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Improvement of Industrial Wastewater Treatment through an Integrated Approach of Methanization and Air Flotation: Case Study of an Experimental UASB Reactor in a Food Industry in Abidjan, Côte d'Ivoire

Adjoumani Rodrigue KOUAKOU[1, 2]*, Ahissan Donatien EHOUMAN[1, 2], Gbangbo Remi KONAN[3], Emmanuella EZEHEHA[2], Benjamin YAO[2]

[1]*Laboratoire de Thermodynamique et de Physico-Chimie du Milieu (LTPCM), UFR Sciences Fondamentales Appliquées, Université Nangui Abrogoua, B.P. 801 Abidjan 02, Côte d'Ivoire*

[2] *Centre d'Excellence Africain pour la Valorisation des déchets en produits à haute valeur ajoutée (**CEA-VALOPRO**), Institut National Polytechnique Félix Houphouët-Boigny (INP-HB); BP 1093 Yamoussoukro, Côte d'Ivoire*

[3] *Laboratoire d'Hydraulique et de Traitement des eaux, Institut National Polytechnique Félix Houphouët-Boigny (INP-HB) ; BP 1093 Yamoussoukro, Côte d'Ivoire*

* *Corresponding author: adjoumanro@gmail.com*

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Abstract: This project focuses on the treatment of wastewater from a food industry in Abidjan, Côte d'Ivoire, using a combination of methanization and air flotation, with a particular emphasis on an experimental UASB reactor. The agro-industrial company Sania Cie, specialized in the processing of crude palm oil, generates a significant amount of wastewater containing various pollutants and organic residues. To address this pollution, it is necessary to implement an effective and sustainable effluent treatment system. This pilot study aims to evaluate the efficiency of removing the organic load, measured by the chemical oxygen demand (COD), as well as the nitrogen load, using an anaerobic biological approach via an upflow anaerobic sludge blanket (UASB) reactor. The methodology of this study includes the installation of the experimental UASB device, the characterization of the sludge containing microbial granule flocs, and the evaluation of the purification performance of the UASB reactor. The results indicate sludge characteristics such as moisture content, dry matter, volatile solids, pH, and nitrogen content, respectively. Additionally, the UASB reactor operates in a mesophilic temperature range with a hydraulic retention time of 30 days, an organic load, and a specific upflow velocity. The purification efficiency of the UASB reactor for COD and nitrogen is also evaluated. To improve the results and meet discharge standards, a post-treatment such as dissolved air flotation is proposed. This should allow for a significant reduction in nitrogen levels. The study of this experimental system in a food industry in Abidjan can provide crucial information on the effectiveness of this approach under conditions specific to this region, as well as its scalability. These results could be used to optimize wastewater treatment processes in other similar facilities, while reducing their environmental impact and the costs associated with wastewater treatment.

1. Introduction

The management of industrial effluents constitutes a crucial issue on a global scale, with significant repercussions on the environment, public health, and economic development. In many countries, industrial growth is accompanied by an increase in the production of liquid waste, often containing organic compounds, suspended solids, heavy metals, and other harmful pollutants. The need to effectively treat these effluents to prevent soil, groundwater, and watercourse pollution is therefore imperative (Bakraoui *et al.*, 2020; Rais *et al.*, 2008;). In this context, wastewater treatment technologies have undergone constant development, aiming to reduce the environmental impact of industrial activities while promoting more efficient use of natural resources. Among these technologies, anaerobic processes stand out for their effectiveness in treating effluents rich in organic matter, while generating energy in the form of biogas (Sheng *et al.*, 2020), (Lokman *et al.*, 2021), (Khatri *et al.*, 2023). The Upflow Anaerobic Sludge Blanket (UASB) reactor is one of the most widely used anaerobic technologies in the treatment of industrial and municipal wastewater(Kamyab *et al.*, 2021), (Iftikhar *et al.*, 2023), (Besharati *et al.*, 2020) , (Cecconet *et al.*, 2022) . This system is based on the principle of anaerobic digestion of sludge, where microorganisms degrade organic compounds in the absence of oxygen to produce biogas and treated water (Musa *et al.*, 2020), (Cao *et al.*, 2020), (Chen *et al.*, 2020), (Tufaner *et al.*, 2020). The UASB reactor is distinguished by its high efficiency, compactness, and simplicity of The Africa Center of Excellence for the Valorization of Waste into High Value-Added Products (CEA VALOPRO), based at the National Polytechnic Institute Félix Houphouët-Boigny (INP-HB) in Yamoussoukro, Côte d'Ivoire, has developed an experimental UASB reactor as part of its research and development activities. INP-HB, as a public institution for higher education and research, is committed to addressing the environmental and industrial challenges of the region by developing innovative and sustainable technological solutions.

In this perspective, this study aims to evaluate the efficiency of the experimental UASB reactor developed by CEA VALOPRO in treating industrial effluents. This research is part of a collaboration between CEA VALOPRO, INP-HB, and SANIA-cie, an Ivorian agro-industrial company specializing in the processing of palm oil and its derivatives. This collaboration illustrates the importance of a multidisciplinary approach and cooperation between the academic and industrial sectors to address the complex challenges related to resource management and environmental sustainability.

This study pursues several specific objectives. Firstly, it aims to characterize the sludge used in the UASB reactor by evaluating its physicochemical and bacteriological properties. Secondly, it focuses on evaluating the operation of the UASB reactor over a period of 30 days, monitoring the physicochemical parameters of the treatment process and biogas production. Thirdly, it evaluates the efficiency of effluent treatment by analyzing the reduction in organic and nitrogen pollution.
Through a rigorous methodological approach and close collaboration between academic and industrial stakeholders, this study aims to provide concrete solutions to address the environmental and industrial challenges of the region. The results obtained will contribute to optimizing effluent treatment processes and promoting sustainable practices in the industrial sector of Côte d'Ivoire and beyond.

2. Methodology

2.1 Description of the Experimental UASB Reactor

The experimental setup used for anaerobic treatment of effluents consists of elements presented in Table 1 and photos 1 to 4. It comprises a main reactor, an inlet tank, an outlet tank, and a control box with the following characteristics:

- A polyethylene outlet tank (**Figure 1 A and Figure 2)** with a capacity of 250 L, used to collect the water treated by the UASB reactor.

- A main polyethylene reactor (**Figure 1 B and Figure 2**) with a total capacity of 2000 L, with a height (H) of 1.44 m, a diameter (D) of 1.24 m, a reaction zone volume of 1.74 m3, and a biogas capture zone volume of 0.26 m^3. This reactor is equipped with a heating resistor.

- A polyethylene inlet tank (**Figure 1 C and Figure 2**) with a capacity of 250 L, intended to collect the raw effluent to be treated and feed the main reactor using a pump with a flow rate of 1.92 L/min.

The total operating time of the pump per day is 15 minutes. Thus, to maintain a hydraulic retention time of 30 days, it is necessary to provide approximately 28.8 L of raw effluent to the main reactor each day.

- A control box (**Figure 3**) for operating the device, equipped with two switches: one to activate the pump and the other to control the heating resistor and the temperature probe.

The upflow anaerobic sludge blanket process requires two inputs for its operation: sludge cultured in anaerobic conditions in 60 L barrels (**Figure 4**), and industrial wastewater. The effluent to be treated comes from the wastewater treatment plant of SANIA Cie, located in the buffer tank just after primary treatment. The rate at which the effluent rises in the UASB reactor is 0.066 m/h. The sludge chosen for anaerobic digestion comes from the wastewater treatment plant of INPHB and was sampled at the INPHB premises in Yamoussoukro, before being preserved.

Figure 1. Experimental UASB reactor setup created by CEA-VALOPRO

Table 1. Experimental UASB Reactor Setup

Items	material	quantity	Specificity
Outlet tank (waste water output)	Polyethylene tank (**Figure 1A and Figure 2**)	1	Capacity: 250L
Main reactor	Polyethylene tank (Photo 1B and 2)	1	Capacity: 2000L
Inlet tank (raw wastewater)	Polyethylene tank (**Figure 1C** and **Figure 2**)	1	Capacity: 250L
One water pump	(**Figure 1D**)	1	Flow rate: 1.92 L/min
One heating resistance incorporated into the main reactor	(**Figure 1** and **Figure 2**)	1	
One control box for the device	(**Figure 3**)	1	
Storage tank for anaerobic sludge	Polyethylene tank (**Figure 4**)	6	Capacity: 60L

Figure 2. Experimental UASB reactor setup installed at SANIA-cie

Figure 3. Control box of the setup

Figure 4. Anaerobic sludge storage tank

2.2 Determination of Physicochemical and Bacteriological Characteristics of Sludge Used in the UASB Reactor

The pH is measured using a pH meter (senSION™+ PH31), calibrated beforehand at two points (pH 4.0 and pH 7.0) to ensure the accuracy of the results. Moisture content, total solids (TS), and volatile solids (VS) are determined according to the AOAC method (2000), ensuring the reliability of the measurements. The total nitrogen concentration is evaluated using the HACH 10072 method, based on persulfate digestion, providing a proven and recognized method for this analysis (Adou *et al.*, 2022). The bacteriological parameters of the biological sludge are evaluated according to NF V08-059:2002, ISO 4832:2006, and NF V08-057-1:2004 standards, ensuring compliance with standardized protocols for this essential analysis (Wohlsen *et al.*, 2006) .

2.3 Determination of Physicochemical and Bacteriological Characteristics of Industrial Wastewater to be treated

- The pH is measured using a pH meter (Bench meter VioLab pH 60) previously calibrated at two points (pH 4.0 and pH 7.0). The pH electrode is immersed in the solution to be analyzed (wastewater), and after a few moments, the stable pH value is displayed at a precise temperature. Measurements are performed in triplicate to ensure result reliability (Adou *et al.*, 2022).

- Determination of chemical oxygen demand (COD) is performed using the HACH 8000 colorimetric method, including a digestion step in a reactor (Adou *et al.*, 2022).

- The test to determine total nitrogen is carried out according to the HACH 10072 method, based on persulfate digestion (Adou *et al.*, 2022).

The effluent pretreatment process involves firstly removing suspended solids, including oil, from the effluent using a skimmer (Figure1). Then, the effluent undergoes physicochemical treatment with coagulation-flocculation using products such as lime ($Ca(OH)_2$), a coagulant (polyaluminium chloride ($AlClH_2O$)), and a flocculant (polyacrylamide ($(C_3H_5NO)n$), all prepared beforehand. Subsequently, dissolved air flotation is performed to remove insoluble matter. Afterwards, the effluent is directed to a buffer tank to regulate its flow and achieve homogeneous concentration. Finally, the UASB reactor, operating on the principle of anaerobic digestion, is utilized.

2.4 Determination of Effluent Treatment Efficiency from COD

To determine the efficiency of effluent treatment from initial and final COD, the following formula is used (Adou *et al.*, 2022):

$$Treatment\ efficiency\ (\%) = (\frac{COD_{initial} - COD_{final}}{COD_{initial}}) \times 100 \qquad \textbf{Eqn. 1}$$

Where:
$COD_{initial}$ is the COD concentration in wastewater before treatment.
COD_{final} is the COD concentration in wastewater after treatment.

2.5 Determination of Efficiency of Nitrogen Pollution Treatment in Effluents

To calculate the efficiency of nitrogen pollution treatment in effluents by the UASB reactor, the following formula can be used (Adou *et al.*, 2022):

$$Treatment\ efficiency\ (\%) = (\frac{C_i - C_f}{C_i}) \times 100 \qquad \textbf{Eqn. 2}$$

Where:
C_i represents the initial nitrogen concentration in the effluents (before treatment).
C_f represents the final nitrogen concentration in the effluents (after treatment).

3. Results and Discussion

3.1 Characteristics of Anaerobic Sludge Digestion

3.1.1 Physico-Chemical Parameters

The physico-chemical parameters of the sludge used in the UASB digester for the experimental setup are summarized in Table 2:

The table summarizes the pH values of the sludge used in the UASB digester, illustrating a range from 6.32 to 7.83. This variation reflects the natural diversity of sludge characteristics, influenced by various factors such as organic composition and environmental conditions. The calculated pH average is 7.22, with a standard deviation of 0.29. These detailed data allow for a thorough evaluation of the acidity or alkalinity of the sludge in the UASB digester, crucial for the proper functioning of anaerobic digestion. Indeed, pH directly influences the activity of microorganisms responsible for the degradation of organic matter (Chen *et al.*, 2020). The pH of sludge intended for anaerobic digestion generally falls within a range close to neutrality, ranging from 6.5 to 8.5. This pH range is considered optimal for promoting the activity of anaerobic microorganisms responsible for the degradation of organic matter (Iftikhar *et al.*, 2023), (Khatri *et al.*, 2023). By maintaining pH within this range, ideal conditions are created for effective and efficient digestion, thus ensuring optimal performance of the wastewater treatment process (Kamyab *et al.*, 2021). Close monitoring of pH is therefore essential to ensure that environmental conditions in the UASB digester remain favorable for the growth and activity of microorganisms, thereby contributing to the overall efficiency of the treatment system (Kamyab *et al.*, 2021), (Khatri *et al.*, 2023).

The moisture content (%H) of the sludge used in the UASB reactor, as determined after analysis, shows significant variation, ranging from 43.54% to 83.59%. These high values indicate a significant amount of water in the sludge, consistent with its wet nature. This variation can be attributed to various factors, such as sludge composition, environmental conditions, and previous treatment processes (Khatri *et al.*, 2023). High moisture values indicate a lower concentration of dry matter in the sludge, which can influence their behavior and properties during treatment (Kocbek *et al.*, 2022). For example, higher moisture can make sludge more difficult to handle and transport, and can also affect their efficiency in anaerobic digestion processes (Li *et al.*, 2018). Thus, the dry matter content of our study sludge averages around 35.20% with significant variation, represented by a standard deviation of 12.23%. The recorded minimum and maximum values are 16.41% and 56.46%, respectively. These results highlight the diversity of sludge samples and underscore the importance of managing dry matter in the anaerobic digestion process (Iglesias *et al.*, 2019). A high dry matter content can influence the reactivity of sludge and biogas production, while a low content can compromise the efficiency of anaerobic digestion (Wang *et al.*, 2023). Thus, these data present us with potential challenges and emphasize the need for effective management of dry matter to optimize the performance of wastewater treatment processes.

The volatile solid content (VS) (%) of the sludge used in the UASB reactor shows a significant range, varying from 15.67% to 71.15%. These high levels of volatile solids indicate a significant amount of organic compounds in the sludge, which are likely to undergo biological decomposition during the anaerobic digestion process (Chen *et al.*, 2020). This diversity in VS contents highlights the variability of sludge samples used, influenced by factors such as organic waste composition and environmental conditions.

These observations suggest that the sludge used in the UASB reactor is rich in potentially biodegradable organic matter. This richness in volatile organic matter provides a favorable substrate for the anaerobic microorganisms present in the digester, thus promoting efficient digestion and increased biogas production (Mainardis *et al.*, 2020), (Liu *et al.*, 2020), (Dohdoh *et al.*, 2021) (Duarte *et al.*, 2021) (Mishra *et al.*, 2023). However, the variability in VS contents also underscores the importance of adequate management and control of these sludges to ensure optimal performance of wastewater treatment processes.

For the nitrogen composition of the sludge samples, analyses reveal a concentration ranging from 15 to 61 mg/L. This range of values reflects diversity in nitrogen content levels of the sludge samples studied. Nitrogen is a crucial element in the wastewater treatment process, and its presence in sludge can come from various sources such as proteins, amino acids, and nitrogenous organic compounds (Cao *et al.*, 2024). These results emphasize the importance of closely monitoring and controlling nitrogen levels in sludge to ensure effective wastewater treatment. Proper nitrogen management is essential to avoid any harmful environmental impact, such as groundwater pollution or excessive algae proliferation in receiving water bodies. Therefore, these data highlight the need for proactive nitrogen management as part of the overall wastewater treatment process to ensure environmental protection and public health.

Table 1. Physico-chemical parameters of sludge

Parameters	Average	Maximum	Minimum
pH	7.22±0.29	7.83	6.32
Humidity (%)	64.80 ±12.23	83.59	43.54
TS (%)	35.20±12.23	56.46	16.41
VS (%)	43.42±18.01	71.15	15.67
Nitrogen (mg/L N)	34.29±12.14	61	15

3.1.2 Bacteriological Parameters

Table 3 presents the results of microbiological analyses of sludge samples, demonstrating the absence of mold, yeast, total coliforms, or staphylococci colonies in the samples examined. The values indicated represent the averages of microbial counts, accompanied by their respective standard deviations, expressed as colony-forming units per unit volume. These results attest to the significant absence of contamination by undesirable microorganisms in the sludge samples intended for the UASB reactor. Regarding specific details:

- Mold: The average number of detected colonies is 0.015 ± 0.005, indicating minimal presence of these fungal microorganisms, typically insignificant from a public health perspective.

- Yeast: The average of 0.008 ± 0.003 colonies also reveals a low presence of yeast in the sludge samples, without raising major concerns.

- Total coliforms: With an average of 0.002 ± 0.001 colonies, the concentration of total coliforms is very low, which is a positive indicator of the microbiological quality of the sludge [28; 30].

- Staphylococci: The samples show minimal presence of staphylococci, with an average of 0.003 ± 0.002 colonies, which is reassuring given their low level of presence.

These results confirm satisfactory bacteriological quality of the sludge, signaling a microbiologically healthy environment favorable to the wastewater treatment process [28; 30]. This observation is crucial to ensure the efficiency of the UASB reactor in removing organic and nitrogenous pollutants, as well as to ensure compliance with regulatory requirements.

Table 3. Detection of microorganisms in the sludge

Microorganism	Number of colonies detected (mean ± standard deviation)
Molds	0.015 ± 0.005
Yeasts	0.008 ± 0.003
Total coliforms	0.002 ± 0.001
Staphylococci	0.003 ± 0.002

3.2 Anaerobic Digestion Monitoring of the UASB Reactor

3.2.1 Operation of the UASB Reactor

The average hydraulic retention time of wastewater in the UASB treatment unit is thirty (30) days. A 30-day hydraulic retention time in the UASB treatment unit is an appropriate approach to ensure efficient degradation of organic pollutants present in the wastewater [21]. This extended duration promotes effective anaerobic digestion, ensures the stability of the treatment process, and contributes to reducing the pollutant load of the treated effluents. The values of the organic load remain constant throughout the period, mainly around 9.69 to 9.75 (1000 kgCOD/day) (see **Figure 5**). This stability suggests consistency in the quantity of organic matter present in the industrial effluents of SANIA Company, which can be attributed to regular production processes. The stability of organic loads indicates consistency in the workload of the UASB reactor. This consistency is beneficial for the efficient operation of the treatment system, as uniform organic loads help maintain optimal conditions for anaerobic digestion (Arthur *et al.*, 2023). By avoiding sudden load fluctuations, the reactor can operate more stably and efficiently, thereby reducing the risk of disturbances and improving the degradation of organic matter (Angelidaki *et al.*, 2005; Madigou et al., 2019).

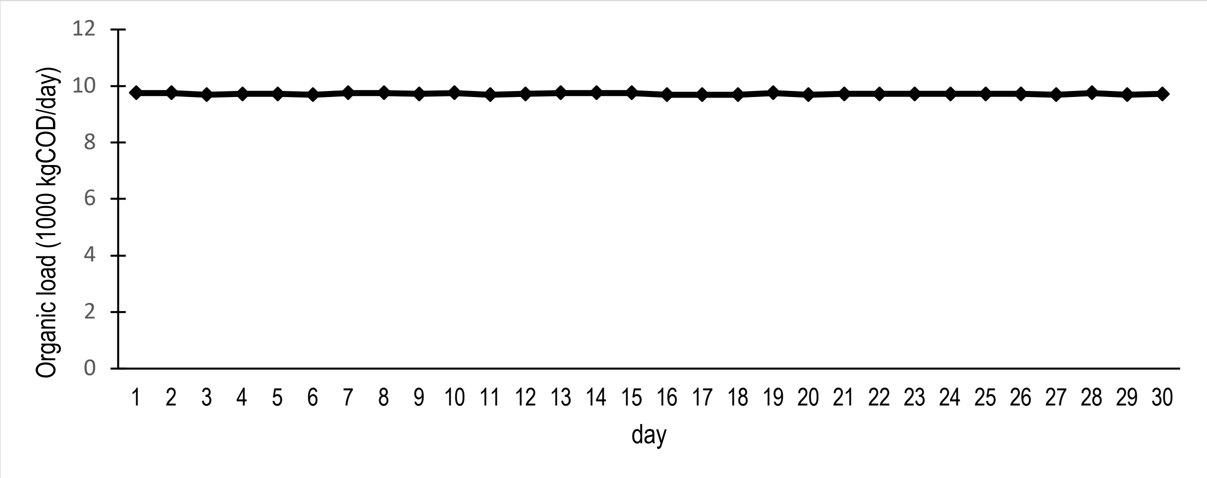

Figure 5. Evolution of the Applied Organic Load in the UASB Reactor

The temperatures recorded at the beginning and end of each day show fluctuations. Morning temperatures range from 26°C to 29°C, while evening temperatures range from 36°C to 38°C (see **Figure 6**). Despite some fluctuations, there is a general trend towards relatively stable temperatures throughout the study period. Daily temperature variations remain within an acceptable range for UASB reactor operation. The recorded temperatures are compatible with the conditions required for anaerobic wastewater treatment (Luostarinen *et al.*, 2007). Higher temperatures generally promote faster biochemical reactions, which can improve the efficiency of the anaerobic digestion process (Uddin *et al.*, 2023).

3.2.2 Evolution of Physicochemical Parameters in the UASB Reactor over a 30-Day Period

The analysis of results shows a significant evolution of parameters during anaerobic digestion in the UASB reactor (see **Table 4**). The initial pH varies between 6.33 and 9.03, while the final pH varies between 6.88 and 7.06 (see Table 4). Overall, there is a downward trend from initial to final pH, indicating acidification during the anaerobic digestion process. However, the variations remain within an acceptable range for the proper functioning of the UASB reactor (Sandberg *et al.*, 1992), (Zhang *et al.*, 2016).

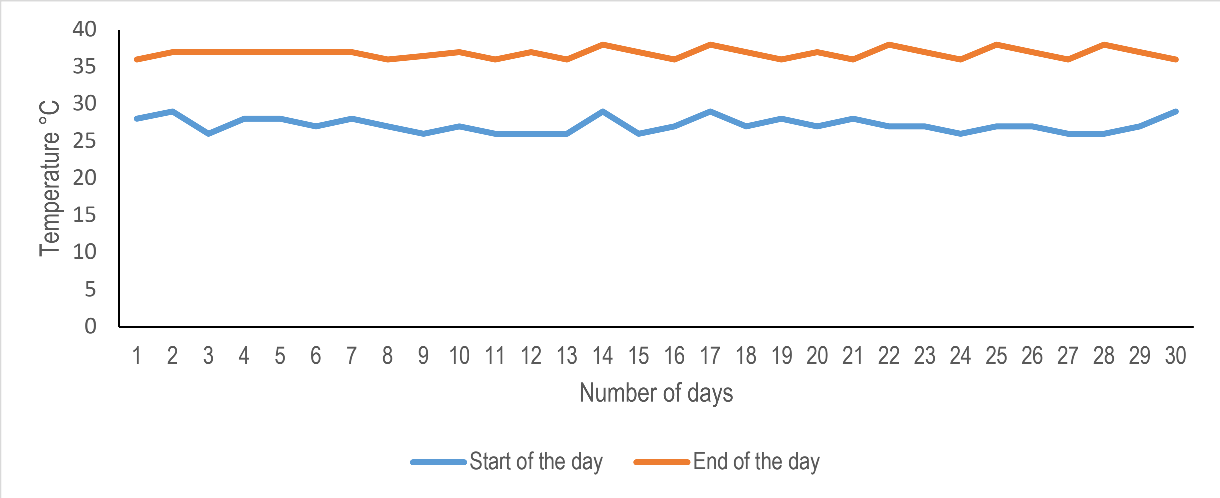

Figure 6. Daily Variation of the Temperature in the UASB Reactor

Initial COD values are relatively constant around 325 mg/L O_2, with minor variations ranging from 323 mg/L O_2 to 325 mg/L O_2 (see **Table 4**). This consistency suggests stability in the composition of wastewater entering the UASB reactor, facilitating management and control of the treatment process. An average initial COD value of around 325 mg/L O2 indicates a substantial pollutant load in the wastewater treated by the UASB reactor (Liu *et al.*, 2020), (Tufaner *et al.*, 2020). This means there is a significant amount of organic matter present in the wastewater, requiring adequate treatment to reduce this load before discharge into the environment. Final COD values show a significant reduction compared to initial values, indicating notable efficiency of the UASB reactor in removing organic matter from wastewater (Liu *et al.*, 2020), (Tufaner *et al.*, 2020). For example, the initial COD of 325 mg/L O_2 is reduced to only 20-50 mg/L O2 in the final samples, representing a significant decrease in organic pollution. The consistency of final COD values throughout the observation period suggests stability in the treatment process. Despite possible variations in the incoming pollutant load, the UASB reactor manages to maintain relatively constant treatment performance, which is essential for ensuring effective wastewater treatment. The results show that the UASB reactor is capable of effectively reducing the organic load of wastewater, even in the presence of variations in the incoming pollutant load. This demonstrates the efficiency of the anaerobic digestion process and the reactor's ability to treat different types of pollutant loads. By reducing the concentration of organic matter in treated effluents, the UASB reactor helps reduce the adverse environmental impacts associated with organic pollution of wastewater. This reduction in final COD helps produce higher quality effluents, less harmful to aquatic ecosystems (Kamyab *et al.*, 2021), (Stazi *et al.*, 2022).

From the analysis of **Table 4** regarding nitrogen concentrations, the following observations emerge: - The least significant reduction in nitrogen concentration is 0.53 mg/L N (from 4.5 to 3.43 mg/L N).

- In contrast, the most significant reduction reaches 4.78 mg/L N (from 10.15 to 5.37 mg/L N).

These results demonstrate the experimental UASB reactor's treatment capacity for nitrogen pollution in effluents. These observations suggest opportunities to improve treatment efficiency. This may require adjustments to the operating parameters of the UASB reactor or improvements in effluent preparation before treatment (Sheng *et al.*, 2020), (Phanwilai *et al.*, 2020). Overall, the results indicate a high efficiency of the UASB reactor in removing organic matter and nitrogen compounds while maintaining acceptable pH levels. However, continuous monitoring is necessary to ensure optimal reactor performance and compliance with current environmental standards.

Table 4. Results of parameters at the beginning and end of the UASB reactor digestion

Day	Initial pH	Final pH	Initial COD (mg/L O2)	Final COD (mg/L O2)	Initial Nitrogen (mg/L N)	Final Nitrogen (mg/L N)
1	8.94	7.03	325	50	4.02	3.06
2	7.14	6.88	325	49	6.03	4.59
3	8.43	6.93	324	40	4.12	3.14
4	7.63	7.04	325	55	5.23	3.99
5	6.97	7.06	325	30	4.89	3.73
6	6.46	6.15	325	58	7.12	5.43
7	6.34	6,93	325	58	8.30	6.32
8	8.44	7.01	324	55	10.15	7.73
9	8,56	6.90	324	49	7.60	5.79
10	9,02	7.00	323	30	9.06	6.90
11	8.95	7.03	325	41	4.12	3.14
12	7.13	6.88	325	51	6.12	4.66
13	8.44	6.93	324	40	4.12	3.14
14	7.64	7.04	325	35	5.60	4.27
15	6.96	7.06	325	39	3.80	2.90
16	6.45	6.15	323	37	7.30	5.56
17	6,33	6.93	325	36	8.60	6.55
18	8.45	7.01	325	35	10.20	7.77
19	8.57	6.9.	323	39	7.60	5.79
20	9,03	7.00	324	31	9,30	7.09
21	8.94	7.03	323	25	4.50	3.43
22	7.14	6.88	324	29	6.80	5.18
23	8.43	6.93	325	20	4.50	3.43
24	7.63	7.04	325	25	5.60	4.27
25	6.97	7.06	324	23	8.61	6.56
26	6.46	6.15	324	26	7.12	5.43
27	6.34	6.93	325	33	9.12	6.95
28	8.44	7.01	323	25	10.15	7.73
29	8.56	6.90	325	29	7.23	5.51
30	9.02	7.00	324	20	9.89	7.54

3.2.3 Evolution of Biogas Production from the UASB Reactor over a 30-day Period

The production of biogas from the UASB reactor appears to be relatively stable over the 30-day period, with values fluctuating between 0.075 m³/day and 0.656 m³/day (Figure 4). Biogas production seems to gradually increase until day 16, after which it remains relatively stable with some slight fluctuations. This stability indicates good performance of the reactor in converting organic matter into biogas (Musa *et al.*, 2020). The peak production seems to occur around day 16, where production reaches 0.656 m³/day. This could be the result of optimizing anaerobic digestion conditions in the reactor, especially concerning the temperature maintained at 37°C by the heating resistance.

The reactor characteristics, such as its total capacity of 2000 L, reaction volume of 1.74 m³, and biogas collection zone of 0.26 m³, appear to be suitable for the observed biogas production. Additionally, the presence of a heating resistance to maintain a temperature of 37°C can promote microbial activity and hence biogas production (Kamyab *et al.*, 2021) (Khatri *et al.*, 2023). Although biogas production is stable, further optimization of the process is still possible. This could involve adjustments in the operational conditions of the reactor, such as organic load, pH, and temperature, as well as improvements in substrate management to maximize the efficiency of anaerobic digestion. Overall, the biogas production of the UASB reactor appears to be satisfactory considering its characteristics and provided operating conditions. However, ongoing efforts for optimization can be undertaken to further improve the performance and efficiency of the anaerobic digestion process.

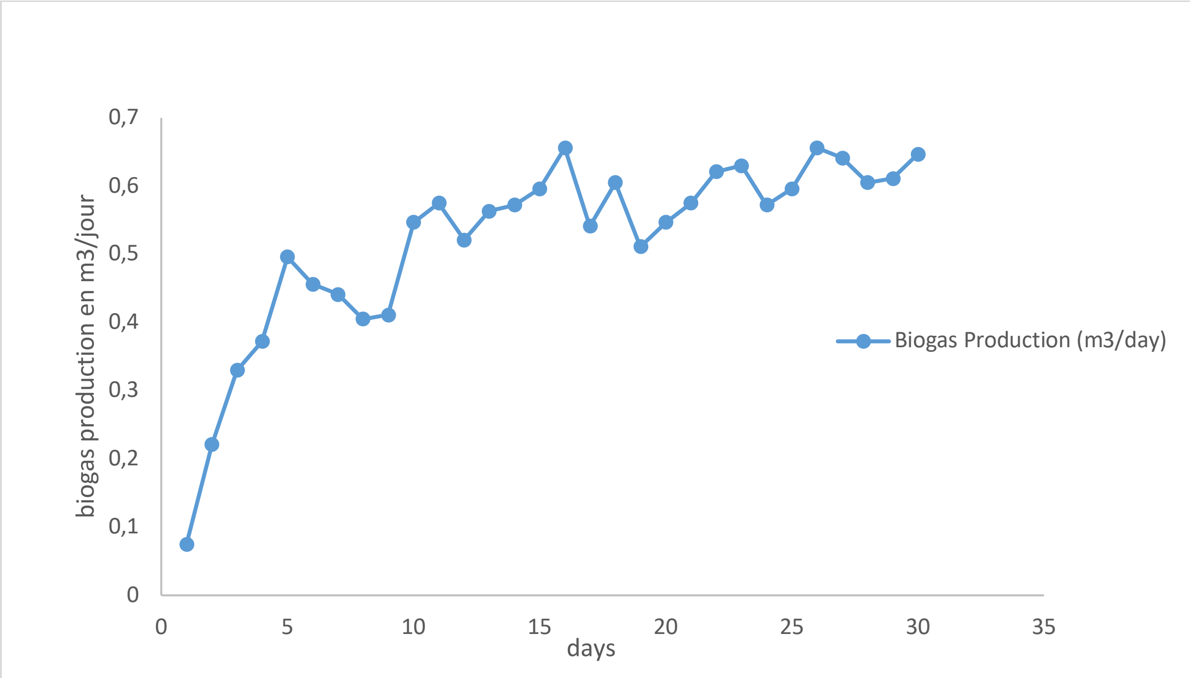

Figure 7. Evolution of biogas production from the UASB reactor over a 30-day period

3.2.4 Evaluation of Treatment Efficiency

The efficiency of effluent treatment by the UASB reactor was evaluated based on initial and final COD. The treatment efficiency (%) is 93.8%. This means that the treatment succeeded in removing approximately 93.8% of the COD present in the initial wastewater. This efficiency demonstrates the performance of the UASB reactor in reducing organic pollution in wastewater and confirms its crucial role in effluent treatment (Musa *et al.*, 2020), (Kamyab *et al.*, 2021), (Khatri *et al.*, 2023). The WHO standard for COD (Chemical Oxygen Demand) of industrial effluents varies depending on the type of industry and local regulations. However, for an agro-food industry after treatment, the recommended COD concentration in effluents is generally less than 100 mg/L (Tufaner *et al.*, 2020), (Lokman *et al.*, 2021). By comparing the final COD results (mg/L O_2) obtained after treating Sania-Cie's industrial effluents with the UASB experimental reactor with the recommended COD standard for an agro-food industry after treatment (generally less than 100 mg/L), it can be observed that most of the final COD values are well below the recommended standard, suggesting significant effectiveness of effluent treatment by the experimental UASB reactor.

The treatment efficiency (%) of nitrogen pollution of effluents by the UASB reactor is 23.8%. An average nitrogen treatment efficiency of 23.8% indicates that the UASB reactor manages to reduce the nitrogen concentration in effluents, albeit relatively modestly (Sheng *et al.*, 2020), (Phanwilai *et al.*, 2020). This reduction, though significant, may be considered relatively low compared to other methods of nitrogen pollution treatment (Phanwilai *et al.*, 2020). This may suggest that the UASB reactor may require adjustments or improvements to achieve higher levels of nitrogen removal (Walia *et al.*, 2020). Further evaluation of the reactor's operating conditions and overall efficiency may be necessary to identify specific areas where improvements are needed. However, even with relatively modest efficiency, the UASB reactor can still significantly contribute to reducing nitrogen pollution in effluents as part of a broader treatment system.

3.2.5 Integration of Air Flotation as Post-Treatment to Reduce Nitrogen Pollution of Effluents Treated by the UASB Reactor

Air flotation as post-treatment has been integrated into our study to reduce nitrogen pollution in effluents treated by the UASB reactor (Walia *et al.*, 2020), (De Nardi *et al.*, 2008). The new nitrogen concentrations after post-treatment are presented in **Figure 8**. These new concentrations indicate a significant reduction in nitrogen pollution in effluents after post-treatment by air flotation, bringing them back to levels below 3 mg/L, in accordance with environmental standards (Sheng *et al.*, 2020), (Phanwilai *et al.*, 2020).

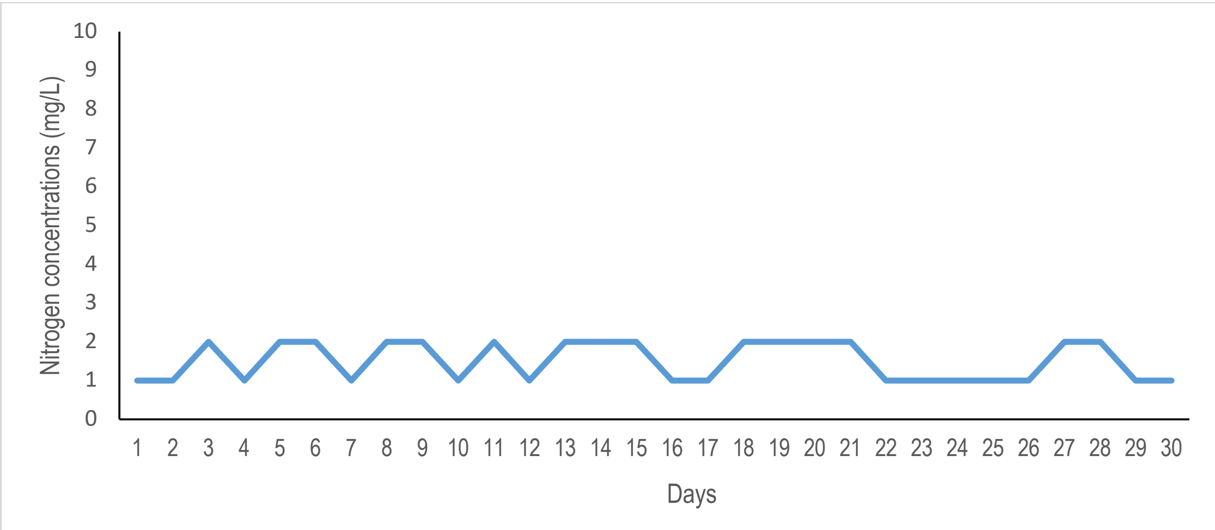

Figure 8. Nitrogen concentrations after post-treatment

Conclusion

In this study, we evaluated the effectiveness of an experimental UASB reactor in treating industrial effluents from Sania-Cie, an Ivorian agro-industrial company specializing in palm oil and its derivatives processing. Through a rigorous methodological approach, we characterized the sludge used in the UASB reactor, monitored the reactor's operation over a period of 30 days, and assessed the treatment efficiency of effluents in terms of reducing organic and nitrogen pollution.

The results obtained demonstrate that the UASB reactor is capable of effectively reducing the organic pollution in industrial effluents, with a treatment efficiency of 93.8% for COD. Additionally, the UASB reactor also contributes to reducing the nitrogen load in effluents, although its efficiency in this area is lower (23.8%). These results indicate that the UASB reactor is a promising technology for industrial effluent treatment, offering high performance in organic pollutant removal and making a significant contribution to nitrogen pollution reduction.

This study has several practical and theoretical implications. On a practical level, the results provide valuable information for optimizing the treatment processes of industrial effluents from Sania-Cie and other similar companies. By identifying the performance and limitations of the UASB reactor, this study guides decisions regarding investment in wastewater treatment technologies and the implementation of sustainable practices in the industrial sector. On a theoretical level, this study contributes to understanding anaerobic digestion processes and their application in industrial effluent treatment. By evaluating physicochemical and bacteriological parameters, as well as the evolution of biogas production, this study sheds light on the underlying mechanisms of anaerobic wastewater treatment and opens new research perspectives in this field.

In conclusion, this study highlights the importance of wastewater treatment technologies in promoting sustainable development and environmental protection. By developing innovative and effective solutions to address the challenges of industrial effluent management, we contribute to creating a cleaner and more sustainable future for future generations.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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