# VALORIZATION OF PALM OIL MILL EFFLUENTS FOR BIOGAS PRODUCTION IN NIGERIA; A REVIEW OF PROCESS PARAMETERS, REACTION PATHWAYS AND APPLICATION OF PRODUCTS

**[1]Akande, T. Y., [1]Mohammed, I. S., [1]Aliyu M., [1]Mohammed, A.I., [2]Abubakar, A. I.**
**[1]Mamudu, N., [1]Bello, K.**

[1]Department of Agricultural and Bioresources Engineering, Federal University of Technology, Minna.
[2]Department of Chemical and Petroleum Engineering, Bayero University, Kano.
Corresponding Author: akandetimothy9@gmail.com 08065187895

## ABSTRACT

Nigeria need to leverage on the strength of being the fifth largest producer of palm oil in the world to solve lingering energy problem and approach the use of zero waste technology and generate renewable energy. There are more than five wastes which can be generated from palm tree, among these wastes, there is palm oil mill effluent (POME) which usually not seen important and has ability to generate biogas for commercial use. The use of POME for anaerobic digestion (AD) allows proper waste management through controlling pollution/waste accumulation and converting organic matter into higher-value products of biogas production. The proper use of POME will disallow usual approach of disposing the palm oil mill effluent to the surrounding and water bodies which is characterized with high human and environmental threats. The review centers on valorizing palm oil mill effluent and it proper managements which can be used for biogas production.

***Keywords:*** *Nigeria Energy Usage, Palm Oil Mill Effluent, Biogas Production, Valorization, Waste management*

## INTRODUCTION

Bio-energy has been recognized as one of the solutions to energy future. It is a renewable source of energy that can provide heat, electrical energy, and transportation fuels which can reduce $CO_2$ emissions, Sulphur and Heavy Metals in the atmosphere (Sam-Anyaoma et al., 2018). As the Nigeria population continues to increase with its associated rapid development, especially in areas where the demand on fossil resources had been very low per capital, it is expected that the energy and material needs of human society will become unprecedented in the near future. This will lead to more demands and increasing cost of fossil resources for energy, fuels, chemicals and materials. It has also become apparent that fossil fuels emit greenhouse gases and the continued emissions of these gases are influencing the world climate. The reduction of global demand for fossil fuel resources has been proposed as a major strategy to better the effects of climate change (Okorie, 2010).

Biomass encompasses materials derived from plants, animals, humans as well as their wastes. Depending on the characteristics of wastes, they can be converted into energy or fuel by combustion, gasification, co-firing with other fuels and ultimately by anaerobic digestion (Sam-Anyaoma et al., 2018). This high percent share of biomass represents its use to meet off-grid heating and cooking, mainly in rural areas and by the urban poor. It has been estimated that about 80% of Nigerian households living in the rural and urban areas use wood fuel and charcoal for cooking and heating (Simonya et. al., 2013). Electricity is therefore needed for economic, development and improved standard of living (Simonya et. al., 2013). Nigeria electricity supply system is an interconnected national grid system (Akinbami, 2001). Access to electricity is however low- about 40% on the average and as low as 18% in the rural areas (Simonya et. al., 2013) because of the low amount of electricity produced in Nigeria (Simonya et. al., 2013). In addition, close to 60% (that is, 80 million) Nigerians are not connected to the national electricity grid. There is also frequent power outages that can last up to 20 hours daily in places connected to the grid (Akande and Olorunfemi, 2009).

With the use of palm oil, which appears as one of the most promising productive alternatives for Nigerian agricultural sector to industrialization (Akinniran et. al., 2013). Research has been widely conducted on potential bio-power from palm oil processing wastes recently, where Nyakuma 2015 and Rahatu reported potential of electricity generation from Malaysia oil palm industry, lignocelluloses biomass which is produced from the oil palm industries include palm kernel cakes (PKC), palm kernels shell (PKS), empty fruit bunch (EFB), oil palm tusk (OPT), oil palm fronds (OPF) press fibers (PPF) and palm oil mill effluent (POME) as shown in figure 1 and 2.

Palm oil mill effluents (POME) have been variously reported with regard to general physico-chemistry and heavy metals, microbiology and possible contributions of POME to greenhouse effects. On the gaseous emissions, studies have been conducted by Ohimain et al. 2014. These wastes typically cause attendant environmental impacts. POME is the effluent from the final stages of palm oil production in the mill. It is colloidal suspension containing 95-96% water, 0.6-0.7% oil and 4-5% total solids including 2-4% suspended solids. POME is always regarded as a highly polluting wastewater generated from palm oil mills. However, re-utilization of POME to generate renewable energies in commercial scale has great potential. Anaerobic digestion is widely adopted in the industries as primary treatment for POME. Biogas is produced in the process in the amount of 20m3 per ton FFB. This effluent could be used for biogas production through anaerobic digestion.

There are some technologies which can be used for POME residue, and to generate high production rates of these residues exploits, resulting in the production of valuable bioproducts and bioenergy (Cruz et. al., 2021), like biohydrogen (Meier et al., 2020), bioethanol (Puteri et al., 2018), fermentation (Kumar et al., 2020), and so on. Anaerobic digestion is a more appropriate solution for addressing this environmental issue as it also produces a biomethane, which is particularly valuable for being used locally to produce heat and electricity (Grando et al., 2017), and an effluent containing nutrients (nitrogen, phosphate, and potassium) which can be applied as biofertilizer in agriculture (Alves et al., 2022).

## NIGERIA ENERGY HISTORY

The first energy era in Nigeria was the pre-industrial era (Edomah et al., 2016), which spans several centuries from 1500 up to mid-1800s. In this era, the primary energy resource used was organized (peasant) agriculture. This resource was effective for the kind of work and society that was needed at that point in time, which mostly related to manual work and walking. Manual work was what was needed to produce agricultural products and for transporting goods to markets (Edomah et al., 2016). In late 1800, the continued use of wood for heating and cooking was still very pre-dominant and there were really no technologies used to produce energy. The available technologies were still leveraging the older forms of energy which had also been used in the pre-industrial era (food palm oil mill effluents calories). However, the extensive use of metallurgical interventions added some new dynamics to energy use during this era.

The Nigeria, electricity is produced mainly from gas fired thermal plants and Hydro dams, other sources from which electricity can be generated include: Nuclear, Clean Coal, Solar PV, Wind, etc. Solar PV, Wind and other Renewable sources of electricity generation hold mixed blessings of exciting prospects and challenges to be overcome.

Until the recent implementation of the power sector reforms and privatization of the Power Holding Company of Nigeria assets, electricity power generation, transmission and distribution were the exclusive responsibilities of the Federal Government of Nigeria which national monopoly PHCN held absolute control (Osueke et. al, 2011).

State Governments in the part only intervene in the provision of power distribution infrastructure due to PHCN's lack-lustre performance in connecting communities to the national grid and/or expanding/maintaining existing power supply networks to meet growing. With the recent electricity bill assented to by Nigeria President in 2023 which authorizes states, companies and individuals to generate, transmit and distribute electricity (Mary C. 2023), there is a need to look further being the fifth largest producer of oil palm in the world which generates large solid waste from the sector with Nigeria population settings towards 200 million, this have been used to estimate potential thermal energy from solid wastes, biogas, biohydrogen, electrical energy and currency equivalent from palm oil mill effluents. Another effective use of managing the solid wastes is through the production of bioelectricity which is due to its energy content, calorific heating value (CHV) of oil palm processing wastes.

The liquid waste released during the palm oil extraction process is known as palm oil mill effluent (POME). Fresh POME is generally acidic (pH 3.3–4.6), high in temperature (60–80 °C), thick, brownish in color with solids (1330–50,700 mg/L), with oils and fats (190–14,720 mg/L), a biochemical oxygen demand (BOD) of 8200–35,000 mg/L, and chemical oxygen demand (COD) of 15,103–65,100 mg/L. Regulations regarding quality standards for the discharge of POME into the environment or water bodies to prevent the negative effects of POME waste have been established. The latest regulations state that the COD and BOD standards were set at lower than 250 mg/L and 100 mg/L, respectively (Saputera et al., 2021).

POME is one of the world's most polluting waste waters due to its high organic matter content and it is 100 times more polluted than municipal sewage. Each tonne of palm oil produces approximately 5.5–7.5 tonnes of POME. While, about more than 50 million $m^3$ of POME is generated globally each year.

With Nigeria several sustainable development goal with it aims by 2030 in clean renewable energy, response consumption and production and climate action, biogas production can contribute to achieve these goals. According to the European Biogas Association (2020), the sector decreases emissions through several different pathways, like avoiding pollution by substituting fossil fuels, preventing methane escapes from manure, producing green fertilizer that substitutes carbon-intensive chemical fertilizers and storing carbon in soils. Therefore, waste generated from palm oil mill residues, would be a valuable feedstock for the development of clean and renewable energy for agro-industrial regions and, simultaneously, a tool for mitigating the environmental effects of agro-industrial production (Cruz et. al., 2021).

## PALM OIL MILL EFFLUENT

Palm oil mill effluent is waste of palm oil (monoecious crop) which is botanically known as Elaeis guineensis, an ancient plant originated from and grown in tropical rain forest region of West Africa, it serves as the sole source of palm oil to humans, brought by a Dutch in 1884 the first African oil palm seedlings from Far East that spawned the Southern Asia oil palm industry and usually grow up to 60 feet and more in height (Simonya et. al., 2013). POME is one of the world's most polluting waste waters due to its high organic matter content and it is 100 times more polluted than municipal sewage. Each tonne of palm oil produces approximately 5.5–7.5 tonnes of POME. While, about more than 50 million $m^3$ of POME is generated globally each year. POME is a viscous, dense brownish liquid with significant quantities of colloidal matter that is acidic (pH 3.7 to 4.5), wastewater sludge that separates from the oily foam when the palm fruits are being boiled, it has unpleasant odour. POME also has a high chemical and biochemical oxygen demand (COD and BOD), ranging between 69,500 and 89,591 mg/L and 34,771 and 48,300 mg/L, respectively.

Anaerobic digestion of POME typically produces biogas which is a mixture of methane and carbon dioxide in 65 and 35% composition respectively, The methane produced from the anaerobic digestion of POME has a good potential for power generation using gas engine. Biogas production from POME range from 20 – 28m$^3$-$CH_4$/m$^3$- biogas. The power generated from POME can be transferred to the grid and consumed locally for domestic, industrial and commercial purposes as shown in table 1.

With this, the attendant environmental pollution associated with POME is prevented (Ohimain et al., 2017).

## AD for POME Approach to Biorefinery

Previous studies had tried to improve the sustainability of the palm oil industry by valorizing the palm oil waste into several products. Yoshizaki et al. 2013, proposed a new approach for the integrated technology of biogas energy and compost production for a palm oil mill. The integrated biogas compost technology was found to be the most economically viable alternative for biomass utilization at the mill. The study by Ali et al. 2015, which extended the work of Yoshizaki et al. 2013, proposed a sustainable and integrated biorefinery concept for the palm oil mill, which showed a huge potential to enhance the economic improvement locally by generating a potential profit about 6 million and 15–20 new jobs at any given mill as well as reducing emissions. Kasivisvanathan et al. 2012, examined an integrated palm oil-based biorefinery by incorporating multiple biomass processing platforms with combined heat and power (CHP).

Tan et al. 2020, presented an integrated palm oil complex concept to utilize POME as it is desired to investigate the trade-offs between POME elimination and biogas utilization strategies as different palm oil based complex configurations come with distinctive benefits and drawbacks. POME evaporation can serve as a consolidated liquid waste treatment for palm oil refinery effluent (PORE).

### 3.1.1 Process parameters affecting biogas production from AD

Several successive chemical and biochemical processes occur during AD process which involves a consortium of microorganisms and enzymes. However, the environmental conditions can alter the behaviors of these microorganisms and, as a result, several studies have indicated that the monitoring and control of operating conditions during which the AD can boost its efficiency and ensure stable methane generation (Cruz et al., 2021). Therefore, some critical operational conditions, which are expected to improve the AD efficiency, may be continuously maintained within optimum ranges. These topics have been elaborated on below:

### 3.1.1 Temperature

The temperature profoundly influences methane production once it affects bacterial performance. AD process may be operated at psychrophilic (10–20°C), mesophilic (30–40°C), or thermophilic (50–60°C) (Ryue et al., 2020). In the psychrophilic range, because of the low temperatures, the microbial growth is limited, and the reaction rates are slow, the reason why it is probably the least studied temperature range (Tassew et al., 2019). The thermophilic range provides some advantages like accelerated reaction rates, high gas production, and higher pathogen removal (Buffi ere et al., 2018). Chavadej et al. (2019) investigated the production of $H_2$ and $CH_4$, separately, from cow waste under thermophilic temperature (55°C). However, thermophilic digesters are generally considered more energy-intensive and less stable than mesophilic ones (Mao et al., 2015). Then, the mesophilic range is the most commonly preferred (Leung and Wang, 2016). Finally, Amorim et al., 2019 investigated the methane production and organic matter removal via the anaeraobic digestion anaerobic digestion of CW at 32°C and 39°C with different inoculums (cattle and goat rumen) (Cruz et al., 2021). After the range choice, it is also essential to give attention to temperature control; once if digestion temperature variations exceed 5°C within a short time, this may lead to a significant decline in the biogas yield (Gaballah et al., 2023).

### 3.1.2 pH

The pH values indicate the acidity/alkalinity of a given solution. A stable pH indicates

system equilibrium and digester stability. A falling pH can point toward acid accumulation and digester instability. Anaerobic bacteria, especially the methanogens, are extremely sensitive to pH in the reaction. During digestion, the two processes of acidogenesis and methanogenesis require different pH levels for optimal process control. Alastair et al. 2008, pointed out that the optimal pH of methanogenesis is around pH 7.0, the optimum pH of hydrolysis and acidogenesis is between pH 5.5 and 6.5 as reported. This is an important reason why some designers prefer the separation of the hydrolysis/acidogenesis and acetogenesis/methanogenesis processes in two-stage processes. It was suggested that pH value below 7 could prevent methanogenesis from acetate and also inhibit the microbial population that is in the system. The reported optimal pH range appears to be at neutral state from 7 to 7.2.

### 3.1.3 Volatile fatty acids (VFA)

Volatile fatty acids (VFA) are intermediate compounds (acetic HAc, propionate HPa, ethanol Het, lactate LA and butyric HBu) that are produced during acidogenesis. Volatile fatty acids can be inhibitory to the production of methane. The increase concentration of acid exhibits the effect of fermentation digestion. Hydrogen plays a significant role in preventing the formation of methane if the accumulation of acids is out of control. The high concentration of VFA will decrease the pH value and indirectly disrupt the fermentation process. AD processes will not work below certain pH value as mentioned above. It has been shown that fermentation of glucose is inhibited at total VFA concentrations above 4gram. Acetic acid is usually present in higher concentrations than other fatty acids during anaerobic digestion, but propionic and butyric acids are inhibitory to the methanogens. Propionic acid concentrations over 3000 mg $l^{-1}$ have previously been shown to cause digester failure. In a more recent study, it was found that propionic acid was an effect rather than a cause of inhibition of anaerobic processes (Cruz et al., 2021).

As shown in many studies, the conversion rates of VFAs to methane vary in the order of acetic acid HAc > ethanol (HEt) > butyric acid (HBu) > propionic acid (HPa).

Lactic acid, which has the potential to be converted to HPa, is an undesirable terminal fermentation product. Therefore, accumulation of HPa always results in failure of methanogenesis. Y. Wang et al. 2009 mentioned that when the highest concentrations of ethanol, acetic acid and butyric acid were 2400, 2400 and 1800 mg $L^{-1}$, respectively, there was no significant inhibition of the activity of methanogenic bacteria. However, when the propionic acid concentration was increased to 900 mgL, significant inhibition appeared, the bacteria concentration decreased from 6 _ 107 to 0.6, 1_ 107$ml^{-1}$.

### 3.1.4 Carbon to Nitrogen Ratio (C/N)

The relationship between the amount of carbon and nitrogen present in organic materials is represented by the C/N ratio. A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a 51 lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C/N ratios in anaerobic digesters are between 20 – 30 in order to ensure sufficient nitrogen supply for cell production and the degradation of the carbon present in the process, and in order to avoid at the same time excess nitrogen, which could lead to toxic ammonium concentrations. Thus, the optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with sewage or animal manure.

### 3.1.5 Effect of toxicity on digestion

Toxic compounds affect digestion by slowing the rate of metabolism at low concentration, or by poisoning or killing the organisms at high concentration. The methanogenic bacteria are generally the more sensitive, although all groups involved in digestion can be affected. In order to control and adjust operation, to minimize toxic effects, it is important to identify inhibition in its early stages. The two main indicators of inhibition are:

- Reduction in methane yield, indicated by two or more consecutive decreases of more than 10 % in daily yield at a constant loading rate;

- Increase in volatile acids concentration, generally occurring when the total volatile acid (expressed as acetic acid), the normal range of about 250 to 500 ppm (mg/L).

The major toxicants usually encountered with feed stocks are ammonia, Hydrogen sulphide, volatile acids, and heavy metals.

Ammonia ($NH_3$) is derived from digestion of protein during the hydrolysis stages of AD process, which is also important source of nutrients for growing plants, thus this compound can be used as fertilizers. High concentration of ammonia is toxic or inhibitory to anaerobic microbial populations, methanogens.

Hydrogen sulphide ($H_2S$) originates from the primary raw materials such as silage and sewage sludge, in which high concentration of sulphide is present. If sulphide concentration is the dominant composition during AD process, it may avoid biomethanization in favour of sulphide production. Sulphide is important in the production of sulphur amino acids in bacteria and it also acts as a chemical reducing agent allowing growth of anaerobic microorganisms.

Heavy metals can be present in significant concentrations in municipal sewage and sludge. The heavy metals identified to be of particular concern include chromium, iron, cobalt, copper, zinc, cadmium, and nickel. An advantage of heavy metals is that, unlike many other toxic substances, they are not biodegradable and can accumulate to

potentially toxic concentrations. The concentration of these heavy metal ions must be

kept low, in order to maintain the growth of certain bacteria and to support methanogenesis.

Nutrients are essential for the growth of bacteria. Municipal wastewater sludge usually contains all the nutrient quantities that is require for optimal growth. These macronutrients are carbon, nitrogen, phosphor and sulphur. The optimal ratio is considered to be 600:15:5:1, in which nutrients must be sufficient to maintain the growth of bacteria, insufficient elements and nutrients may lead to inhibition effect and cause disruption in the AD process.

### 3.1.6 Organic loading rate (OLR)

The organic loading rate (OLR) is the quantity of organic matter fed per unit volume of the digester per unit time, (kgVS/$m^3$/day). OLR plays an important role in anaerobic wastewater treatment in continuous systems and is a useful criterion for assessing performance of the reactors. A higher OLR feed rate may cause crashing of

anaerobic digestion if the acidogenic bacteria multiply and produce acids rapidly (Buekens 2005). Many industrial plants have reported system failures due to overloading (Fdez-Güelfo et.al.,2012). Maximum OLR for an anaerobic digester depends on a number of parameters, such as reactor design, wastewater characteristics, the ability of the biomass to settle, and activity among others.

### 3.1.7 Hydraulic retention time

The Hydraulic Retention Time (HRT) is the time needed to achieve the complete degradation of the organic matter. The retention time varies with process parameters,

such as process temperature and waste composition. The retention time for waste treated is from 15 to 30 days and 12-14 days for thermophilic digester (Singh et. al., 2009). Reducing HRT reduces the size of the digester, resulting in cost savings. Therefore, there is an active incentive to design a system that can achieve a complete digestion in shorter HRT. A shorter HRT will lead to a higher production rate per reactor volume unit, but a lower overall degradation. These two effects have to be balanced in the design of the full-scale anaerobic digester.

### 3.1.8 Mixing

The objective of mixing in a digester is to improve the contact between the microorganisms and substrate. Mixing distributes the heat and bacteria uniformly in the digester; furthermore, mixing prevents scum formation and avoids temperature gradients within the digester. However, excessive mixing can disrupt the microbes thus slow mixing is preferred, also Alastair et al. 2008, noted that evidence suggests that minimal mixing in the digester is preferable unless there is some form of microbial support material used which prevents the active microbial biomass. However, the optimal mixing pattern is still a topic of debate. Mixing can be achieved through several methods, including mechanical mixers, re-circulation of digester contents, or by re-circulation the produced biogas to the bottom of the digester using pumps.

### 3.1.9 Available feedstock for AD

Various types can be used for the production of biogas: animal manure and slurries, crop residues, organic wastes from dairy production, food industries, wastewater sludge, organic fraction of municipal solid wastes, organic wastes from households and from catering business as well as energy crops. Biogas can also be collected, with special installations, from landfill sites. One main advantage of biogas production is the ability to use “wet biomass” types as feedstock (Dumitru, M. 2012), all characterized by moisture content higher than 60–70% sewage sludge, animal slurries, flotation sludge from food processing etc.). In recent years, a number of energy crops (grains, maize, grass silage), have been largely used as feedstock for biogas production in countries like Austria or Germany (Dumitru, M. 2012). Besides energy crops, all kinds of agricultural residues, damaged crops, unsuitable for food or resulting from growing and weather conditions, can be used to produce biogas. A number of animal by-products, not suitable for human consumption, can also be processed in biogas plants.

### 3.1.10 Inoculums

Inoculums biomass is very important not only for start-up of anaerobic digesters, but also during long lasting biochemical processes, since it has been noticed that anaerobic digestion of organic matter such as municipal solid waste which do not completely stopped even after 360 days of processing. Different types of inocula have been used in the anaerobic digestion, such as swine manure, sewage sludge, cattle manure, and solid urban residues (Forster-Carneiro et al., 2007; Gu et al., 2014).

Carmen Mateescu 2011 reported the effect of inoculums to biogas production which was conducted by several researchers with the results inoculums are substantially relevant in process kinetics of biogas production; amount of methane produced seemed proportional to the initial inoculums; the higher percentage of inoculums gave the higher production of biogas; and the food to inoculums affected the biogas production rate. A more economically viable alternative is the use of inoculum because, besides reducing the hydraulic retention time (HRT), the addition of this material maintains the biochemical processes lasting, reaching a high-quality biogas production (Gu et al., 2014; Maamri & Amrani 2014).

### 3.1.11 Nature of substrate

The first biogas plants, modeled on technologies used in Germany, were based on corn silage and liquid co-substrates from agriculture(manure) and processing. Research into biogas production has found that the addition of mixed substrate co-digestion can yield significantly higher production yields than manure alone. Therefore, it is common practice among companies that use biogas for energy production to use manure and slurry or other components, such as energy crops, grass silage, corn silage, etc., in various combinations and different proportions (Ignatowicz et al., 2023). Raw materials for biogas production are divided into mono-substrates and co-substrates. Mono-substrates have the ability to ferment due to the presence of methane bacteria, such as slurry, manure, the stomach contents of animals, especially ruminants, and have a broad composition of macro-and micronutrients necessary for the growth of microorganisms. Co-substrates are added to the digester to increase the efficiency of the process, achieve adequate hydration or prevent inhibition.

### 3.1.12 Pressure

High pressure produced in the biogas digester during anaerobic treatment could affect the production rate of methane. Ohimain et al., 2017 reported that barophilic microorganisms may be present in POME, although none have been reported. At high pressure, the microbial and chemical equilibrium of the system could be challenging if the methane produced is not tapped instantly into use. Low methanogenic bacteria population in POME could result to low yield of methane (Ohimain et al., 2017). The overall pressure that occurs during biogas production could adversely affect bacteria if the weight of the gases outside the reactor is greater than the force inside the system. Negative pressure will pull air into the reactor and the mixture (biogas and air) may explode. When such an explosion occurs, the oxygen in the air destroyed the microbial properties of the POME and methane production ceases. This could be adverted by tapping the methane as its being produced (Ohimain et al., 2017).

### 3.1.13 Chemical Oxygen Demand (COD)

Chemical Oxygen Demand (COD) content describes the amount of oxygen needed to completely oxidize the waste under aerobic conditions, and is determined experimentally by measuring the amount of a chemical oxidizing agent needed to fully oxidize a sample of the waste. It is used as a measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant. Oxygen is not consumed in anaerobic digestion, and so, no reduction of COD can occur. In this situation, COD is removed by converting organic compounds to methane ($CH_4$), a significant amount of $CO_2$, $H_2$ and negligible amounts of other gases like $H_2S$ (Mathew et al. 2016). So the methane potential of a waste (by microorganisms) is related to the concentration of organics (COD) in it and in the efficiency of the system.

### 3.2 Co-Digestion and Design Mechanism for AD of POME

Anaerobic co-digestion (AcoD) is the concurrent digestion of more than one organic matter to overtake certain mono digestion disadvantages (Kainthola et al., 2019). The AcoD process presents some main benefits: balancing the nutrients content and optimizing the C/N ratio, reducing inhibitory effects by dilution, increasing the feedstock digestibility, and enhancing methane production (Ghosh et al., 2020).

Nonetheless, selecting substrates for co-digestion depends on the synergy between mixing two or more substrates. These synergies include improving the biodegradability that may be absent for a specific substrate type and balancing out nutrients for achieving the optimal condition (Ryue et al., 2020). AcoD also decreases the amount of alkali needed for pH control and provides a methanogen inoculum (Wadjeam et al., 2019).

#### 3.2.1 Mechanism of AD for POME

Biogas production by palm oil mill effluent is a combinational activity of diverse microbial populations. According to Heeg et al. 2014, the AD chain is initiated by bacteria that are responsible for the hydrolysis of high molecular weight organic substances. Subsequently, the mono- and oligomers produced are further degraded to volatile fatty acids (VFAs) (acidogens) and then to acetic acid, as well as $CO_2$ and $H_2$ (acetogens). The final stage (methanogenesis) is accomplished by acetoclastic and hydrogenotrophic Archaea, which convert acetic acid or $CO_2$ /$H_2$ into methane.

The anaerobic digestion mechanism processes involved in POME showed in figure 4.

##### 3.2.1.1 Hydrolysis

The very first stage of AD is very important as large organic molecules are not readily absorbable. In this stage several microbes secrete different enzymes, which cleave the macromolecules into simpler forms. Organisms that are active in biogas process during the hydrolysis of polysaccharides include various bacterial groups such as Bacteriodes, Clostridium, and Acetivibrio (Cirne et al. 2007; Doi 2008; Heeg et al. 2014).

##### 3.2.1.2 Acidogenesis

The diversity of the microbial consortium involved in AD reaches its peak during this stage. Most of the microbes involved in hydrolysis stages are also involved in fermentation. Along with them, microbes belonging to the general like Enterobacterium, Acetobacterium and Eubacterium also carry out the process of fermentation (Schnurer and Jarvis 2010). Through various fermentation reactions, the products from hydrolysis are converted mainly into various organic acids (acetic, propionic acid, butyric acid, succinic acid, lactic acid, etc.), alcohols, ammonia (from amino acids), carbon dioxide and hydrogen. Exactly which compounds are formed depends on the substrate and environmental process conditions, as well as on the microbes present (Schnurer and Jarvis 2010).

The fermented products are oxidized into simpler forms. According to Heeg et al. (2014), the AD process requires close co-operation between the microbes that carry out oxidation and the methanogens that are active in the next stage (which actually produce methane). Substrates for acetogenesis consist of various fatty acids, alcohols, some amino acids and aromatics (Heeg et al. 2014). In addition to hydrogen gas, these compounds primarily form acetate and carbon dioxide (Heeg et al. 2014). Syntrophomonas, Syntrophus, Clostridium, and Syntrobacter are examples of generic in which there are numerous organisms that can perform acetogenesis in syntrophy with an organism that uses hydrogen gas (McInerney et al. 2008).

### 3.2.1.3 Methanogenesis

Methanogenesis (final stage inside AD) is the methane production pathway which methanogens follow to obtain energy. This process involves the fermentation of various organic compounds with methane gas as the major end product along with carbon dioxide, hydrogen and traces of other gases. Methanogenesis has six major pathways, each converting a different substrate into methane gas. The six major substrates used are carbon dioxide, formic acid, acetic acid, methanol, methylamine, and dimethyl sulfate (Slonczewski and Foster 2014). The most common pathway converts carbon dioxide into methane through the reduction of $H_2/CO_2$ (Slonczewski and Foster 2014). The other five pathways may be converted into two according to various methanogen specific-cofactors. The pathway which leads to the methane production solely depends on the methanogenic consortia and the availability of the suitable substrates that favors the digestion process. Methane is, therefore, a by-product of this anaerobic decomposition process that aims to break down organic acids and produce energy for the microbes present in the environment (Wang et al. 2011).

The pathway processes of anaerobic digestion in POME showed in figure 3.

## 3.3 Application of AD Products

In the search for maximizing the economic and environmental feasibilities of AD plants, this section brings information about the main products of AD processes:

### 3.3.1. Biogas

Among all sustainable and renewable energy sources, biogas has significantly received attention as a relevant biofuel (Qyyum et al., 2020). Its utilization in energy generation brings several economic, environmental, and climate advantages (Gaballah et al., 2020) as shown in figure 5. Biogas depend on the source of organic matter used, it mainly consists of methane (50–75%), carbon dioxide (25–50%), and traces of other gases, such as ammonia, hydrogen, and hydrogen sulfide (Merico et al., 2020). It can be applied for heating/electricity production or upgraded to biomethane and employed as vehicle fuel or pumped into natural gas grids (Westerholm et al., 2020). In the latter cases, the upgrade process must clean the biogas from $CO_2$ and other impurities and thus increase the methane content and its heating value (Gustafsson et al., 2020).

Biogas and Bio-Natural Gas (BNG) have played relevant roles in renewable energy strategies, mainly in European and Asian countries, which understood the necessity to formulate relevant policies and regulations to support this industry growth (Xue et al., 2020). In Europe, for example, 18,202 biogas installations were in operation in 2018, which represented a Europe-wide installed electric capacity (IEC) of 11,082 MW and 63,511 GWh produced from biogas (EBA, 2019).

The report said on a year-on-year basis, electricity supply declined by 1.74 per cent compared to 5,956 (Gwh) reported in first quarter 2022. The National Bureau of Statistics (NBC) said power supply in Nigeria increased in the first quarter of 2023 to 5,852 gigawatt hours (Energy Times, 2023). Yet, traditional biomass (wood fuel and charcoal) accounted for 85% of total energy consumption which has contributed to desertification, deforestation and erosion in the country. Therefore, this is the right time for Nigeria to embrace the strength gotten in palm oil production and quickly harness POME high chemical and biochemical oxygen demand (COD and BOD), which ranges between 69,500 and 89,591 mg/L and 34,771 and 48,300 mg/L respectively.

### 3.3.2 Digestate

Digestate is composed of mineral which is not entirely degraded organic molecules. It is a valuable AD by-product once it contains vital nutrients (N, P, K, etc.), which allows its use as organic fertilizer (Slepetiene et al., 2020). When compared with undigested manure and chemical fertilizers, the digestate application leads to higher available nutrients, increased microbial activity, increased nitrogen mineralization capacity and soil respiration (Kataki et al., 2017). Therefore, the digestate application as fertilizer allows the circular economy approach and decreases the mineral fertilizer demands, which is usually associated with a negative impact on the environment (Banaszyk et al., 2020).

Despite the digestate beneficial properties, it has to meet quality standards in terms of pathogens, heavy metals, and polychlorinated biphenyls (PCBs) (DaRos et al., 2018); besides that, digestate management and consumer demand rely on the digestate legal status as waste or by-product (Cruz et al., 2021). Still, many countries do not have a specific legal framework for digestate use, obligating it to be classified as waste, which leads to more expensive legal procedures for allowing its recovery and marketing (Guilayn et al., 2019). The variation in digestate composition has been indicated as a bottleneck for its marketing (Dahlin et al., 2015). Even minor variations in substrates used in an AD process can lead to changes in digestate properties (Czeka et al., 2020). Although some authors reported the digestate efficiency as fertilizers or soil amendment, other studies demonstrated potential biological adverse effects, e.g., due to the presence of heavy metals (Kupper et al., 2014), antibiotics (Jiang et al., 2018), pathogenic bacteria (Nag et al., 2020), and necessity of applying pretreatments to increase its quality to acceptable levels before its application (Alburquerque et al., 2012). These significant variations in the digestate quality resulted in more scientific debates about the behavior of anaerobic digestates as fertilizer agents. Risberg et al. (2017), for example, investigated a wide variety of organic fertilizers (20 digestates, 10 cow manures, and 10 pig slurries) concerning their chemical composition and their impact on soil microbial activity, it can be evaluated that three types of anaerobic digestate (cow dung, cow dung, rice straw/green gram stover/cow dung); each digestate feedstock was processed as separated solid, liquid and ash from solid digestate and characterized to understand their fertilizer prospects. From the FTIR spectra, it was inferred that the solid digestates could be used as organic amendments, while limited organic functionalities in liquid digestate implied its potential as a source of inorganic minerals. It was also observed that digestates from rice straw/green gram/cow dung were not phytotoxic in any application, whereas Ipomoea digestates in the liquid phase showed a relevant inhibitory effect on Vigna radiate.

Phytotoxicity or ecotoxicity analysis is an important parameter to evaluate the real digestate impact on crops, and it represents an index of its ecotoxicological impact (DaRos et al., 2018). Coelho et al. (2018) analyzed eleven samples of commercial liquid anaerobic digestates, using Lepidium sativum as bioindicators, and compared them to the concentrations recommended in the Irish digestate standards. Cruz et al. (2019) used Lactuca sativa as toxicity level bioindicators to evaluate the digestate from dairy wastewater inoculated with sewage sludge.

## CONCLUSION AND RECOMMENDATION

As a matter of urgency with the recent energy bill signed into law by Nigeria government, Southwest States which soil is adaptable for palm fruit should expand this study and tap this as a means of energy generation, that is, waste into energy and finance it extensively as shown in figure 5. This will not only produce biogas but will also bring economical, environmental and social gain to the state.

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Figures

Biogas Production Flow Chart

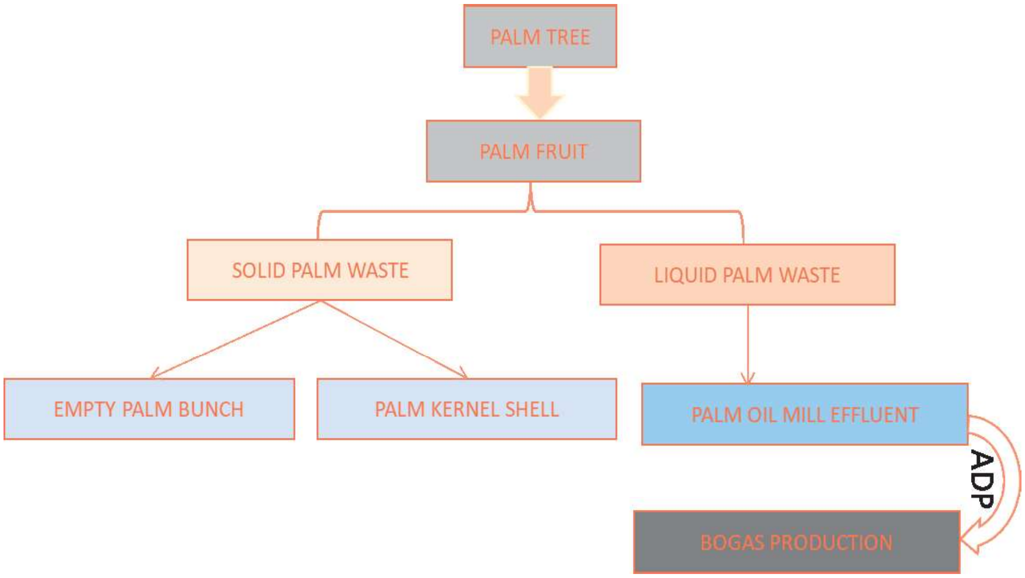

Figure 1: Palm oil to biogas production flow chat

Biogas Pathway

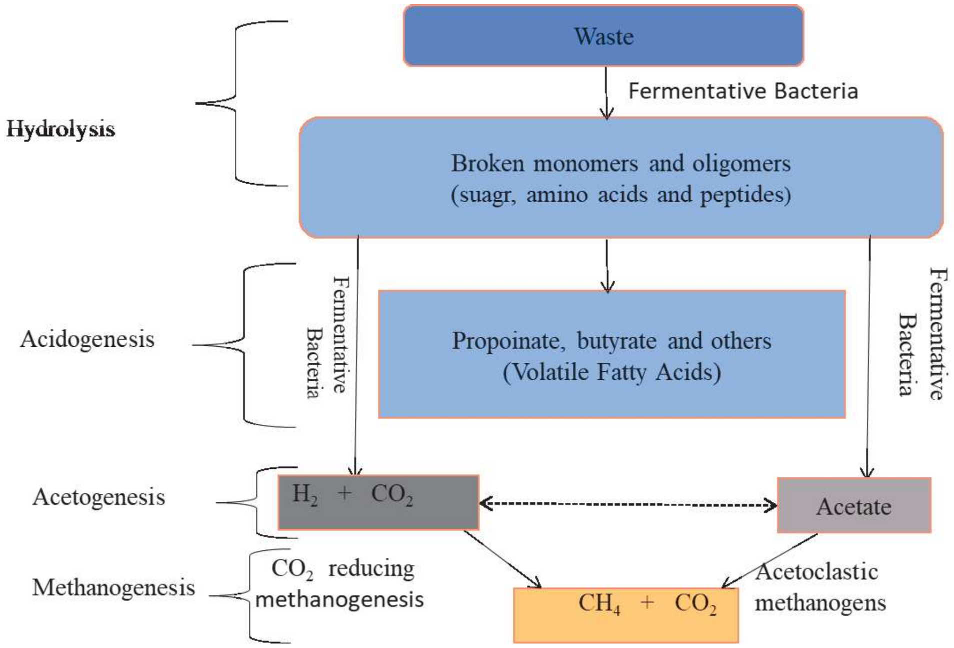

Figure 2: Volatile Fatty Acid to Methane pathway

Anaerobic Digestion Process Usage

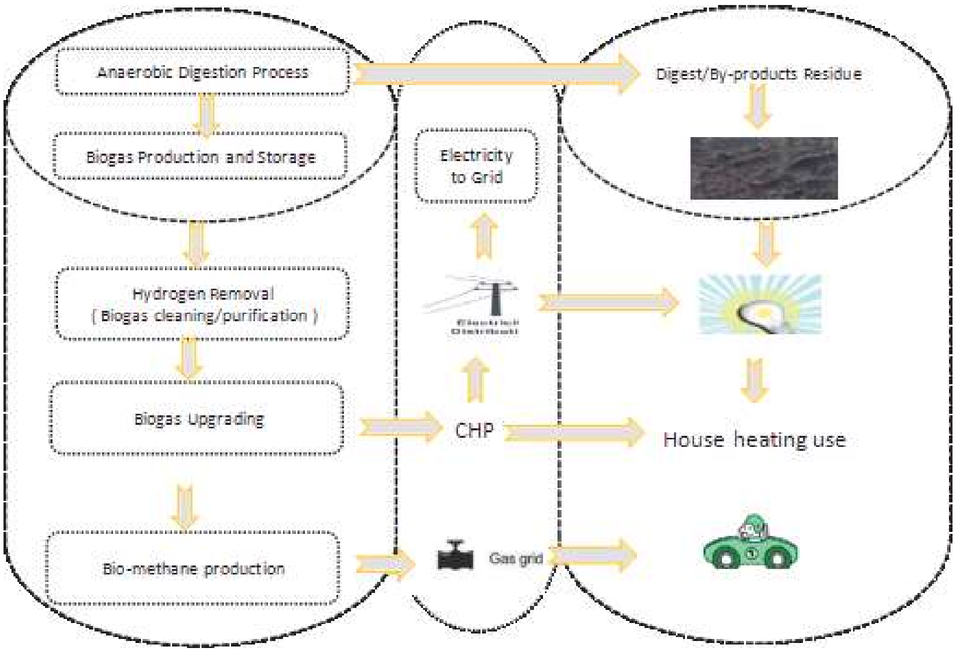

Figure 3: Anaerobic Digestion process for both Heating and Power System

AD Mechanism for POME

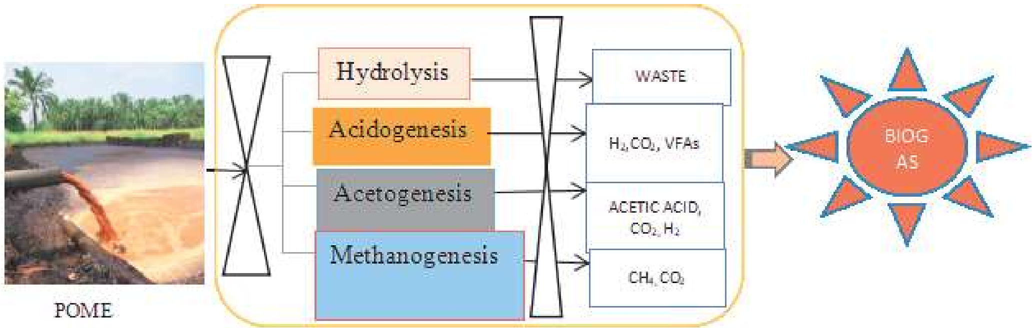

Figure 4: Anaerobic Digestion mechanism for POME

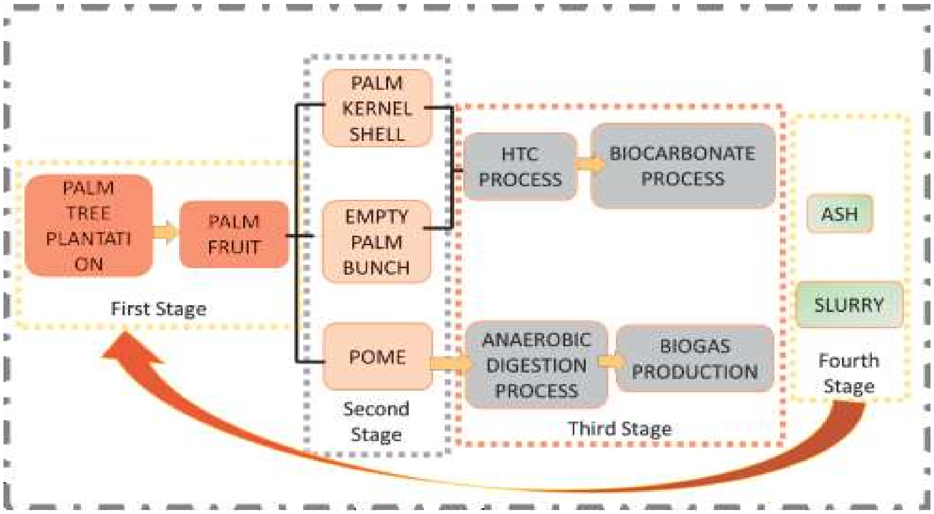

Figure 5: Resources maximization chart showing first stage to fourth stage

Tables

Table 1: Projected Potential Power from POME

| POME Capacity | POME Produced | | Potential Power |
|---|---|---|---|
| (FFB ton/hr) | m3/hr | m3/day | (nWe) |
| 30 | 21 | 400 | 1.1 |
| 45 | 31.5 | 600 | 1.6 |
| 60 | 42 | 800 | 2.1 |
| 90 | 63 | 1200 | 3.2 |
| 34,280 | 23,996 | 479,920 | 1280 |

Source: Rahayu 2015

Table 2: Oil Palm Waste generated from Crude Palm Oil (CPO) Production

| Oil Palm Wastes | Symbol | %OPW | OPW Generated (Tons) |
|---|---|---|---|
| Empty Fruit Bunches | EFB | 22.00 | 15,472,600 |
| Mesocarp Fiber | MCF | 13.50 | 9,494,550 |
| Palm Kernel Shell | PKS | 11.50 | 8,087,950 |

Source: Nyakuma 2015.