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Experimental Investigation of Optimal Methanization Conditions for Cotton Residues: Case Study

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Abstract

For optimum methanization of cotton residues, four (4) samples were made up in vases, with cotton residues as the main component. The first sample consisted of 30g of cotton residue and 270 ml of inoculum, the second of 30g of cotton residue, 270 ml of inoculum and 0.1g of sodium, the third of 15 g of cotton residue, 270 ml of inoculum and 15g of cow dung, and the fourth of 15g of cotton residue, 270 ml of inoculum, 15g of cow dung and 0.1g of sodium. It took 75 days to digest the 30 g of organic matter contained in each sample. The results of this study showed that the sample 4, made up of cotton residue, inoculum, cow dung and sodium, gave the highest biogas volume (1.068 m3), methane volume (0.66 m3) and methane content in the biogas (89%). The best conditions for optimal biogas production from cotton residues are those of a combination of cotton residues, inoculum, cow dung and sodium ash. The results of this study provide knowledge for choosing the optimum conditions for the methanization of organic matter from agricultural waste.

Keywords: Cotton residue, Sample, Methanization, Biogas, Optimization

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1. Introduction

With ever-increasing and more diversified consumption throughout the world, waste production is constantly increasing in quantity and quality. This poses enormous risks to the environment, and consequently to people's health. This situation is much more worrying in developing countries because of their considerable backwardness in the biotechnology field [1]. Sub-Saharan Africa faces a dual challenge: environmental protection and sustainable access to energy. On the one hand, the spread of modern production and consumption models in large cities has led to a sharp increase in municipal waste production. On the other hand, with the less developed electricity sector, sub-Saharan Africa is unable to meet the consumption needs of its inhabitants.

There are two technological options for recovering energy from municipal solid waste: the biochemical option and the thermochemical option [2]. The biochemical option involves recovering landfill gas and using it as fuel in various types of power plant [3]. There is also anaerobic digestion or methanization of the organic fraction of solid waste to generate biogas [4].

Methanization is a technical, ecological and social innovation that recovers organic waste by producing renewable energy and organic products that can be used to improve soil fertility, while preserving the environment [5]. Waste methanization enables sustainable waste management, reducing nuisances, odors and emissions of greenhouse gases such as methane into the atmosphere [6]. It also allows to recycle unused or polluting by-products in the form of energy products and fertilizers [7]. With the rapid development of technologies, biogas production techniques have reached a level of technological maturity and reliability, which minimizes the cost of biogas production [8].

Biogas is an alternative to traditional fuels [9]. Its combustion reduces atmospheric emissions, cutting particulate emissions and reducing CO emissions by 20 to 30% [10]. The energy value of one cubic meter (1 m^3) of biogas corresponds, for example, to 0.42 kg of LPG (liquefied petroleum gas), 0.60 liters of petroleum, 4.34 kg of dry wood [11]. Biogas combustion is chemically much cleaner than conventional fuels. It produces 25% less CO_2, 80% less nitrogen oxide than gasoline and generates no solid particles [12]. Converting biogas into electricity could therefore help meet the dual challenge facing African populations, namely the depletion of fossil fuels and greenhouse gas emissions [13].

To support its energy transition, Africa is counting on biomass, among other things [14]. The valorization of agricultural waste is a technology for collecting and treating the biogas produced by this organic waste [15]. With three (3) tones of waste per cultivated hectare at the beginning of the chain, the potential profits from cotton residues are far from negligible for cotton growers. In Zambia alone, they are estimated at three million dollars a year [16]. This new source of income could benefit the entire African cotton industry, which accounts for almost 10% of global production. By adding value to their cotton residues, African

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producers could significantly diversify and improve their income.

In Burkina Faso, 472,000 tones of seed cotton were harvested during the 2020/2021 cotton season. Cotton production now occupies around 10-15% of the country's cultivable land. It provides income for more than 5 million Burkinabè, i.e. around 30% of the population. Cotton cultivation covers an area of 500,000 ha [17].

Burkina Faso's 2014 - 2025 energy sector policy also recommends research into the evaluation and exploitation of biomass, with a view to increasing the share of renewable energies in the country's energy mix to 50% and avoiding the emission of around 22,0100 tones of CO_2 per year, by 2025 [18], [19]. In Burkina Faso, projects have been set up to produce biogas for lighting, cooking and soil fertilization. The Biogas Project aims to install a digester in households in rural areas of Burkina Faso, in order to supply them with electrical energy. Among these projects, there is the Plataforma multifunctional, which aims to produce electricity and digestate from cow dung [20]. These projects have experienced problems related to optimizing biogas production [21].

Methanogenesis is influenced by numerous environmental factors such as temperature, pH, nutrients, carbon to nitrogen (C/N) ratio, toxic or inhibiting compounds, etc [22]. For optimal anaerobic digestion, the carbon-to-nitrogen (C/N) ratio of organic matter should be between 20 and 30. A carbon-to-nitrogen ratio of 25 is ideal [23]. If this ratio becomes high, biogas production is reduced due to the lack of nitrogen. Also, if this ratio is too low, ammonia is produced in excessive quantities, which can become toxic to the survival of microorganisms. Referring to the literature, the carbon to nitrogen (C/N) ratio of cotton residue is between 60/1 and 120/1 [24]. In general, cotton residues contain around 1% to 2% nitrogen.

Hydrogen potential (pH) is a measure of the chemical activity of hydrogen ions in solution, particularly in aqueous solutions. It is used to determine the degree of alkalinity or acidity. The pH scale ranges from 0 to 14. pH plays a major role in the biochemical and physico-chemical functioning of anaerobic digestion media. Anaerobic bacteria are sensitive to pH variations. Controlling this parameter is essential for optimizing anaerobic digestion [25], [26].

The level of volatile dry matter (VDM) is important for optimizing anaerobic digestion. The VDM concentration is calculated by subtracting the weight of the residue after calcination from the weight of the dry matter (DM) after drying [27]. The work carried out here falls within the framework of agricultural waste treatment and recovery. The present article deals with the optimal methanization of cotton residues from cotton ginning plants [28].

The aim of the present work is to investigate the optimum conditions for producing biogas from cotton residues from cotton ginning plants in Burkina Faso, located in West Africa.

2. Materials and Methods

The aim is to identify the conditions for optimizing biogas production from cotton gin residues. The aim is to find, through experimentation, what needs to be added to cotton residues to create optimal biogas production conditions. The procedure involves sampling cotton residues, characterizing the waste by analyzing a number of important physicochemical parameters, and carrying out biogas production tests to determine the best combination for producing significantly more biogas with a high methane content. The choice of the best anaerobic digestion conditions is based on the high values of biogas volume and methane content.

2.1 Equations for the anaerobic digestion of organic matter

Methanization of organic matter or biogas production involves two stages: aerobic and anaerobic degradation. The anaerobic degradation of organic matter can be summarized in a very general way according to chemical equation (1) [29].

$$OM + H_2O \xrightarrow{\mu} n_\mu + OM_{reclacitrante} + CO_2 + CH_4 + Gas \tag{1}$$

where :

- OM is the organic matter,
- H_2O is the chemical formula for water,
- n_μ is a new biomass,
- $\mathrm{OM}_{\mathrm{recalcitrante}}$ is the recalcitrant organic matter,
- $\mathrm{CO_2}$ is the chemical formula for carbon dioxide,
- $\mathrm{CH_4}$ is the chemical formula of the methane obtained,
- Gas are various trace of gases.

Assuming total degradation of organic matter, the quantity of biogas formed by anaerobic digestion of degradable organic matter (of the form:$C_nH_aO_b$) can be determined theoretically, using Buswell's equation (2) [30].

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 \tag{2}$$

where:

- $C_nH_aO_b$ is the general formula for organic matter,
- H_2O is the chemical formula for water,
- $\mathrm{CO_2}$ is the chemical formula for carbon dioxide,
- $\mathrm{CH_4}$ is the chemical formula of the methane obtained,
- n the mole number,
- a and b are constants.

This balance equation was balanced by considering a total conversion of organic matter into CH_4 and CO_2, under anaerobic conditions, i.e. in the presence of water (H_2O) only. The theoretical maximum biogas, methane and carbon dioxide production potential in liters of biogas, under normal temperature and pressure conditions, per gram of organic matter are given in equations (3), (4) and (5).

$$P_{Biogas} = \frac{22.4n}{12n + a + 16b} \tag{3}$$

$$P_{CH_4} = \frac{22.4\left(\frac{n}{2} + \frac{a}{8} + \frac{b}{4}\right)}{12n + a + 16b} \tag{4}$$

$$P_{CO_2} = \frac{22.4\left(\frac{n}{2} + \frac{a}{8} + \frac{b}{4}\right)}{12n + a + 16b} \tag{5}$$

where:

- P_{Biogas} is the biogas production potential in liters of biogas,
- P_{CH4} is the methane production potential in liters of biogas,
- P_{CO2} is the carbon dioxide production potential per liter of biogas.

2.2 Description of cotton residues

Raw cotton residues are the remains of the cotton gin after the cotton fibers and seeds have been separated. These residues are first sorted to remove impurities. Figure 1 shows a sample of cotton residues before and after sorting.

Fig. 1. Photos of cotton residues used.

The sorted cotton residue is then ground to accelerate the methanization process. Figure 2 shows the mortared cotton residue.

Fig. 2. Photo of crushed cotton residue after sorting.

2.3 Characterization of cotton residues

The results of the physico-chemical characterization of cotton waste are shown.

Table 1. Composition of cotton waste

Cotton residue	Dry matter	Dry volatile matter
Rate (%)	94.36	5.64

In table 1, the dry matter content of 94.36% indicates that the cotton residues are well dried. The portion degradable by microorganisms (VDM) to produce biogas is 5.64%. This indicates that the proportion of cotton residue that can be converted into biogas is very low.

2.4 Pre-treatment of cotton residue

The volatile dry matter (VDM) content is important for methanization [31]. It is necessary to increase the VDM rate by drying in an oven at 150°C, then calcining cotton residues in an oven at 550°C [32], [33]. Figure 3 shows a drying oven for cotton residues.

Fig. 3. Photo of drying oven used.

Figure 4 shows a kiln for calcining cotton residues.

Fig. 4. Photo of the furnace used.

2.5 Measuring equipment

The pH meter is the device used to measure the pH of a solution. It consists of two components: an electronic box that displays the pH value, and an electrode that measures this value. It will be used to measure the pH of the various samples used in the experiment.

Fig. 5 Photo of pH meter used.

The biogas analyzer is used to measure the quantity of biogas and the methane content of the biogas produced. Figure 7 shows a photo of the biogas analyzer.

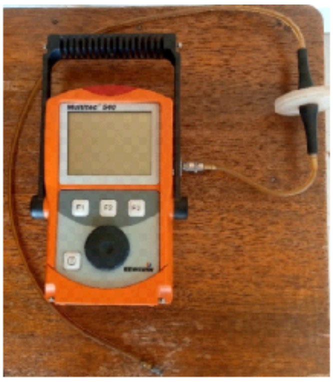

Fig. 6. Photo of the biogas analyzer used.

2.6 Sampling and experimentation

In order to carry out the cotton residue methanization experiment, it is first necessary to sample the various elements that go to make up the samples to be studied. For the methanization of cotton residues, the samples used are cotton residues, cow dung, sodium ash and inoculum. The samples taken and their composition are presented.

Since cotton waste is rich in fiber, the addition of other substances is necessary to improve biogas production yields. Inoculum, a substrate rich in microorganisms, is added to each mixture to enable the bacteria to digest the dry volatile matter contained in the cotton residues. Concentrated sodium at 1% is added to accelerate the decomposition of the residues. Cow dung is added at a ratio of 50% to improve the carbon-to-nitrogen (C/N) ratio and increase the dry volatile matter content of the cotton residues. A combination of sodium pre-treatment and codigestion with cow dung is likely to improve biogas productivity.

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Table 2. Composition of each sample

Sample	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
Composition	Cotton waste + inoculum	Cotton waste + inoculum + soda	Cotton waste + inoculum + cow dung	Cotton waste + inoculum + cow dung + soda

The four (4) mixtures are placed in four (4) bottles composed as follows:

- bottle 1 contains 30 g of cotton residue and 270 ml of inoculum,
- bottle 2 contains 30 g cotton residue, 270 ml inoculum and 0.1 g sodium hydroxide,
- bottle 3 contains 15 g cotton residue, 270 ml inoculum and 15 g cow dung,
- bottle 4 contains 15 g cotton residue, 270 ml inoculum, 15 g cow dung and 0.1 g sodium hydroxide.

Figure 7 shows the bottled samples.

Fig.7 Photo of bottled samples.

Samples are hermetically sealed to prevent air penetration. Figure 8 shows the hermetically sealed vessels.

Fig. 8. Photo of closed vases.

2.7 Experimental set-up

The experimental set-up consists of:

- one (1) thermostatically controlled sea bath to maintain a temperature of 40°C for organic matter degradation,
- one (1) water-filled basin to prevent biogas leakage,
- four (4) 1-litre biodigester vessels,
- four (4) 1-liter test tubes for biogas storage,
- gas pipes connecting cylinders to test tubes.

Figure 9 shows the experimental setup.

Fig. 9. Photo of the experimental device used.

This device enables the four (4) samples to be fermented and biogas to be produced.

3. Results and Discussion

In this study, optimal conditions for biogas production from cotton residues were sought. It took 75 days to digest 30 g of the organic matter contained in each sample. The pH of each sample, at the start and end of the process, and the volume of biogas and methane produced in each sample were measured at the end of the digestion.

The pH of the various samples was measured at the start and end of anaerobic digestion. The pH values at the start and end of anaerobic digestion for each sample are measured.

Table 3. pH value of each sample

Sample	**1**	**2**	**3**	**4**
Starting pH	7.32	8.0	7.3	7.8
End pH	7.2	6.7	7.6	6.7

The highest pH at the start of anaerobic digestion is that of sample 2, i.e. 8.04. The lowest pH is that of sample 1, at 7.2. Samples 3 and 4 have pH values of 7.35 and 7.85 respectively. The pH values of the samples range from 6.5 to 8. These pH values are favorable for anaerobic digestion.

The pH values of the samples at the end of the anaerobic digestion process were 7.18, 6.68, 7.63 and 6.7 respectively for samples 1, 2, 3 and 4. The pH values of the samples at the end of the anaerobic digestion process did not vary to such an extent as to inhibit biogas production. These pH values remained in the 6.5 to 8 range, which are pH values favorable to methanization.

3.2. Quantity of biogas obtained from samples.

Figure 10 shows the volume of biogas produced during the anaerobic digestion period.

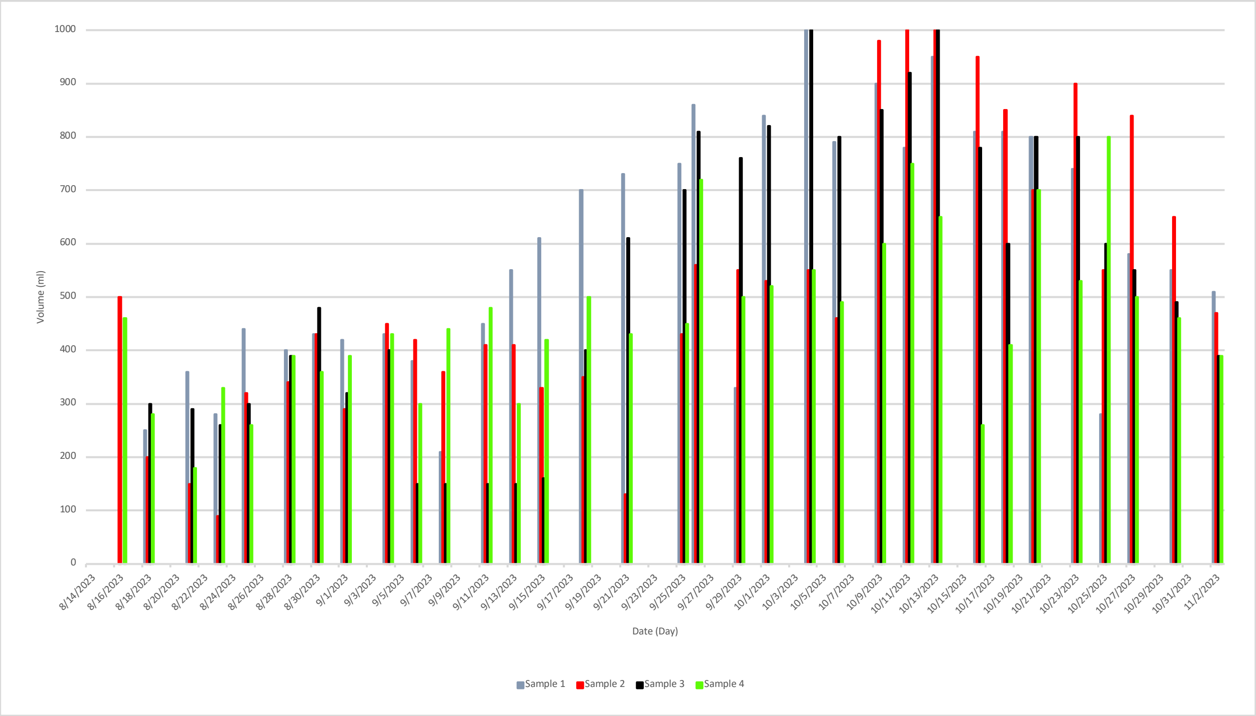

Fig. 10. Histograms of biogas volumes obtained.

Figure 10 shows that during the first week, sample 2 and sample 4 produced a high volume of biogas, at 500 ml and 450 ml respectively. Furthermore, in the middle of the experiment, it was the cotton residue samples with inoculum and the cotton residue sample with cow dung that had a high volume. Finally, the sample of cotton residues with soda predominates. The biogas volume of each sample is measured.

The results in Table 4 show that sample 3 has significant potential, with 1.207 m^3, followed by sample 4, with 1.068 m^3. Samples 1 and 2 yielded volumes of 0.66 m^3 and 0.601 m^3 respectively.

Table 4. Volume of biogas

Sample	**1**	**2**	**3**	**4**
Volume (m^3)	0.66	0.60	1.21	1.07

3.3. Quantity of methane obtained from the various samples

Methane is the main component of biogas. The biogas analyzer was used to measure the percentage of methane in the biogas. Figure 11 shows the percentage of methane obtained for each sample taken

The percentage of methane is quantified using a gas analyzer. Samples with soda in their composition show a higher methane content than other samples. The mixture of cotton residues associated with cow dung and sodium is the best sample for a high methane percentage, i.e. over 60%. The cumulative volume of methane obtained from each sample is given.

Table 5. Volume of methane

Sample	**1**	**2**	**3**	**4**
Volume (m^3)	0.02	0.03	0.01	0.06

Table 5 shows that the sample 4 has a high potential (0.06 m^3), followed by the sample (0.03 m^3). Samples 1 and 3 produced 0.02 m^3 and 0.01 m^3 respectively. Sample 4 produced more biogas than the other samples.

The percentage of methane in the biogas obtained from each sample at the end of fermentation are presented.

Table 6. Methane content

Sample	**1**	**2**	**3**	**4**
Content (%)	49	59	30	89

In Table 6, the methane content in the biogas produced by sample 4 is the highest (89%), followed by sample 2 (59%), then sample 1 (49%) and finally sample 3, which totals 30% methane content in the biogas produced.

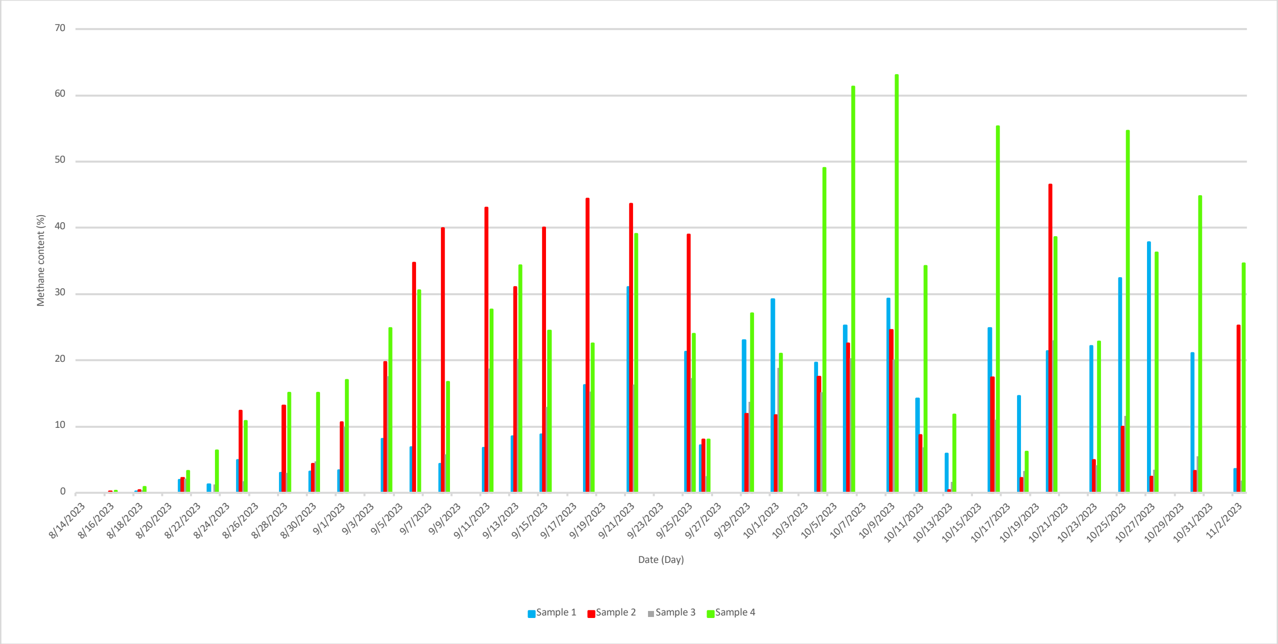

Fig. 11. Histogram of methane content in the biogas obtained

The summary of the biogas volume, methane volume and methane content in the biogas produced by each sample is given.

Table 7. Quantity of biogas, methane and methane content

Sample	**1**	**2**	**3**	**4**
Biogas (m^3)	0.66	0.60	1.21	1.07
Methane (m^3)	0.02	0.03	0..01	0.06
Content (%)	49	59	30	89

According to Table 7, sample 4, made up of cotton residues, inoculum, cow dung and soda, gives the volume of biogas (1.068 m^3), the volume of methane (0.66 m^3) and the methane content in the biogas (89%). The best conditions for optimum biogas production from cotton residues are those for the combination of cotton residues, inoculum, cow dung and sodium ash.

3. Conclusion

This study investigates the optimum conditions for biogas production from cotton residues. Four (4) samples were set up in bottles, with cotton residues as the main component. The first sample consisted of 30 g of cotton residue and 270 ml of inoculum, the second of 30 g of cotton residue, 270 ml of inoculum and 0.1 g of sodium, the third of 15 g of cotton residue, 270 ml of inoculum and 15 g of cow dung, and the fourth of 15 g of cotton residue, 270 ml of inoculum, 15 g of cow dung and 0.1 g of soda. It took 75 days to digest 30 g of the organic matter contained in each sample. The dry matter content of 94.36% indicates that the cotton residues are well dried. The proportion degradable by microorganisms to produce biogas was 5.64%. This indicates that the proportion of cotton residue suitable for biogas conversion is very low.

The pH of each sample, at the start and end of the process, as well as the volume of biogas and methane produced in each sample, were measured at the end of anaerobic digestion. The highest pH at the start of anaerobic digestion was that of sample 2, i.e. 8.04. The lowest pH was 7.2 for sample 1. Samples 3 and 4 have pH values of 7.35 and 7.85 respectively. The pH values of the samples range from 6.5 to 8. These pH values are favorable for anaerobic digestion.

The results of this study showed that sample 4, made up of cotton residues, inoculum, cow dung and soda, gave the highest biogas volume (1.068 m^3), methane volume (0.66 m^3) and methane content in the biogas (89%). The best conditions for optimal biogas production from cotton residues are those of a combination of cotton residues, inoculum, cow dung and sodium ash. The results of this study can provide insights into the choice of optimum conditions for the methanization of organic matter from agricultural waste in general.

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