Anaerobic digestion of calotrops procera for biogas production in arid and semi-arid regions: A case study of Chad

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Abstract: Chad is among the many African countries having the most electrification problems (8.8% access in 2019) relating to the country’s poor economy and dependency on fossil fuels. On the other hand, the utilization of biomass for energy needs has been proven successful in various economies. Calotrops Procera, a bush latex plant wildly known for its multiple merits, is abundant in Chad, with an annual average of 6.3 tons per hectare on a wet basis. However, these are considered nuisance and resources are invested in getting rid of them. This study presents the first attempt to assess the biogas potential and prospects from Calotrops Procera for energy production in Chad. Theoretical estimations, field visits and experimental approaches were employed in this study. The experimental results were favourable as it was found that the stem of the plant achieved a biogas yield of 17,744 ± 12 mL and a biomethane production of 1.439 ± 0.31 L/g.VS while its leaves produced 8500 ± 4 mL of biogas for 0.4409 ± 0.15 L/g.VS of Biomethane. Estimations showed that the average annual availability of 6.3 tons of Calotrops Procera in Chad could produce 891.61 m³ and 9150.884 m³ of biogas from the leaves and stem, respectively. The theoretical energy potential of the Calotrops Procera leaves was estimated at 4.0861 MWh/yr and that of the Calotrops Procera stem at 13.104 MWh/yr. The findings from this study are useful to complement efforts in finding sustainable energy alternatives and resources in Chad and similar contexts. Also, this gives a technical basis for further research in economic and environmental sustainability as well as for policymakers on the production of energy from Calotrops Procera towards significant gains.

Keywords: Renewable Energy; Energy & Fuels; Biotechnology

1. Introduction

According to the United States Energy Information Administration, Global energy consumption will increase by 50% by 2050, along with the current trends (Nalley & Larose, 2021). On the other hand, the depletion of fossil fuels and the need to reduce greenhouse gas (GHG) emissions have increased the quest for alternative energy supply, especially in most developing countries where energy poverty is evident. Biomass resources are proven globally, as a sustainable alternative source of energy for their availability, being renewable and carbon neutral (Segurado et al., 2019). There is an active and efficient utilization of biomass and biomass residues for energy in advanced economies such as in the US and Europe via different conversion routes (Lee et al., 2021).
Biogas technology is one of the matured processes of converting organic materials into energy (Mahmoud et al., 2020). Also known as anaerobic digestion (AD), it is the utilization of biological procedures to break down organic materials and balance these materials by changing them into methane and carbon dioxide gas and an almost stable residue, in the privation of oxygen. (Marchaim, 1992). Biogas primarily comprises methane (50–80%), carbon dioxide (10–30%) and other gases and impurities such as hydrogen sulfide, ammonia, and carbon monoxide (Bridgewater et al., 2018). This is utilized for cooking, heating and lighting, while the process serves as a matrix for clean water and fertilizers (Ani, 2014). The proportions depend on the organic material and the method employed. However, the quantity of methane must be more than 40% for the biogas to be flammable. Today, this technology is widely spread around the globe and still developing every day with a very wide range of feedstocks used from animal waste to human waste.

In most developed countries, the use of organic waste in biogas plants is principally for heat generation and electricity (Al-Wahaibi et al., 2020). Biogas technology has become a solution for both waste disposal and energy generation. The production of biogas does not require oxygen, so the resources are preserved by not consuming additional fuel. It is therefore considered non-polluting by nature (Bhardwaj, 2017). Another advantage is that it reduces water and soil pollution and decreases deforestation (Beil & Beyrich, 2013). There are also disadvantages associated with biogas production, which include the fact that biogas has a low calorific value. There is also the release of greenhouse gases due to defective treatment within the process and also the high cost of cleaning and upgrading the biogas (Al-Wahaibi et al., 2020; Hosseini et al., 2014). Although some operating parameters influence the outcome of the anaerobic digestion process, the substrate composition remains crucial (Hundal et al., 2019). This means that the optimum biogas yield depends on the biodegradability of the feedstock.

In Chad, the primary energy supply sources are fossil fuels, contributing to about 96.87% of the energy mix, aside from solar and wind. Consequently, only about 314 MW of installed generation capacity serves a population of over 15 million people (USAID, 2022). Hence, energy poverty is very evident, recording about 8.8% electricity access and 3% for non-solid fuels for cooking and heating (SE4All, 2022). There is, therefore, the need to investigate other alternative sources of energy with a less environmental impact that will complement the current situation. The lack of assessment of various options and investments has been a significant hindrance to progress in transitioning to renewable energy sources. This is also a great limitation to the country’s development although rich in renewable resources including biomass, Calotropis procera, a major wild crop growing in the southern region.

Calotropis procera, although it has been identified as a potential petro crop and considered as a potential plant for bioenergy and biofuel production in the early ages (Rathore & Meena, 2010), it was in 1992 that (Traore, 1992) proved the fermentation ability of Calotropis Procera for biogas production. In 2010 research by (Manikandan & Arumugam, 2010) confirmed Traore’s results. Calotropis Procera is a fast-growing natural shrub, which disseminates in arid and semi-arid regions. In contrast to trees that take years to grow, Calotropis procera plants with their short production cycle could be a very interesting option for biogas production. However, works and pieces of literature on biogas production from Calotropis procera are limited. In addition, no other research has been found on biogas or energy production and its potential utilization from Calotropis Procera in Chad. Hence, the current study aimed to assess the biogas production from Calotropis Procera and further estimate the energy potential from the produced biogas.

Herein, the biogas production potential from Calotropis procera leaves and stems collected in Sarh (study area) was investigated. First, the dry matter and nutrient composition of both the leaves and the stems were analysed. An anaerobic digestion process was carried out to obtain and measure the gas production from each sample. Furthermore, the methane content of the gas was determined and the energy potential from that methane was estimated.
2. Methodology

2.1. Study area
Chad is one of the largest countries in Africa (fifth) with an area of 1,284,000 km². The study area Sarh, presented in Figure 1 is the third largest city in Chad after N'djamena (the administrative capital) and Moundou (the economic capital) with an area of 30 km² (Kolmagne, 2018). Sarh is located at 9° 09 “00” north, 18° 23 “00” east, and the city is the capital of the Moyen-Chari region and the Barh Kôh department. The city is wedged between two large rivers: The Chari in the northeast, and the Barh-Kôh in the southeast (PADUR, 2011). The city has a dry tropical climate, which is favourable for the proliferation of Calotropis Procera.

The presence of Calotropis procera in various sizes is noticed throughout the city (from roadsides and empty spaces to residential areas). The plant is highly avoided by most of the population for its poisonous property (the milky sap is believed to cause blindness), but its sap is used (in very little quantities) by a few farmers in yoghurt preparation for its coagulating property.

2.2. Feedstock description
Calotropis procera (shown in Figure 2) is a species of flowering plant in the family Apocynaceae, popularly known as silk flower, the apple of Sodom, rubber bush, milkmaid, Sodom’s milkweed, Sodom apple, silk cotton, beach cotton, etc. (de Sousa et al., 2018; Heuzé et al., 2016). It is a wild growing bush latex plant of medium size, measuring from 1 to 6 m long with wild leaves of around 10–30 cm wide (Heuzé et al., 2016; Traore, 1992) that primarily reproduces itself by seeds and vegetative propagation through half-strains (each plant gives rise to two half-strains) but also by propagation through stems, suckers and root cuttings (Hassan et al., 2015). This natural shrub from Africa and Asia present in regions extending from the coasts of Senegal and Mauritania in northwest Africa, crossing the Arabian Peninsula, Afghanistan and Pakistan, to India has an efficient capacity for dissemination in the arid regions and semi-arid regions (de Sousa et al., 2018) as it can sustain its productivity and adapt to arid conditions (Ramadan et al., 2014). The plant can survive extreme temperatures, salinity, high vapour pressure and high active radiation (Kaur et al., 2021). It grows easily in extended dry seasons with precipitation of less than 150 mm

Figure 1. Map of the study area, the city of Sarh.
per year and can survive under xerophilic (“dry”) environmental conditions on a diverse range of soils, with no need for irrigation, chemical fertilizers, pesticides or other agronomic practices (Hassan et al., 2015). The multiple processes in Calotropis procera are instrumental in its strength, endurance and recoverability under stressful subsistence conditions, making it capable of overcoming the damage caused by road traffic and polluted soils (Kaur et al., 2021). The plant may have either molecular or biological characteristics that contribute to its high tolerance to both radiation and minimal water supply (Frosi et al., 2013). An active antioxidant capacity, foliar carbohydrate dynamics and photoprotective enzymes protect the photosynthetic mechanism of the plant under extreme conditions (Kaur et al., 2021).

The plant contains a milky sap which contains a complex mix of chemicals, some of which are steroidal heart poisons known as “cardiac aglycones”. The stems and leaves of C. procera are characterized by a broad cuticle, milk canals and a thin leaf area (Kaur et al., 2021). The stems and leaves of C. procera are characterized by a broad cuticle, milk canals and a thin leaf area. Under favourable wet conditions, the leaves are slimmer and thicker, while in dry weather they are wider and thinner (Pompelli et al., 2019). According to Frosi et al. (2013), Calotropis procera also demonstrates both physiological and biochemical adaptive properties regarding the flow of gases and metabolic regulation.

The use of Calotropis procera dates back to ancient civilizations, such as the Cyprus of 2000 BC, Oman and the Indian cultures, where its fibres were used as textile materials (Al Sulaibi et al., 2020). In Africa, the Middle East in general and Central Asia the plant has been used in traditional medicine. Poisonous arrows were made from a plant in ancient African culture (Al Sulaibi et al., 2020). Nowadays, Calotropis Procera is highly valued in the pharmaceutical field for its numerous virtuous (anti-inflammatoriy, anthelmintic, anti-diarrheal) purposes (Khairnar et al., 2012). Calotropis procera is used as a construction material, reinforcement material and absorbent but also as a pesticide, insecticide and anti-fungicide (Al Sulaibi et al., 2020). Due to its capacity to grow in polluted areas, the plant is considered environmental monitoring and bioremediation culture (Kaur et al., 2021). Calotropis procera is also used as cooking fuel in some areas in Africa and several studies have been focusing on the bioenergy potential of the plant (Kalita & Salkia, 2006; Padmaja et al., 2009; Radhaboy et al., 2019).

Despite its multiple uses and benefits, Calotropis procera is still classified as an invasive species in many countries (Mexico, Australia, South America) due to its ability to spread on vast areas and the negative impact it has on the native ecosystems of the regions (Dhileepan, 2014). Calotropis seeds are spread by wind and animals and can be carried long distances in flood waters (the silky seed coat of the seeds allows them to be dispersed by wind over several hundred meters) (Hassan...
et al., 2015). Thanks to its adaptive system, Calotropis procera can grow in a diverse range of open habitats, including roadsides, riverbeds, watercourses, coastal dunes, deserts, semi-deserts, scrublands, overgrazed pastures and disturbed areas (Hassan et al., 2015). Although this plant generally grows near unmanaged crop fields where it can impose harmful effects on crops by allelopathy, its tolerance to high levels of heavy metals gives it the ability to invade polluted areas, contaminated sites, rehabilitated mines, iron ore breakage fields, etc. (Kaur et al., 2021). Another cause of the large distribution of the plant is its ornamental value: it was imported to many countries for ornamental purposes.

To fight the spread of Calotropis Procera, invaded regions are adopting various management practices with constant monitoring over the following years to prevent the growth of new seedlings. These management methods are mechanical removal, which consists of extracting the whole plant (including the roots) to prevent reproduction. According to Kaur et al. (2021), this technique allows 72% removal efficiency although it results in new seedling emerging. Chemical removal is the use of pesticides such as 2,4-D butyl ester, fluroxypyr, triclopyr and triclopyr/picloram... This process reached an 80% efficiency on plants below 5 cm close to the ground (Vitelli et al., 2008). Biological removal consists of using biocontrol agents to inhibit the growth of the plant. These control agents consist of insects (up to 65 species), mites (5 species) and fungal pests (Kaur et al., 2021). According to (S. Ali et al., 2020), Dacus persicus Hende, a fruit fly is a potential biocontrol agent causing up to 100% damage to young seeds.

2.3. Feedstock collection

The Calotropis Procera was harvested with the help of shears from a random location in Sarh (Chad). The leaves were then separated from the stems and washed to remove dust and impurities. The leaves and stems were dried, airtight packed and transported to Ghana for further treatment and analysis. The samples were dried to avoid biodegradation before arriving in Ghana where the analysis was conducted. Figure 3 represents the pretreatment process of the feedstock.

2.4. Analytical method

Before the anaerobic digestion process, a proximate analysis of the samples was carried out. The analysis of the samples for total solid (TS), total volatile solids (TVS), carbon content, nitrogen content, moisture, carbohydrate and ash were determined as described by the AOAC protocol 2005 (Al-mentafji, 2016). Crude fibre, fat and protein contents were identified using Pearson's Methods (Pearson & Cox, 1976), while pH and electroconductivity were measured using a pH meter. All samples were analysed in triplicates.
2.4.1. Ph and electroconductivity
The pH of the Inoculum and digestate was measured immediately after mixing to minimize pH fluctuations due to the venting of dissolved CO₂ in the liquid. The pH and electroconductivity parameters were determined using a Milwaukee pH meter with a glass electrode. The probe was calibrated using pH 7.0 and 9.2 buffers.

2.4.2. Total solids (TS) and moisture content
A known weight (the gravimetric method) of a thoroughly mixed sample was evaporated to a constant weight in a crucible (porcelain or silica), in a drying oven at 105°C; the remaining solids were cooled down to room temperature in a desiccator to avoid absorption of air moisture and then re-weighed. The residual material remaining in the crucible is TS. This consists of organic and inorganic material and dissolved suspended or volatile matter. TS was determined using Equation 1.

\[
\%\text{TS} = \frac{W_3 - W_1}{W_2 - W_1} \times 100
\]

(EPA, 2001)

Where \(W_1\) = the weight of the empty crucible.

\(W_2\) = the weight of the crucible containing the fresh sample.

\(W_3\) = the weight of the crucible and sample after drying at 105°C.

2.4.3. Volatile solids
The dry sample residue from the determination of total solids and moisture content was ignited at 550°C until constant weight (around 30 minutes). The remaining ash represented the fixed (inorganic) solids, while the weight lost on ignition represented the volatile solids (organic matter) in faecal sludge. VS was determined using Equation 2.

\[
\%\text{VS} = \frac{W_3 - W_4}{W_3 - W_1} \times 100
\]

(EPA, 2001)

Where \(W_1\) = the weight of the empty crucible.

\(W_3\) = the weight of the crucible and sample after drying at 105°C.

\(W_4\) = the weight of the crucible and sample after heating to 550°C.

2.4.4. Crude fat
5.0 g of dried sample was transferred to a paper thimble and a small ball of cotton was placed into the thimble to prevent loss of the sample. 150 ml of petroleum spirit was added to a previously dried 250 ml round bottom flask. A condenser was connected to the soxhlet extractor and was refluxed for 4 hours on high heat on the heating mantle. After extraction, the thimble was removed and the solvent was recovered by distillation. The flask and fat were heated for 30 minutes in an oven at 103°C. The flask and contents were cooled to room temperature in a desiccator. The flask was weighed accurately and the weight of the cooled fat was determined using Equation 3.
\[
\%\text{Fat} = \frac{A}{M} \times 100
\]

(Anon, 2006)

where \(A\) is the mass (g) of extracted matter and \(M\) is the mass (g) of the tested sample.

2.4.5. Crude fibre

The sample from crude fat determination was transferred into an Erlenmeyer flask and approximately \(\frac{1}{2}\) g of asbestos was added. Then 200 ml of boiling 1.25% \(\text{H}_2\text{SO}_4\) was added, and the flask was immediately set on a hot plate and connected to a condenser. The flask was removed after 30 minutes and immediately filtered through linen cloth in a funnel and then washed with a large volume of boiling water until the residue is no longer acidic. Afterwards, the filtrate and asbestos were washed into a flask with 200 ml boiling 1.25% \(\text{NaOH}\) solution, which was connected and left to boil for 30 mins. The sample was then filtered through a linen cloth and washed thoroughly with boiling water until the residue is no longer basic. The residue was then washed with approximately 15 ml alcohol and transferred residue to the crucible quantitatively with water. The crucible and contents were dried for 1 hour at 100°C and cooled in a desiccator and reweighed before they were ignited in a furnace for 30 minutes then cooled and reweighed again. The loss of weight was reported as crude fibre using Equation 4.

\[
\%\text{Crude Fibre} = \frac{W_3 - W_1}{W_2 - W_1} \times 100
\]

(EPA, 2001)

Where \(W_1\) = weight of the empty crucible

\(W_2\) = weight of empty crucible + wet sample

\(W_3\) = weight of crucible + ash sample

2.4.6. Protein and total nitrogen

2 g of the sample, half of the selenium-based catalyst tablets and a few anti-bumping agents were added to the digestion flask. 25 ml of concentrated \(\text{H}_2\text{SO}_4\) was added and the flask was shaken till the entire sample was thoroughly wet. The flask was placed on a digestion burner and heated slowly until boiling ceases and the resulting solution is clear, then allowed to cool at room temperature. The digested sample solution was transferred into a 100 ml volumetric flask and made up to the mark. The digested sample solution (ammonia) was then distilled into a trapping solution (\(\text{NaOH}\)) before it was titrated with an acid solution (0.1 N \(\text{HCl}\) solution). Equations 5 and 6 were used to determine the protein and nitrogen contents:

\[
\%\text{Total Nitrogen} = \frac{100 \times (V_a - V_b) \times NA \times 0.01401}{W \times 10}
\]

(Nitrogen Determination by Kjeldahl Method, n.d.)

where \(V_a\) = volume in ml of standard acid used in titration

\(V_b\) = volume in ml of standard acid used in blank

\(NA\) — normality of acid (\(\text{HCl}\))

\(W\) — weight in grams of sample
And

\[
\% \text{Protein} = F \times \% \text{Total Nitrogen}
\]

\hspace{1cm} (6)

(Al-mentafji, 2016)

where \(F\) is the protein factor.

2.4.7. Carbon content

The carbon content was calculated using Equation 7

\[
\% \text{Carbon} = 100 - \% \text{weight of moisture} + \% \text{weight of volatile matter} + \% \text{weight of ash}
\]

\hspace{1cm} (7)

(Al-mentafji, 2016)

2.5. BMP essay

The anaerobic digestion was conducted in 8 treatments using the CJC Labs BMP essay system (Figure 5). A control with only inoculum (B1 and B2) was used to determine biogas production due to endogenous respiration, and each treatment was run in triplicate: B3 (Calotropis Procera leaves plus inoculums), B4 (Calotropis Procera stem plus inoculums). The content of each digester is presented in Table 1. The samples were mixed with liquid inoculum to facilitate anaerobic digestion (Figure 4).

The reactor which is a strong high-density polyethylene (HDPE) vessel is made with a gas-tight push-fit lid, which is arranged on a geared motor and a stirring mechanism. The digestion is housed in a tough rotomolded polypropylene water bath into which a thermostatic heater is inserted to maintain temperature. The system has eight reactors allowing you to run a pair of controls alongside three duplicates of samples. Each reactor is connected to a gas counter using a “tipping bucket” principle. The gas tight lid allows the off gases to be collected in a small gas-sampling bag (6 ml) for compositional analysis or to confirm the volume by measurement in

| Content       | Feedstock          | Weight Inoculum (g) | Weight Sample (g) |
|---------------|---------------------|---------------------|-------------------|
| Inoculum      | -                   | 406                 | 0                 |
| Inoculum      | -                   | 408                 | 0                 |
| Sample A      | Calotropis Procera leaves | 405             | 10.01             |
| Sample B      | Calotropis Procera stem | 407              | 10.18             |

Figure 4. Feedstock mixed with liquid inoculum.
a water displacement gasometer (Products—CJC Labs, n.d.). The data captured is sent to a data acquisition unit for interpretation. Each BMP set connected can be started and stopped independently allowing multiple users. Figure 6 presents the process flow diagram of the system.

The biogas yield of each sample was obtained under mesophilic temperature (36°C) for 20 days and corrected to normal conditions, considered 273.15 K and 101.325 kPa. The inoculum used for the BMP assays was originally from the large-scale biogas plant at SAFI SANA, which uses municipal solid waste, abattoir waste and human excreta as substrates. The experimental biochemical methane potential (BMP) tests were performed in a 1 L bottle continuously shaken at 50 r/min.

2.6. Feedstock availability and energy potential
Based on a study by (Nasser et al., 2012), Calotropis procera can reach an annual branch yield of 5.41 t/ha for an average tree production of 525 trees per hectare (Al Sulaibi et al., 2020). According to (Noxious Weeds of Australia—W. T. Parsons, William Thomas Parsons, E. G. Cuthbertson—Google Books, n.d.), the plant can be harvested twice a year. In the current study, the leaves and branches of a fully grown Calotropis procera tree were removed and weighed separately. The data obtained were used to estimate the fresh weights of potential leaves and branch yields for

Figure 5. CJC labs BMP essay system.

Figure 6. The process flow diagram of the CJC labs BMP essay system.
five (5) hectares of land of planted Calotropis procera in Sarh. A coefficient of 20% was applied to obtain the dry weights of the estimated fresh yields.

The energy potential for the estimated dry yields of Calotropis procera on 5 ha was calculated based on the calorific value of their methane content. The potential of electricity generation from the biogas was calculated according to Equation 8.

\[ e_{\text{sample}} = E_{\text{methane}} \times \eta \]  

(Abdeshahian et al., 2016; Hosseini et al.,)

Where \( e_{\text{sample}} \) is the energy potential of the sample (kWh), \( E_{\text{methane}} \) is the raw energy in the methane (kWh) and \( \eta \) is the overall conversion efficiency, which was assumed at 35%. The quantity of raw energy in methane \( E_{\text{methane}} \) was calculated using Equation 9.

\[ E_{\text{methane}} = \text{Energy Content}_{\text{methane}} \times m_{\text{methane}} \]  

(Abdeshahian et al., 2016; Hosseini et al.,)

Where \( \text{Energy Content}_{\text{methane}} \) is the calorific value of methane (kWh/m³) and \( m_{\text{methane}} \) the quantity of methane (m³). \( \text{Energy Content}_{\text{methane}} \) was assumed as 10 kWh/m³ by considering a calorific value of 36 MJ/m³ of methane (Kozani, 2014; Suhartini et al., 2019).

3. Results and discussion

3.1. Chemical characteristics of feedstock

The result of the proximate analysis of the different feedstock on a dry basis is presented in Table 2. The leaves of Calotropis Procera contain 11.32% moisture, 17.45% crude fibre, 15.17% total ash, 43.96% protein, 9.14% NFE carbohydrate (Nitrogen-free extract carbohydrate) and 2.96% fat. While the stems consist of 11.63% moisture, 32.86% crude fibre, 10.43% total ash, 27.95% protein, 15.16% NFE carbohydrate and 1.98% fat. Also, the stem of Calotropis Procera has higher percentages of Total Solid (TS), Volatile Solid (TVS) Organic Carbon Content (90.2%, 89.6%, 51.95% respectively) as opposed to 88.7% TS, 83.9% TVS and 49.21% Organic Carbon for the

### Table 2. Characteristics of the feedstock

| Parameters          | Calotropis Leaves | Calotropis Stem |
|---------------------|-------------------|-----------------|
| TS (%)              | 88.7              | 90.2            |
| TVS (%)             | 83.9              | 89.6            |
| Organic Carbon (%)  | 49.20733          | 51.95267        |
| Nitrogen (%)        | 7.03413           | 4.47147         |
| C:N Ratio           | 6.99551           | 11.61870        |
| Fat (%)             | 2.96              | 1.98            |
| Crude Fibre (%)     | 17.45333          | 32.85667        |
| Total Ash (%)       | 15.16667          | 10.43333        |
| Moisture (%)        | 11.31667          | 11.62667        |
| Protein (%)         | 43.96333          | 27.94667        |
| NFE Carbohydrate (%)| 9.14              | 15.15667        |
| pH                  | 5.62              | 5.65            |
| EC (mS/cm)          | 6.59              | 3.07            |
leaves. However, the higher C:N Ratio of 11.62% from the Calotropis Procera stems is mostly a result of its lower Nitrogen content (4.47%).

Although the results of the percentage of the total solid, total ash, carbon and nitrogen in the current study are higher than those found in (Heuze et al., 2016), the values are very close. The results from (Radhaboy et al., 2019) also present lower values for the moisture content, the total ash, the total volatile solid as well the carbon and nitrogen content. The research from (Jilani et al., 2015), on the other end, presented a higher carbohydrate content but lower values of total ash, moisture content, crude fibre and protein. The total ash content which is lower than that found in (Orwa et al., 2009), reveals the presence of minerals such as potassium, calcium, sodium, phosphorus and others. It is also a good indicator of possible biogas production. The low moisture content is recorded because the samples were pre-dried before analysis. However, the study (Manikandan & Arumugam, 2010) obtained a harvest moisture content of 67.60% ± 0.8510 and 51.53% ± 0.4060 for the leaves and stem, respectively.

Another important process parameter for the anaerobic digestion process is the pH of the feedstock (Cioabla et al., 2012). The two samples have practically the same pHs (5.62 and 5.65 for the leaves and stems respectively). Both pHs are in the acidic region which according to (Adebiempe et al., 2020), (AgStar, 2012) and (Jayaraj et al., 2014) are inhibitory to the biogas production process. The electrical conductivity (EC) of the Calotropis procera leaves is higher than this of the stems (6.59 mS/cm for the leaves and 3.07 mS/cm for the stems).

The C/N ratio is a decisive parameter in biogas production as an inappropriate C/N ratio can easily put a stop to gas production. Based on studies by (Aguilar et al., 2017; Beniche et al., 2021; Dioha et al., 2013; Jos et al., 2018), the range of C/N ratio for optimal biogas yield is deduced to be between 25:1 and 30:1. According to the study by Alfred S. Traore (Traore, 1992), the C/N ratio of Calotropis procera was 16–88 ± 1.67 for a biogas yield of up to 3.6 l/day. Thus, the C/N ratio of 11.62% from the Calotropis Procera stem obtained from this study does not deviate totally. The C/N ratio of the leaves, on the other hand, represents a lower biogas production potential than the stem. Comparatively, a maximum of 394 ml/gVS of CH4 potential at 26.31. The C/N ratio was observed in wheat straw, a similar lignocellulose feedstock. However, the wheat straw was co-digested with dairy manure and chicken manure, hence a higher ratio.

The concentration of carbohydrate, protein and lipids in a feedstock provides a broad indication of its behavior in the digestion process (Al-Wahaibi et al., 2020). Carbohydrates have a high degradability and transform rapidly, thus produce more biogas. Calotropis procera stem has a higher carbohydrate content and therefore has chances of producing a higher biogas yield.

### 3.2. BMP results

Figure 7 shows the raw plot of biogas production per hour for each sample. It is visibly clear that the stem of Calotropis Procrea had the highest biogas production, which was 17,744 ± 12 mL when the experiment was stopped at 686 hours (day 28). Sample B which contained the leaves of Calotropis Procera yielded 8500 ± 4 mL of biogas in 686 hours (28 days). These results attest to the fermentability of Calotropis procera, from the study which obtained 5,490 cm³ (5,490 mL) and 4,384 cm³ (4,384 mL) of biogas from the anaerobic digestion of Calotropis procera stems and leaves, respectively (Manikandan & Arumugam, 2010). Both results are significantly low compared to the current study’s results. However, the leaves generated a higher amount of biogas than the stem within the period of that study. The results of the current study were comparable to studies (Gunaseelam, 2009; Sen et al., 2013; Staubmann et al., 1997) on biogas production from Jatropha Curcas, another tropical plant studied for its biogas potential. It was found that the quantity of biogas produced from Calotropis Procera leaves is much lower compared to that produced from Jatropha Curcas leaves and seed cake. However, Calotropis Procera stems produce a higher biogas quantity with a higher methane content compared to both Jatropha Curcas leaves and seed cake.
The cumulative methane production is 1.439 ± 0.31 L/g.VS for Calotropis procera stem and 0.4409 ± 0.15 L/g.VS for Calotropis procera leaves. The BMP curve of the Calotropis procera stems reflects the high biodegradability potential of this sample (Remigi & Buckley, 2006). This is justified by the higher carbohydrate content of the stems compared to the leaves (Al-Wahaibi et al., 2020).

From these results, the proportions of methane in the biogas obtained were calculated and gave 48.12% of methane for Calotropis Procera leaves and 75.18% for Calotropis Procera stems. A study by (Ali et al., 2010) on Jatropha Curcas presented an average annual biogas yield of 181.25 L/Kg TS (0.181 L/g TS) which is lower than the biogas yield obtained in the current study. Dhanya et al. also researched the biogas potential of Jatropha Curcas fruit coat and the results revealed a cumulative biogas yield of 162.52 L/Kg TS (0.163 L/g TS; Dhanya et al., 2009). Based on the results from (Staubmann et al., 1997), (Gunaseelan, 2009), (Sen et al., 2013), (Ali et al., 2010) and (Dhanya et al., 2009), it can be concluded that Calotropis procera has a higher cumulative methane yield than Jatropha Curcas. The current results were also compared to results obtained from the anaerobic digestion of other tropical plants: Calotropis procera has a higher cumulative biogas yield than cassava peels (Adelekan, 2014), sweet potato peels (Adeyosoye et al., 2010), as well as wild cocoyam (Kumar, 2012). The methane content from the Calotropis procera leaves is quite close to that of the sewage sludge studied by (Dido et al.,...
Table 3. Estimated annual yields of calotropis procera

|                | Wet weight of one tree (kg) | Estimated annual wet weight of tree population on 1 hectare (tons) | Estimated annual wet weight of tree population on 5 hectares (tons) | Estimated annual dry weight of tree population on 5 hectares (tons) |
|----------------|-----------------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Leaves         | 1                           | 1.05                                                          | 5.25                                                          | 1.05                                                          |
| Stems          | 5                           | 5.25                                                          | 26.25                                                         | 5.25                                                          |
| Total          | 6                           | 6.3                                                           | 31.5                                                          | 6.3                                                           |

Table 4. Estimated annual energy potential of calotropis procera

|                        | Estimated annual dry weight of tree population on 5 hectares (tons) | Biogas Quantity (m³) | Biomethane Quantity (m³) | Raw Energy In Methane (kwh) | Energy Potential (kwh) |
|------------------------|-------------------------------------------------------------------|-----------------------|--------------------------|---------------------------|------------------------|
| Leaves                 | 1.05                                                              | 891.61                | 429.04                   | 4290.4                    | 1501.64                |
| Stem                   | 5.25                                                              | 9150.884              | 6879.63                  | 6879.63                   | 24 078.705            |

n.d.) who found a methane content of 48.31% from the biogas produced from sewage sludge. The current results, however, fall into the methane proportion ranges given in the studies (Biogas and Fuel Cells Workshop Summary Report Biogas and Fuel Cells Workshop Summary Report, n.d.), (Sherman, 2016) and (Kozani, 2014). The current study as well as the foregoing ones confirm that the anaerobic digestion of organic materials is largely dependent on the chemical composition of the feedstock (Dido et al., n.d.) and the cumulative methane yield of these feedstocks is principally subjective to the biodegradability of their organic compounds (Kumar, 2012). Calotropis procera is therefore a biodegradable material suitable for biogas production.

3.3. Feedstock availability and energy potential from biogas production
Table 3 presents the estimated annual yields of both Calotropis procera leaves and stems while Table 4 discusses the energy potential from the obtained dried feedstock. The total annual yield of the Calotropis procera tree is presented in Table 3. On a land surface of 5 hectares, the Calotropis Procera tree population can yield an annual wet weight of 31.5 tons. The dry weight of the feedstock was estimated at 6.3 tons. The raw energy potential of the Calotropis Procera leaves was estimated at 1.5016 Mwh and that of the Calotropis Procera stem at 24.0787 Mwh. An average household in Sarh consumes around 1.454 MWh of electricity in a year.

4. Limitation of the study
The main limitation of this work is the lack of appropriate laboratories and equipment in Chad. The samples had to be transported to another country for analysis.

5. Conclusion
The methane yield achieved by the Calotropis Procera leaves and stem proves the high potential of biogas production from the plant. The current study accentuates and confirms the fermentation ability of Calotropis Procera and its great potential for biogas production. Generating energy from
biomass or biomass’ residue is of growing importance as it is proved to be a carbon-neutral source of energy through a sustainable conversion pathway.

The current study revealed that the stem of the plant achieved a biogas yield of 17,744 ± 12 mL and a biomethane production of 1.439 ± 0.31 L/gVS while its leaves produced 8500 ± 4 mL of biogas for 0.4409 ± 0.15 L/gVS of Biomethane. It was also estimated that the average annual quantity of 6.3 tons of Calotropis Procera in Chad could produce 891.61 m³ and 9150.884 m³ of biogas from the leaves and stem, respectively. The theoretical energy potential of the Calotropis Procera leaves was estimated at 4.0861 MWh/yr and that of the Calotropis Procera stem at 13.104 MWh/yr. The study focused on the biogas potential analysis of the feedstock only, in a batch process, which proved feasible. Future or further studies could examine the techno-economic and environmental feasibility of the process. As well, optimization of the process in terms of varying process parameters and co-digestion of different feedstock could be examined.

Funding
This research was funded by the Regional Centre for Energy and Environmental Sustainability (RCEES), UENR.

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Conceptualization, S.S.D.; formal analysis, S.S.D., K.S., N.S.D and F.A.K.; original draft preparation: S.S.D.; writing, reviewing and editing, S.S.D. and K.S.; supervision: N.S. D. and F.A.K. All authors have read and agreed to the published version of the manuscript.

Disclosure statement
No potential conflict of interest was reported by the author(s).

Citation information
Cite this article as: Anaerobic digestion of calotropis procera for biogas production in arid and semi-arid regions: A case study of Chad, Stephanie Solal Djimtoingar, Nana Sarfo Ayegmang Derkyi, Francis Atta Kuranche & Khadija Sarquah, Cogent Engineering (2022), 9: 2143042.

References
Abdeshoahian, P., Shiu, J., Shin, W., Hashim, H., & Lee, C. T. (2016). Potential of biogas production from farm animal waste in Malaysia. Renewable and Sustainable Energy Reviews, 60, 714–723. https://doi.org/10.1016/j.rser.2016.01.117
Adebimpe, O. A., Edem, I. E., & Ayodele, O. L. (2020). Investigation of the effects of starting pH, mass and retention time on biogas production using poultry droppings as feedstock. Nigerian Journal of Technology, 39(1), 203–211. https://doi.org/10.4314/njt.v39i1.23
Adelekan, B. A. (2014). Cassava as a potent energy crop for the production of ethanol and methane in tropical countries cassava as a potent energy crop for the production of ethanol and methane in tropical countries. November, 24–32. https://doi.org/10.5383/jitee.04.01.004
Adeyoye, O. I., Adesokan, I. A., Afolabi, K. D., & Ekeocha, A. H. (2010). Estimation of proximate composition and biogas production from in vitro gas fermentation of sweet potato (Ipomoea batatas) and wild cocoyam (Colocasia esculenta) peels. 4(June), 388–391. Corpus ID: 85990544
AgStar. (2012, September). Increasing anaerobic digester performance with codigestion. www.Epa.Gov.www.epa.gov/agstar.%0Ahttp://www.epa.gov/agstar/documents/codigestion.pdf
Aguilar, A. F. A., Nelson, D. L., Pantjoa, L. D. A., & Soares Dos Santos, A. (2017). Study of anaerobic co-digestion of crude glycerol and swine manure for the production of biogas. Revista Virtual de Quimica, 9(6), 2384–2403. https://doi.org/10.21577/1984-6835.20170142
Ali, N., Kurchania, A. K., & Babel, S. (2010). Biomethanisation of Jatropha curcas defatted waste. Journal of Engineering and Technology Research, 2(3), 38–43. Corpus ID: 54196864
Ali, S., Shabbir, A., & Dhileepan, K. (2020). Biomass and damage potential of fruit fly Dacus persici (Diptera: Tephritidae): a prospective biological control agent of Calotropis procera (Apocynaceae). Biocontrol Science and Technology, 30(7), 716–727. https://doi.org/10.1080/09583157.2020.1765982
Al-mentafj, H. N. (2016). Of fl ial methods of analysis of AOAC International. Aoac, 2005(Febraury). https://www.researchgate.net/publication/292783651_AOAC_2005
Al-Salaib, M. A. M., Thiemann, C., & Thiemann, T. (2020). Chemical constituents and uses of calotropis procera and calotropis gigantea - A review (part I – the plants as material and energy resources). Open Chemistry Journal, 7(1), 1–15. https://doi.org/10.2174/187484222007010001
Al-Wahabi, A., Osman, A. I., Al-Muhtaseb, A. H., Alqaisi, O., Baawain, M., Fawzy, S., & Rooney, D. W. (2020). Techno-economic evaluation of biogas production from food waste via anaerobic digestion. Scientific Reports, 10(1). https://doi.org/10.1038/s41598-020-72897-5
Ani, N. C. (2014). Biogas technology Reasons why the industry is being undermined in Nigeria. Seminar on “Biogas”. Anon. (2010). Crude fat determination - soxhlet method. Meat Technology Information Sheet, (November). https://docpub/documents/crude-fat-determination-soxhlet-method-1998pdf-d4pq3jy69np
Beil, M., & Beyrich, W. (2013). Biogas upgrading to biomethane. The Biogas Handbook, 342–377. https://doi.org/10.15339/9788075097415.3.342
Beniche, I., Hungria, J., El Bani, H., Siles, J. A., Chica, A. F., & Martin, M. A. (2023). Effects of CN ratio on anaerobic co-diggestion of cabbage, cauliflower, and restaurant food waste. Biomass Conversion and Biorefinery, 11(5), 2133–2145. https://doi.org/10.1007/s13399-020-00733-x

Bhardwaj, S. (2017). A Review: Advantages and Disadvantages of Biogas. International Research Journal of Engineering and Technology (IRJET), 4(10), 890–893. www.irjet.net

Bridgewater, T., Lea-Longton, A., Ross, A., & Watson, I. (2018). Biomass Conversion Technologies. In P. Thornley & P. Adams (Eds.), Greenhouse Gas Balances of Bioenergy Systems (pp. 107–139). Academic Press. https://doi.org/10.1016/B978-0-12-810135-8.00008-2

Cioabla, A. E., Ionel, I., Dumitrel, G.-A.-A., & Popescu, F. (2012). Comparative study on factors affecting anaerobic digestion of agricultural vegetal residues. Biotechnology for Biofuels, 5(1), 1. https://doi.org/10.1186/1756-834X-5-39

de Souza, L. V., Santos, A. P. B. A. G. D., Do Souza, L., Santos, A. P. B. A. G. D., & Beirat, A. (2018). Evaluation of the properties of Calotropis procera oil aiming the production of biodiesel. Orbitol, 10(2), 147–152. https://doi.org/10.17807/orbitol.1001.1002.1061

Dhanya, M. S., Gupta, N., & Joshi, H. C. (2009). Biogas potentiality of agro-wastes jatropha fruit coat. 13(3), 70–74. https://doi.org/10.5281/zenodo.1077473

Dhileepan, K. (2014). Biocontrol Science and Technology Perspectives for the classical biological control of Calotropis procera (Apocynaceae) using coeaved insects https://doi.org/10.1080/09558315.2014.912611

Dieyo, I. J., Ikeme, C., Nof, T., Soba, N. I., & Mbs, Y. (2013). Effect of carbon to nitrogen ratio on biogas production. International Research Journal of Natural Sciences, 1(3), 1–10. https://corvus.ccsenet.org/index.php/innovations/article/view/125277362

EPA. (2001). Method 1684: Total, fixed, and volatile solids in water, solids, and biosolids. U. S. Environmental Protection Agency, EPA 821-R (January).

Frosi, G., Oliveira, M. T., Almeida-Cortez, J., & Santos, M. G. (2013). Ecophysiological performance of Calotropis procera: An exotic and evergreen species in Catinga, Brazilian semi-arid. Acta Physiologiae Plantarum, 35(2), 335–344. https://doi.org/10.1007/s11738-012-1076-x

Ganoth, L. N. (2009). Biomass estimates, characteristics, biochemical methane potential, kinetics and energy flow of Jatrophacum curcus on dry lands. Biomass & Bioenergy, 33(4), 589–596. https://doi.org/10.1016/j.biombioe.2008.09.002

Hassan, L. M., Galal, T. M., Farahat, E. A., El-Midany, M. M., Galal, M., Farahat, E. A., El-Midany, M. M., Galal, M., Farahat, E. A., and El-Midany, M. M. (2013). The biology of Calotropis procera (Alton) W.T. Trees - Structure and Function, 29(2), 311–320. https://doi.org/10.1007/s00468-015-1158-7

Heuze, V., Tran, G., Baumont, R., & Bastianelli, D. (2016). Calotropis (calotropsis procereol. http://www.seedpedia.org/node/58811east

Hosseini, S. E., & Wahid, M. R. A. (2016). Development of biogas combustion in combined heat and power generation. Renewable and Sustainable Energy Reviews, 40, 868–875. https://doi.org/10.1016/j.rser.2015.07.204

Hundal, J. S., Wadhwa, M., & Bakhsh, M. P. S. (2019). Herbal feed additives containing essential oil: 1. Impact on the nutritional worth of complete feed in vitro. Tropical Animal Health and Production, 51(7), 1909-1917. https://doi.org/10.1007/s11250-019-01887-1

Jayaraj, S., Deepanjali, B., & Velumugan, S. (2016). Study on the effect of pH on biogas production from food waste by anaerobic digestion solar heat pumps view project domestic refrigerators view project. International Green Energy Conference, 5(August), 799–803. https://www.researchgate.net/publication/264545493

Jilani, M. I., Ahmad, M. I., Hanif, R., Nadeem, R., Hanie, M. A., Hanif, M. A., & Khan, M. A. (2015). Proximate, mineral element, antibacterial activity and phytochemical screening of bombusunu leaves (calotropsis procera). International Journal of Contemporary Applied Sciences, 2(9), 40–51.

Jos, B., Hundagi, F., Pindy Wisadwati, R., Budijono, & Sumardiono, S. (2018). Study of CN ratio effect on biogas production of carica solid waste by SS-AD method and LS-AD. MATEC Web of Conferences, 156, 7–11. https://doi.org/10.1051/matecconf/201815603055

Kalita, D., & Saikia, C. N. (2004). Chemical constituents and energy content of some latex bearing plants. Bioresource Technology, 92(3), 219–227. https://doi.org/10.1016/j.biotech.2003.10.004

Kaur, A., Batish, D. R., Kaur, S., & Chouhan, B. S. (2021). An Overview of the Characteristics and Potential of Calotropis procera From Botanical, Ecological, and Economic Perspectives. Frontiers in Plant Science, 12 (June). https://doi.org/10.3389/fpls.2021.698086

Khairam, A. K., Bhamare, S. R., & Bhamare, H. P. (2012). Calotropis procera: An ethnomedicinal analysis update. Advance Research in Pharmaceuticals and Biologics, 2(II), 142–156.

Kolmogrov, M. F. (2018). Fiche de presentation-bourse-partenariats. https://www.diplomatie.gouv.fr/IMG/pdf/sahr-tchad-fiche_presentation_bourse_partenariat_cie896f1.pdf

Kozani, J. S. (2014). Basics of the biogas production process. https://ppeepe préses gp/wp-content/uploads/2014/06/Kozani_Workshop_Sjanne1.pdf

Kumar, S. (2012). Biogas BoD-Books on Demand. In S. Kumar (Ed.), Janaza Traine (Vol. 9, pp. S1000).

Lee, S., Lo, Y., Shen, B., Dong, W., Yong, S., Abkar, M., & Suners, J. (2021). Techno-economic analysis for biomass supply chain: A state-of-the-art review. Renewable and Sustainable Energy Reviews, 135 (August 2020), 110164. https://doi.org/10.1016/j.rser.2020.110164

Mohammad, M. Estango, M., Bilal, B., Yelimesoz, K., Youm, L., & Bahramian, M. (2020). Mapping of biogas production potential from livestock manures and slaughterhouse waste: A case study for African countries. Journal of Cleaner Production, 256, 120499. https://doi.org/10.1016/j.jclepro.2020.120499

Manikanadan, M., & Arumugan, R. (2010). Potentality of Calotropis procera on the yield of biocrude and biogas production. Journal of Phytology, 2(4), 33–40. https://www.cabdirect.org/cababstracts/abstract/2011304693

Marchaim, U. (1992). Biogas process for sustainable development. Food and Agricultural Organization. https://doi.org/10.2520/daos.scbook.2014.09

Meena, M. R. (2010). Potential of utilizing calotropsis procera flower biomass as a renewable source of energy. The Journal of Phytology, 2, 78–83.

Nalley, S., & Larose, A. (2021). IE02021 highlights. Energy Information Administration, 2021. 21. https://www.eia.gov/outlooks/ieo/pdf/IE02021_ReleasePresentation.pdf

Nasser, R. A., Al-Mefarrej, H. A., Khan, P. R., & Alalhafa, K. H. (2012). Technological properties of calotropsis procera (AIT) wood and its relation to Utilizations. Journal of
Agriculture and Environmental Sciences, 12(1), 5–16. https://www.idosi.org/j2.pdf

Noxious weeds of Australia - W. T. parsons, William Thomas Parsons, E. G. Cuthbertson - google books. (n.d). Retrieved April 22, 2022, from https://books.google.com/og/books?hl=en&dr=&id=3Cg5QzmpwC&oi=fnd&pg=PPA15dq=Parsons,+W.+T.+%3B+Cuthbertson,+E.+G.,+2001.+Noxious+weeds+of+Australia.+CSIRO+Publishing,+712

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., & Simons, A. (2009). Calotropis procera Calotropis procera. Agroforestry Database, 4, 1–5. https://doi.org/10.12691/ajfn-6-5-2

Padmaoja, K. V., Atheya, N., Bhatnagar, A. K., & Singh, K. K. (2009). Conversion of Calotropis procera biocrude to liquid fuels using thermal and catalytic cracking. Fuel, 88 (5), 780–785. https://doi.org/10.1016/j.fuel.2008.11.020

PADUR. (2014). Tchad PADUR Cadre de Politique de RéInstallation des Populations Déplacées du Financement Additionnel au Don.

Pearson, D., & Cox, H. E. (1976). The chemical analysis of foods. 575. https://books.google.com/books/about/The_Chemical_Analysis_of_Foods.html?id=fpoveAAAAIAAJ

Pompelli, M. F., Mendes, K. R., Ramos, M. V., Santos, J. N. B., Youssef, D. T. A., Pereira, J. D., Endres, L., Jamra-Orozco, A., Solano-Gomes, R., Jamra-Arroyo, B., Silva, A. L. J., Santos, M. A., & Antunes, W. C. (2019). Mesophyll thickness and sclerophyll among Calotropis procera morphotypes reveal water-saved adaptation to environments. Journal of Arid Land, 11(6), 795–810. https://doi.org/10.1007/s40333-019-0016-7

Radhakay, G., Pugazhuvadi, M., Ganeshan, P., & Ramshankar, P. (2019). Analysis of thermo chemical behaviour of calotropis procera parts for their potentiality analysis of thermo chemical behaviour of calotropis procera parts for their potentiality. International Journal of Ambient Energy. https://doi.org/10.1080/01430750.2019.1630309

Ramadan, A., Sabir, J. S. M., Alkilili, S. Y. M., Shokry, A. M., & Gadalla, N. O. (2014). Metabolomic Response of Calotropis procera Growing in the Desert to Changes in Water Availability. PLoS ONE, 9(2), 87895. https://doi.org/10.1371/journal.pone.0087895

Remigi, E. U., & Buckley, C. A. (2006). Co-digestion of high strength/toxic organic effluents in anaerobic digesters at waste water treatment works Pretoria, South Africa: Water Research Commission, (1074).

SEOAll. (2022). Sustainable energy for all country data-Chad. https://databank.worldbank.org/source/sustainable-energy-for-all

Segurado, R., Pereira, S., Correia, D., & Costa, M. (2019). Techno-economic analysis of a trigeneration system based on biomass gasification. Renewable and Sustainable Energy Reviews, 103 (November 2018), 501-514. https://doi.org/10.1016/j.rser.2019.01.008

Sen, K., Mahalingam, S., & Sen, B. (2013). Rapid and high yield biogas production from Jatropha seed cake by co-digestion with bagasse and addition of Fe2+. Environmental Technology (United Kingdom), 34(22), 2989–2994. https://doi.org/10.1080/09593330.2013.798000

Sherman, E. (2016). Quantitative characterization of biogas quality a study of biogas quality at stormossey. https://urn.fi/URN:NBN:fi-ankm-201604299562

Staubmann, R., Foidl, G., Foidl, N., Gübitz, G. M., Lafferty, R. M., Valencia Arbizu, V. M., & Steiner, W. (1997). Biogas productions from jatropha curcas press-cake. Applied Biochemistry and Biotechnology - Part A Enzyme Engineering and Biotechnology, 63–65 (1), 457–467. https://doi.org/10.1007/BF02920446

Suhartini, S., Lestari, Y. P., & Nurika, I. (2019). Estimation of methane and electricity potential from canteen food waste. IOP Conference Series: Earth and Environmental Science, 230(1). https://doi.org/10.1088/1755-1315/230/1/012075

Troare, A. S. (1992). Biogas production from Calotropis procera: A latex plant found in West Africa. Bioresource Technology, 41(2), 105–109. https://doi.org/10.1016/0960-8524(92)90178-Z

USDA. (2022). Chad. Vitelli, J., Madigan, B., Wilkinson, P., & van Haaren, P. (2008). Calotrope (Calotropis procera) control. The Rangeland Journal, 30(3), 339. https://doi.org/10.1071/R0706
