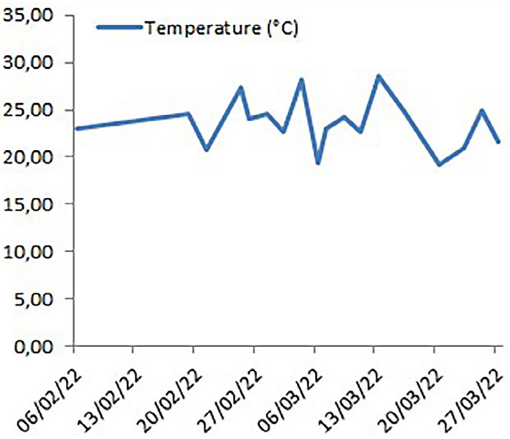

Figure 15. Temporal variation in temperature in digester Ml

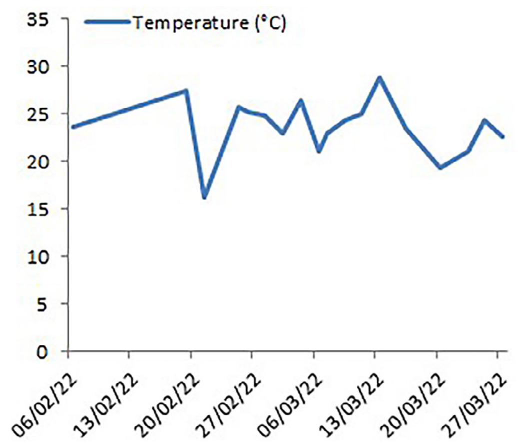

Figure 16. Temporal variation in temperature in digester M2

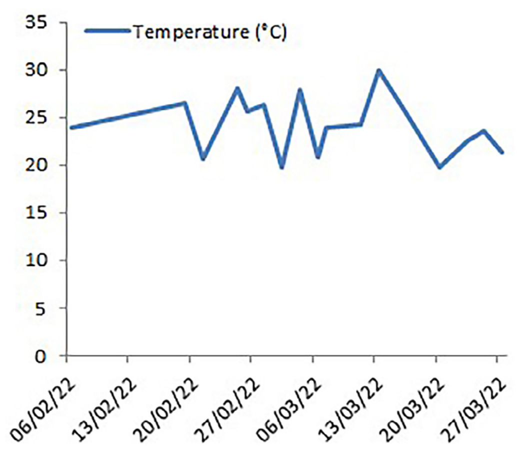

Figure 17. Temporal variation in temperature in digester RE outlet

The anaerobic digestion process of leachate from the Moulay Abdallah landfill resulted in the production of biogas with a quality inferior to that generally accepted for energy recovery processes (Dos Santos et al., 2018). Indeed, the methane content reached a maximum of 28% in digester M_2, whereas energetically recoverable biogas typically contains between 50% and 70% methane. Additionally, hydrogen sulfide (H_2S) was present at excessive concentrations, exceeding the measurement range of the biogas analyzer used in the study. The quality of the biogas obtained can be attributed to competitive nutrient interactions within the microbial ecosystem established in the system's facilities (Wang, 2014). Widdel (1980) demonstrated the ability of sulfate-reducing bacteria to utilize various sources of organic carbon by isolating and describing new species capable of growing on acetate, propionate, butyrate, fatty acids, and benzoate, some of which can fully oxidize organic matter to CO_2. In biomethanation processes, the direct toxicity of hydrogen sulfide (H_2S) is linked to the permeabilization of cell membranes and the formation of disulfide bridges between polypeptide chains, denaturing cytoplasmic proteins (Delmer, 1977). Inhibition thresholds are often calculated based on the doses that inhibit 50% of biogas production and are measured at different pH levels. The quality of the biogas is likely influenced by the consistency of the leachate, particularly its organic matter content. The amount of organic matter available to methane-producing microorganisms is the most significant factor in methane generation.

Excessive H_2S levels are probably due to high concentrations of sulfide ions (S^{2-}) in the leachate (Galbraith et al., 1972; González-Cortés et al., 2021). These ions can precipitate metals, which inhibit methanogenesis (CH_4 production). Furthermore, the S^{2-} form may have a toxic effect at very high pH levels (Dordević et al., 2021). The quality of the biogas may also be affected by the internal structure of the facilities as well as the lack of supports in digesters M_1 and M_2. Such supports could have provided a platform for biofilm formation. In a biofilm, sulfate-reducing bacteria are at a disadvantage compared to methanogenic bacteria due to their poorer aggregation properties (Rosa-Masegosa et al., 2024; Zielinski et al., 2023).

CONCLUSIONS

The anaerobic digestion of leachate from the Moulay Abdallah landfill did not achieve the goal of producing biogas suitable for direct energy recovery. The resultant biogas was of inadequate quality, failing to meet the standards for efficient energy utilization. The primary novelty of this study lies in revealing the specific limitations of biogas production from the leachate of this particular landfill, specifically the low methane yield and the unexpectedly high hydrogen sulfide concentrations. This study bridged the gap in understanding the challenges associated with biogas production from this type of leachate in the Moroccan context. It highlighted that the imbalance within the microbial ecosystem, influenced by factors such as competition between different bacterial groups and leachate composition, presents a significant hurdle. Looking ahead, this research opened the prospects for further investigation into optimizing the anaerobic digestion process. Future work should focus on the strategies to suppress sulfate-reducing bacteria, pretreat leachate to modify its characteristics, and explore digester design modifications to promote more efficient methane production and ultimately enhance biogas quality for energy applications.

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