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Enhancing Environmental Preservation through Biomethanation of Solid Waste from the Sisal Industries of South Amboasary

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Abstract: *The primary objective of this study is to explore sustainable alternatives to address the accumulation of waste resulting from the sisal exploitation in South Amboasary. Laboratory tests involving 8,000 g of defibration residues mixed with 1,600 g of inoculum over 69 days produced 355 liters of biogas, equating to 335 L/kg of dry matter with a methane content of 58% and a lower calorific value of 20,807 kJ/Nm^3. These results suggest that biomethanation can valorize the 212,630 tons of sisal waste available annually, potentially replacing the 2,030 m^3 of diesel consumed each year and meeting the domestic fuel needs of 16,575 households with eight members each. Additionally, a production of 137,800 tons of compost is projected to prevent the emission of approximately 7,000 tons of CO_2-equivalent toxic gases into the atmosphere. The technical feasibility studies for infrastructure implementation and project organization address several issues: local treatment of organic waste, creation of local jobs, energy independence, agricultural sustainability, and economic development.*

Keywords: *biogas, development, anaerobic digestion, fertiliser, sisal*

I. Introduction

The seven sisal industries in South Amboasary exploit over 20,000 hectares of sisal fields. They export more than 6,000 tons of fibers annually, a production that requires 218,890 tons of sisal leaves, 2,030 m^3 of diesel, and over 570,000 m^3 of water. This activity generates more than 680,000 m^3 of liquid waste and over 200,000 tons of solid waste. The waste produced by these industries is directly discharged into the environment and the Mandrare River without treatment, posing a threat to terrestrial and aquatic biodiversity. Currently, there is no organized valorization or appropriate treatment system, even on a small scale, available to manage this exponentially increasing waste.

An industrial unit, ZEMA, was established in 1982 in the city of Amboasary to produce organic fertilizer from sisal defibration waste. This state initiative failed because the commercialized product was too expensive for the amount of fertilizing units it

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contained, leading to the abandonment of the project. In addition to odor and visual nuisances, the formation of artificial lakes and the acidification of groundwater have occurred. The waste overflow from the region creates pollutants, leading to uncontrolled biodegradation that directly impacts the environment. This process contributes to the emission of greenhouse gases (CO_2, CH_4, etc.), causing atmospheric pollution (Yu et al., 2002). This complex situation poses significant health risks to the surrounding populations. Beyond ecological risks, it also represents an economic loss for society.

For all these reasons, developing alternative and remedial solutions tailored to this local context is urgent, particularly by valorizing this waste through biomethanation. The objective of this research is to valorize this waste through anaerobic digestion to:

a. Produce biogas, a source of clean and renewable energ
b. Produce digestate, an organic fertilizer to improve sisal cultivation
c. Minimize environmental damage caused by sisal exploitation.

II. Research Methods

2.1 Study sites and choice of sample

The study was conducted in the seven sisal exploitation industries along the banks of the Mandrare River in the commune of South Amboasary, Anosy Region. Sisal plantations in this area cover over 20,000 hectares. The exploitation generates solid waste, which is neither treated nor valorized, and is discharged in various forms into the Mandrare River. The selection of the sample is based on the consistent availability of this waste over time and space.

Figure1. Sisal field and waste at Berenty South Amboasary The sisal plantation at Berenty encompasses several hectares.

2.2 Assessment of available waste

To obtain reliable information about the sisal industry, surveys were conducted in the seven industries where the study was carried out. The survey method was based on the Accelerated Participatory Research Method, divided into three stages. The first stage involved interviews with the seven sisal operators in the exploitation areas, focusing on their cultivated areas, yields, diesel consumption for exploitation, waste, and industry-related issues. The second stage involved interviews with local authorities to better understand the socio-economic and environmental challenges of sisal exploitation. The final stage was based on direct observation in the different exploitation and cultivation areas to validate the consistency of the information obtained from the operators and local authorities

2.3 Provision of the necessary equipment

a. Fermentation substrate

The substrate used in this experiment is the solid residue from the defibration of Agave sisalana, commonly known as sisal. This plant belongs to the Agavaceae family and is native to eastern Mexico. Its botanical classification is as follows:

Table 1. Botanical classification of sisal grown at South Amboasary

Kingdom:	Plantae	**Order :**	Liliales
Sub-region :	Tracheobionta	**Family :**	Agavaceae
Division :	Magnolyophita	**Genus :**	Agave
Class :	Liliopsida	**Species :**	Sisalana
Sub-class :	Liliidae	**Vernacular name :**	Taretra ou Laloasy

To conduct this experiment, 10 kg of solid sisal residue from the defibration industry in Berenty were collected on the same day of cutting. The samples were kept in a cooler during the journey from South Amboasary to Toliara. Upon arrival at the CREADE Toliara laboratory, the samples were stored at 4°C until use. They were then characterized to determine their dry matter (DM), organic matter (OM), and mineral matter (MM) content.

To achieve this, a known quantity M_0 of the substrate was placed in an oven maintained at 105°C until a constant mass M_1 was obtained. Following this, the M_1 mass was incinerated at 600°C in a furnace until a constant weight M_2 was reached after more than 6 hours (Apha, 1998).

$$\%MS = \frac{M_1}{M_0} * 100 \qquad \%MO = \frac{M_1 - M_2}{M_1} * 100 \qquad \%MM = \frac{M_2}{M_1} * 100$$

b. Inoculum

In this experiment, wastewater from the Befanamy Toliara slaughterhouse, primarily composed of bovine rumen, was used as an inoculum. The rumen was chosen due to its presumed richness in methanogenic bacteria, which naturally develop in the intestinal tracts of cattle (**Ynagata, et *al.*, 2000**). It was pre-activated by being left for 6 days in another biodigester.

c. Experimental set-up

The experiments were conducted using a 20-liter batch-type digester assembled from a 20-liter paint can. Its lid was perforated and fitted with a hydraulic seal created by two plastic buckets without their lower bases.

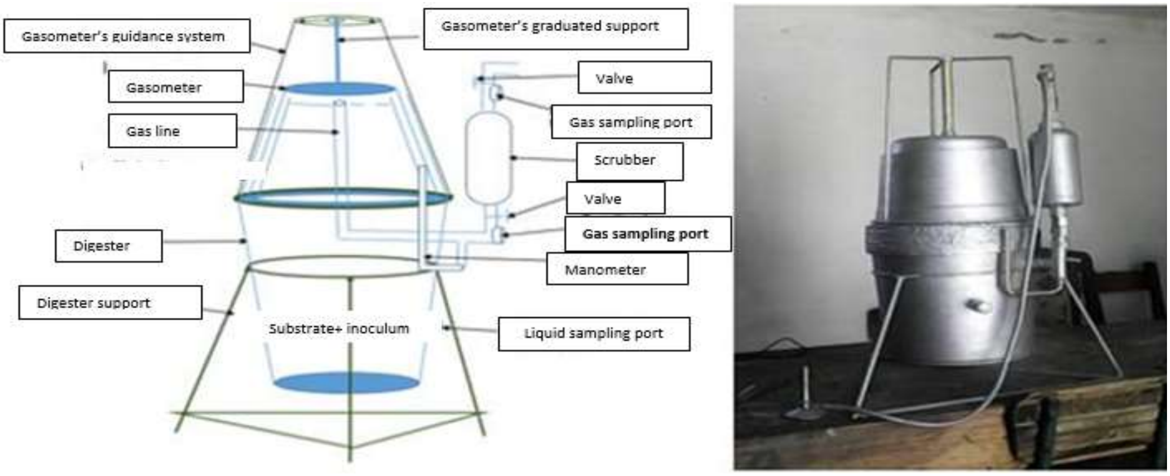

Figure *2*. Experimental digester

A cut upper section of a bucket, with a base area of 444 cm^2, moved vertically within this hydraulic seal. Its vertical displacement was measured using a graduated PVC tube ranging from 0 to 28 cm. The digester was equipped with a biogas conduit connected to a liquid manometer, a biogas analyzer port, two shut-off valves, and a burner. A shut-off valve on the paint can allowed for sampling of mixed liquor during fermentation without opening the biodigester.

d. Experimental protocol

The fermentation mixture comprised 4,285 g of finely ground fresh substrate, introduced into the digester along with 857 g of inoculum (20% by mass of the substrate). Following this, 10 liters of water were added to fill the digester, after which the gasometer bell and all shut-off valves were sealed. Subsequently, the hydraulic seal was filled with water to ensure airtightness, and the device was placed outdoors at ambient temperature.

2.4 Fermentation monitoring

a. Measuring pH and temperature

These two parameters are measured daily at the same time using a HANNA-type pH meter equipped with a precision glass electrode (0.01). The initial step involves calibrating the device using two pH buffer solutions, pH=4 and pH=7. Following calibration, the electrode is immersed in the mixed liquor, and stable values are directly read from the display.

b. Daily production and composition of biogas

The daily biogas production is calculated by multiplying the base area of the gasometer by the vertical height measured on the graduated scale.

Biogas consists predominantly of methane and carbon dioxide, with trace amounts of other gases (H_2S, H_2…). Due to the lack of sophisticated equipment, an Orsat apparatus was used to determine the major components of biogas in this study. The principle of this method relies on the ability of a 40% KOH alkaline solution to absorb carbon dioxide at ambient temperature, forming soluble K_2CO_3 salt (**Tjalfe & Poulsen, 2003**).

Injecting a known volume of biogas using a syringe with agitation allows us to determine the absorbed carbon dioxide content. The remainder, which is not absorbed, is considered the methane content (**Abdel-Hadi, 2008**).

c. Calorific value and energy equivalence

The calorific value of the produced biogas is obtained by multiplying the methane content of the biogas by 35.874 kJ/Nm³, which is the calorific value of pure methane. The energy equivalence of biogas compared to other energy sources is determined by dividing the calorific value of one cubic meter of biogas by that of the energy source unit under comparison (**Ramampiherika, 1997**).

Table 2. Lower calorific value of some fuels

Fuels	Lower calorific value
Ethanol	21.4 10^6 kJ/Nm^3
Petrol	33.3 10^6Kj/Nm^3
Duesel	34.5 10^6kJ/Nm^3
Charcoal	18,804kJ/kg
Methane	35,874kJ/Nm^3

The table illustrates the varying energy potentials of different fuels, highlighting the superiority of diesel and methane in terms of lower calorific values. These values are essential for evaluating fuel efficiency and suitability for various applications, from transportation and industrial uses to domestic heating and cooking.

III. Results and Discussion

3.1 Results of the field inspection

In the Mandrare Valley, there are seven sisal exploitation companies supporting over 6,000 workers. These companies consume more than 218,890 tons of sisal leaves annually and produce between 6,262 to 6,566 tons of fiber, requiring 570,000 m³ of water and 2,030 m³ of diesel per year. They discharge approximately 212,630 tons of solid waste and 113,710 m³ of sisal juice into the environment.

Table 3. Annual sisal harvesting of South Amboasary

Company	**SSM**	**SADP Beval**	**SADP Apopo**	**SPSM**	**SAMA**	**Gallois**	**HAH**
Cultivated area (ha)	3,000	4,000		2,714	2,000	4,500	4,400
Production (t/an)	23,500	46,950		45,100		60,000	43,340
Fibres (t)	705	1,407		1,350		1,500	1,300
Diesel consumed (m^3/an)	230	530		400		470	400
Solid waste (t/an)	22,797	45,543		43,750		58,500	42,040
Mobilisable juices (m^3/an)	12,126	24,226		23,271		30,960	22,363

SSM:	Société de Sisal Maki (Sisal Maki Company)
SPSM:	Société de Plantation de Sisal de Mandrare (Mandrare Sisal Plantation Company)
SADP:	Société Anonyme du Domaine Pechpeyrou (Pechpeyrou Estate Public Limited Company)
SAMA:	Société Anonyme de MAndrare (Mandrare Public Limited Company)
HAH:	Henry Alain Heaulme

This data highlights the scale and efficiency of sisal production among different companies in South Amboasary. SAMA stands out with the highest production and corresponding by-products, while SSM operates on a smaller scale. The variability in diesel consumption and solid waste generation indicates differences in operational practices and efficiencies. This information is crucial for optimizing sisal production and improving sustainability practices within the industry

3.2 Experimental results

The table outlines the key characteristics of the substrate, providing detailed information on its composition. This includes the proportions of dry matter, moisture, organic matter, and mineral matter. Understanding these parameters is essential for evaluating the substrate's suitability for various applications, particularly in agricultural and environmental contexts.

Table 4. Characteristics of the substrate

Constituents	Value
Dry matter	22%
Moisture	88%
Organic matter	86% of dry matter
Mineral matter	14% of dry matter

The table provides a detailed analysis of the substrate's composition, emphasizing its dry matter, moisture content, organic matter, and mineral matter. With 22% dry matter, the substrate consists largely of solid material, while the high moisture content of 88% indicates significant water presence, affecting its physical properties and applications. The substrate's organic matter, constituting 86% of the dry matter, highlights its potential for composting and soil enrichment, contributing to soil fertility and structure. The 14% mineral matter within the dry fraction provides essential nutrients and structural stability, influencing the substrate's suitability for various agricultural and environmental uses. This balanced composition of high organic content and mineral matter underscores the substrate's versatility, making it valuable for sustainable agricultural practices and environmental management.

Figure 3 illustrates the dynamic variations in temperature and pH within the digester environment. These parameters are pivotal in anaerobic digestion processes, influencing microbial activity, biogas production rates, and the overall efficiency of organic matter decomposition. Understanding the temporal changes in temperature and pH profiles depicted in the figure is crucial for optimizing digester performance and ensuring stable biogas yields.

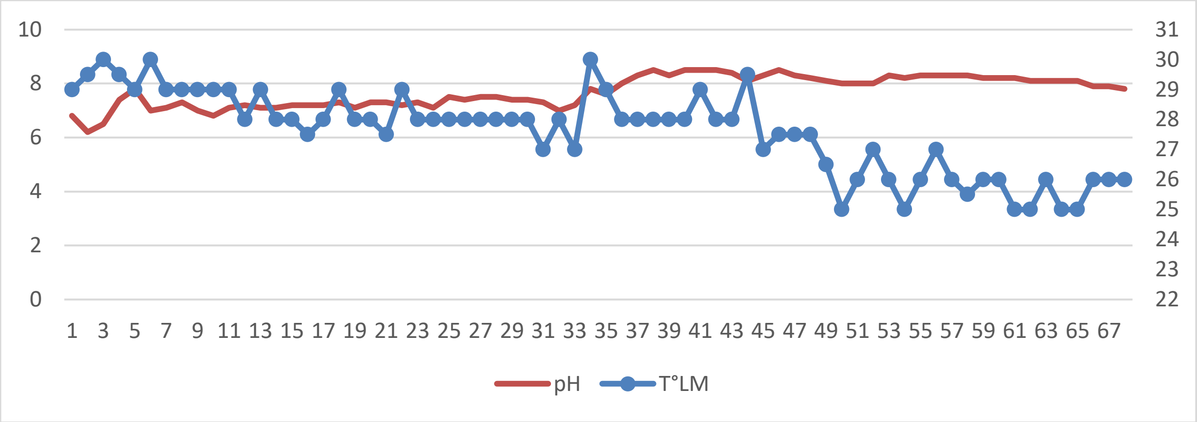

Figure 3. Changes in temperature and pH in the digester

Figure 3 depicts the temporal trends of temperature and pH variations within the digester system. These dynamics are critical factors influencing the efficiency and stability of biochemical processes such as anaerobic digestion. Temperature fluctuations, as shown in the figure, directly impact microbial activity rates, influencing the breakdown of organic matter and subsequent biogas production. Similarly, pH changes play a pivotal role in maintaining optimal conditions for microbial consortia involved in the digestion process. The data presented in Figure 3 provides valuable insights into the operational parameters necessary for maintaining optimal digester performance and maximizing biogas production efficiency.

Figure 4 presents an analysis of biogas production trends over a specified period. Biogas, primarily composed of methane and carbon dioxide, is generated through anaerobic digestion of organic materials. This figure provides a graphical representation of the temporal variations in biogas production, illustrating the effects of substrate composition, digester operational conditions, and environmental factors on gas yield. Understanding these trends is essential for optimizing biogas production systems, enhancing renewable energy generation efficiency, and advancing sustainable waste management practices.

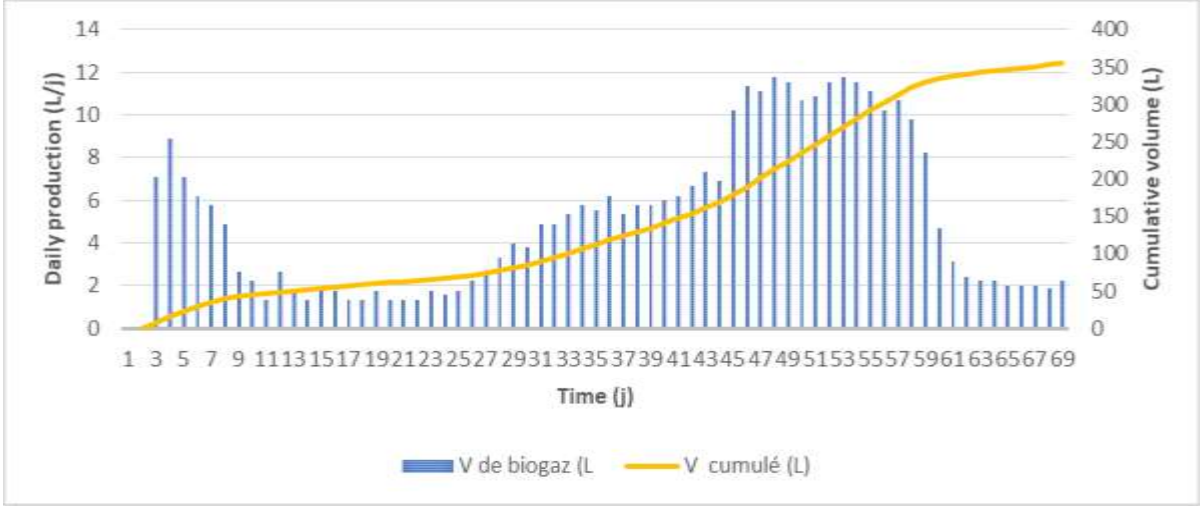

Figure 4 . Biogas production trends

Figure 4 depicts the temporal evolution of biogas production, showcasing fluctuations in methane and carbon dioxide yields over the observation period. These trends are crucial indicators of anaerobic digestion efficiency, influenced by factors such as substrate composition, temperature, and digester operation. Peaks and valleys in biogas production reflect variations in organic material digestion rates and microbial activity within the digester. Understanding these dynamics is essential for optimizing biogas yield and ensuring stable operation of renewable energy production systems. The data presented in Figure 4 underscores the importance of monitoring and adjusting operational parameters to maximize biogas output and enhance the overall sustainability of waste-to-energy processes.

Figure 5 presents the chronological changes in the primary components of biogas over time. It provides a graphical representation of the proportions of methane (CH_4) and carbon dioxide (CO_2) within the biogas mixture during the observation period. Understanding the evolution of these gas components is crucial for assessing the efficiency of anaerobic digestion processes and optimizing biogas quality for energy applications.

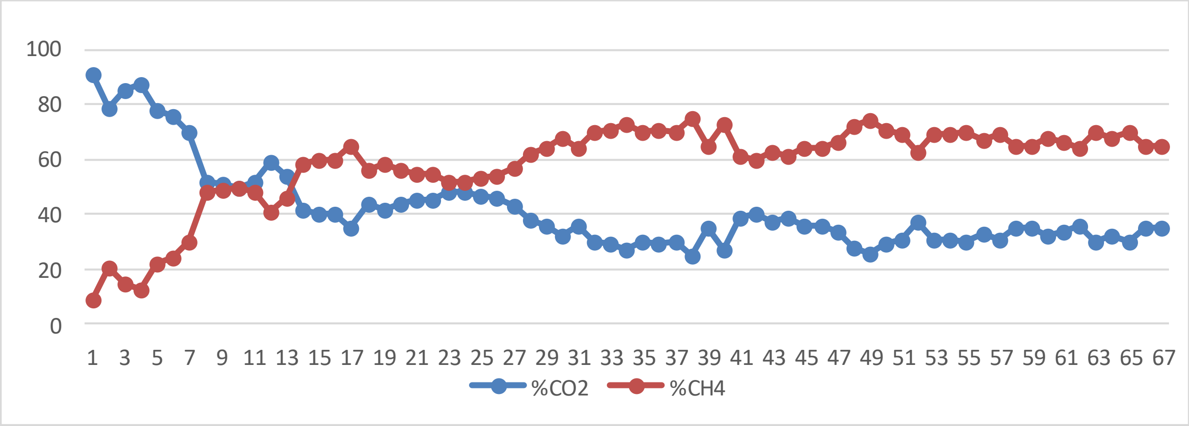

Figure 5 . Evolution of the main components of biogas

Figure 5 illustrates the temporal evolution of methane (CH_4) and carbon dioxide (CO_2) concentrations in biogas. This data is crucial for assessing the efficiency of anaerobic digestion processes. Changes in CH_4 and CO_2 levels reflect variations in microbial activity, substrate composition, and operational conditions within the digester. Monitoring these components helps optimize biogas production and quality, ensuring effective utilization in renewable energy applications.

The following table provides a quantitative assessment of energy equivalents derived from various types of available waste.

Table 5. Energy equivalents for all available waste

Available waste	Other energy sources	Equivalents
212,630 t	Ethanol	4,125 m^3
	Charcoal	4,650 t
	Diesel	5,660 m^3
	Firewood	255,000 m^3

The table illustrates the potential energy outputs from 212,630 tons of available waste, expressed in equivalents of ethanol (4,125 m^3), charcoal (4,650 tons), diesel (5,660 m^3), and firewood (255,000 m^3). These equivalencies underscore the diverse energy recovery options possible through efficient waste utilization strategies. Such data informs decision-making processes aimed at maximizing renewable energy production while managing waste resources sustainably.

Discussions

3.3 Downhill terrain

According to these results, only 3% of sisal biomass is recycled, and the remaining 97% is released into the environment. These values correspond to those found by **Lock G.** (1969). In addition, the diesel consumed sends 5,480 tonnes of CO_2 into the atmosphere every year. This figure is based on an emission of 2.695 kg of CO_2 per litre of diesel (**ADILCA, n.d.; Ramampiherika, 2012**). On the other hand, the 218,890 tonnes of sisal leaves available per year sequester 403,187 tonnes of CO_2. This theoretical estimate is based on the method used by Ramampiherika: knowing the carbon content C% of the biomass and the photosynthesis equation:

$$n\,CO_2 + n\,H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} (CH_2O)_n + n\,O_2,$$

The mass M_{CO2} of carbon dioxide sequestered during the production of a mass M of biomass is obtained by the formula:

$$M_{CO2} = 3{,}67\ C\ \%\ M \quad (\mathbf{1})$$

The carbon content of sisal is 48.3 in relation to the dry matter and the dry matter content is 14% (**Muthangya et *al.*, 2009**). The carbon content (C%) of the fresh matter is therefore 6.762%. The quantity of sisal processed per year is 218,890 tonnes, so:

$$M_{CO2} = \frac{6{,}76}{100} \times 3{,}67 \times 218890$$

i.e. M_{CO2} = 54,271.6 tonnes.

Given that only 3% of the biomass, i.e. 6,566.7 to 7,000 tonnes of fibre from 1,628 t of captured CO_2, is recovered (sold as fibre). The remaining 52,643t of CO_2 are unused, dumped in the natural environment and not recovered in any other way.

3.4 Physico-chemical characteristics of sisal waste

The dry matter content of these wastes exceeds 15%, categorizing them as solid substrates (**S3D & APESA, 2014**). They exhibit a higher water content, making them highly resistant to combustion. Significant time would be required for them to be incinerated, aside from the pollution caused by smoke and the loss of 90% of the raw material. In comparison to waste treatments such as incineration and landfilling, anaerobic digestion remains the least environmentally aggressive waste treatment technology.

3.5 Changes in temperature and hydrogen potential

pH serves as a crucial indicator for the stability and successful progression of anaerobic digestion. Throughout this experiment, all measured pH values ranged between 6.2 and 8.5, with an average of 7.7 falling within the optimal range for methanogenic bacteria requirements.

The temperatures recorded during the 91-day anaerobic digestion of this substrate ranged from 20 to 30°C, with an average of 27.60°C. This indicates that the active bacterial populations during fermentation are mesophilic bacteria, thriving between 20 to 45°C, with a digestion time exceeding 20 days (**Ramampiherika, 1997**).

3.6 Production de biogaz

The 69-day fermentation period was chosen, during which daily gas production remained below 1 liter, although it continued in small quantities. No production blockages or latency phases were observed. Gas production commenced immediately after introduction into the digester, characterized initially by a high carbon dioxide content. This phenomenon can be attributed to the prior activation of rumen bacteria from cattle.

The total volume of biogas obtained was 355 liters from 8 kg of sisal defibration residue, equivalent to 335 liters/kg of dry matter or 44 liters/kg of raw substrate. Gas production occurred over time: 50% was formed within 44 days, reaching a peak of 11.79 liters on the 54th day; 35% was produced between the 44th and 55th days, with the remaining 15% generated slowly after the 55th day until the end of fermentation.

The results obtained are consistent with findings from other literature on biogas potential and composition. Agricultural residues typically yield an average of 450 liters per kilogram of dry biomass (**Goma & Yamego, 1981**). In this study, sisal defibration waste produced 335 liters/kg of dry matter or 205 liters of methane/kg of dry matter, a lower yield influenced by operational conditions during experimentation and the cellulose content of sisal.

These findings align closely with those reported by Mshandete et *al.* who anaerobically digested chopped sisal waste to produce approximately 220 liters of CH_4 per kilogram of dry matter (**Mshandete et *al.*, 2006**). Based on the available waste, it is estimated that 9,435,456 cubic meters of biogas could be produced annually from these 212,630 tons of sisal residue.

3.7 Evolution of biogas composition

During the 69-day retention time, the CO_2 content varied between 91% and 25%, while methane ranged from 9% to 75%, with average values of 42% for CO_2 and 58% for methane. This represents an average biogas with a calorific value of approximately 20807 kJ/Nm³. In this fermentation process, the biogas flame became ignitable on the 21st day after digestion commenced but was not sustained. It only became stable from the 23rd day onward, coinciding with a CO_2 content of 44%.

According to Figure 3, at the beginning of fermentation, there was a sharp increase in CO_2 content (1st to 3rd day) accompanied by a pH drop to around 6.2, indicative of the hydrolysis and acidogenesis phases. This rise was attributed to volatile fatty acid accumulation.

From the 4th day onward, there was a gradual decrease in CO_2 content and an increase in methane content. This phenomenon marks the onset of the acetogenesis and methanogenesis phases. (**Wheatley,1990**).

3.8 Available energy equivalents for waste

Knowing that one cubic meter of biogas is sufficient for the cooking needs of a household of 8 people, preparing three meals per day using a single burner together (**Ramampiherika, 1997**), and approximately 37 cubic meters of biogas can replace one cubic meter of firewood for heating purposes.

According to Table 4, we can deduce that an annual production of 9,435,456 cubic meters of biogas is projected from 212,630 tons of available residues. This amount could replace the 2,030 cubic meters of diesel consumed with 3,385,456 cubic meters of biogas.

The remaining 6,050,000 cubic meters of biogas would suffice for the annual energy needs of 16,000 households of 8 people each, considering that this fuel is exclusively used for cooking meals (**Ramampiherika, 1997**). Investing in the construction of digesters and their equipment could replace the expenditures typically allocated to diesel purchases. Thus, cultivating sisal without impacting forests or importing diesel becomes feasible through the valorization of waste via anaerobic digestion.

Biomethanization produces two types of products, thereby mitigating greenhouse gas emissions. (**ADEME, 2016**) :

a. Methane, utilized for heat or electricity, avoids 44 kg CO_2 eq./t
b. Compost, used as an amendment to substitute synthetic fertilizers; the average production is 650 kg per ton of waste entering methanization, avoiding emissions of 33 kg CO_2 eq./t. Thus, emissions avoided through biomethanization are 77 kg CO_2 eq./t of waste.
c. Based on 212,630 tons of sisal waste available annually, it is possible to produce 138,200 tons of compost and avoid 16,370 t CO_2 eq. emissions per year.

Valorizing these wastes through biomethanization facilitates the establishment of a new circular economy, as opposed to a linear one, based on the principle of "closing the life cycle" of products, services, and wastes. This approach enables the production of goods and services while limiting the consumption and waste of raw materials.

IV. Conclusion

The overarching objective of this study is to explore sustainable alternatives to address the accumulation of sisal waste in South Amboasary and to substitute fossil fuels used in sisal processing with biomethane. Laboratory trials involving 8,000g of sisal waste mixed with 857g of inoculum over 69 days yielded an average of 335 liters of biogas with a calorific value of 20,807 kJ/Nm3. Extrapolating these results to the valorization of 212,630 tons of available waste could replace 2,030 cubic meters of diesel consumed annually for operations and the wood energy needs of 16,000 families of eight people each. Additionally, the production of 138,200 tons of compost is anticipated, with an estimated avoided emission of 16,370 tons of CO2-equivalent.

The valorization of sisal waste from South Amboasary through biomethanation aligns with several strategic objectives:

a. Halting deforestation
b. Treatment and valorization of biodegradable organic materials
c. Massive utilization of low-carbon renewable energies (methane)
d. Substitution of synthetic fertilizers with locally produced organic fertilizers

These avenues represent promising prospects as they meet present needs without compromising the ability of future generations to meet their own. Sustainable development comes at this cost, emphasizing the imperative to adopt environmentally friendly practices and renewable energy sources in resource management strategies.

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