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Dimensioning of an Anaerobic Digester for the Treatment of Chicken Manure and for the Production of Biogas: The Case Study of a Chicken Farm in Yaokokoroko (Côte d'Ivoire)

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Abstract

This study allowed us to highlight the level of pollution of a BAYA River water near several poultry farms and the sizing of an anaerobic digester that will be able to treat chicken manure from a poultry farm (BRIN FOUNDATION). To evaluate this pollution, the parameters such as ammonium (NH_4^+), Phosphate (PO_4^{3-}), Biochemical Oxygen Demand (DBO_5) and Nitrate (NO_3^-) were determined. For sampling point P1, the concentrations in mg/L of these parameters are (25.00 ± 4.25), (0.40 ± 0.20), (98.00 ± 6.35) and (96.00 ± 5.35), respectively. On the other hand, for sampling point P2, the concentrations in mg/L of these parameters are respectively (33.00 ± 9.05), (0.70 ± 0.12), (123 ± 7.13) and (93 ± 7.10). These values indicate a strong organic pollution of the BAYA River. The determination of the different concentrations of the organic pollution parameters allowed us to evaluate the degradation and the quality of the water of the BAYA River water, by the poultry activity. However, considering the physicochemical properties of the waste (chicken manure), which is the main source of organic pollution, we have considered an energy recovery through the production of biogas. This requires the design, sizing, and implementation of an anaerobic digester in a poultry farm. Therefore, the project would require the construction of an adapted masonry type anaerobic digester with a capacity of 10 m^3.

Keywords

Biogas, Organic Pollution, Surface Water, Biodigester, Chicken Manure, Anaerobic Digestion

1. Introduction

In Côte d'Ivoire, the poultry industry is in full expansion. However, poultry farms generate organic waste that is not valorised, thus creating a real environmental problem, especially in rural areas. They are sources of organic pollution and cause a degradation of the quality of surface and ground water [1].

The village of YAOKOKOROKO, located in the sub-prefecture of TABAGNE in the GONTOUGO region, is an essentially rural area where water resources are heavily used for agricultural activities. The degradation of natural water quality in this village is caused by organic waste (chicken droppings) from poultry farms where there is a high density of this type of operation. Moreover, the load of these wastes is increasing with the socio-economic development of these farms.

The BAYA River water located in the watershed of a high density of poultry farms in the village of YAOKOKOROKO is heavily used for agricultural activities and as a source of drinking water. Consequently, it seemed necessary for us to evaluate the organic pollution of this river.

On the other hand, anaerobic digestion is an efficient process for the biological treatment of organic waste. It receives particular attention because it is a means of energy recovery from organic waste [2]. Indeed, the anaerobic digestion of organic waste offers possibilities for energy and nutrient recovery [3]. Thus, it reduces the impact of waste on the environment, while producing renewable energy and thus contributing to a reduction in greenhouse gas emissions [2]. However, improper sizing of the anaerobic digester can affect the performance of this process [4].

The general objective of this study is to evaluate the organic pollution of the BAYA River water, and to propose a sizing of biodigesteur, which is capable of treating and valorizing the chicken manure coming from a poultry exploitation in the proximity. To this effect, it was necessary to determine the parameters of organic pollution of the BAYA River water, to evaluate the index of the organic pollution of this river and, to propose a dimensioning of biodigester which can treat and valorise in energy, the chicken manure resulting from a poultry exploitation (FONDATION BRIN).

2. Materials and Methods

2.1. Description of the Study Area

The village of YAOKOKOROKO is located in the North-East of Côte d'Ivoire, in the BONDOUKOU region. This village has many poultry farms. There are small farms (3000 heads) and large farms (200,000 heads). These farms generate nearly three hundred (300) direct and indirect jobs in the village. However, they are potential sources of pollution for the BAYA River water. There exists a chicken manure discharge as shown in Figure 1.

2.2. Sampling and Analysis Methods

2.2.1. Sampling Methods

The selection of the sampling site was based on its accessibility for sampling and its crossing of some high density poultry farms. For a better evaluation of the organic pollution of the poultry activities on the BAYA River water due to the phenomenon of soil leaching, two samples were taken during the rainy season (September and October 2021) on the sites indicated in Figure 2.

2.2.2. Methods for the Determination of the Different Parameters of Organic Pollution

The methods for the determination of the various organic pollution parameters are listed in the collection of French standards "Eaux Méthodes d'essai" of the French Association for Standardization (AFNOR). The World Health Organization (WHO) recommends a quality table for organic pollution parameters (Table 1) [5].

Figure 1. Chicken manure discharge in the village of YAOKOKOROKO.

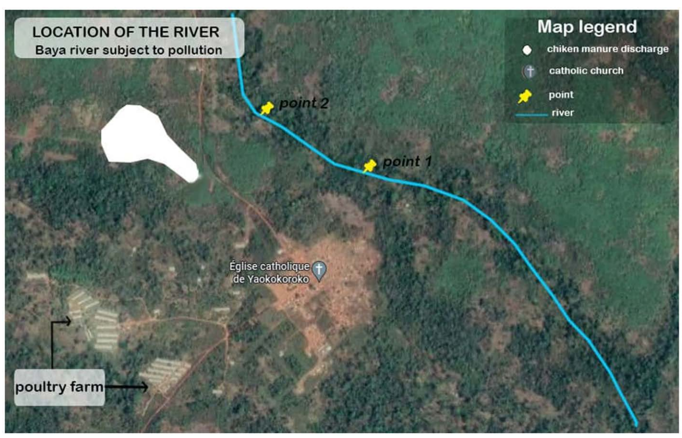

Figure 2. Location of the BAYA River water and sampling sites.

Table 1. Drinking water quality table [5].

organic pollution parameters	Quality limits for drinking water
Ammonium (NH_4^+)	0.5 mg/L
Nitrate (NO_3^-)	50 mg/L
Phosphate (PO_4^{3-})	500 µg/L
5-day Biological Oxygen Demand (DBO_5)	3 mg_{O2}/L

2.2.3. Method of Evaluation of Organic Pollution

The data processing method is based on the Organic Pollution Index (OPI). The Organic Pollution Index (OPI) is calculated according to the method of Leclercq and Maquet, whose principle is to divide the values of the polluting elements in 05 classes according to the following **Table 2** [5]:

The Organic Pollution Index (OPI) is equal to the average of the class number of the four (04) parameters:

OPI = class 1: no organic pollution.

OPI = class 2: low organic pollution.

OPI = class 3: moderate organic pollution.

OPI = class 4: strong organic pollution.

OPI = class 5: very strong organic pollution.

OPI = class 6: extremely high organic pollution.

2.3. Sizing of the Anaerobic Digester

2.3.1. Physicochemical Characterization of Chicken Manure

In order to treat the organic pollution of chicken manure by anaerobic digestion and its energy recovery by this process, the physical and chemical parameters of chicken manure, which are essential for the sizing of the anaerobic digester, have been determined [6].

1) Humidity content ($\%H$)

The humidity ($\%H$) was determined according to the method reported by [7]. The sample of initial mass m_0 was dried in an oven at 105˚C for 24 hours. When it was removed from the oven, its new mass was m_1. The calculation of the humidity rate is done according to the relation:

$$\%H = \frac{m_0 - m_1}{m_0} \times 100 \quad (1)$$

$\%H$: the humidity content;

m_0: the initial mass of the sample before drying;

m_1: the mass of the sample after drying.

2) Dry matter ($\%DM$)

The determination of the dry matter content ($\%DM$) is made from the humidity content.

$$\%MS = 100 - \%H \quad (2)$$

3) Determination of volatile solids (VS)

Table 2. Organic pollution indices [5].

Parameters \ Classes	1	2	3	4	5	6
DBO_5 (mg_{O2}/L)	<1	1 - 3	3 - 6	6 - 15	>15	
Ammonium (NH_4^+) (mg/L)	<0.1	0.1 - 0.5	0.5 - 2	2 - 8	>8	
Phosphate (PO_4^{3-}) (mg/L)	<10	10 - 50	50 - 150	150 - 300	300 - 500	>500
Nitrate (NO_3^-) (mg/L)	<1	1 - 3	3 - 5	5 - 10	10 - 15	>15

The volatile solids content (% *VS*) was determined according to the method reported by [14]. It consists in making the difference in mass between the dried waste m_1 and the calcined waste m_2. The calcination was carried out at 550˚C for 4 hours.

$$\%VS = \frac{m_1 - m_2}{m_1} \times 100 \tag{3}$$

With, m_1 the mass of the sample after drying in the oven and m_2, the mass of the calcined waste.

4) Determination of the density

A container of 22 L is filled and then weighed. The densities (ρ) are calculated by the following formula [7]:

$$\rho = \frac{M}{V} \tag{4}$$

With: ρ the density in kg·m^{-3}; *M*, the weight obtained in kg and *V*, the volume of the container in m^3.

2.3.2. Sizing of the Anaerobic Digester

The sizing of the anaerobic digester was done using the physicochemical characteristics of chicken manure [8].

1) Determination of the reactor volume (V_r)

The volume of the reactor (V_r) is equal to the product of the volumetric flow rate (*Q*) and the hydraulic retention time of the feedstock (*HRT*) [9].

$$V_r = Q \times HRT \tag{5}$$

where *HRT* is the hydraulic retention time of the feedstock in days.

2) Determination of the volume of the biogas tank (V_g)

The volume of the gas tank V_g is equal to half the volume of the reactor [9]

$$V_g = \frac{V_r}{2} \tag{6}$$

3) Determination of the total volume of the anaerobic digester

The total volume of the digester is the sum of the reactor volume and the biogas tank volume [9]

$$V_d = V_r + V_g \tag{7}$$

4) Selection and sizing of the anaerobic digester

Physicochemical characterization of chicken manure was used to select the appropriate anaerobic digester model from a list of identified technologies. After the selection of the appropriate model, the dimensions of the anaerobic digester were determined based on the standard dimension of the selected anaerobic digester model from Equation (8) [9]. The reactor is a cylindrical tank with volume (V_r) given by:

$$V_r = \frac{\pi D^2 H}{4} \tag{8}$$

where: D is the diameter of the tank and H is the height of the tank. Supposing that the height of the reactor is equal to its diameter:

$$V_r = \frac{\pi D^3}{4} \tag{9}$$

The diameter D can therefore be given as follows:

$$D = \sqrt[3]{\frac{4V_r}{\pi}} \tag{10}$$

Considering that the radial clearance of the biogas from the digester is 20 mm, we obtain the diameter (d) of the biogas tank:

$$d = D - 0.04 = \sqrt[3]{\frac{4V_r}{\pi}} - 0.04 \tag{11}$$

Considering the volume of the biogas tank (V_g), the height (h) of the biogas tank is therefore given by the following formula:

$$h = \frac{4 \times V_g}{\pi d^2} = \frac{4 \times V_g}{\pi} \times \left(\sqrt[3]{\frac{4V_r}{\pi}} - 0.04 \right)^{-2} \tag{12}$$

3. Results and Discussion

3.1. Organic Pollution of the BAYA River by Chicken Manure

3.1.1. Organic Pollution Parameters

Ammonium, nitrate, phosphate and BOD_5 levels at the different sampling stations are shown in **Table 3**. These values are above the recommended concentration for surface waters, which are 8 mg/L for ammonium ions; 0.5 mg/L for phosphate ions; 50 mg/L for nitrate and 3 mg O_2/L for BOD_5 [5].

The high levels in the different sampling stations allow us to classify this water in the "polluted" category [10] [11]. In addition, the high concentration of NH_4^+ would affect the water quality, the self-cleaning capacity of the water sources and, the death of fish and aquatic organisms [3]. The high concentrations of PO_4^{3-} may be due to the influence of waste from the residential community. The simultaneous presence of dissolved NH_4^+ and PO_4^{3-} can lead to eutrophication. A concentration of NH_4^+ greater than 500 µg/L and PO_4^{3-} greater than 20 µg/L can cause eutrophication [10] [11]. This river would no longer be suitable for aquatic animal development. These PO_4^{3-} concentrations could also cause aquatic plants to appear as (**Figure 3**), hindering water transport and exchange.

Table 3. Nutrient and BOD_5 contents of the BAYA River water.

parameters		Ammonium (mg/L)	Phosphate (mg/L)	Nitrate (mg/L)	DBO_5 mg_{O2}/L
sampling stations	P1	25.00 ± 4.25	0.40 ± 0.20	96.00 ± 5.35	98.00 ± 6.35
	P2	33.00 ± 9.05	0.70 ± 0.12	93 ± 7.10	123 ± 7.13

Figure 3. Plant development in the BAYA River water.

The high nitrate concentrations are due to intense agricultural activities in the proximity. The high concentrations observed are due to two main factors: fertilizer use and wastewater management. Indeed, in the village of YAOKOKOROKO, there are large farms growing cashew nuts and yams. Market garden crops using chemical fertilizers are grown there. BOD_5 is considered to be a measure of the concentration of biodegradable organic compounds present in water. The large quantity of decomposable matter is related to the high oxygen demand [10] [11]. This would explain the high BOD_5 values. In this study, the high BOD values recorded in the plants could be an indication of organic pollution due to wastewater loads from poultry activities. According to [11], effluents coming from poultry farms, have a significant content of biodegradable organic compounds. Moreover, these values (much higher than 6 mg/L) reflect an insufficient amount of oxygen for the needs of microorganisms present in the effluent necessary for their metabolic reactions [10] [11].

3.1.2. Evaluation of the Organic Pollution Index

The determination of the different concentrations of the organic pollution parameters permitted to evaluate the degradation and the quality of the water of the BAYA River water, by the chicken farming and agricultural activities of the village of YAOKOKOROKO. The evaluation of the pollution of the river water by the Organic Pollution Index (OPI) (OPI = 4) shows a strong organic pollution. The water, by its high dissolving power, dissolves the substances rejected by the human activity. The chemical pollutants are numerous and of various origins and the most harmful are the nitrogen compounds such as nitrates, causing serious disorders in children by degradation of blood haemoglobin and by the production of toxic methaemoglobin (methaemoglobinaemia of infants). They can cause hypertension and are precursors of carcinogenic nitrosamines [5] [11].

3.2. Physicochemical Characteristics of Chicken Manure

3.2.1. Sensorial Evaluation

Chicken manure is characterized by a moderately strong odour with a pasty texture. It contains some small fractions of undigested feed input. It is observed that the colour of chicken manure varies from maroon to black (**Figure 4**). In fact, this malodour and colour variation are influenced by the feed, but also by the digestive metabolisms of the feed. In addition, manure production is influenced by several factors such as the rearing system, genetics and physiology of the chickens [12].

3.2.2. Physicochemical Characteristics of Chicken Manure

Table 4 summarizes the physicochemical characteristics of the chicken manure that will be used for biogas production.

Figure 4. Texture of chicken manure to be used for biogas production.

Table 4. Physicochemical characteristics of chicken manure.

Parameters	Values
Volumetric mass (kg/m^3)	400
Humidity level (%)	65. 19 ± 0.81
Dry matter content (%)	34.81 ± 0.73
Volatile Solid Matter (%)	72.98
pH	8.45
TOC (% DM)	27.50%
C (% DM)	14.62%
N (% DM)	3.21%
C/N	9.01

The mean density of chicken manure at the exit of the buildings or after storage (in kg/t or kg/m^3 of raw product) is 400. The samples were taken from manure from chicken houses on litter. The mean moisture content obtained was 65.19% ± 0.81% while the dry matter content was 34.81% ± 0.73%.

The high moisture content of chicken manure is due to its presence of faeces and urine [13]. It is not combustible, so methane fermentation is the best technique to valorise the manure.

The volatile solid matter (or organic matter) content of chicken manure, which is 72.98% ± 0.91%, is associated with the feeding of the chickens [13]. This result is close to that of the literature, which is 74.50% organic matter per dry matter. These values show that chicken manure is characterized by a much higher amount of organic matter than ash. This is why the chicken manure is classified as an organic waste.

The pH of the chicken manure is rated at 8.45. This means that the chicken manure is basic in nature. The ideal pH of the substrates to be used in the anaerobic digestion process should be between 6.5 and 8.5. These results show that these chicken manures can be degraded by the anaerobic digestion process [13].

The TOC meter analysis showed that the manure had an organic carbon content of 27.50% DM (Dry Matter) and a mineral carbon content of 14.62% DM. These results indicate that these chicken manures are more organic than mineral residues, which explains their high capacity to be degraded by the anaerobic digestion process.

The results obtained in this study show a high nitrogen content of 3.21% DM. This high nitrogen content would be mainly due to the high amount of urine present in the manure. These results are superior to those obtained by [13]. In their study on the evaluation of the biogas production potential of chicken manure, they found a nitrogen amount of 1.83% DM.

The C/N value for these chicken manures is 9.01. This value is lower than the optimal range for anaerobic digestion, which is between 20 and 30. The low C/N value obtained would be explained by the high nitrogen content. A similar result (C/N = 8) was obtained by [13] on the survey of *Hyline* laying hen manure. Although the C/N ratio is low compared to the recommended range of values, the manure can produce biogas [13]. However, obtaining optimal biogas yield requires optimization of the anaerobic digestion process (co-digestion) [13].

3.3. Sizing and Selection of the Anaerobic Digester Model

Sizing of the Anaerobic Digester

1) Volume of the anaerobic digester

The Reactor Volume (V_r) is equal to the product of the volumetric flow rate (Q) and the hydraulic retention time of the feedstock (HRT). Using a density of 400 kg/m^3, a feedstock flow rate Q_1 = 42.4 kg/day, the calculated volumetric flow rate (Q) is 0.106 m^3/day. To achieve substrate fluidity, the feedstock was mixed with water in a 1:1 ratio. Therefore, an additional 0.106 m^3 of water must be added, resulting in a total feedstock flow rate of approximately (Q) = 0.211

m^3/day.

According to the literature, the optimal hydraulic retention time (HRT) values for organic wastes with volatile solid content (MSV) greater than 70% are between 21 and 30 days [9]. Using an upper limit of HRT of 30 days results in a reactor volume (V_r) of 6.33 m^3.

2) Organic Load Rate (OLR) Verification

The optimum organic loading rate for this type of waste (MSV ≥ 70%) is between 1 and 5 kgVS/m^3. This results in an organic loading rate of 3.25 kgVS/m^3. This organic loading rate is in the range of 1 to 5 therefore, the reactor size of 6.5 m^3 is acceptable.

3) Volume of the biogas tank V_r

The volume of the biogas tank V_g being equal to $V_r/2$, the value obtained is 3.17 m^3.

4) Total volume of the anaerobic digester V_d

The total volume of the biodigester is the sum of the volumes of the reactor and the biogas tank;

$$V_d = 9.5 \approx 10 \text{ m}^3$$

5) Anaerobic digester model selection

The physicochemical characterization of chicken manure was used to select the appropriate the anaerobic digester model from a list of identified technologies summarized in **Table 5** [9].

The best anaerobic digester model selected for the project is the PUXIN digester, available in 10 and 6 m^3 capacities. Therefore, the project would require the construction of a 10 m^3 PUXIN type digester *in situ*. The various dimensions required for the design of the biodigester are summarized in **Table 6**.

Table 5. List of technologies identified for the construction of the anaerobic digester [9].

Model	Capacity (m^3)	Temperature Control	Materials	Origin	Agitation
PUXIN	10 max	Buried underground	*In-situ* Concrete	China/South Africa	Hydraulic
Bio4gas	≥200	Incorporate/ Co generator	*In-situ* Concrete	Germany/South Africa	Incorporated
GREENBOX	≥100	Isolated	Steel on site	Germany/South Africa	Incorporated
WELTEC	2500	Incorporated	Stainless Steel	Germany	Incorporated
ÖKOBIT	2500	Incorporated	Stainless Steel	Germany	Incorporated
BioConstruct	2400	Incorporated	Steel on site	Germany	Incorporated
BITECO	600	Incorporated	Steel on site	Italy	Incorporated
Helios®system	≥2000	Incorporated	*In-situ* concrete casting	Germany	Incorporated

Table 6. Dimensions of the anaerobic digester.

Parameters	Values
Total volume of biodigester (m^3)	10.0
Volume of the reactor (m^3)	6.33
Volume of the biogas tank (m^3)	3.17
Height of the biogas tank (m)	1.06
Diameter d of the biogas tank (m)	2
Diameter of the reactor (m)	2.04

4. Conclusions

At the end of this study, it should be noted that the level of organic pollution of the BAYA River water is high. The pollution index found (OPI = 4) allows to classify this river in the categories of much polluted surface waters. This pollution is not without consequences for the aquatic environment, and on the health of the surrounding population. The measured parameters show a low quantity of oxygen for the needs of the micro-organisms present in the environment necessary for their metabolic reactions. Moreover, it is not surprising to note the invasion of the water body by plants (eutrophication).

This degradation of the water quality has accelerated with the development of poultry activities whose discharges are made not far from the river. To remedy this problem, it was proposed to treat this organic waste by anaerobic digestion in order to recover energy by producing biogas. This approach is in conformity with the vision of the objectives of sustainable development, which aim essentially at the preservation of resources. The dimensioned anaerobic digester has a capacity of 10 m^3, and is of the PUXIN type. This work continues with the construction and operation of several anaerobic digesters.

Thus, the site of YAOKOKOROKO presents itself as a privileged field of experimentation. We can count on our technical and financial partners for the conduct and development of this research work that takes place there.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Removal of Hydrogen Sulfide from Biogas by the *Acacia Auriculeaformis* Activated Carbon

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Abstract: Biogas is one of the most attractive renewable resources because of its ability to convert waste into energy. Biogas is produced during an anaerobic digestion process from various organic waste resources. It is composed of mainly CH_4, CO_2, and some trace gases such as hydrogen sulphide (H_2S) which is a very toxic, deadly and corrosive gas. Therefore, raw biogas must be cleaned of hydrogen sulphide (H_2S) before being used in many applications. Activated carbon is commonly used for adsorption due to its high surface area, micro porosity, thermal stability, high removal capacity and low cost compared to other adsorbents. The general objective of this work was to study the removal efficiency of hydrogen sulphide (H_2S) by the *acacia auriculeaformis* activated carbon. The *acacia auriculeaformis* is a tree that can be exploited for wood charcoal because of its rapid growth, even on infertile sites, and its tolerance to very acidic and alkaline soils. The carbonization of the *acacia auriculeaformis* branches were done using an oven at 550°C for four hours and activated by a 1 mol/L sodium hydroxide solution. The physicochemical parameters such as Iodine adsorption number, ash content, point zero-charge pH (pH_{ZPC}), and tapped density were determined to characterize the synthesized activated carbon. The tests of H_2S elimination by adsorption on activated carbons were carried out at the poultry farm FONDATION BRIN, located in the village YAOKOKOROKO, sub-prefecture of TABAGNE in the GONTOUGO region. This farm has an anaerobic digestion with a capacity of $15m^3$ for the treatment of the chicken manure it produces. Two types of filtration columns were used: a 15 cm column with a capacity of 15 g of carbon and a 30 cm column with a capacity of 30 g of carbon. The iodine value, ash content, moisture content, pH_{ZPC}, tapped density of the prepared activated carbon were 609.12 mg/g, 2.38%, 11.16%, 7.73 and 1.51 respectively. These results indicate that the prepared activated carbon is microporous (0-2 mm), of good quality and lightweight. Furthermore, the prepared activated carbon samples have a removal efficiency (RE) of H_2S, during the working time (10 h), higher than 97% for both types of columns used with H_2S output concentrations lower than 10 ppm which is the tolerance threshold for prolonged exposure. These results are similar with commercial activated carbon. The *acacia auriculeaformis* activated carbon can be used to remove hydrogen sulphide from biogas.

Keywords: Biogas, Hydrogen Sulphide, Activated Carbon, Adsorption, *Acacia Auriculeaformis*

1. Introduction

Biogas is formed by the anaerobic microbial decomposition of organic substances that produces not only the potential component methane (CH_4), but also undesirable impurities such as hydrogen sulphide (H_2S) and carbon dioxide CO_2 [1, 2]. Hydrogen sulphide (or H_2S) is a pollutant present in most biogas. Its purification is necessary to preserve the equipment from premature corrosion and also to protect humans and the environment [3].

Several methods have been investigated to remove hydrogen sulphide from the biogas stream. These methods include chemical methods [4, 5]; biological methods [6] and physical methods [7]. In addition, scrubbing is one of the methods for hydrogen sulphide removal that employs the use of various scrubbing agents such as water and chemicals. However, a large quantity of scrubbers is required, so they are expensive. Some scrubbers, especially chlorinated chemicals, produce secondary pollutants [3].

The adsorption method is one of the most practical technologies to remove hydrogen sulphide from biogas [8]. To avoid the problem of cost, especially in low-income settings, researchers are focusing on finding cheap adsorbents using available natural resources [9].

The activated carbon is among the adsorbents for hydrogen sulphide removal from biogas as a result of its surface properties that make it effective in the adsorption process. In a recent study, authors prepared activated carbon from water hyacinths that achieved hydrogen sulphide removal efficiencies up to 93% [7].

The Acacia auriculeaformis is an exploitable tree for charcoal (stem and branches larger than 4 cm in diameter) because of its rapid growth, even on infertile sites, and its tolerance to highly acidic and alkaline soils [10-12]. It is used for stabilization and revegetation of mines [13]. In Côte d'Ivoire, the National Centre for Agronomic Research has a plantation of this species near Abidjan (ANGUELEDOU forest) [14].

The general objective of this work is to study the performance of activated carbons for the adsorption of hydrogen sulphide from biogas, prepared from a local biomass that can be exploited for coal production. Specifically, this will involve: (i) synthesize activated carbons from acacia, (ii) characterize the obtained carbon, (iii), study the removal efficiency of hydrogen sulphide generated by the *acacia auriculeaformis* activated carbon.

2. Materials and Methods

2.1. Synthesis Protocol of Activated Carbon

The preparation of activated carbon from the *acacia auriculeaformis* branches was done according to the usual method [15, 16]. The dried *acacia auriculeaformis* branch pieces (figure 1) were carbonized at 350°C for 4 hours using the muffle furnace. Any carbonization residues were removed by washing thoroughly with distilled water. The obtained materials were oven dried at 105°C for 24 h, then ground to have particles with diameters between 125 µm and 2 mm and dispersed in a 1 mol/L sodium hydroxide solution. After stirring for 30 min, the mixture was kept at rest for 24 h. Finally, the resulting slurry was filtered and oven dried at 105°C for 24 h. The dry residue was washed with distilled water until the wash water was neutralized. The material was then oven dried at 105°C for 24 h.

Figure 1. *The dried acacia auriculeaformis branch pieces.*

2.2. Characterization of the Acacia Auriculeaformis Activated Carbon (AAC)

2.2.1. Humidity Content

The humidity content is determined by drying the adsorbent in an oven. For this, 0.5 g of activated carbon (AAC) is introduced into a ceramic crucible and the whole is weighed. After drying in an oven at 105°C for 24 h [16], the assembly is cooled to room temperature and weighed again. The humidity content (% H) is calculated from the following formula:

$$\%H = \frac{(m_2 - m_3)}{m_1} \times 100 \quad (1)$$

m_1: the initial mass of the AAC used (in g).
m_2: the mass of the crucible + AAC before drying (in g).
m_3: The mass of the crucible + AAC after drying (in g).

2.2.2. Ash Content

The ash content is the inorganic, inert, amorphous and unusable part present in the activated carbon. Thus, a 3 to 4 g sample of activated carbon is placed in a ceramic crucible. The sample is weighed and then introduced into the oven set at 650°C for 3 hours. After cooling down to room temperature, the sample is weighed again [16]. The ash content (C) is calculated from the following formula:

$$C\ (\%) = \frac{m_2 - m_0}{m_1 - m_0} \times 100 \quad (2)$$

m_0: the initial mass of the AAC used (in g).
m_1: The mass of the crucible +AAC before carbonization (in g).
m_2: The mass of the crucible +AAC after carbonization (in g).

2.2.3. Iodine Adsorption Number

The Iodine adsorption number is an indicator of the mesoporosity of an activated carbon. For its determination, a mixture of 0.05 g of activated carbon and 15 mL of a 0.1N iodine solution is stirred for 4 min. After filtration, 10 mL of the filtrate was titrated with a 0.1N sodium thiosulfate solution in the presence of two drops of the starch solution. A blank test was performed under the same conditions in the absence of activated carbon. The iodine value can be calculated from the following formula:

$$I_d = \frac{(V_b - V_s)\times N\times 126.9\times(\frac{15}{10})}{m} \quad (3)$$

Id: Iodine adsorption number (mg/g).

(V_b-Vs): difference of the results of the blank and adsorbent titration (in mL of sodium thiosulfate).

N: normality of the sodium thiosulfate solution in (eq.g/L).

126.9: atomic mass of iodine (in g/mol).

m: the mass of activated carbon in (g).

2.2.4. Determination of Point Zero-Charge pH (pH_{ZPC})

The pH_{ZPC} or pH of zero point charge corresponds to the pH value for which the net charge at the activated carbon surface is zero. A stock solution of NaCl (0.1 mol/L) was prepared. Different NaCl solutions (0.1 mol/L) at different (initial) pH (2, 4, 7, 9 and 10) were prepared. The pH was adjusted with NaOH (1M) or HCl (1M). Then 0.1 g of carbon was added to the different solutions and the whole was stirred with a magnetic stirrer for 48h. After stirring, the solutions are filtered and the (final) pH of the filtrate is noted. Finally, the isoelectric point (zero charge pH) was obtained by plotting the ΔpH curve according to Equation (4) [16].

$$\Delta pH = pH_f - pH_i \quad (4)$$

2.2.5. Tapped Density

The tapped density of the materials was calculated by measuring the volume of a compacted sample mass in a graduated cylinder. However, this measurement is not very precise. It can be calculated by the following formula:

$$d = \left(\frac{m2 - m1}{V}\right)/\rho \quad (5)$$

m_1 and m_2 the respective masses of the empty and filled test tube.

V: The volume of the graduated cylinder (10 mL).

ρ: The density of the water (1 g /cm^3).

2.3. H_2S Removal Tests by Adsorption with Activated Carbon Based on Acacia Auriculeaformis

The collection of biogas was carried out at the poultry farm FONDATION BRIN, located in the village YAOKOKOROKO, sub-prefecture of TABAGNE in the GONTOUGO Region. This farm has an anaerobic digester with a capacity of 15m^3 for the treatment of the manure it produces.

The unfiltered biogas is stored in the air chamber (tank). It is conveyed through the pipes to the filtration column. Two types of filtration column were used:

1) a column of 15 cm with a capacity of 15g of carbon;
2) a column of 30 cm with a capacity of 30 g of carbon.

The H_2S concentration is determined at the inlet and outlet of the filter column using a portable biogas detector (figure 2). During the test period; the biogas flow rate was kept constant with a value of 0.146 m^3 /min or 0.00244 m^3/s. The figure 3 shows the adsorption test setup.

Figure 2. *Portable biogas detector.*

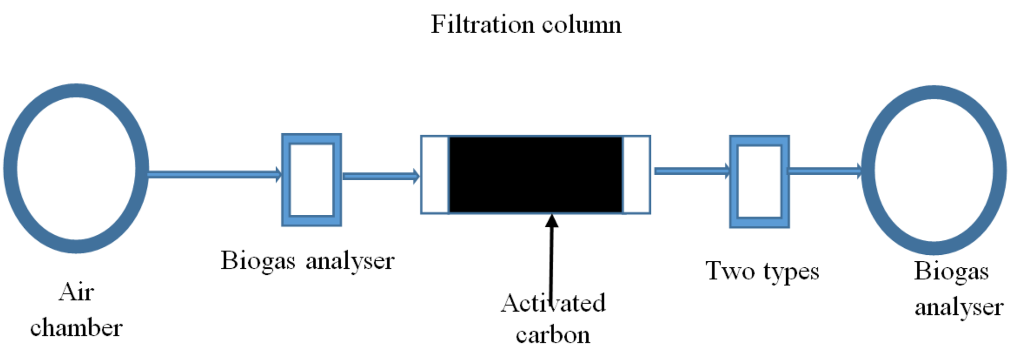

Figure 3. *Schematic of the adsorption test.*

3. Results and Discussion

3.1. Characteristics of Activated Carbon

The knowledge of activated carbon characteristics is necessary to contribute to the understanding of many phenomena such as adsorption, desorption, exchange, etc.

Table 1 shows some of the characteristics of the prepared activated carbon.

The Humidity content of the *acacia auriculeaformis* activated carbon (AAC) is 11.16 %. With a low Humidity content, this activated carbon could have a high higher heating value (HHV) [17, 18]. The ash content is 2.38%. The ash content for AAC is low. One of the parameters influencing the adsorption properties of carbon is its ash content. This parameter has a significant effect on the quality of the activated carbon. It appears that a high ash content decreases the specific surface area. Therefore, the ash content of a good adsorbent should not be too high, i.e. below 20% [19]. Too high an ash content (>20%) reduces the activity of the carbon, its reactivation potential and may generate impurity (mineral salt) leakage. The ash content reported in this study is an indication of the good adsorption capacity of this activated carbon [19]. The pH value of the zero charge point (pH_{ZC}) was obtained using the graph in Figure 4. The pH_{ZC} of the activated carbon is 7.73. The *Acacia auriculeaformis* activated carbon has a basic character. This would indicate a low oxygen content in this carbon [20]. The pH_{ZC} corresponds to the pH value for which the net charge of the adsorbent surface is zero. It makes it possible to determine the acid or basic character of the activated carbon and to know, according to the pH of the solution, its net surface charge. The density value is 1.51. The density varies according to the type of materials used. This value indicates that the *Acacia auriculeaformis* activated carbon is lightweight.

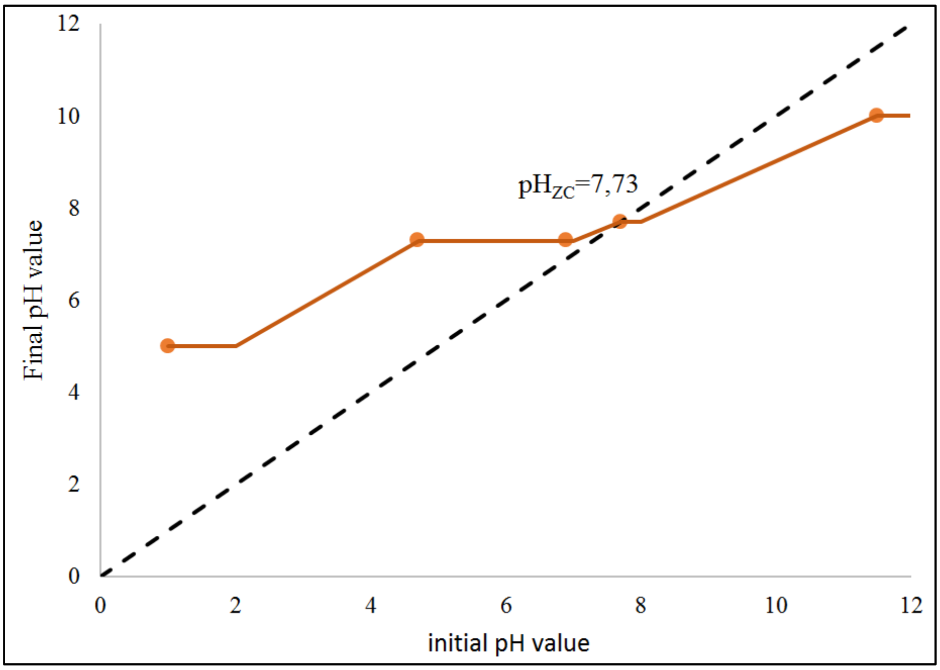

Figure 4. *PH_{ZC} of the acacia auriculeaformis activated carbon.*

Table 1. *Characteristics of activated carbon.*

Iodine adsorption number (mg/g)	point zero-charge pH pH_{ZPC})	Ash content (%)	Humidity content (%)	Tapped density
609.12	7.73	2.38	11.16	1.51

The activated carbons with sodium hydroxide (NaOH) contain pores accessible to iodine molecules. The iodine value is 609.12 mg/g. Lower iodine values (319.67 and 286.26 mg/g) have been reported in the characterization of acacia activated carbons prepared with basic agents [21]. The iodine adsorption number depends on the surface porosity and is thus useful in characterizing the surface area of carbon black. [21]. In the case of our study, the *acacia auriculeaformis* carbon activated with sodium hydroxide presents better results (values higher than 500 mg/g) [21, 22].

3.2. Study of Hydrogen Sulphide (H_2S) Removal from Biogas by the Acacia Auriculeaformis Activated Carbon

The installation includes a anaerobic digester which produces a biogas composed of methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO) and hydrogen sulphide (H_2S), as shown in Table 2. Changes in H_2S concentration before adsorption were also monitored during the working time and showed no change in the initial H_2S concentration (Table 2). This means that the initial H_2S

concentration is constant during the working time.

Table 2. *Biogas composition.*

Constituent	Measure 1	Measure 2	Measure 3	Measure 4
CH_4	85-90 %	85-90 %	85-90 %	85-90 %
CO	10-15 %	85-90 %	85-90 %	85-90 %
H_2S	80 – 100 ppm	80 – 100 ppm	80 – 100 ppm	80 – 100 ppm

The AAC was used to remove hydrogen sulphide (H_2S) from the biogas. Figure 5 shows the H_2S concentrations at the outlet of the filtration column. This graph is a function of time for a 15 g mass of CAA. Using a 15 g mass, the AAC did not reach their piercing time within the working time (10 hours). The piercing time is the time for which, the H_2S concentration of filtration column outlet becomes half of the initial concentration (40-50 ppm). Furthermore, the CAA samples have a removal efficiency (RE) of H_2S greater than 97% (Figure 6). This indicates development of pores essential for adsorption [23, 24].

Using a mass of 30 g, the ACC did not reach their piercing time as in the 15 cm filtration column in the working time (figure 7). Furthermore, CAA has a very high H_2S removal efficiency (RE) of over 98 % (figure 8). It is due to the increase of the number of adsorption sites with the increase of the activated carbon mass.

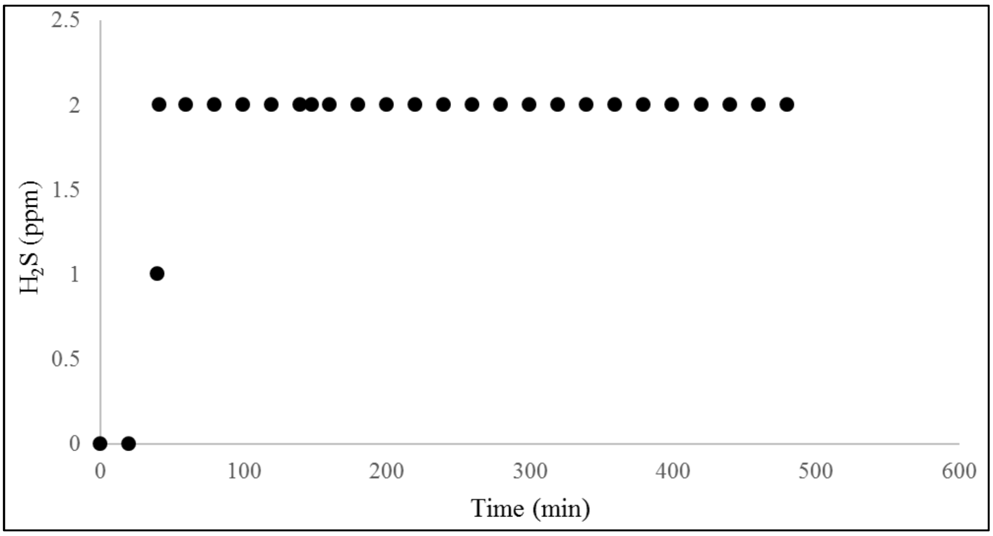

Figure 5. *Variation of H_2S concentration for 15 g of CAA.*

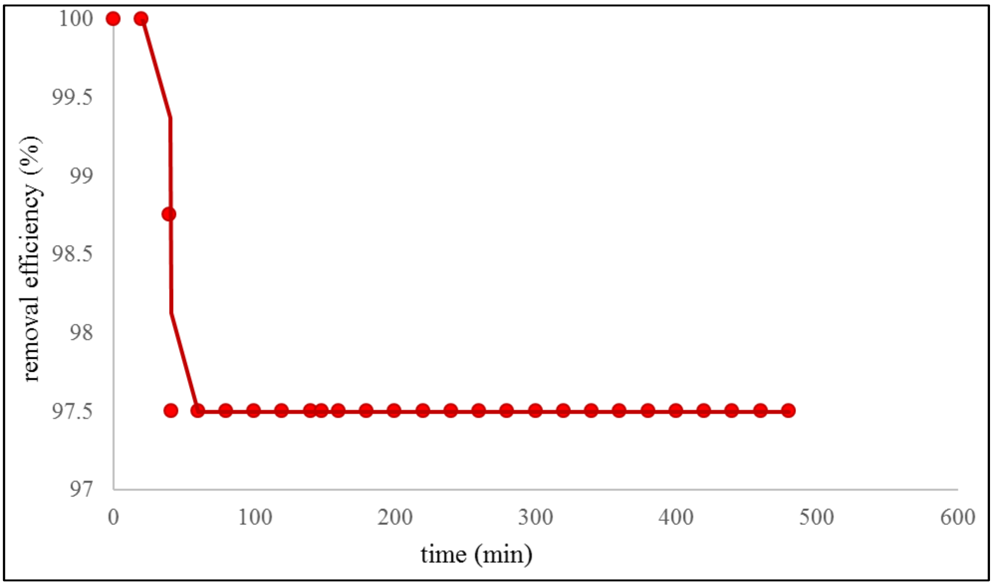

Figure 6. *H_2S removal efficiency (RE) for 15g of CAA.*

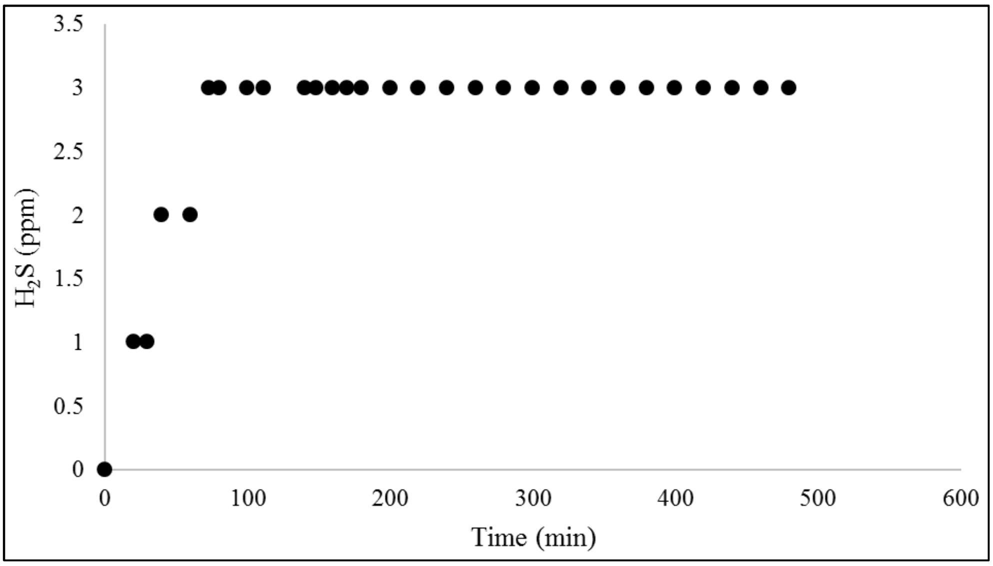

Figure 7. *Variation of H_2S concentration for 30 g of CAA.*

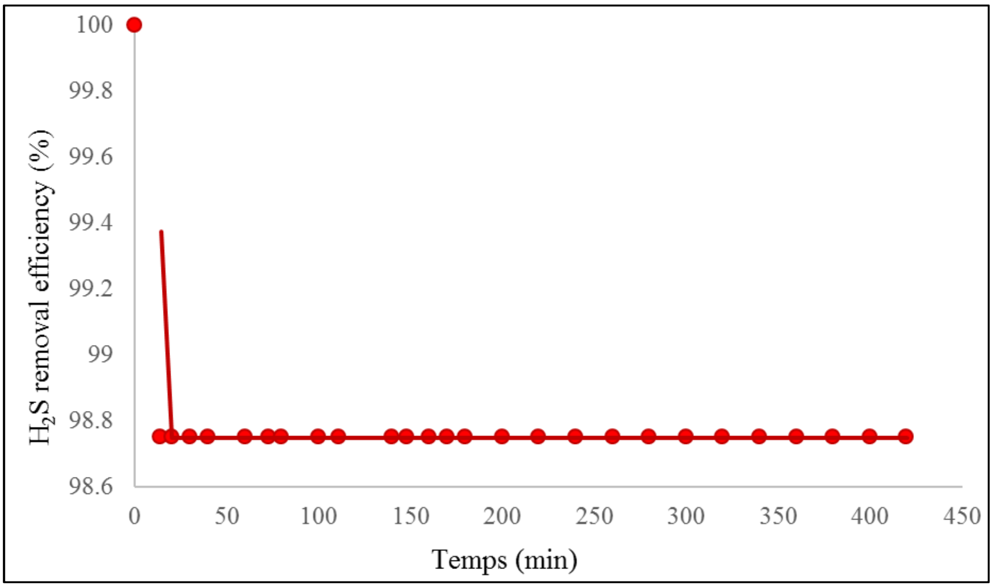

Figure 8. *H_2S removal efficiency (RE) for 30 g of CAA.*

4. Conclusion

This study aims to investigate the removal efficiency of hydrogen sulphide (H_2S) by the activated carbon of *acacia auriculeaformis*. The carbonization of *acacia auriculeaformis* is done using an oven at 550°C for four hours and activated with a 1 mol/L sodium hydroxide solution. The iodine value, ash content, humidity content, point zero-charge pH, tapped density of activated carbon were 609.12 mg/g, 2.38%, 11.16%, 7.73 and 1.51 respectively. These results indicate that this activated carbon is microporous (0-2 mm), of good quality and lightweight. Furthermore, the activated carbon samples have a removal efficiency (RE) of H_2S, during the working time (10 h), higher than 97% for both types of columns used with H_2S output concentrations lower than 10 ppm which is the tolerance threshold for prolonged exposure. The *acacia auriculeaformis* activated carbon can be used to remove hydrogen sulphide from biogas. However, the results obtained in this study should be completed. For this purpose, it is envisaged to perform the biogas filtration test over a long period of time in order to determine the breakthrough time and to carry out other tests with different masses of activated carbon in order to determine the optimal mass.

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Abstract: Biogas is one of the most attractive renewable resources because of its ability to convert waste into energy. Biogas is composed mainly of CH_4, CO_2, and some trace gases such as hydrogen sulphide (H_2S) which is a very toxic, deadly and corrosive gas. Therefore, raw biogas needs to be cleaned of hydrogen sulphide before it can be used in many applications. The overall objective of this work was to investigate the removal efficiency of hydrogen sulphide (H_2S) by activated carbon based on borassus aethiopum. Borassus aethiopum, also known as roast tree, is an abundant agricultural resource in the rural areas of western, central and northern Côte d'Ivoire. Physico-chemical parameters such as iodine value, ash content, pH at zero load point, tapped density were determined to characterize the synthesized activated carbon. The tests for the elimination of H_2S by adsorption on activated carbons were carried out at the BRIN FOUNDATION poultry farm, located in the village of YAOKOKOROKO, sub-prefecture of TABAGNE in the GONTOUGO region. This farm has a methaniser with a capacity of 15 m^3 for the treatment of the chicken droppings it produces. The results of the elimination of H_2S from the biogas are between 95 and 98%. Activated carbon based on borassus aethiopum can be used to remove hydrogen sulphide from biogas.

Keywords: biogas; hydrogen sulfide; activated carbon; adsorption; *borassus aethiopum*

1. INTRODUCTION

The high global demand for energy is due to the galloping population growth and accelerating economy, which affects the socio-economic landscape and human welfare [1]. Biogas which is the degradation of organic matter caused by several microorganisms under anaerobic conditions is formed from a mixture of gases such as methane (CH_4), but also undesirable gases such as hydrogen sulphide (H_2S) which is a toxic gas and carbon dioxide CO_2 [2 -6].

In addition, some researchers have recommended the removal of H_2S at the beginning of the purification process because of the many possibilities that can affect the quality of biomethane production, cause corrosion of mechanical wear and tear and emit harmful substances. Thus, the removal of H_2S and CO_2 gases is done by several technologies, such as biological adsorption [7], chemical adsorption (washing with active liquids) [8], adsorption using a mesoporous material [9-12], etc. Activated carbon is commonly used for adsorption due to its high surface area, microporosity, thermal stability, high removal capacity and low cost compared to other mesoporous materials, such as zeolite, organic materials, porous silica and organic silica. Several works on the use of activated carbon in water treatment have been carried out. Some authors have used granular activated carbon to remove nitrate at 96.59% [13].

Côte d'Ivoire imports large quantities of activated carbon. For example, in 2019, according to a United Nations report, Côte d'Ivoire spent $60.61 million on activated carbon from Malaysia. These imports continue despite the existence of agricultural by-products, most of which could be used to manufacture activated carbon for use in the removal of impurities such as hydrogen sulphide (H_2S) from biogas. Thus, the abundance of roast tree (borassus aethiopum) plants in the V-Baoulé region up to the North, whose branches are not valorised and which constitute an immense source for the production of activated carbon, was the subject of our study for the elimination of H_2S from biogas. The general objective of this work is to study the performance of an activated carbon for the adsorption of hydrogen sulphide from biogas, prepared from a local biomass that can be exploited for charcoal production (borassus aethiopum).

2. MATERIALS AND METHODS

2.1 Activated carbon synthesis protocol: The preparation of activated carbon based on borassus aethiopum for filtration was carried out in several stages [14-15]. The pieces of roast tree branches were taken to the traditional oven to be carbonized for 2 h 30 min at a temperature of 400 ± 10 °C. After carbonisation, the charcoal obtained was crushed with a laboratory mortar, then ground and sieved to obtain grains between 0.25 mm and 0.5 mm.

The grains obtained were impregnated in a 1000 ppm copper sulphate solution for 24 h, then heated to 450 ± 10 °C for 3 h in the oven. The activated carbon thus obtained was washed with distilled water until a rinsing water with a pH of between 6 and 7 was obtained, then dried again in an oven at 105°C for 24 h. The figures below represent the different steps in the manufacture of an activated carbon:

Figure 1: Preparation stage of activated carbon in the traditional oven

2.2 Characterization of activated carbon borassus aethiopum (CAB): The use of adsorbent supports requires knowledge of their physico-chemical properties. Knowledge of these characterization parameters helps to explain the phenomena that govern the efficiency and adsorption capacity of the carbon used [15].

2.2.1 Moisture content: The moisture content is determined by drying the adsorbent in an oven. To do this, 0.5 g of activated carbon is placed in a ceramic crucible and weighed. After drying in an oven at 105°C for 24 h [16], the whole is cooled to room temperature and then weighed again. The moisture content (%H) is calculated from the following formula:

$$\%H = \frac{(m_2 - m_3)}{m_1} \times 100 \qquad \text{Eq (1)}$$

Where:

m_1: the initial mass of activated carbon (AC) used (in g); **m_2**: the mass of the crucible + activated carbon (AC) before drying (in g); **m_3**: The mass of the crucible + activated carbon (AC) after drying (in g)

2.2.2 Ash content: The ash content is the inorganic, inert, amorphous and unusable part of the activated carbon. Thus, a 3 to 4 g sample of activated carbon is placed in a ceramic crucible. The whole is weighed and then introduced into the oven set at 650°C for 3 hours. After cooling down to room temperature, the assembly is weighed again [17]. The ash content (C) is calculated from the following formula:

$$C\,(\%) = \frac{m_2 - m_0}{m_1 - m_0} \times 100 \qquad Eq\,(2)$$

m_0: The initial mass of the AC used (in g).; **m_1**: The mass of the crucible +CA before carbonisation (in g);**m_2:** The mass of the crucible + AC after carbonisation (in g)

2.2.3 Iodine value: The iodine value is an indicator of the mesoporosity of an activated carbon. For its determination, a mixture of 0.05 g of activated carbon and 15 mL of a 0.1N iodine solution is stirred for 4 min. After filtration, 10 mL of the filtrate was titrated with a 0.1N sodium thiosulphate solution in the presence of two drops of starch starch. A blank test was carried out under the same conditions in the absence of activated carbon. The iodine value can be calculated from the following formula:

$$I_d = \frac{(V_b - V_s) \times N \times 126{,}9 \times (\frac{15}{10})}{m} \qquad \text{Eq(3)}$$

Where:

Id: Iodine value (mg / g); **(Vb-Vs):** difference of the blank and adsorbent titration results (in mL of sodium thiosulphate);**N:** normality of the sodium thiosulphate solution in (eq.g/L);**M:** 126.9 atomic mass of iodine in (g/mol); **m:** the mass of the activated carbon in (g)

2.2.4 Determination of pH at zero charge point: A stock solution of NaCl (0.1 mol/L) was prepared. Different NaCl solutions (0.1 mol/L) at different (initial) pH values (2, 4, 7, 9 and 10) were prepared. The pH was adjusted with NaOH (1M) or HCl (1M). Then 0.1 g of carbon was added to the different solutions and the whole was stirred with a magnetic stirrer for 48h. After stirring, the solutions are filtered and the (final) pH of the filtrate is noted [18]. Finally, the iso-electric point (pH at the point of zero charge) is obtained by plotting the curve

$\Delta pH = pHfinal - pH\ initial$ Eq(4)

2.2.5 Tapped density: The tapped density of the materials was calculated by measuring the volume of a compacted sample mass in a graduated cylinder. However, this measurement is not very accurate. It can be calculated by the following formula:

$$d = \left(\frac{m2-m1}{V}\right)/\rho \qquad Eq(5)$$

m_1 and m_2 the respective masses of the empty and filled test tube.

V: The volume of the graduated cylinder (10 mL). **ρ** :The density of the water (1 g /cm 3).

2.3. Removal tests on H2S by adsorption on activated carbons: The collection of biogas was carried out at the FONDATION BRIN poultry farm, located in the village YAOKOKOROKO, sub-prefecture of TABAGNE in the GONTOUGO region. This farm has a methaniser with a capacity of 15 m^3 for the treatment of the hen droppings it produces.the unfiltered biogas is stored in the air chamber (tank). The unfiltered biogas is stored in the air chamber (tank) and is conveyed through the green pipes (duct) to the filter column. Two types of filtration column were used:

A 15 cm column with a capacity of 15g of carbon

A 30 cm column with a capacity of 30 g of carbon.

The H_2S concentration is determined at the inlet and outlet of the filter column using a portable biogas detector. **Figure 2** below shows the adsorption test setup.

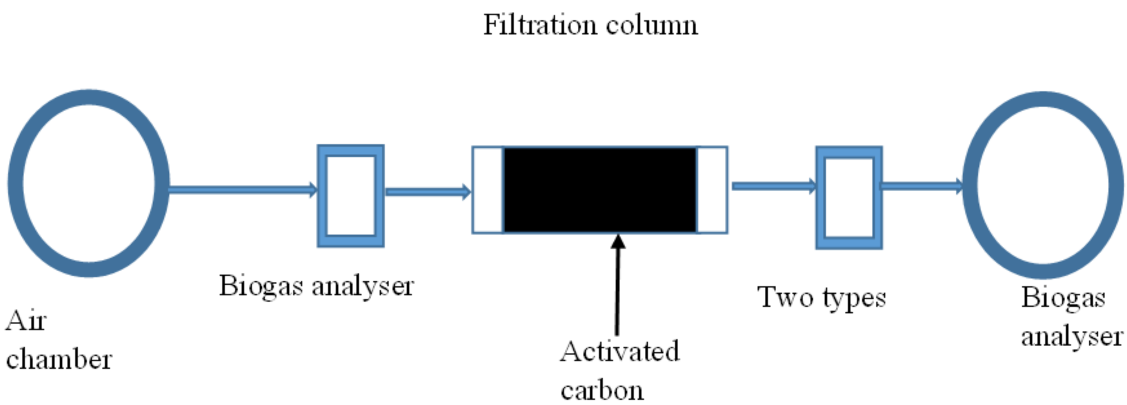

Figure 2: Schematic of the adsorption test

The biogas flow rate was kept constant during the test period with a value of 0.146m3/min or 0.00244 m^3/s. Figure 3 below shows our portable biogas analyser used to find out the composition and different concentrations of the biogas during the tests.

Figure 3: Photograph of the portable biogas detector

3. RESULTS AND DISCUSSION

3.1 Characteristics of activated carbon: The study of the characteristics of activated carbons is necessary to contribute to the understanding of several phenomena such as adsorption, desorption, exchange, etc. Table 1 shows some of the characteristics of the activated carbon prepared.

Table 1: characteristics of activated carbon

Iodine adsorption number (mg/g)	point zero-charge pH (pH_{ZPC})	Ash content (%)	Humidity content (%)	Tapped density
958.09	5.0	2.38	11.1551	0.955

The moisture content of activated carbon prepared from borassus aethiopum (CAB) is 11.1551%. With a low moisture content, the prepared activated carbon could have a high gross calorific value (GCV) [19]. The ash content of the prepared activated carbon based on borassus aethiopum (CAB) is 2.38%. The ash content for CAB is low. one of the parameters influencing the adsorption properties of the carbon. This parameter has a significant effect on the quality of the activated carbon. It appears that a high ash content decreases the specific surface area. On the other hand, the ash content of a good adsorbent should not be too high, i.e. below 20% [20].

An excessively high ash content (>20%) reduces the activity of the carbon, its reactivation potential and can lead to leakage of impurities (mineral salts). The ash content obtained in this study shows a very good adsorption capacity of our synthesised activated carbon [21].

The pH of the zero-charge points of the synthesised activated carbon obtained through figure 4 below is 5.0. The activated carbon borassus aethiopum has an acidic character. The pH of the zero-charge point corresponds to the pH value for which the net charge on the surface of the adsorbents is zero. It makes it possible to determine the acid or basic character of the activated carbon and to know, according to the pH of the solution, its net surface charge. The value of the apparent density is 0.955.

The bulk density varies according to the materials used. This value indicates that the prepared CAB activated carbon is light. Activated carbons contain pores accessible to iodine molecules. The iodine value of our activated carbon is 958.09 mg/g. Lower iodine values (319, 67 and 286.26 mg/g) have been reported in the characterisation of activated carbons of borassus aethiopum prepared with basic agents [20]. The higher the iodine value, the more microporous the adsorbent (0-2 mm) and the better its specific surface [20]. Activated carbon based on borassus (CAB) activated with soda gives good results (values above 500 mg/g) [20; 21].

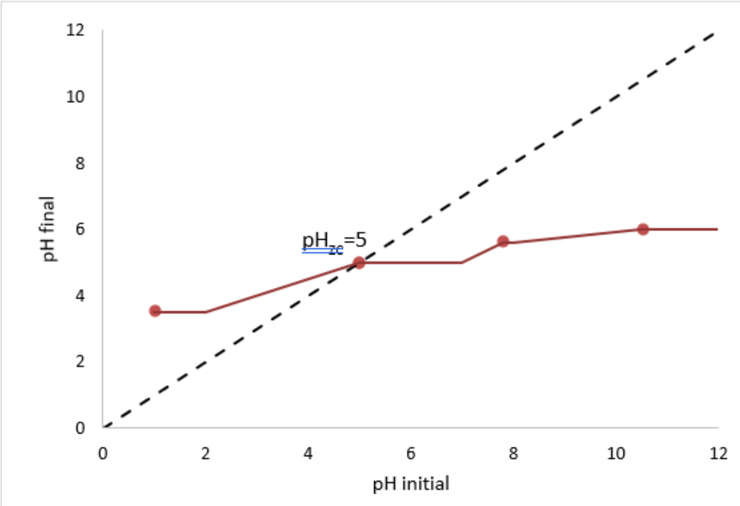

Figure 4: pH at zero charge point for CAB

3.2 Investigation of hydrogen sulphide (H_2S) removal from biogas by borassus aethiopum: The plant includes a methaniser which produces biogas consisting of methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO) and hydrogen sulphide (H_2S), as shown in **Table 2**. The changes in H_2S concentration before adsorption were also monitored during the working time and showed no change in the initial H_2S concentration **(Table 2).** This means that the initial H_2S concentration is constant during the study time.

Table 2: biogas composition

Constituent	Measure 1	Measure 2	Measure 3	Measure 4
CH_4	85-90 %	85-90 %	85-90 %	85-90 %
CO	10-15 %	85-90 %	85-90 %	85-90 %
H_2S	80 – 100 ppm	80 – 100 ppm	80 – 100 ppm	80 – 100 ppm

The synthesized activated carbon CAB was used to remove hydrogen sulphide (H_2S) from the biogas. **Figure 5** shows the H_2S concentrations at the outlet of the filtration column as a function of time for a 15 g mass of CAB. Using a mass of 15 g, the breakthrough time in the working time (10 hours). The breakthrough time is the time for which the H_2S concentration of the filtration column outlet becomes half of the initial concentration (40-50 ppm).

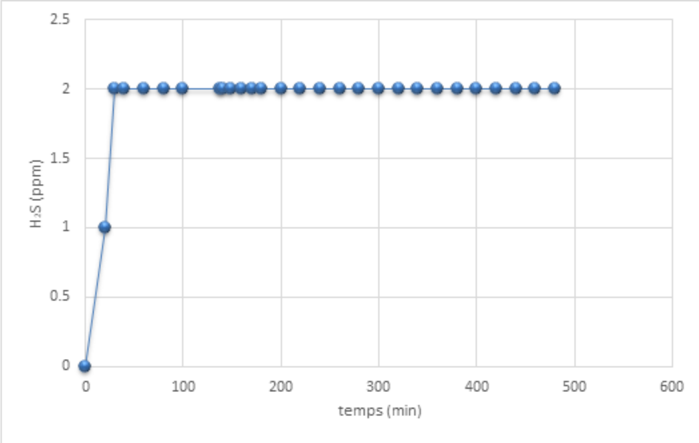

Figure 5: Variation of H_2S concentration with time for 15 g CAB

Furthermore, the activated CAB samples have a removal efficiency (RE) of H_2S greater than 97% **(Figure 6).** This indicates a development of the pores essential for adsorption [22; 23]. Using a mass of 30 g, not all carbons reached their breakthrough times as in the 15 cm filtration column within the working time (10 hours). It should be remembered that the breakthrough time is the time for which the H_2S concentration at the exit of the filtration column becomes half of the initial concentration (40-50 ppm). Furthermore, the CAB has a very high H2S removal efficiency (RE) of over 97.5% **(Figure 7**). This indicates a development of the pores essential for adsorption [24-26].

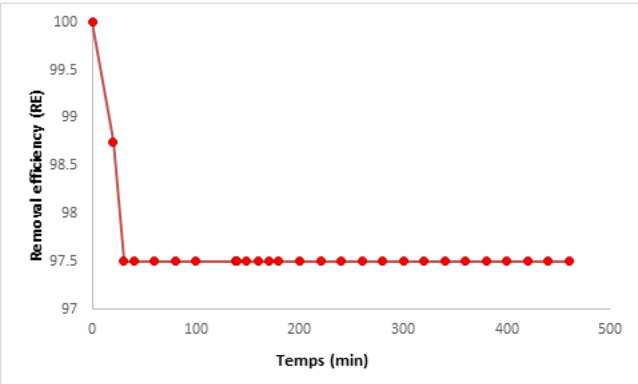

Figure 6: H_2S removal efficiency (RE) versus time for 15 g CAB

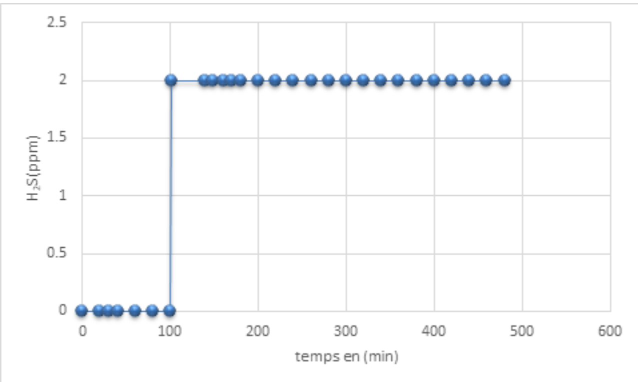

Figure 7: Variation of H_2S concentration with time for 30 g CAB

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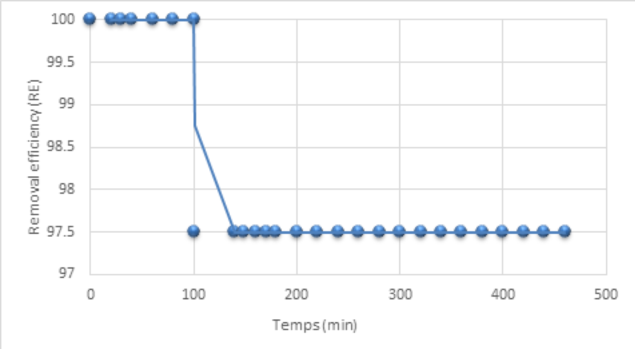

Figure 8: H_2S removal efficiency (RE) versus time for 30 g CAB

CONCLUSION

The general objective is to study the efficiency of hydrogen sulphide (H_2S) removal by activated carbon based on *borassus aethiopum*., known as roan tree, is a very abundant agricultural resource in the rural areas of western, central and northern Côte d'Ivoire. The carbonization of *borassus* is done using a traditional oven at 550°C for four hours and activated by a 1 mol/L sodium hydroxide solution. The iodine value, ash content, moisture content, pH at zero charge point, tapped density of the prepared activated carbon were 958.09 mg /g, 2.38%, 11.16%, 5.0 and 0.955 respectively. These results indicate that the prepared activated carbon is microporous (0-2 mm), of good quality and light. Furthermore, the prepared activated carbon samples have a removal efficiency (RE) of H_2S, during the working time (08 h), higher than 97% for both types of columns used with H_2S output concentrations lower than 10 ppm which is the tolerance threshold for prolonged exposure. These results are similar with commercial activated carbon. Activated carbon based on *borassus aethiopum* can be used to remove hydrogen sulphide from biogas.

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