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RESEARCH PAPER

# Deployment of treated and compressed biogas as a sustainable fuel for ceramic kiln firing

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**Abstract.** Inefficiency, emission of greenhouses gases and the deleterious effects of carbonaceous fuels on both human health and the environment are responsible for the increased in exploration and adoption of eco-friendly and sustainable fuels to various aspects of human development and production processes. This study was aimed at the generation, treatment and compressing of biogas into Liquefied Petroleum Gas Cylinder (LPGC) for deployment to firing ceramic kiln. The methodology involved the anaerobic digestion of cow dung and the treatment of the generated gas using water scrubbing technology. The results of the study showed an increased in methane content from an untreated value of 43.5% to 93.98%, the elimination of CO<sub>2</sub>, and H<sub>2</sub>S; reduction in volume of gas used in firing a ceramic kiln to 1030 °C from 22,300 L of untreated biogas to 492 L of treated biogas, as well as the prevention of 108,000 g of methane, 124,00 g of CO<sub>2</sub>, 74,400 g of CO and 173.6 g of NO<sub>2</sub> from venting into the climate system.

**Keywords:** biogas; ceramic; deployment; emissions; fuel; inefficiency; kiln; treated

## 1. Introduction

Energy is a basic requirement for industrial development and socio-economic well-being of individuals, communities and nations. However, in spite of the obvious importance of energy in the overall growth, and development of the people; there appears to be a lack of commitment to the provision of this basic amenity in Sub-Saharan Africa, especially Nigeria (Bayart, 2009; Yagboyaju & Akinola, 2019). For example, while 35% of households are reported to have access to clean cooking energy in Asia, only 17% of the population have access to clean energy in sub-Saharan Africa (Clean Cooking Alliance 2018; IEA, 2019). The situation is even more acute in Nigeria, where a study has showed that, up to 94% of households do not have access to clean energy (IEA, 2019). The lack of access to energy in general and especially the sustainable ones, has led to the adoption of ineffective, inefficient and unsustainable sources of energy by households and businesses.

One area of production process that is severely affected by energy deficiency in Nigeria is ceramic production process; which currently rely on traditional fuels such as wood, kerosene, waste engine oil and sawdust as source of energy. These fuels are not only known to be

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unsustainable, inefficient, tiring and demanding in their use (Abubakar et al., 2019), but are also known to cause human respiratory problems and the emissions of Greenhouse Gases (GHG) (Peng et al., 2012). For example, fossil fuel, transportation, forestry and industrial activities which include ceramic processing and firing using both fossil, and traditional ceramic fuels were reported to emit 33 billion metric tons of CO<sub>2</sub> into the climate system in 2021 (IEA, 2021). Furthermore, human exposure to gaseous pollutants (CO<sub>2</sub> and NO<sub>2</sub>) from these processes, have been estimated to cause around 4.3 million annual premature deaths globally (WHO, 2016). These deaths comprise of 27% pollutants induced pneumonia, 18% stroke, 27% Ischaemic heart diseases, 20% chronic obstructive pulmonary disease and 8% lung cancer (WHO, 2021). These statistics are worrying and show clearly the environmental and health impacts of fossil-based fuels and the necessity for the adoption of sustainable and renewable alternative fuels.

However, prior to the deployment of renewable alternative energy, as ceramic fuel, the green credentials of ceramic processing were poor, and tainted with high carbon footprint, mainly due to its heavy dependency on traditional and fossil-based fuels and their attendant health and environmental consequences (IEA, 2021; WHO, 2021). To mitigate these negative environmental and health impacts; attempts have been made on the adaption of untreated biogas (raw biogas) as alternative fuel for ceramic kiln and furnaces (Abubakar & Sadiq, 2018).

Although firing ceramic kiln using raw biogas has some advantages such as the conversion of waste organic matter into energy, reduction in natural gas consumption, and overall reduction in CO<sub>2</sub> from non-fossil based fuels use (Fiehl et al., 2017; Bernal et al., 2017); however, increased NO<sub>2</sub> emission index, reduced burning capacity, low frame temperature, and narrow range of flame stability, lead to the increased of CO<sub>2</sub> emissions, as well as increased mass fraction of chain carrier radicals are disadvantages associated with the use of raw biogas (Sun et al., 2021; Hosseini & Wahid, 2013).

Similarly, the adaption of raw biogas to kiln firing has raised some concerns, with regards to the impact of the impurities contained in raw biogas on product quality, combustion behaviour, refractoriness of the kiln and furnaces, as well as the volume of gas required to fire a kiln (Fiehl et al., 2017). The main objective of this study, therefore, is to explore the possibility of upgrading the quality of biogas by removing the impurities contained in the gas via water scrubbing, compressing, and deploying it, to fire a ceramic kiln, with a view to address the concerns associated with the use of traditional ceramic fuels and untreated biogas in ceramic firing.

## **2. The concept of biogas scrubbing**

Biogas has been produced from a variety of biodegradable matter and utilized as a source of energy for a wide range of purposes, such as lumbering, lighting, cooking and for transportation purposes (Ali et al., 2013; Deepanraj et al., 2014; Kumar et al., 2015; Zhao et al., 2010)

Other studies, on the utilization of biogas for utilitarian purposes, including a study by Agrahari & Tiwari (2013), who investigated the generation of biogas from kitchen waste (Ye et al., 2013), and who investigated the anaerobic co-digestion of kitchen waste, rice straw and pig manure. Findings from the studies indicated that methane derived from the digestion of kitchen waste could be used for cooking, and lighting while the co-digestion of kitchen waste, rice straw and pig manure could generate biogas with up to 70% methane content- which is appropriate for cooking and lighting. A study by Njogu et al (2015), also showed that internal combustion engines, coupled with electricity generator could be powered successfully using water hyacinth generated biogas. Similarly, Matheri et al (2017) reported on biogas generation from anaerobic co-digestion of chicken manure, and organic fraction of municipal solid waste. Findings from the study showed that the generated biogas could successfully be used as an environmentally friendly and clean energy for industries, residential homes, and the transport sector.

The use of biogas is increasing. However, the complex composition of the gas, particularly, the presence of large amount of CO<sub>2</sub>, and other impurities have led to a reduced calorific value,

corrosion, and toxicity, as well as increased transportation cost, thereby limiting its economic viability for uses that occur at the far end of production (Shah & Nagarsheth, 2015; Zhao et al., 2010). The concept of biogas scrubbing, therefore, emanated from the need to make biogas more efficient, increase storage capacity, reduce storage space requirement, and make it readily usable by the end user.

Biogas is scrubbed to increase its calorific value, and convert it to higher fuel standard (Sun et al., 2015), first, by cleaning to remove minor unwanted components, and followed by upgrading to remove CO<sub>2</sub> (Kárászová et al., 2015; Raboni & Urbini, 2014); and the end product of such processes is called Biomethane.

Traditional biogas scrubbing techniques are based on the use of physical and chemical sorption (absorption and adsorption), separation (membrane and cryogenic), and methods (Adnan et al., 2019). However, the limitation of the traditional technologies to only the removal of CO<sub>2</sub> and H<sub>2</sub>S (García-Gutiérrez et al., 2016; Aziz et al., 2019) has led to the adaption of more advanced technologies, such as methanation of CO<sub>2</sub> and conversion of CO<sub>2</sub> using chemical and biological processes which are also not without some limitations.

Methanation is based on the reaction between CO<sub>2</sub> contained in biogas and H<sub>2</sub> to produce methane and other chemical materials (Gao et al., 2018). However, the requirement for high energy inputs, the kinetic, and thermodynamic stability of CO<sub>2</sub> (strong bond) are major drawbacks to the methanation process (Williams, 2013). Similarly, the conversion of CO<sub>2</sub> to methane requires the use of energy intensive reagents which could lead to the generation of waste and the increase of GHG footprint (Adnan et al., 2019). Consequently, hydrogenation, which is another process of converting CO<sub>2</sub> to CH<sub>4</sub> also depended on the use of catalyst (Su et al., 2016).

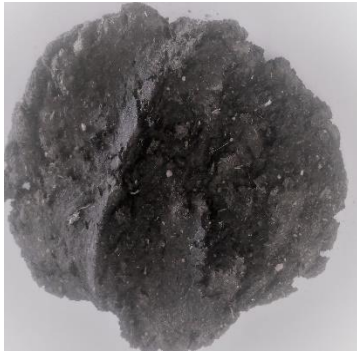
Biogas is also upgraded using microorganisms to convert CO<sub>2</sub> to valuable products through hydrogen fixation (Wu et al., 2017). However, the low volumetric energy density of H<sub>2</sub>, which is a responsible for the gas storage difficulties, is a major disadvantage of the process (Jürgensen et al., 2014). Recent studies have shown that, bacterial fermentation could also be used to convert the CO<sub>2</sub> contained in biogas, to high purity methane, while simultaneously producing carboxylic and succinic acid [SA] (Gunnarsson et al., 2014).

Consequently, the simultaneous upgrade of biogas, and the production of carboxylic, and succinic acid using organic fraction of kitchen waste has been investigated by Babaei et al. (2019). The results showed great potentials for biogas upgrade, and the substrate replacement of glucose with kitchen waste. However, as technology advances, it is expected that, more sustainable, cost effective, and novel technologies for biogas upgrade will continue to emerge. To this end, improving the calorific value of biogas for ceramic kiln firing, as well as the elimination of the concerns associated with its use, forms the basis of this study.

### **3. Methodology**

#### **3.1. Materials**

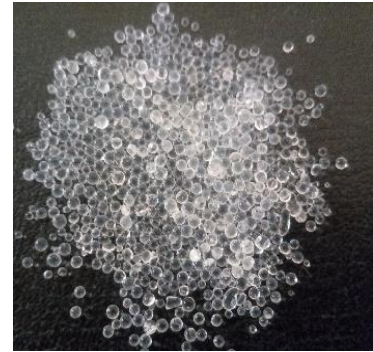
Dry cow dung (Figure 1) weighting 200kg containing 84% of organic matter, 4.4% nitrogen, 1.2% phosphorus, 3.1% potassium, biological and chemical oxygen demand of 20, and 92 respectively was sourced from the dairy farm of Abubakar Tafawa Balewa University Bauchi, and used as substrate for the anaerobic digestion process. As a digester, a 1000-liter plastic drum was used. For the upgrading of the produced biogas, a 21 liter clear plastic bucket submerged in water was used as a scrubber (Figure 2). The enhanced biogas was stored in 20 kilogram and 12.5 kg liquefied petroleum gas cylinders. A 3.5 horse power compressor used in the study was improvised at the Mechanical Engineering Department of Abubakar Tafawa Balewa University Bauchi. Silica gel (Figure 3), was sourced from the chemistry laboratory of Abubakar Tafawa Balewa University Bauchi, and a 4.5 Cubic Feet (CF) cross draft kiln (Figure 4), used in the study, was located at the Department of Industrial Design, Abubakar Tafawa Balewa University, Bauchi.



**Figure 1.** Dry Cow Dung



**Figure 2.** Water Scrubber



**Figure 3.** Silica Gel



**Figure 4.** 4.5 Cubic feet (CF) cross draft kiln

### 3.2. Methods

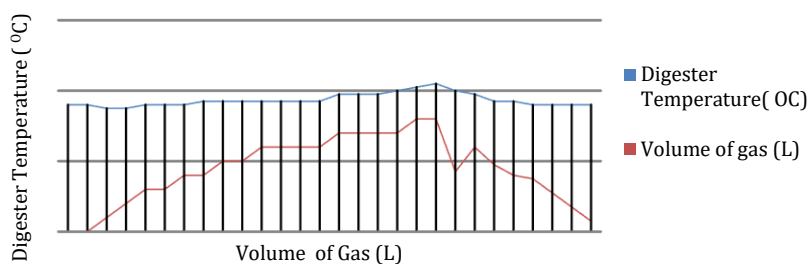
The biogas was derived from the anaerobic digestion of dry cow dung at a pH of 8.5 and carbon nitrogen ratio of 26:1 for the purpose of ceramic kiln firing. Although biogas with high methane content has been generated from chicken waste and other biodegradable matter (Singh et al., 2008); the selection of cow dung as a substrate was based on its accessibility and less than 1% hydrogen sulphide content (hydrogen sulphide is a very toxic gas) (Ofori-Boateng & Kwofie, 2009; Shah & Nagarsheth, 2015). The heating value of the generated gas was enhanced by removing hydrogen sulphide ( $H_2S$ ), carbon dioxide ( $CO_2$ ), moisture ( $H_2O$ ) and carbon monoxide ( $CO$ ) using water scrubbing technology and dried using silica gel. The generated gas was analysed using NDIR gas analyser model 3100P, Pack 2 gas analyser, and tested for combustibility using simple flame test. Water scrubbing technology was adopted for the cleaning of the generated biogas based on the high solubility of  $CO_2$ , and  $H_2S$ , in water, as well as the efficiency and effectiveness of the technology (Ofori-Boateng & Kwofie, 2009; Shah & Nagarsheth, 2015). Similarly, water scrubbing technology has the advantage of eliminating  $CO_2$ , and other environmental contaminants associated with other methodologies used for cleaning and upgrading biogas such as the use of electricity and chemically based treatment regimen (Fiehl et al., 2017).

The cleaned biogas was compressed into 20 kg and 12.5 kg LPG cylinder at 210 bars under ambient temperature using a 3.5 horsepower compressor and deployed to fire across draft ceramic kiln of 4.5 CF internal diameter.

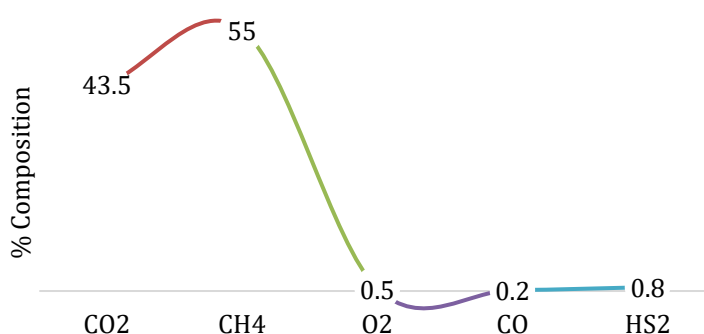
#### 4. Results and discussion

##### 4.1. Characteristic of the generated gas

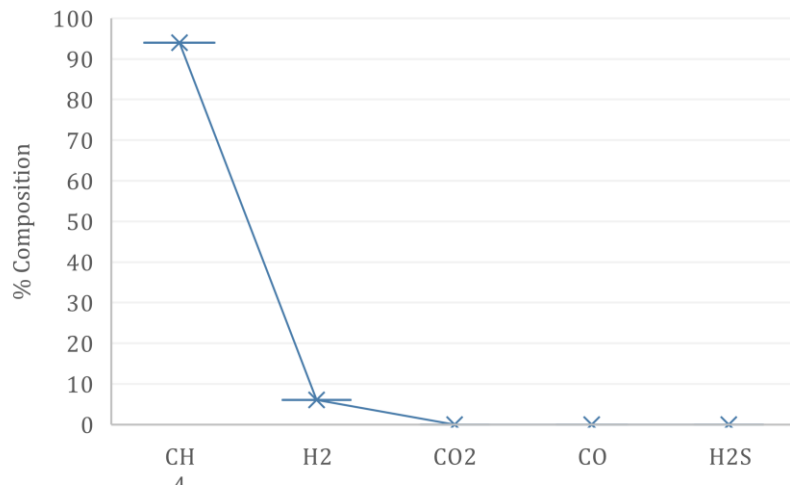
Biogas production started on day three of the anaerobic digestion process, and got to a peak (20 L) on day 19 and 20 of the digestion process. A total of 200 kg of cow dung was used to generate 6000 L of biogas at the rate of 30 L/kg over a digestive period of 27 days (Figure 5). The appreciable volume of biogas generated, was attributed to the stability of the methanogenic bacteria, favourable ambient temperature of 38°C, digester operating temperature of 40°C, and digester pH of 8.5. Analysis of the generated gas showed that it contained CO<sub>2</sub>, CH<sub>4</sub>, O<sub>2</sub>, CO and H<sub>2</sub>S, with values of 43.5%, 55%, 0.5%, 0.2% and 0.800% respectively (Figure 6). However, after treatment of the gas, CO<sub>2</sub>, CO and H<sub>2</sub>S were undetectable, while the values for CH<sub>4</sub> and O<sub>2</sub> increased to 93.98% and 6.02% respectively (Figure 7). The increase in methane content, is an indication that, the essence of the scrubbing process, which was to upgrade the gas to a standard fuel, by increasing its volume, and heating value, for better application have been achieved. The high methane value recorded in this study is comparable with Ray et al (2015) and Nallamotheu et al (2013) who reported up to 96.3% , and 98% methane respectively from water scrubbed biogas. However, due to the lack of appropriate storage and gas compressing facility, a substantial volume of the generated gas was lost.



**Figure 5.** Relationship between digestion temperature and volume of gas



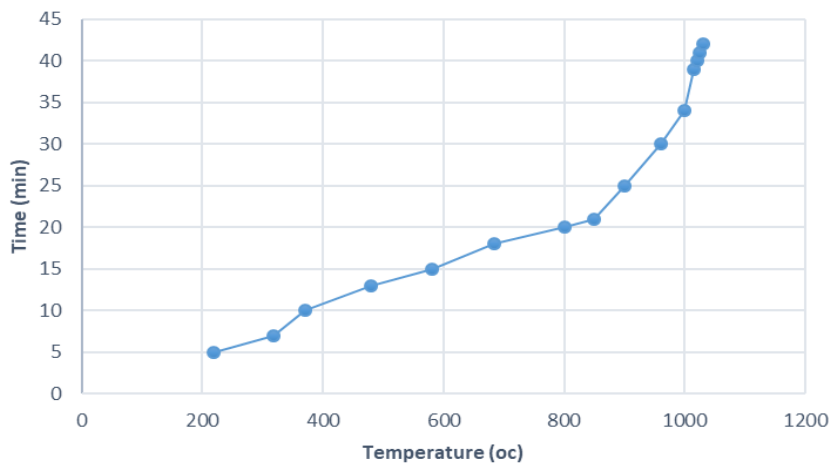
**Figure 6.** Composition of untreated biogas



**Figure 7.** Composition of treated biogas

## 4.2. Firing

Two hundred and nineteen degrees centigrade (219 °C) of kiln temperature was recorded in the first 10 minutes of firing using treated biogas (Figure 8); this was followed by a continued rise in temperature at an average of two minutes. However, from nine hundred degrees centigrade, the rise in temperature become very slow; until the firing was stopped at 1030 °C, when cracks were observed on the kiln arch, and side of the chimney base (Figure 9). The cracks on the surface of the kiln led to stalling, and subsequent decrease in the kiln temperature due to the heat lost. These limitations which were attributed to the kiln structure, limited the attainment of the targeted 1250 °C, which is the maximum firing temperature for stoneware ceramic bodies.



**Figure 8.** Relationship between temperature and firing time

### 4.2.1. Reduction in the volume of gas usage

In an earlier study, 22,300 liters of raw biogas was expended to attain a firing temperature of 900 °C (Abubakar et al., 2018). However, in this study, 492 liters of treated biogas was used to fire a ceramic ware (Figure 10), in a ceramic kiln of the same size with the one in a previous study to 1030 °C. The result of the firing showed a significant reduction in the volume of gas usage - an indication of the influence of impurities on gas quality, volume and combustion property. This

finding confirmed the theory that, the presence of impurities in biogas has the tendency to lower the calorific value of the biogas (Ayats et al., 2007; Shah & Nagarsheth, 2015; Zhao et al., 2010). This assertion was made, based on the fact that, raw biogas contains 60% methane and 40% CO<sub>2</sub>. And with the exception of methane, the other constituents of biogas (CO<sub>2</sub>, H<sub>2</sub>S, NO<sub>2</sub>) are considered contaminants, with the capacity to decrease the heating value of the gas. However, the successful elimination of these impurities will result in high quality gas with methane content of up to 99% (Adnan et al., 2019). The recorded increase in methane content of the scrubbed gas, therefore, validated the reduced fuel consumption and increased firing temperature.



**Figure 9.** Cracks on kiln arch and chimney base



**Figure 10.** Ceramic ware fired to 1030°C

#### **4.3. The environmental sustainability of deploying treated biogas to ceramic kiln firing**

Firing ceramic kiln using biogas prevented the emission of 108,000 g of methane from cow dung into the atmosphere. Similarly, 124,000 g of CO<sub>2</sub>, 74,400 g of CO, and 173.6 g of NO<sub>2</sub> (Table 1) have also been prevented from contributing to human respiratory problem, and global climate change resulting from the use of wood fuel for ceramic firing.

Firing ceramic kiln using wood fuel also takes longer time, leading to increase in CO<sub>2</sub>, CO, and NO<sub>2</sub> emissions. However, firing a ceramic kiln using the treated biogas showed a reduction in firing time with no emissions (Table 1). Although, lesser firing time was reported using Liquefied Petroleum Gas (LPG), its carbonaceous source is still a source of concern for environmentalist.

Therefore, the full adaptation of treated biogas as fuel for ceramic firing will not only aid the protection of carbon sink and reducing deforestation, whose impact is already affecting lives and livelihood in developing countries such as Nigeria, where this study was carried out, but will also

play a significant role in enhancing the green credentials of ceramic firing through a reduction in carbon footprint, as well as a boost to the target of the IPCC Paris Agreement of keeping Greenhouse Gas (GHG) emissions, and global average temperature, well below 2 °C pre-industrial.

**Table 1.** Comparative analysis of greenhouse gas emissions and global warming potentials of fuels used to ceramic kiln to 1030°C

| Fuel      | Firing time | Energy consumed | Greenhouse gas emitted | Volume of greenhouse emitted (g) | Global warming potential | Life span in the atmosphere (years) |
|-----------|-------------|-----------------|------------------------|----------------------------------|--------------------------|-------------------------------------|
| Wood      | 8           | 248 kg          | CO                     | 74,400                           | 2                        | 2                                   |
|           |             |                 | CO <sub>2</sub>        | 124,000                          | 1                        | 30-90                               |
|           |             |                 | NO <sub>2</sub>        | 173.6                            | 300                      | 120                                 |
| Methane   | 6           | 492 L           | -                      | -                                | 24                       | 55                                  |
| Waste oil | 7           | 20 L            | CO <sub>2</sub>        | 31,920                           | 1                        | 30-90                               |
| LPG       | 5           | 12 kg           | -                      | -                                | -                        | -                                   |
| Kerosene  | 6           | 18 L            | CO <sub>2</sub>        | 46,440                           | 1                        | 4.2                                 |

#### 4.3.1. The social sustainability of firing ceramic kiln with treated biogas

The application of treated biogas to ceramic kiln firing eradicates the tiring, and demanding procedure related to the use of traditional ceramic fuels; resulting in saving human energy, and a reduction in fatalities, and respiratory problems linked to the inhalation of CO<sub>2</sub> and NO<sub>2</sub> due to exposure to fossil burning fuels (Peng et al., 2012). The elimination of these deleterious consequences will also lead to improved wellbeing of ceramicist. Furthermore, the funds which should have been used to seek medical help and the purchase of drugs for the treatment of smoked induced health challenges can be channeled into other social aspects of human development.

#### 4.3.2. The economic sustainability of treated biogas application to ceramic kiln firing

The current economic realities in Nigeria (increase in inflation) have led to increment in prices of the goods and services. For example, crank shaft oil (used/waste engine oil) which prior to this time was discarded, now costs ₦400/gallon, while kerosene which now costs ₦320 at official rate, is not readily available, and the price is expected to rise in the future due to its demand as aeronautic fuel. LPG is now sold at ₦357/kg, while 10 kg of wood is now sold for ₦100.

Electricity whose generation and transportation is also depended on carbonaceous fuel is now sold for ₦62.92 kwhr; with price expected to rise in the future. Similarly, the epileptic supply of electricity has hampered its use as a source of energy for ceramic kiln firing. The above analysis showed that it is more economically viable to fire a ceramic kiln using treated biogas compared to other traditional ceramic fuels (Table 2). However, it sufficed to note that biogas has not been commercialized in Nigeria. Therefore, only the haulage cost of the cow dung from the source to the experimental site was considered.

**Table 2.** Relationship between price and cost of fuels used to fire a 4.5 CF kiln to 1030°C

| Fuel      | Price (₦)  | Cost (₦) |
|-----------|------------|----------|
| LPG       | 357/kg     | 4,284    |
| Wood      | 248 kg     | 2,480    |
| Waste oil | 400/gallon | 2,000    |
| Kerosene  | 320/l      | 5,760    |
| Methane   | -          | 1,000    |

Although it was expected that the kiln firing time using the treated biogas would be less than the recorded 6 hours (Table 1), the study assumed that the material composition of the kiln (dense refractory brick), the kiln furniture, and the fuel burning systems, had influenced the firing



efficiency resulting in the extended firing time. However, research is continuing to see if the aforementioned factors contributed to the increased firing time and fuel consumption.

#### 4.4. Findings

The results of this study revealed that ceramic firing using treated biogas require less volume of gas, compared with using raw biogas which require large volume of gas, and by extension large gas storage area. The presence of CO<sub>2</sub> in raw biogas has been found to reduce the burning aptitude of biogas; while the use of scrubbed biogas has lowered the cost of fuel, the CO<sub>2</sub> emission into the atmosphere, and exposure to gaseous pollutants from fossil-based-fuel consumption, as well as improved human health and well-being. The study also found out that lowering the melting point (Vitrification temperature) of ceramic ware to reduce fuel consumption has effect on product strength, and durability. Furthermore, the adaption of scrubbed gas a single firing fuel has proved to be a viable option in curtailing the possible effects of contaminants contained in biogas on combustion behavior, and refractory quality of kiln surfaces. These findings are consistent with Fiehl et al (2017), Sun et al (2021) and Hosseini & Wahid (2013).

#### 4.5. Theoretical and practical implication of the findings

The results of this study showed that high temperature ceramic firing is achievable in sustainable, and efficient manner using treated biogas. Similarly, the use of treated biogas has eliminated the earlier concerns raised on the negative impact of untreated biogas on ceramic firing process. Furthermore, the use of treated biogas has proved to be a viable option for ceramic kiln firing, particularly in developing countries such as Nigeria, where the severity of energy deficiency has led to the collapse of business, and the relocation of others to the neighboring countries where energy supply is readily available and reliable. The lack of adequate, and reliable energy has also led to increase in the cost of production, resulting in increased prices of goods and service.

### 5. Conclusion

Methane content of biogas can be improved successfully using water scrubbing technology. Similarly, the deployment of biogas compressed at 210 bars under ambient temperature to fire a ceramic kiln to 1030 °C has highlighted the economic viability of biogas, its efficiency, and its potential as sustainable ceramic fuel in comparison to traditional ceramic fuels. Improvement in the quality of the treated biogas has also led to the reduction of the volume of gas consumption during firing, reduction in the exposure of humans to toxic gases, and the impact of GHG emissions on human health and the environment.

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