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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.

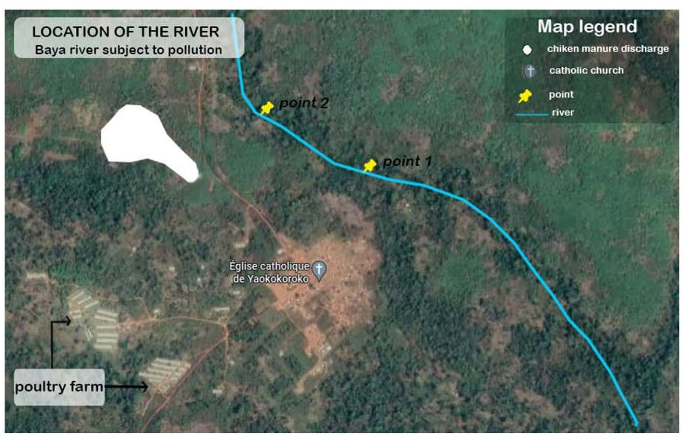

Figure 2. Location of the BAYA River water and sampling sites.

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:

$$\%H = \frac{m_0 - m_1}{m_0} \times 100 \tag{1}$$

%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.

$$\%MS = 100 - \%H \tag{2}$$

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

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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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