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Biogas Potential of Wastewater Sludge from a Palm Oil Refinery Plant

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ABSTRACT

An agri-food company specializing in the processing of crude palm oil into refined oil generates physico-chemical and biological sludge from its SN Cie-coded wastewater treatment plant. This sludge is therefore a management issue. The aim of this study is to valorize the sludge from a wastewater treatment plant located in an industrial zone in Vridi/Abidjan (Côte d'Ivoire) into biogas. The physico-chemical characteristics of the sludge and its methanogenic potential were assessed, followed by optimization of biogas production. These results revealed that the biological sludge (73.08% MS) contained more organic matter than the physico-chemical sludge (55.55% MS). The relatively average organic matter content of the physico-chemical sludge necessitated the use of cow dung as an inoculum to enhance biogas production. Biodegradability tests carried out with different ratios of Substrate/Inoculum led to the conclusion that the presence of a significant quantity of microorganisms is necessary for optimum biogas production. As a result, 6510mL of biogas were produced from the SN Cie wastewater treatment plant's biological sludge, with a methane composition of 71.33%, which is required for power generation.

Keywords: Anaerobic, Biogas, Sludge, Treatment, Valorization.

1. INTRODUCTION

Rampant demographics and increasing industrialization in many developing countries are one of the causes of pollution, as these countries lack adequate sanitation infrastructures to treat liquid and solid effluents. This waste is a threat to public health and the quality of life [1,2]. However, recent studies have focused on the possibility that this waste could be an invaluable resource for developing countries through mechanisms for recycling it into biobased products [3,4].

Indeed, wastewater treatment sludge is the product of biological or physico-chemical processes. It is generally extracted from clarifiers after a period of thickening, before being drawn off for storage or land application. Increasingly, the management of these sludges (5% solid substance)[5] requires financial efforts in terms of transport costs and subsequent disposal in landfill sites.

Faced with the growing problems posed by sludge and its fate, anaerobic digestion would appear to be a very interesting sludge treatment solution to study, as part of the development of a suitable and reliable disposal and recovery process. Indeed, anaerobic digestion is the transformation of organic matter into energy by bacteria in the absence of oxygen[4]. It produces a combustible gas, biogas, essentially composed of methane, while reducing the organic matter content by half. [6]. The final digestion residue (or digestate) is stable, deodorized, largely free of pathogens and can even be used as a fertilizer for farmland [7,8].

The anaerobic digestion of sludge from wastewater treatment plants produces renewable energy (biogas). This inexpensive, non-polluting energy should be used to reduce greenhouse gas emissions. Biogas production is also seen as an economical, decentralized and environmentally-friendly solution for the sustainable development of certain regions[9].

Furthermore, anaerobic sludge treatment has proven to be an efficient technique for reducing pollutant loads and pathogen concentrations. And unlike aerobic treatment, anaerobic sludge digestion and stabilization can be achieved rapidly, while reducing sludge volume and providing significant quantities of energy. [10]. Indeed, sludge contains fertilizing elements and can be a source of energy. [11].

Yoon et al[12] and Li et al [13] reported that digestion of the organic fraction of municipal solid waste (OFMSW) in the presence of cow dung as inoculum represents an option for controlling the anaerobic digestion stability process and maximizing biogas production.

The overall aim of this study is to optimize biogas production by co-digesting physicochemical and biological sludge with bovine dung. More specifically, this research focused on (i) assessing the methanogenic potential of sewage sludge (ii) determining the conditions for optimum biogas production in the co-digestion of primary sludge (PS) , physical-chemical sludge (P-C B) , primary sludge and biological sludge (BS) with bovine dung (BD) by varying the ratio between substrate and inoculum (S/I ratio) and (iii) Determine the influence of the quantity of cow dung (inoculum) on biogas yield.

2. MATERIALS AND METHODS

Primary sludge and physico-chemical sludge come respectively from the grease silo and the sludge silo of the SN Cie wastewater treatment plant at the crude palm oil refinery. This plant is located in the Vridi/Abidjan industrial zone (Côte d'Ivoire). Physico-chemical sludge results from the formation of flocs after the addition of polyaluminium chloride (coagulant) and polyacrylamide (flocculant) during effluent treatment. In addition, the biological sludge comes from the treatment plant's anaerobic basin. The cow dung used as inoculum for biogas production was collected from the municipal slaughterhouse in Yamoussoukro (Côte d'Ivoire). Indeed, cow dung provides fresh bacteria and has a strong buffering capacity (pH stabilization), to facilitate bacterial reactions. Figure 1 shows photographs of primary sludge (a), physico-chemical sludge (b), biological sludge (c) and cow dung (d).

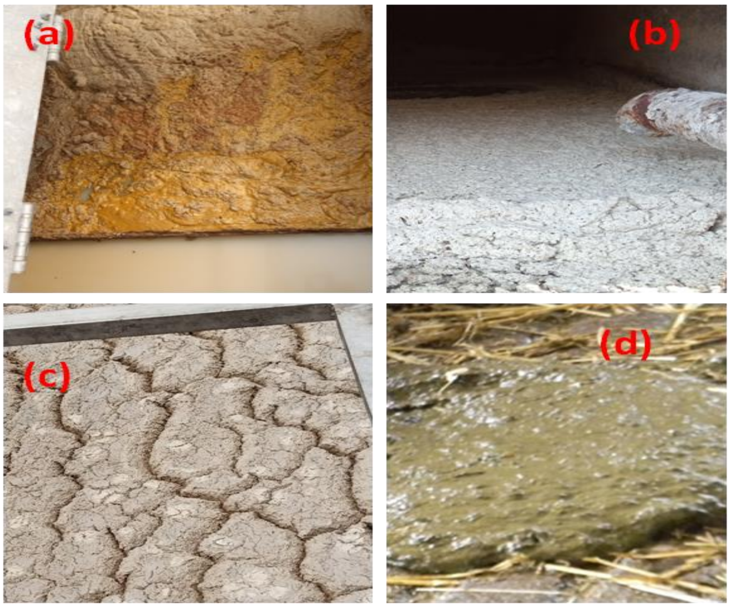

Figure 1 : Photograph of primary sludge (a), physico-chemical sludge (b), biological sludge (c), cow dung (d)

2.1. Sludge characterization

The sludge was characterized by determining the following parameters : pH, moisture, dry matter, organic matter, mineral matter, total carbon, total nitrogen, volatile fatty acid (VFA) content, Complete alkalimetric titre

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(TAC) and chemical oxygen demand (COD). The pH was determined using a HANNA HI 8424 pH meter by introducing the electrode into the hydrated sludge sample.
To determine moisture content, a sludge sample was placed in a porcelain crucible, weighed and then dehydrated in an oven at 105°C for twenty-four hours. The gross weight of each sludge sample was 30 g. The moisture content (M) of the sludge samples, expressed as a percentage, was obtained by drying 30 g of sludge in porcelain crucibles for 24 hours in an oven at 105°C, then calculated according to the Following formula :

$$M\ (\%) = \frac{m_0 - m_1}{m_0} * 100 \qquad \textbf{(1)}$$

Where m_0 and m_1 are the sludge masses before and after drying, respectively.

Dry matter (DM) content expressed as a percentage was calculated using the Following formula :

$$DM\ (\%) = 100 - H \qquad \textbf{(2)}$$

The Organic Matter (OM) content is obtained by calcining the dry matter at 550°C for 4 hours [8]. The difference in mass before and after calcination is used to calculate MO according to the following formula :

$$MO\ (\%) = \frac{m_1 - m_2}{m_1} * 100 \qquad \textbf{(3)}$$

Where m_1 and m_2 are the masses of dry residue at 105°C and calcined residue at 550°C respectively. This makes it possible to systematically determine the mineral matter (MM) content or ash content according to the Following expression :

$$MM\ (\%) = \frac{100 * m_2}{m_1} * 100 \qquad \textbf{(4)}$$

Total carbon and total nitrogen were determined using an Analytikjena multi N/C 3100 TOC meter through the solid module of the instrument.

Complete alkalimetric titre (CAT) and volatile fatty acid (VFA) content were obtained using the titrimetric method[6]. Indeed, a 50 mL volume of sludge sample was centrifuged at 3000 rpm for 3 min to recover the supernatant. This supernatant was titrated by pH-metry with a sulfuric acid solution (0.04 N), to pH = 5.75 and 4.3, corresponding respectively to the volume at equivalence (V1) for partial alkalinity (PA) and that (V2) for CAT.

$$AP\ (méq/L) = \frac{V1 * N * 1000}{V}$$

$$CAT\ (méq/L) = \frac{V2 * N * 1000}{V} \qquad \textbf{(5)}$$

Intermediate Alkalinity (IA), associated with AGV, is obtained by the difference between TAC and AP.

$$VFA(mg/L\ CaCO_3) = (CAT - AP) * 50 \qquad \textbf{(6)}$$

Chemical oxygen demand (COD) was obtained using the potassium dichromate oxidation method in an acid medium, in accordance with the AFNOR standard (NF T 90-101, 1988). COD is expressed in mg/L O_2.

2.2. Practical assessment of biogas production

All tests were carried out in batch digesters for 21 days. The digesters are 1200 mL vessels with a useful volume of 1000 mL and a headspace of 200 mL (dead volume of the digester). They are each fitted with two ports, the first for syringe sampling of liquids, and the second for collecting and measuring the volume of biogas produced (Figure 2).

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After substrate incubation, the digesters were placed in a 35°C water bath, ideal for biomethanization. These were then connected to inverted 1000 mL graduated test tubes, fitted with taps and immersed in a container of water. For each experiment, the masses of substrate (S) and inoculum (I) were varied according to the ratio (S/I). Physico-chemical parameters such as pH, Carbon/Nitrogen and VFA/TAC ratios were measured at the start and end of the experiments. After addition of inoculum and substrate, the final volume was adjusted to 800 mL with tap water. The digester was then sealed with a rubber septum and screw cap. It was manually stirred for two minutes twice a day to prevent the formation of a layer on the surface of the digester. When biogas is produced, it exerts pressure on the water in the inverted test tubes. The volume of biogas was therefore measured using the water displacement method. Blanks were run with substrates (sludge) only, to assess their methanogenic potential. Three batch reactors were run to obtain an average methanogenic potential

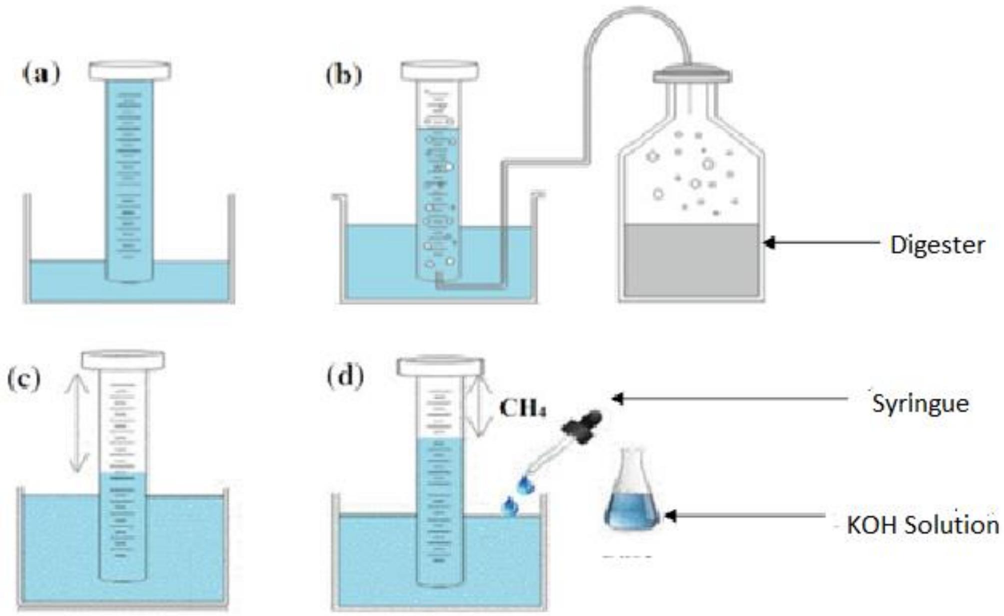

Figure 2 : Device for biogas production in a bioreactor (a), Inverted graduated cylinder (b), Biogas production(c), Biogas sampling (d), Injection of biogas into KOH solution.

2.2.1 Anaerobic digestion of various substrates without inoculum

The tests were carried out to determine the experimental biomethanogenic potential (BMP) of each substrate. The mass used for each sludge was 700 g.

2.2.2 Anaerobic digestion of various substrates with inoculum

In order to optimize the methanogenic potential of SN Cie's sewage sludge, we carried out co-digestion. For each trial, ratios (S/I = 2/1, 3/1, 4/1) were used. The different substrate masses (primary sludge, physico-chemical sludge and biological sludge) used were 462 g, 525 g and 560 g, respectively for the 2/1, 3/1 and 4/1 ratios. As for the inoculum (cow dung), the different masses used are 238 g, 175 g and 140 g.

2.2.3 Codigestion of physical-chemical and biological sludge

Physico-chemical and biological sludges were mixed at a ratio of (Physico-chemical sludge) (Biological sludge) =1. The different S/I ratios used for co-digestion tests are 2/1, 3/1 and 4/1. Table 1 shows the composition of the digesters.

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Table 1 : Quantity of sludge and inoculum according to the Substrate-Inoculum ratio (S/I) during the anaerobic co-digestion process

Ratios	Physical-chemical sludge mass (g)	Biological sludge mass (g)	Cow dung mass (g)	Total
Ratio 2/1	231	231	238	700
Ratio 3/1	262.5	262.5	175	700
Ratio 4/1	280	280	280	700

A blank was run with a mixture of the two sludges, without the addition of inoculum, with a mass of 350 g of sludge each.

2.2.4. Determination of CH_4 content in biogas

The determination of CH_4 content in biogas is based on the dissolution of CO_2 in a KOH solution [14,15]. As the inverted test tubes have gas taps, a septum plug is applied to each of these taps to with[illegible] volume of biogas with a 50 mL syringe (Figure 2). This volume of gas is introduced into a CH_4 and CO_2 anal[illegible] is is a 100 mL precision graduated cylinder, filled with KOH (9 N) solution and inverted into a beaker also containing the same solution. Passing the biogas stream through the KOH solution neutralizes the CO_2, allowing only CH_4 to pass through. Since CH_4 is not soluble, it displaces this solution. The volume of solution displaced therefore corresponds to the volume of methane. The volume of CO_2 correspond to the différence between the volume of biogas injected and that of CH_4.

3. Results and discussion

3.1. Inoculum characteristics

The physico-chemical parameters of the inoculum used in this study are summarized in Table 2.

Table 2 : Inoculum physico-chemical parameters

Parameters	Values
pH	6.78
Moisture%)	79.31
MS (%)	20.69
VMC (%)	80.91
MM (%)	19.09
CT (mg/L)	46.5
NT (mg/L)	2.15
C/N	21.62
VFA/TAC	0.03
DCO (mgO_2/L)	30220

The initial pH of the inoculum used for these experiments was 6.78. This value falls within the optimum pH range required for anaerobic digestion, i.e. between 6.5 and 8[16]. The VFA/TAC ratio of the inoculum (0.03) is below the threshold value (0.4) beyond which anaerobic digestion is unstable. [17]. The Carbon/Nitrogen (C/N) ratio obtained is 21.62. This ratio is within the optimum range for anaerobic digestion, which is 20 to 30 [18]. These values indicate that cow dung is suitable as an inoculum for sewage sludge methanization to enhance methane production.

3.2. Characteristics of sewage sludge

The main primary sludge physico-chemical and biological parameters are summarized in Table 3.

Table 3 : Physico-chemical parameters of sewage sludge

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Parameters	Primary Sludge	Physical-chemical sludge	Biological sludge
pH	5.25	6.19	6.67
Moisture (%)	79	94	91.33
DM (%)	21	6	8.67
VMC (%)	26.98	55.55	73.08
MM (%)	73.02	44.45	26.92
CT (%)	116.8	38.10	67.67
NT (%)	12.75	3.28	4.07
C/N (%)	9.16	11.61	16.87
VFA/TAC	0.5	0.1	0.33
COD (mg O2/L)	1989.63	12335	17110

The pH of the primary sludge and the physico-chemical sludge are below the optimum pH for methane production (6.5). On the other hand, the pH of the biological sludge is above 6.5, within the optimum range for biogas production[19]. The acidic nature of the substrates is certainly due to the presence of organic acid in the various sludges. A pH below 6.5 in these sludges inhibits the activity of the micro-organisms involved in the anaerobic digestion process, in particular methanogenic bacteria[20]. Biological sludge, which promotes the growth of the methanogenic bacterial population, can be used as a co-substrate to adjust the pH of primary sludge and physico-chemical sludge.

The AGV/ CAT ratios are 0.1 and 0.33 for physico-chemical and biological sludge respectively. These values are below the limit value for inhibition of biogas production, which is 0.4[20] . In the case of primary sludge, the AGV/ CAT ratio (0.5) is higher than the inhibition limit value. High VFA concentrations in primary sludge reduce pH. At low pH, VFAs become more toxic to methanogenic bacteria and promote instability in anaerobic digestion[6]. AGV/ CAT ratios below 0.4 are indicators of the stability of the anaerobic digestion process [21].

Substrate MVs are 26.69%, 55.55% and 73.08% for primary, physico-chemical and biological sludges respectively. Among the latter, the volatile matter content of the biological sludge is the highest. This high value suggests that the organic load is high, resulting in significant energy potential. [22]. These contents are lower than those obtained in other studies (85.14%) where sewage sludge was recovered for energy by anaerobic digestion. [23]. The C/N ratios of primary, physicochemical and biological sludge are 9.16, 11.61 and 16.87 respectively. These ratios are all lower than the smallest bound of the optimum interval [20,24] for methane production. [18,24]. The C/N ratio of primary sludge is the lowest compared to that of physico-chemical and biological sludge. This may be due to the high nitrogen content of primary sludge compared to other sludges. [25]. However, it has been observed that mixing sewage sludge with cow dung makes it possible to adjust the C/N ratio within the range of values considered optimal[19,26]. Analysis of the various physico-chemical parameters shows that sewage sludge can be a good raw material for an anaerobic digestion process.

3.3 Evolution de certains paramètres au cours de la digestion anaérobie

Table 4 presents a summary of the pH values and the C/N and AGV/CAT ratios at the start and end of the tests.

Table 4 : **Comparison of parameter values monitored at the start and end of the anaerobic co-digestion process**

Substrates	S/I Ratio	pH		C/N		VFA/ CAT	
		In	Fin	In	Fin	In	Fin
	C	6.62	6.94	7.35	5.2	0.7	0.7
	R 2/1	6.08	7.89	10.2	9.4	0.8	0.8

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Primary sludge	R 3/1	5.82	5.9	7.3	6.5	0.8	0.8
	R 4/1	5	7.22	6.8	6.4	0.8	0.8
Physical-chemical sludge	C	6.19	6.4	12.61	10.4	0.2	0.4
	R 2/1	6.3	6.54	15.2	13.2	0.1	0.4
	R 3/1	6.27	6.64	26.61	21.6	0.2	0.4
	R 4/1	5.5	7.02	9.3	8.5	0.4	0.6
Biological sludge	C	6.67	6.72	16.87	15.3	0.1	0.4
	R 2/1	6.82	6.87	20.5	17.08	0.2	0.4
	R 3/1	6.91	6.98	25.05	20.3	0.1	0.4
	R 4/1	6.12	6.76	9.9	8.4	0.35	0.5
Physical-chemical sludge + Biological sludge	C	6.19	6.95	10.8	9.3	0.1	0.4
	R 2/1	6.38	7.02	15.5	14.6	0.15	0.4
	R 3/1	6.42	6.86	12.3	11.2	0.1	0.4
	R 4/1	5.63	5.93	3.76	2.8	0.35	0.65

C : Control ; S/I : Substrate/inoculum ratio ; In : Initial ; Fin= Final

As far as pH and VFA/ CAT ratios are concerned, their increase at the end of the tests is linked to the presence of methanogenic bacteria, which are responsible for consuming the volatile fatty acids and acetic acid released in the acidogenesis and acetogenesis stages. Moreover, the methanogenesis stage can be inhibited at low pH 27]. This is why we see an increase in pH towards the end of anaerobic digestion.

3.4. Daily biogas production kinetics

3.4.1 Anaerobic sludge digestion without inoculum

Daily biogas production kinetics are shown in Figure 3. Indeed, during 21 days of digestion at ambient temperature, biogas production peaks were 20 mL on day 2, 200 mL on day 8, and 750 mL on day 10, respectively from primary sludge, physico-chemical sludge and biological sludge, before decreasing. These results confirm that biological sludge is indeed the site of a biological reaction leading to strong bacterial fermentation of organic compounds. In other words, fermentation kinetics are faster in the case of digestion of biological sludge, which is certainly richer in bacteria than primary and physico-chemical sludge. Finally, this result for biological sludge is in line with some previous work [16,19].

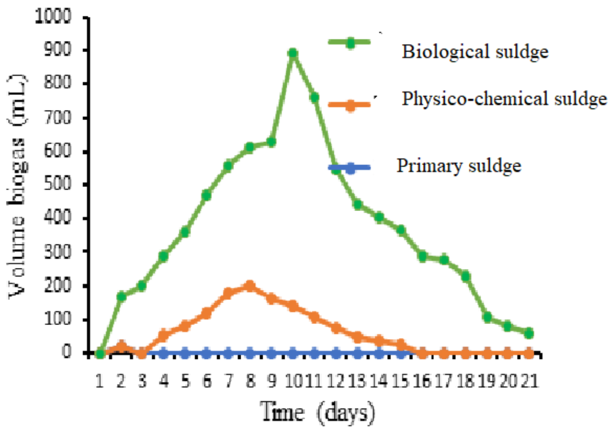

Figure 3 : Daily biogas production kinetics in the absence of inoculum

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3.4.2 Anaerobic sludge digestion with inoculum

Primary sludge with inoculum

Figure 4 shows the volume of biogas produced in digesters **P1** (S/I = 2/1), P2 (S/I = 3/1) and **P3** (S/I = 4/1) as a function of time. Biogas production was 75 mL for the 2/1 ratio versus 120 mL for the 3/1 and 4/1 ratios. The results show that the C/N ratio has a strong influence on biogas production. Indeed, the C/N ratio of S/I (2/1) is relatively higher than those of S/I (3/1) and S/I (4/1). As a result, there are more carbonaceous substrates to degrade in relation to the quantity of microorganisms contained in the inoculum. A substrate low in microorganisms, volatile matter content (VMC) and nutrients does not produce biogas. All this means that biogas production stops after day 4, despite the addition of inoculum at various ratios.

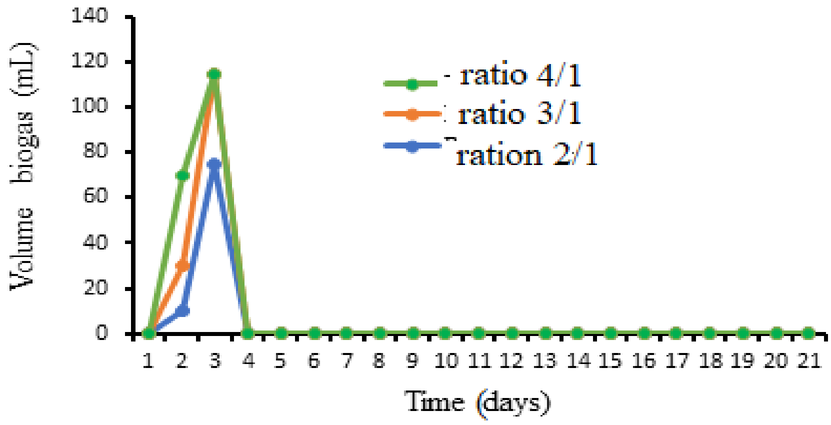

Figure 4 : **Daily biogas production kinetics for primary sludge with inoculum**

Physical-chemical sludge with inoculum

Les productions brutes journalières de biogaz enregistrées à partir des boues physico-chimiques en présence d'inoculum sont appréciées à travers la figure 5. Soient **PC_1, PC_2 et PC_3**, les digesteurs à boues physico-chimiques dont les rapports S/I sont respectivement 2/1, 3/1 et 4/1.

Gross daily biogas production from physico-chemical sludge in the presence of inoculum is shown in Figure 5. PC1, PC2 and PC3 are the physical-chemical sludge digesters with S/I ratios of 2/1, 3/1 and 4/1 respectively.

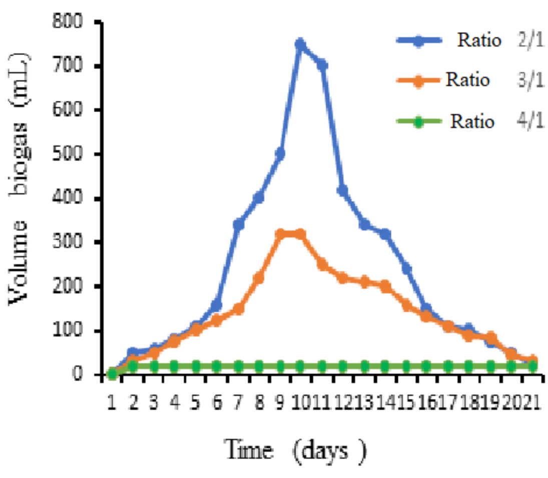

Figure 5 : Daily biogas production kinetics for physico-chemical sludge

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We note that biogas production in the experimental batch digesters PC1 (ratio 2/1) and PC2 (ratio 3/1) starts after the start-up phase with a gradually increasing quantity to reach a stable production level, then it starts to drop. The same phenomenon is observed in the gas production curves reported by Ntakiyiruta et al 2021[19].

During the first four days, gas production was low in both PC1 and PC2 bioreactors. It began to increase in a variable manner after day 4, with the PC1 digester recording a peak production of 750 mL of biogas corresponding to day 10, and the PC2 digester a peak of 320 mL corresponding to day 9. As for digester PC3, production remained constant from day 2 until the end of digestion. The best results were achieved in digester PC1, composed of 66% sludge and 34% cow dung, with an average daily production of 237.14 mL. On the other hand, low values were recorded for digesters PC2 (75% sludge and 25% cow dung) and PC3 (80% sludge and 20% cow dung), with average daily outputs of 139.05 mL and 19.05 mL respectively.

Daily production in digesters PC1 and PC2 starts to decrease from day 11. This phenomenon was observed by Tize et al 2015 [28], during studies on the influence of mechanical and biological pretreatment of dead neem (azadirachtaindica) leaves on biogas productionAccording to the same author, production gradually decreases from day 15 onwards, due to the depletion of nutrients for the microbial flora in the reaction medium.

These production kinetics confirm the studies carried out on the quantitative and qualitative characterization of the energy productivity of pilot sewage sludge digesters according to M'Sadak et al 2015 [29].

Biological sludge with inoculum

Figure 6 shows plots of daily biogas production from biological sludge digesters. Let B1, B2 and B3 be the physical-chemical sludge digesters with S/I ratios of 2/1, 3/1 and 4/1 respectively.

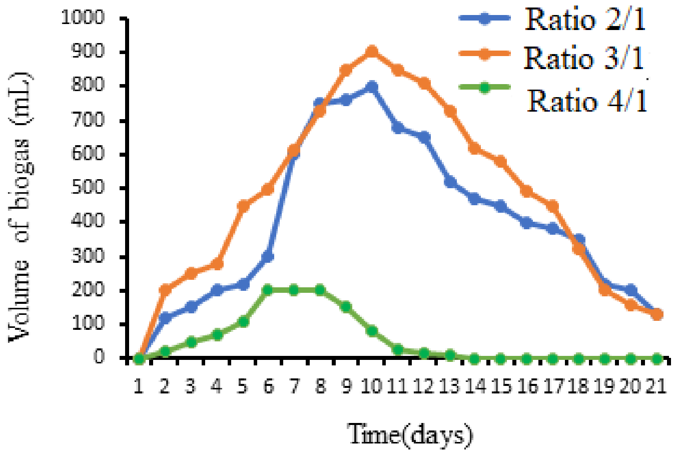

Figure 6 : **Daily biogas production kinetics for biological sludge**

This figure shows that biogas production in experimental digesters B1 (2/1 ratio) and B2 (3/1 ratio), starts gradually to reach a maximum before decreasing until day 21. This phenomenon was also reported by M'Sadak et al 2015[29]. Biogas production was recorded on the 2nd day of digestion start-up. It began to increase variably after day 2, with digesters B1 and B2 recording peak biogas production of 800 mL and 900 mL respectively on day 10, and digester B3 recording a peak of 200 mL on day 6. The best results were recorded in digester B2, made up of 75% sludge and 25% cow dung, with an average daily production of 481.43 mL, putting it in first place. The lowest values were recorded in digester B3 (80% sludge and 20% cow dung), with an average daily production of 53.80 mL. Digester B1 (66% sludge and 34% cow dung) came second with an average daily production of 397.61 mL. Daily production levels start to fall from day 11 for digesters B1 and B2, and from day 9 for digester B3.

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II.3.2.3. Anaerobic co-digestion of sludge

Gross daily biogas production from the co-digestion of physical-chemical and biological sludge is shown in Figure 7. Let B-PC1, B-PC2 and B-PC3 be the physical-chemical + biological sludge digesters with S/I ratios of 2/1, 3/1 and 4/1 respectively.

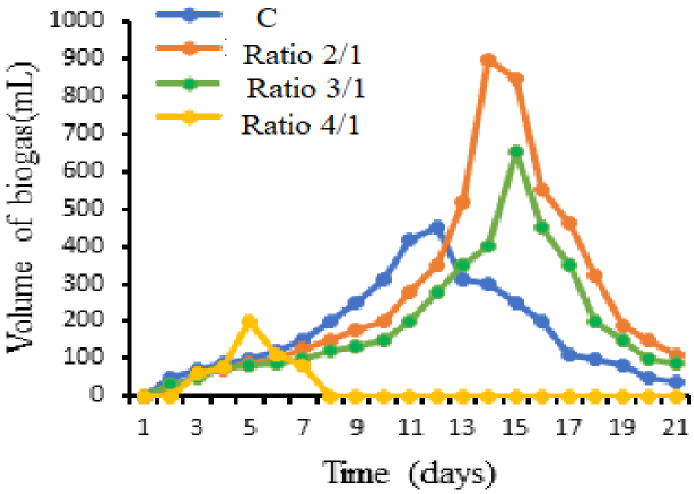

Figure 7 : Daily biogas production kinetics for the mixture (physico-chemical and biological sludge)

We note that biogas production was recorded on the 2nd day of start-up for digesters B-PC1 and B-PC2, and on the 3rd day for digester B-PC3(Figure 7). Biogas production was low for the first ten days in digesters B-PC1 and B-PC2, and for the first five days in digester B-PC3. It begins to increase after day 10, with maximum daily production recorded for digesters B-PC1 and B-PC2 respectively on day 14, corresponding to 900 mL and 650 mL of biogas on day 15. Maximum daily production was recorded on day 5 for digester B-PC3.

Daily production decreased progressively from day 15, 16 and 6 for digesters B-PC1, BP-C2 and B-PC3 respectively. The best results were recorded in digester B-PC1, made up of 66% sludge and 34% inoculum, with an average daily production of 269.52 mL; whereas the lowest values were recorded in digester B-PC3, made up of 80% sludge and 20% cow dung, with an average daily production of 25 mL. As for digester B-PC2 (75% sludge and 25% cow dung), an average daily production of 192.85 mL was recorded.

The B-PC1, B-PC2 and B-PC3 digesters come into production thanks to the presence of cow dung and biological sludge, which guarantees the existence of bacterial populations. Another dimension in assessing biogas production is the dynamism of the process over time. This is a fundamental factor in the design of large-scale continuous biogas production units[30].

In this regard, the biogas production kinetics for physico-chemical sludge illustrated in figure 7 shows that low daily production rates are recorded from the start of anaerobic digestion to day 4, and from day 11 to the end of digestion. On the other hand, biogas production from physico-chemical and biological sludge in the presence of inoculum (cow dung) shows that low daily production rates are recorded from the start of anaerobic digestion to day 4, and from day 15 to the end of digestion. The mixture of physico-chemical and biological sludge without inoculum gives a volume of 3650 mL, i.e. an average daily production of 173.80 mL. By comparison, the biogas volume of the sludge mixture with inoculum in the ratios 2/1 and 3/1 is greater than that of the mixture without the addition of inoculum.

3.4. Cumulative biogas production kinetics

3.4.1. Anaerobic sludge digestion without inoculum

Based on daily production, the cumulative quantity of biogas was calculated and its temporal evolution is shown in figure 8.

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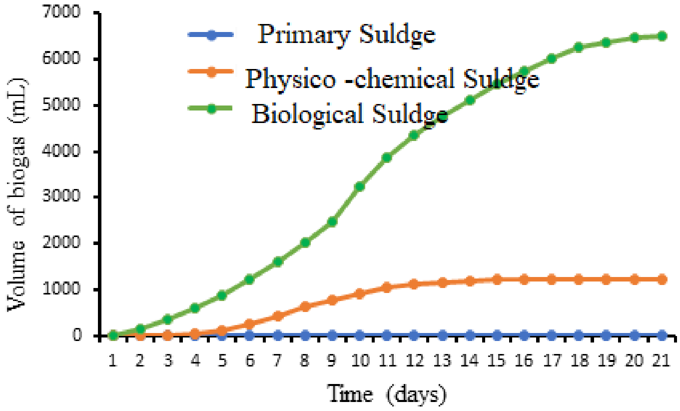

Figure 8 : **Cumulative biogas evolution for the three sludges of the wastewater treatment plant over time**

The cumulative biogas production curves for the three substrates show different patterns. The last two curves show low production at the start of biogas production, followed by an acceleration of production, before declining or slowing down at the end. These kinetics are in line with the results of several other authors [30] . It is divided into three phases:

- The First Phase : **Latency phase**, the duration of which depends on the nature of the substrate. It lasts 2 days with a production of 20 mL and 150 mL respectively for primary and biological sludges, and 4 days for physico-chemical sludges. This period corresponds to the liquefaction phase, during which hydrolysis, acidogenesis and acetogenesis take place [31].
- The second phase : **exponential phase**, corresponding to the central part of the production curves. This phase lasted 5 days (from day 4 to day 8 for physico-chemical sludge, and 9 days from day 2 to day 11 for biological sludge). It is absent in primary sludge. Maximum biogas values were obtained during this second phase: 200 mL for physico-chemical sludge and 750 mL for biological sludge..
- The third phase: the plateau phase, corresponds to low biogas production due to substrate depletion[30]. It begins on day 9 for physico-chemical sludge and day 11 for biological sludge, until digestion ceases.

Biological sludge has the highest biogas yield with 6510 mL, i.e. an average daily production of 310 mL. Physico-chemical sludge came second, with a biogas yield of 1220 mL, or an average daily production of 58.09 mL. Primary sludge yielded smaller quantities of biogas (20 mL, i.e. an average daily production of 0.95 mL). The low biogas yield of the primary and physico-chemical sludges may be linked to their low volatile matter content. The exponential growth in biogas volume observed in biological sludge is due to the accumulation of a large mass of biodegradable organic matter[32]. The sharp drop in biogas production observed during the decline phase could be explained by the fact that methanogenic bacteria produce less biogas due to the progressive lack of organic matter.[33]. This decrease indicates that the degradation process is nearing its end.

3.4.2. Digestion anaérobie des boues avec inoculum

Cumulative biogas volumes from the three sewage sludge digesters according to the different ratios 2/1, 3/1 and 4/1 are shown in the graphs below. PC1, PC2 and PC3 are the physical-chemical sludge digesters, and B1, B2 and B3 are the biological sludge digesters with S/I ratios of 2/1, 3/1 and 4/1 respectively.

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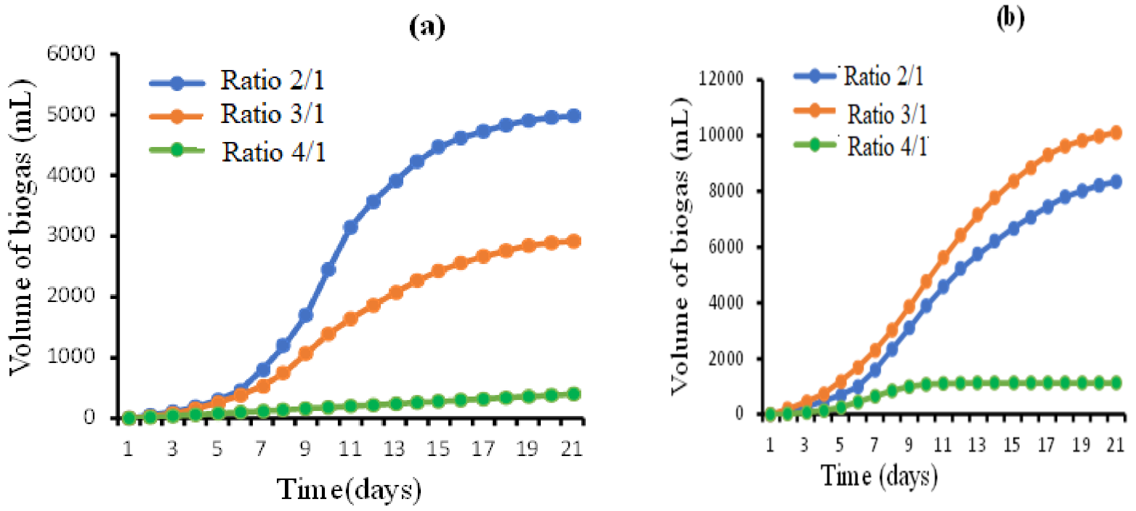

Figure 9 : Cumulative biogas production kinetics:(a) Physico-chemical sludge;(b) Biological sludge.

At first, we can see a slight increase in production, followed by an acceleration and then a decline or slowdown at the end (Figure 9). We can see the latency phase (2 days), the exponential phase (5 days for physico-chemical sludge and 7 days for biological sludge) and the plateau phase (from day 11).

We note 2/1 PC (66% physico-chemical sludge, i.e. 462g and 34% cow dung, i.e. 238g), 3/1 PC (75% physico-chemical sludge, i.e. 525g and 25% cow dung, i.e. 175g) and 4/1 PC (80% physico-chemical sludge, i.e. 560g and 20% cow dung, i.e. 140g), 2/1 B (66% biological sludge, i.e. 462g and 34% cow dung, i.e. 238g), 3/1 B (75% biological sludge, i.e. 525g and 25% cow dung, i.e. 175g) and 4/1 B (80% biological sludge, i.e. 560g and 20% cow dung, i.e. 140g). The cumulative biogas volumes of the 2/1PC, 3/1PC and 4/1PC mixtures are 4980 mL, 2920 mL and 400 mL respectively (Figure 17a). We can deduce that the cumulative biogas volume increases with increasing S/I ratio from 4/1 to 2/1. As for the cumulative biogas volume of these three biological sludge mixtures, they give 8350 mL for the 3/1B ratio, 10110 mL for the 2/1B ratio and 1130 mL for the 4/1B ratio (Figure 10b). The cumulative biogas volume of the 3/1B mixture is the highest.

The higher biogas volume of the 2/1P-C blend could be attributed to its greater biodegradability compared to other blends [34]. This high biodegradability would appear to be linked to the high inoculum content of this mixture in relation to the organic load. Indeed, a high level of inoculum provides more microorganisms and thus favors the biodegradation process. Biodegradation rate, latency time and substrate degradation depend on the concentration of microorganisms in the digester[12,25,35]. The increase in cumulative biogas volume, as the substrate/inoculum ratio rises, could also be explained by the increase in organic load. Indeed, biogas production is linked to organic load. [12,13]. In biological sludge digestion, the decrease in biogas volume observed at the S/I 2/1 ratio would be linked to an overload of organic matter leading to an accumulation of volatile fatty acids in the digesters. The low percentage of biogas volume accumulated during the plateau phase would be due to a depletion of biodegradable organic matter in the digester, or to a large accumulation of VFAs.[16] .

3.3.3. Sludge co-digestion

The kinetics of the cumulative biogas volumes of the physico-chemical and biological sludge mixture with and without inoculum addition as a function of the different ratios 2/1, 3/1 and 4/1 are illustrated in Figure 9. Let B-PC1, B-PC2 and B-PC3 be the physical-chemical+biological sludge digesters with S/I ratios of 2/1, 3/1 and 4/1 respectively.

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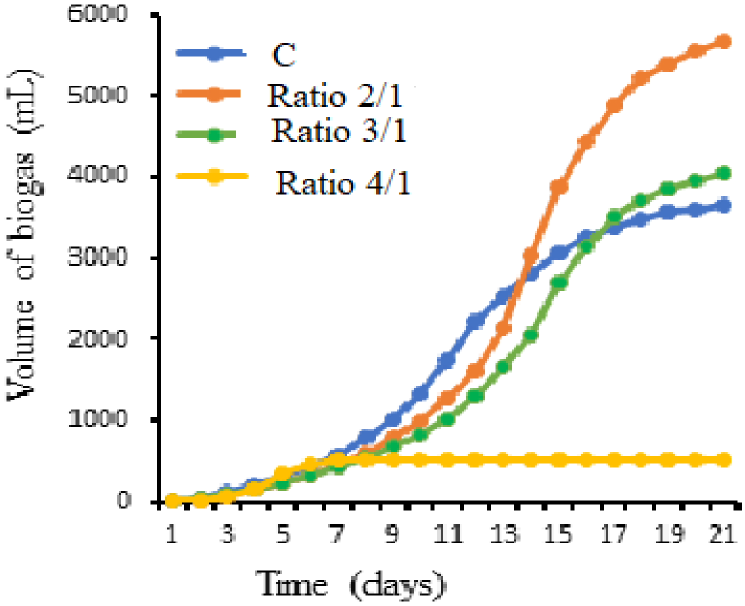

Figure 10 : Cumulative biogas production kinetics for the mixture (physico-chemical and biological sludge)

Figure 10 shows a similar trend between daily and cumulative production. A slight increase in production can be seen at the start, followed by an acceleration, then a decline or slowdown at the end. Remember that the S/I= 2/1B-PC1, 3/1B-PC2 and 4/1 B-PC3 ratios correspond to the mixtures (66% physico-chemical and biological sludge mixture, i.e. 462g and 34% cow dung, i.e. 238g), (75% physico-chemical and biological sludge mixture, i.e. 525g and 25% cow dung, i.e. 175g) and (80% primary sludge, i.e. 560g and 20% cow dung, i.e. 140g).

The cumulative biogas volumes of the three mixtures (Substrate/Inoculum) 2/1P-C+B, 3/1P-C+B and 4/1P-C+B after 21 days of digestion are 5660, 4050 and 525 mL respectively. The mixture without inoculum produced a volume of 3650 mL. The cumulative biogas volume of the 2/1 B-PC1 mixture was higher than those of the 3/1 P-C+B and 4/1 P-C+B mixtures. Cumulative biogas volume increases with increasing S/I ratio from 4/1 to 2/1.

The higher biogas volume of the 2/1B-PC mixture could be attributed to the good biodegradability of this mixture compared to the mixture without inoculum[34]. This biodegradability is linked to the high level of inoculum in the mixture. Indeed, a high level of inoculum provides a greater number of microorganisms and thus favors the biodegradation process. L'augmentation du volume cumulé de biogaz, avec la croissance du rapport S/I, pourrait s'expliquer aussi par l'augmentation de la charge organique. En effet, la production de biogaz est liée à la charge organique [19].

II.4. Cinétique de production cumulée de méthane

Figure 11 shows the cumulative amount of methane (CH_4) produced during the anaerobic digestion process for the three sludges.

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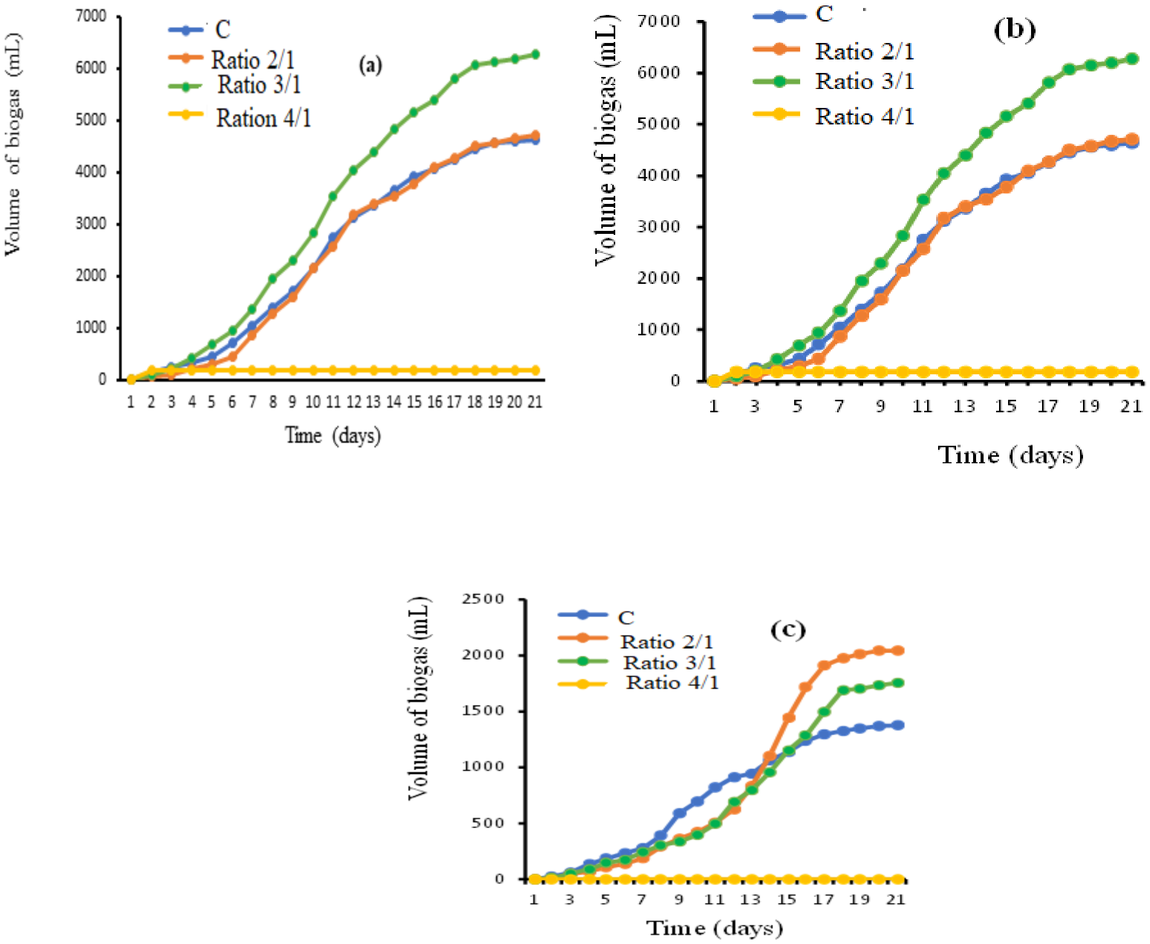

Figure 11 : Evolution of cumulative methane (CH4) production for physical-chemical sludge (a), biological sludge (b) and the mixture of physical-chemical sludge + biological sludge (c) over time

Figure 11 shows that physical-chemical sludge alone produces less methane than biological sludge when the S/I ratio is equal to 3/1. Anaerobic co-digestion of physico-chemical and biological sludge also increases methane (CH_4) yield. This may be explained by the increased OM content when the two substrates are combined (see Table 4). In addition, this higher methane (CH4) yield for the 3/1 ratio would be linked to the C/N ratio of the physico-chemical and biological sludge mixture (between 20 and 30, the optimum range for methane production in anaerobic digestion). Looking at figure 10, we can say that it took at least 10 days to observe the exponential increase in cumulative methane. This latency period corresponds to the first stages of anaerobic digestion (hydrolysis, acidogenesis and acetogenesis) before reaching the last stage (methanogenesis) responsible for methane production [36,37]**.** The methane (CH4) composition of the biogas produced is shown in Table 5. The mixture of physico-chemical and biological sludge in the S/I 3/1 ratio produces 43.34% methane. In the case of physico-chemical sludge, the S/I mixture in the 2/1 ratio produces 46.86% methane. Biological sludge alone produces methane-rich biogas at 71.33%. As for the quantity of cumulative methane produced over a 21-day anaerobic digestion period, these are respectively cumulative methane volume yields of 2334 mL (physico-chemical sludge), 4643.6 mL (biological sludge), and 1755.6 mL (physico-chemical + biological sludge mix).

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Table 5 : Cumulative quantity and composition of biogas produced

Substrate types	Digester types	Cumulative volume of biogas (mL)	Cumulative volume of CH_4 (mL)	% CH_4	% CO_2
Primary Suldge	Control	20	-	-	100
	S/I (2/1)	85	15	17.64	82.36
	S/I (3/1)	60	9.2	15.33	84.67
	S/I (4/1)	40	-	-	100
Physico-chemical Suldge	Control	1220	237.5	19.46	80.54
	S/I (2/1)	4980	2334	46.86	51.14
	S/I (3/1)	2920	1025.7	35.12	64.87
	S/I (4/1)	400	8	2	98
Biological Suldge	Control	6510	4643.6	71.33	28.67
	S/I (2/1)	8350	4713.8	56.45	43.55
	S/I (3/1)	10110	6277.4	62.09	37.91
	S/I (4/1)	1130	180	15.92	84.08
Mix Physical-chemical and biological suldge	Control	3650	1377.2	37.73	62.27
	S/I (2/1)	5660	2043.8	36.10	63.9
	S/I (3/1)	4050	1755.6	43.34	56.66
	S/I (4/1)	425	-	-	100

III.5. stimating the amount of energy produced

Table 6 gives an estimate of the electrical energy produced by digestion of the various substrates per tonne per year. The amount of electrical energy produced by anaerobic digestion of one tonne of physico-chemical sludge at S/I=2/1, biological sludge at S/I=3/1 and their mixture at S/I=2/1 is estimated at 562.11kW, 1511.84kW and 492.17kW per year respectively (Table 9). This amount of energy could be used by the SN Cie plant. This is not only a solution to the energy problem, but also to the management of SN Cie's sewage sludge.

Table 6 *:* Estimated energy output for each substrate type per tonne per year

Substrate types	Digester types	Volume CH_4 (m^3/T/Year)	Energy (kW)
Primary Suldge	Control	-	-
	S/I (2/1)	0.37	3.59
	S/I (3/1)	0.22	2.13
	S/I (4/1)	-	-
Physico-chemical Suldge	Control	5,89	57,13
	S/I (2/1)	57,95	562,11

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	S/I (3/1)	25,46	246,96
	S/I (4/1)	0,19	1,84
Biological Suldge	Control	115,3	1118,41
	S/I (2/1)	117.04	1135.28
	S/I (3/1)	55.86	541.84
	S/I (4/1)	4.46	43.26
Mix Physical-chemical chemical + biological biological suldge	Control	39.19	380.14
	S/I (2/1)	50.74	492.17
	S/I (3/1)	43.59	422.82
	S/I (4/1)	-	-

***1 m^3 of CH4 = 8570 kcal = 9.7 KW** [19]

4. CONCLUSION

The aim of this study was to contribute to the reduction of global warming and a cleaner environment through the conversion of sewage sludge into biogas.

Indeed, the physico-chemical characteristics of sewage sludge were determined. Next, the methanogenic potential of the sludge was assessed, followed by optimization of biogas production. The results showed that SN Cie's sewage sludge can still be valorized by methane fermentation in the presence of cow dung to generate a renewable energy source (biogas). To optimize the biomethanization of these sludges, it is necessary to control several factors, including water content, agitation, quantities and activity of bacteria present, pH, temperature and composition. Suitably humidified material can be homogenized to promote material transfer. The medium can be buffered to avoid significant pH variations. Nutrient deficiencies or excesses can be limited by mixing the material to be degraded with other materials of suitable characteristics. Temperature can be maintained within a given range, and reducing conditions can be ensured by sealing the reactor. At the end of this study, it should be noted that converting industrial sewage sludge into biogas can be an attractive, economically feasible management policy in terms of energy savings, greenhouse gas emission reduction potential and environmental pollution risk mitigation for sustainable development. This study opens up new horizons for better management of industrial waste, thus avoiding harmful landfill disposal.

REFERENCES

[1] Faye C. Les défis de la pollution de l'eau, une menace pour la santé publique : atouts et défauts des lois et politiques de l'eau au Sénégal. Larhyss J 2017:107–26.

[2] Ntakiyiruta P, Nsavyimana G, Briton BGH, Adouby K, Nahimana D, Ntakimazi G. Actions combinées de Eichhornia crassipes et Pistia stratiotes pour traitement tertiaire de l'effluent des bassins facultatifs de la station d'épuration de Buterere, Burundi. Int J Biol Chem Sci 2020;14:2463–75. https://doi.org/10.4314/ijbcs.v14i7.8.

[3] Adou KE, Alle OA, Kouakou AR, Adouby K, Drogui P, Tyagi RD. Anaerobic mono-digestion of wastewater from the main slaughterhouse in Yamoussoukro (Côte d'Ivoire): Evaluation of biogas potential and removal of organic pollution. J Environ Chem Eng 2020;8:103770. https://doi.org/10.1016/j.jece.2020.103770.

[4] Ntakiyiruta P, Briton BGH, Mpawenayo P, David N, Niyungeko C, Yao B, et al. Energetic Valorization of Eichhornia crassipes and Pistia stratiotes by Methane Production in an Anaerobic Co-digestion Process. Sci J Energy Eng 2021;9:59–69. https://doi.org/10.11648/j.sjee.20210904.13.

[5] Robert P, Claus B. Chimie de l'environnement. Air, eau, sols, déchets. 2001.

DOI: 10.31695/IJASRE.2024.10.1

[6] Adou KE, Alle OA, Kouakou AR, Adouby K, Drogui P, Tyagi RD. Anaerobic mono-digestion of wastewater from the main slaughterhouse in Yamoussoukro (Côte d'Ivoire): Evaluation of biogas potential and removal of organic pollution. J Environ Chem Eng 2020;8:103770. https://doi.org/10.1016/j.jece.2020.103770.

[7] Almoustapha O, Millogo-Rasolodimby J. Production de biogaz et de compost à partir de eichhornia crassipes, (mart) solms-laub (pontederiaceae) pour un développement durable en Afrique sahélienne. VertigO - Rev Électronique En Sci Environ 2006. https://doi.org/10.4000/vertigo.2221.

[8] Rezania S, Md Din MF, Kamaruddin SF, Taib SM, Singh L, Yong EL, et al. Evaluation of water hyacinth (Eichhornia crassipes) as a potential raw material source for briquette production. Energy 2016;111:768–73. https://doi.org/10.1016/j.energy.2016.06.026.

[9] Demirbas A, Taylan O, Kaya D. Biogas production from municipal sewage sludge (MSS). Energy Sources Part Recovery Util Environ Eff 2016;38:3027–33. https://doi.org/10.1080/15567036.2015.1124944.

[10] Nacera L, Yahiaoui F, Benrachedi K. Contribution à l'étude de la production d'un biocarburant à partir de la boue des stations d'épuration des eaux usées. 2012.

[11] Béline F, Girault R, Buffet J-P, Bridoux G, Nauleau F, Poullain C. Co-digestion of waste water treatment plant sludge and of organic peri-urbain waste. Rev Eau Ind Nuis 2011:77–82.

[12] Yoon Y-M, Kim S-H, Shin K-S, Kim C-H. Effects of Substrate to Inoculum Ratio on the Biochemical Methane Potential of Piggery Slaughterhouse Wastes. Asian-Australas J Anim Sci 2014;27:600–7. https://doi.org/10.5713/ajas.2013.13537.

[13] Li C, Anderson B. Enhanced biogas production from anaerobic co-digestion of municipal wastewater treatment sludge and fat, oil and grease (FOG) by a modified two-stage thermophilic digester system with selected thermo-chemical pre-treatment. Renew Energy 2015;83. https://doi.org/10.1016/j.renene.2015.04.055.

[14] Pantawong R, Chuanchai A, Thipbunrat P, Unpaprom Y, Ramaraj R. Experimental Investigation of Biogas Production from Water Lettuce, Pistia stratiotes L. Life Sci 2015;1:41–6.

[15] Mahmoodi P, Karimi K, Taherzadeh MJ. Hydrothermal processing as pretreatment for efficient production of ethanol and biogas from municipal solid waste. Bioresour Technol 2018;261:166–75. https://doi.org/10.1016/j.biortech.2018.03.115.

[16] Adou KE, Alle OA, Kouakou AR, Adouby K, Drogui P, Tyagi RD. Anaerobic mono-digestion of wastewater from the main slaughterhouse in Yamoussoukro (Côte d'Ivoire): Evaluation of biogas potential and removal of organic pollution. J Environ Chem Eng 2020;8:103770. https://doi.org/10.1016/j.jece.2020.103770.

[17] Thanh NP, Matsui Y. Assessment of potential impacts of municipal solid waste treatment alternatives by using life cycle approach: a case study in Vietnam. Environ Monit Assess 2013;185:7993–8004. https://doi.org/10.1007/s10661-013-3149-8.

[18] Wang X, Chen Y, Sui P, Gao W, Qin F, Wu X, et al. Efficiency and sustainability analysis of biogas and electricity production from a large-scale biogas project in China: an emergy evaluation based on LCA. J Clean Prod 2014;65:234–45. https://doi.org/10.1016/j.jclepro.2013.09.001.

[19] Ntakiyiruta P, Briton BGH, Mpawenayo P, David N, Niyungeko C, Yao B, et al. Energetic Valorization of Eichhornia crassipes and Pistia stratiotes by Methane Production in an Anaerobic Co-digestion Process. Sci J Energy Eng 2021;9:59–69. https://doi.org/10.11648/j.sjee.20210904.13.

[20] Abbas Y, Yun S, Mehmood A, Shah FA, Wang K, Eldin ET, et al. Co-digestion of cow manure and food waste for biogas enhancement and nutrients revival in bio-circular economy. Chemosphere 2023;311:137018. https://doi.org/10.1016/j.chemosphere.2022.137018.

[21] Kafle GK, Kim SH. Anaerobic treatment of apple waste with swine manure for biogas production: Batch and continuous operation. Appl Energy 2013;103:61–72. https://doi.org/10.1016/j.apenergy.2012.10.018.

[22] Castro L, Escalante H, Jaimes-Estévez J, Díaz LJ, Vecino K, Rojas G, et al. Low cost digester monitoring under realistic conditions: Rural use of biogas and digestate quality. Bioresour Technol 2017;239:311–7. https://doi.org/10.1016/j.biortech.2017.05.035.

[23] Weldehans MG. Optimization of distillery-sourced wastewater anaerobic digestion for biogas production. Clean Waste Syst 2023;6:100118. https://doi.org/10.1016/j.clwas.2023.100118.

DOI: 10.31695/IJASRE.2024.10.1

[24] Xu H, Wang K, Holmes DE. Bioelectrochemical removal of carbon dioxide (CO2): An innovative method for biogas upgrading. Bioresour Technol 2014;173:392–8. https://doi.org/10.1016/j.biortech.2014.09.127.

[25] Pavi S, Kramer LE, Gomes LP, Miranda LAS. Biogas production from co-digestion of organic fraction of municipal solid waste and fruit and vegetable waste. Bioresour Technol 2017;228:362–7. https://doi.org/10.1016/j.biortech.2017.01.003.

[26] Brémond U. Optimisation de la gestion des digestats : post-traitements et recirculation pour une amélioration de l'efficacité énergétique des sites de méthanisation. phdthesis. Montpellier SupAgro, 2019.

[27] Bautista Angeli J-R. Etude de faisabilité de la micro-méthanisation par co-digestion à l'échelle des quartiers. Ghent University, 2019.

[28] Tize Coda J, Ngakou A, DARMAN Djoulde R. Influence du prétraitement mécanique et biologique des feuilles mortes de neem (azadirachta indica) sur la production du biogaz [Influence of mechanical and biological pretreatment of dead neem leaves (azadirachta indica) on biogas production]. Int J Innov Sci Res 2015;16:505–13. http://www.ijisr.issr-journals.org/.

[29] M'sadak Y, M'barek AB. Valorisations environnementale, énergétique et agronomique de la biométhanisation industrielle appliquée à la biomasse avicole récupérée en Tunisie. Rev Marocaine Sci Agron Vét 2015;3:54–66.

[30] Rodrigue KA, Essi K, Cyril KM, Albert T. Estimation of Methane Emission from Kossihouen Sanitary Landfill and Its Electricity Generation Potential (Côte d'Ivoire). J Power Energy Eng 2018;06:22–31. https://doi.org/10.4236/jpee.2018.67002.

[31] Hanni Z, Drissi F, Tahri A/ P. Optimisation de taux de charge organique moyenne pour La digestion anaérobie des déchets ménagers de la ville D'Adrar. Thesis. UNIVERSITE AHMED DRAIA- ADRAR, 2022.

[32] Enitan AM, Adeyemo J, Swalaha FM, Kumari S, Bux F. Optimization of biogas generation using anaerobic digestion models and computational intelligence approaches. Rev Chem Eng 2017;33:309–35. https://doi.org/10.1515/revce-2015-0057.

[33] Hashemi S, Solli L, Aasen R, Lamb JJ, Horn SJ, Lien KM. Stimulating biogas production from steam-exploded birch wood using Fenton reaction and fungal pretreatment. Bioresour Technol 2022;366:128190. https://doi.org/10.1016/j.biortech.2022.128190.

[34] Haider MR, Zeshan, Yousaf S, Malik RN, Visvanathan C. Effect of mixing ratio of food waste and rice husk co-digestion and substrate to inoculum ratio on biogas production. Bioresour Technol 2015;190:451–7. https://doi.org/10.1016/j.biortech.2015.02.105.

[35] Mitraka G-C, Kontogiannopoulos KN, Batsioula M, Banias GF, Zouboulis AI, Kougias PG. A Comprehensive Review on Pretreatment Methods for Enhanced Biogas Production from Sewage Sludge. Energies 2022;15:6536. https://doi.org/10.3390/en15186536.

[36] Bayard R, Brauer CD, Ducom G, Naquin P, Sarrazin B, Achour F, et al. Influence du prétraitement mécanique et biologique des ordures ménagères résiduelles sur leurs caractéristiques bio-physico-chimiques. Tech Sci Méthodes 2007:93–106.

[37] M'Sadak Y, Barek M, Zoghlami rahma ines, Ben A. Caractérisation des co-produits de la biométhanisation appliquée à la biomasse animale. J Renew Energ 2011;14:343–56. https://revue.cder.dz/index.php/rer.

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