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 ISSN: 2488-9229
 FEDERAL UNIVERSITY
 GUSAU-NIGERIA

INTERNATIONAL JOURNAL OF SCIENCE FOR GLOBAL SUSTAINABILITY
**Abundant Catalyst Resources for Applications in the Nigerian
Energy Sector: A Research Perspective**

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Received on: August, 2022

Revised and Accepted on: September, 2022

Published on: October, 2022

ABSTRACT

Efficient energy supply represents one of the important indicators of a country's readiness to provide fundamental amenities for its citizens. It similarly indicates the possibility of industrial growth associated with a nation of interest. In Nigeria today, energy supply is greatly insufficient and the government's approach for handling the situation remained inefficient. Therefore, both scientific and policy based researches with focus on enhanced energy production are desirable for national interest. This specific manuscript targeted a discussion on how the abundant natural resources in Nigeria could be transformed into industry based catalysts and successfully applied for both biomass and fossil fuels valorization. It was successfully demonstrated herein that fly ash from coal processing, waste materials from cement manufacture, rock-based natural zeolites and many other industrial wastes could be converted into affordable catalysts for utilization in energy production via catalysis. Emphasis was also placed on the need for research intensification on catalyst development, characterization with advanced methods and evaluation at laboratory and industrial scales. This way, the challenges of energy production in Nigeria would be reduced effectively.

Keywords: Energy; Waste Resources; Catalysts; Industries; Further Researches

1.0 INTRODUCTION

The country Nigeria is on those countries predicted by the United Nations to have serious human population problems specifically due to the high annual growth rate with poor economic status/improvement. Accordingly, the population of Nigeria was only 88.5 million based on the 1991 census reports. However, Nigeria is currently on the verge of having a population explosion as the United Nations predicts that the country will have one of the largest populations in the world by 2050 (UN, 2022). This trend of rapid growth has severe consequences in terms of energy availability, environmental degradation, hunger threats and massive poverty affecting the entire national regions. Specifically, energy (i.e. including electricity, petrol, kerosene, diesel and jet fuel) consumption is witnessing rapid increase with purchasing costs been unstable. As at September, 2022, the country's total energy consumption had been estimated at 24.72 billion kWh, with only 31.8% availability (WD, 2022). This trend on insufficiency is consistent in other areas of human basic needs. Therefore, any mechanism for handling these challenges would

be very important in the interest of sustainable development.

One of the areas recently considered by countries around the world is the proper exploration of the abundant natural resources and subsequent utilization for industrial advances. This way, resources such as biomass, mineral deposits, coal, rocks, natural gas, crude oil and water resources must appropriately be extracted for direct utilization or conversion into more useful products required in line with the escalating population (Pearce et al., 1990; Melina et al., 2016). In Nigeria today, effort toward sustainability in the energy sector is seriously required and for the purpose of advances "catalysis" has a great role to play. The concept of catalysis was viewed by many authors from different perspectives; however, a more recognised view is that "catalysis involved the acceleration of the rate of chemical and or engineering process for the purpose of attaining maximum efficiency in terms of product(s) yield through the application of small amount of substance called catalyst" (Ma et al., 2009;

Okolie et al., 2022). All the energy industries around the world employ one or more form of catalysts to achieve particular production process. In fact, catalysts are applied in crude oil and natural gas production, processing and utilization. Similarly, in coal exploitation, cement production and the manufacture of polymers and petrochemicals. Therefore, the relevance of catalyst development to economic sustainability cannot be over emphasized. The catalyst materials could be homogeneous in nature (i.e. existing in the same phase with the reactants) or heterogeneous exhibiting different phase properties from the reacting feedstock (Albayrak et al., 2022; Gorbunov et al., 2022; Zaera, 2022). The former categories of catalysts that include mineral acids and bases, organic liquids and allied derivatives have attracted limited usage in the recent times due to production, recycling and environmental problems as well as cost inconsistencies. On the other hand, the heterogeneous counterparts including acidic and basic oxides, zeolites, heteropoly acids and many other solid materials are gaining serious industrial and research attention. These materials could be found naturally and processed for application or synthesized and characterized artificially at the laboratory or industrial scales. For the purpose of this paper, emphasis would be placed on

providing highlights on the catalyst materials that are abundant in Nigeria (but ignorantly ignored). Important details on how these catalytic systems could successfully be utilized for industrial development would be provided. Further highlights would similarly be provided in terms of suitable research directions.

2.0 POTENTIAL CATALYST RESOURCES

Catalyst resources are increasingly becoming important commodities for application in the energy and allied industries. According to the available records, the global catalyst market is huge and fast growing (see Figure 1). By the year 2014, the market was valued at 19.2 billion USD per annum, but as at today (i.e. 2022), the market exhibited an increase reaching 29.2 billion USD and the trend had been projected to be linear for the future years (LA, 2017). The statistics covered both homogeneous and heterogeneous catalyst materials, although the former systems are becoming less-attractive due to earlier highlighted challenges. In Nigeria today, almost all the catalyst systems used by industries are imported with no clear plan for local production. Therefore, the next subsections of the paper will provide highlights on the opportunities for local catalysts development.

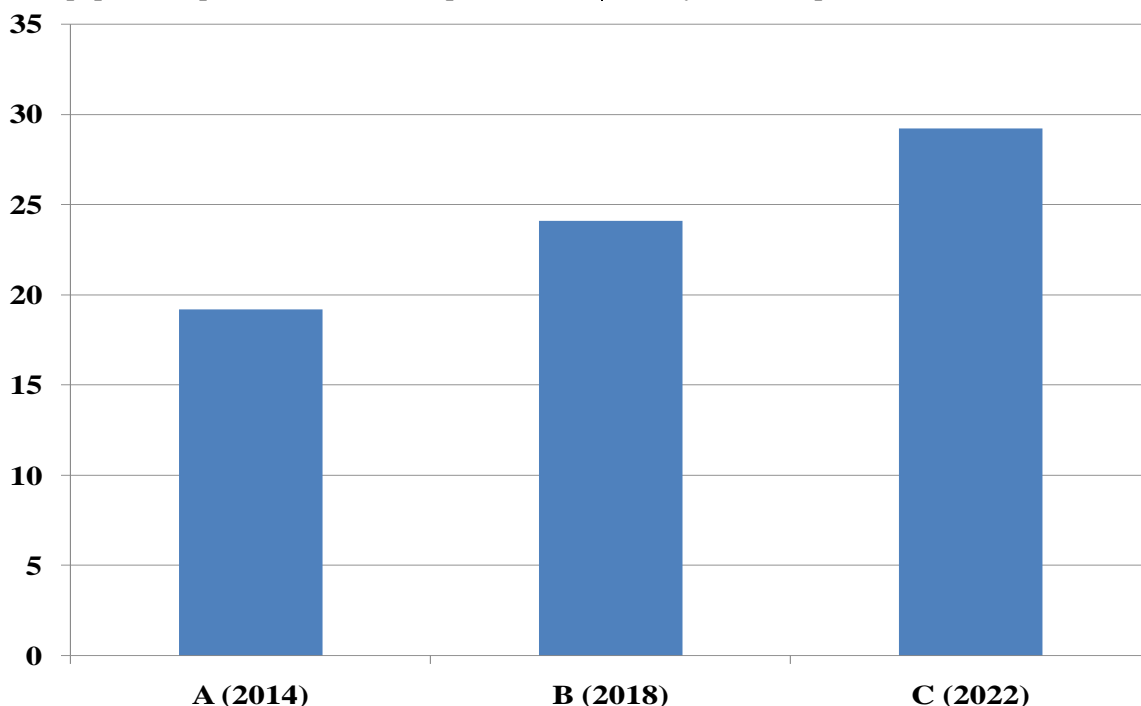


Figure 1: Annual global growth rate of market (billion USD per annum) for catalyst materials. Data source: LA (2022)

2.1 Catalysts from Coal Processing

Coal is a naturally occurring material that is generated via a procedure similar to that for petroleum. It has been considered to be mostly made up of carbon, with varying proportions of additional elements such as hydrogen, sulphur, oxygen, and nitrogen. Specifically, coal deposits are formed when dead plant matters underwent a series of decay processes and transformed into peat, which is then further converted into coal over millions of years by the action of heat and

pressure subject to consequential burial process. Available data showed that coal (mainly sub-bituminous stream coals except for the Lafia-Obi bituminous coking coal) is available in more than 22 coalfields spread over 13 States in Nigeria. The proven coal reserves are about 639 million metric tonnes while the inferred reserves are about 2.75 billion metric tonnes (BPE, 2022). Coal is extracted via a range of physical and chemical methods and then converted into energy using coal processing plant (Figure 2).



Figure 2. A typical of coal processing plant. Source: AT Minerals (2022)

The method of coal processing to be employed has a direct link with the purpose and net applications of the derived material (i.e. for energy production or other purposes including steel manufacture). Some of these methods encompassed pulverized coal combustion, cyclone combustion, oxy-fuel combustion; entrained flow gasifiers and transport gasifiers; and fluidized bed combustors and gasifiers. Other allied technologies involved the use of stoker firing and fixed bed gasifiers, where the heating rates are typically too slow (Niksa, 2021).

At the important stages of coal processing, a fly ash is been produced. The fly ash had been characterized to compose of silica, alumina, iron oxide, and calcium, with varying amounts of

carbon, as determined using different spectroscopic and non-spectroscopic methods by different researchers (Hower et al., 2022; Murukutti and Jena, 2022). Owing to this important composition, fly ash from coal processing and/or combustion can be converted into zeolite materials popularly known as “Coal Fly Ash Zeolites (CFAZ)”. The procedures for CFAZ both based on laboratory and industrial scales. In their comprehensive review, Querol and co-workers (2002) have demonstrated that zeolites from fly ash could be derived using cheap and fast processes involving alkali, acid and other treatment methods. A typical synthesis procedure involved three steps in alkali hydrothermal reaction of zeolite synthesis: the dissolution step of Si^{4+} and Al^{3+} in coal fly ash, the condensation step of silicate and aluminate ions in alkali

solution to make aluminosilicate gel, and the crystallization step of aluminosilicate gel to make zeolite crystal (Murayama et al., 2022). The net zeolites could have properties comparable to those derived from the conventional hydrothermal crystallization technology.

2.2 Catalysts from Cement Manufacture

Cement production is a complex process with a well defined chemistry. The application of the cement industry and the operational feasibilities in Nigeria are positive and clear particularly due to the abundant of raw-materials in strategic geopolitical zones. In fact, Nigeria possesses the largest cement industry within West Africa, with at least 12 registered companies amounting to a merged cement capacity of 58.9 Mt/yr. According to recent analysis, local cement production capacity may hit 60 million tonnes per annum (mtpa) by the end of 2022 as BUA plans to establish three million metric tonnes cement plants in the country.

According to Siddique (2007), the waste materials and by-products associated with cement production and allied industrial processes are; granulated blast furnace slag, metakaolin, waste and recycled plastics, scrap-tire, waste glass, coal fly ash, rice husk ash, municipal solid waste ash, wood ash, volcanic ash, cement kiln dust and foundry sand. According to Galadima and Muraza (2020), these waste materials could appropriately be upgraded into catalytic systems for applications in the energy industry. For example, the derived oxides and fly ash can be transformed into hybrid catalysts and zeolites and subsequently employed for processes such as biodiesel production, hydrocracking, aquathermolysis of heavy crude oil and catalytic fast pyrolysis of biomass resources. Despite these opportunities, in Nigeria today, these byproducts of cement manufacture are inappropriately disposed into the environment causing pollution. Thus, shifting the scope towards catalysts production would be profitable for the operational companies and government.

2.3 Catalysts Based on Natural Zeolites from Rocks

The zeolites chemistry is a well known developed concept recognized by researchers and industries around the world. Their unique properties in terms of porosity, acidity and structural features accounted for their continuous exploitations and utilization. According to Corma and Martinez (2005), zeolites are hydrated, crystalline microporous aluminosilicates, whose structures enclose channels and/or cavities of molecular dimensions (0.3–1.5 nm diameter). These materials are significantly employed for applications in our everyday life, being widely applied as sorbents, as ion exchangers in detergents, or as catalysts in industrial processes, and as diverse as oil refining or petrochemistry and chemicals and fine chemicals. The common examples of zeolites in wide utilization are Analcime, chabazite, clinoptilolite, heulandite, natrolite, phillipsite, and stilbite are some of the more common types of zeolites. The typical formula for natrolite is $\text{Na}_2\text{Al}_2\text{Si}_3\text{O}_{10}2\text{H}_2\text{O}$, which is an example of a zeolite mineral (Corma and Martinez, 2005). The global zeolite market size is expected to reach USD 44.24 billion by 2028. It is expected to expand at a CAGR of 6.5% from 2021 to 2028. The growth of the chemical sector, coupled with the increasing demand for natural products in industries such as agriculture and concrete, is expected to propel the market growth in the coming years (Dublin, 2022).

Although the zeolite materials could be synthesized, they are abundant in rocks and associated deposits. These kinds of grass root sources are abundantly distributed in different parts of Nigeria (Kovo, 2011). As demonstrated in Figure 3, the nature of the rock (i.e. sedimentary or volcanic) is key to the type of obtainable zeolite materials. These natural zeolites are processed for further application via a range of procedures that include crushing, acidification, treatment with base solutions, ion exchange and allied industrial methods. According to several earlier literature surveys, specific treatments are necessary to modify the structural-acidity properties of the zeolite systems for them to fit the desired applications (Galadima et al., 2022a; Galadima et al., 2022b).



NATROLITE



CHABAZITE



MORDENITE



PHILIPSITE

Figure 3. Typical scheme of zeolite materials obtainable from Nigerian rocks

2.4 Catalysts from Biomass Resources

In general terms, biomass resources are abundant in all the Nigerian geographical regions. Such resources are typical materials that come from living organisms, such as plants and animals. The most common biomass materials used for energy are plants, wood, and wastes. These are otherwise referred to as biomass feedstocks. Biomass energy can also be a non-renewable energy source.

According to Adams and co-workers (2018), several processing steps are required to convert raw biomass into useful energy using the three main process technologies available: bio-chemical, thermo-chemical, and physio-chemical. Bio-chemical conversion encompasses two primary process options: anaerobic digestion (to biogas) and fermentation (to ethanol). Similarly, thermochemical conversion of biomass can be performed via three primary pathways, i. e. combustion, gasification, and pyrolysis. Gasification is the partial oxidation of biomass to produce a synthesis gas (syngas), consisting primarily of CO, H₂ and CH₄. Steam gasification enables thermal treatment under a reducing atmosphere that leads to enhanced H₂ production.

One important factor here is that “waste products from the various biomass conversion processes could be transformed into catalytic materials and

employed for other applications”. Specifically, biochar from biomass pyrolysis can be valorized by homogenization and allied treatments to generate active sites for catalyzing heterogeneous reactions. Carbonization products from biomass processing could be functionalized by treatment with acids (e.g. sulphuric, sulfonic or hydrochloric) to generate activated carbon catalysts. Activated carbon is a material that has all the required characteristics to be used as a catalyst or support system. When compared to other carriers, like silica or alumina, activated carbons provide greater internal surface area to have higher reaction rate and lower cost per cubic meter (Cameron et al., 1990; Zhang et al., 2022). Similarly, they can allow stable inertness in harsh process conditions such as acidic and alkaline solutions. These properties are very important for industrial catalysts design.

3.0 APPLICATIONS IN ENERGY PRODUCTION

The Nigerian energy industry is relatively weak when compared to the developed nations. Raw-materials required for the sector are substantially imported, operational methodologies are not frequently upgraded and the worst is that less than 35% of the required energy is available to the inhabitants despite the abundant of resources. Therefore, any approach for improving the overall energy production-consumption cycle will be beneficial for the interest of sustainability.

Energy production via catalysis is a very big research area that the scope of this paper cannot fully cover. However, instances where selected catalysts have been employed for either fossil fuels production/upgrading or biomass valorization would be considered. Crude oil refining is generally achieved through a range catalytic processes that include hydrocracking, hydrotreating (deoxygenation, desulfurization, denitrogenation), hydroisomerization, alkylation, reforming via aromatization and many other catalytic methods.

These catalytic processes are employed to ensure the production of high quality petrol, diesel, kerosene and jet fuels. For example, the Kaduna Refining and Petrochemical Company (KPRC) uses zeolites (especially the mordenite and modified derivatives) to achieve the alkylation of aromatic hydrocarbons. Silica-alumina and nickel-molybdenum materials are severally employed as good candidates for hydrocracking and hydrotreating processes at various reaction temperatures and pressures to reduce the level of sulphur, nitrogen, oxygen and bulky hydrocarbons from the feed (Galadima et al., 2009; Galadima et al., 2012). This is to ensure high quality fuel that meets the environmental specifications.

Enhanced heavy crude oil production (EHCOP) is another area of interest in the energy industry, especially due to the fact that the current proven reserves of light crude oil will only last for the few decades to come. One unique catalytic method considered for the EHCOP is the “Catalytic Aquathermolysis”, which involved the application of oxides, zeolites or related catalysts to conduct the steam-assisted thermolysis of heavy compounds such as resins and asphaltenes in the heavy crude oil into lighter and more desirable products (Muraza and Galadima, 2015). The technology if appropriately employed can enhance production by more than 50% compared to the available options. This therefore presents an opportunity for the exploration of bitumen, tar sand and other heavy hydrocarbon deposits available in the Nigerian territory.

Nigeria is one of the global countries with the highest reserves of natural gas. However, the commodity is under-utilized either due to

technology deficit or poor government strategies. From the catalysis point of view, a range of metal-modified oxides (including silica, alumina, zirconia, ceria, titania, etc.) and zeolite systems could be employed to upgrade the natural gas into hydrogen fuel, alcohols and higher hydrocarbon fuels. Processes such as dry and steam reforming, direct methane-to-methanol, direct methane-to-hydrocarbons and methane to ethylene conversions are strongly relevant and already being practiced in some parts of the world (Le Sache and Reina, 2022; Cortazar et al., 2022; Yang et al., 2022).

Biomass conversion into energy feedstocks is another area of recent industrial interest that should be given appropriate consideration in Nigeria. Specifically, biomass resources could be transformed into energy via physical, chemical and biological methodologies that all involved the application of catalytic materials. For example, catalytic fast pyrolysis of wood and/or papers can be achieved at 450-600°C with the aid of zeolite catalysts to produce hydrocarbons in the range of petrol and diesel fuels (Jiang et al., 2022; Zhou et al., 2022). Catalytic gasification followed by subsequent Fischer-Tropsch reactions have also proven very effective in the production hydrocarbon fuels from biomass resources (Arpia et al., 2022; Wang et al., 2022). In fact, hundreds of biomass conversion processes (including biodiesel, bioethanol and biogas conversion methods) are employed strategically to achieve energy production in the recent times.

Figure 4 illustrates some of the important routes where catalytic materials could be employed for the production of fuels or most valuable chemicals (Vedrine, 2019). Specifically, natural gas, coal, biomass, CO₂ and/or anthropogenic wastes could be upgraded via gasification/reforming reaction to generate synthesis gas (CO + H₂). The latter can further be transformed into a range of valuable products required by the industry and our daily operations. For instance, the synthesis gas derived from either gasification or reforming reaction can be converted into various fuels and alcohols via FT process. Alternatively, syngas to methanol or aromatics can be achieved by employing oxides and zeolitic catalysts at the working temperatures

of 250 to 450°C. Therefore, Nigerian researchers and industries should be more committed toward

actualizing the various paths raised at the local scale.

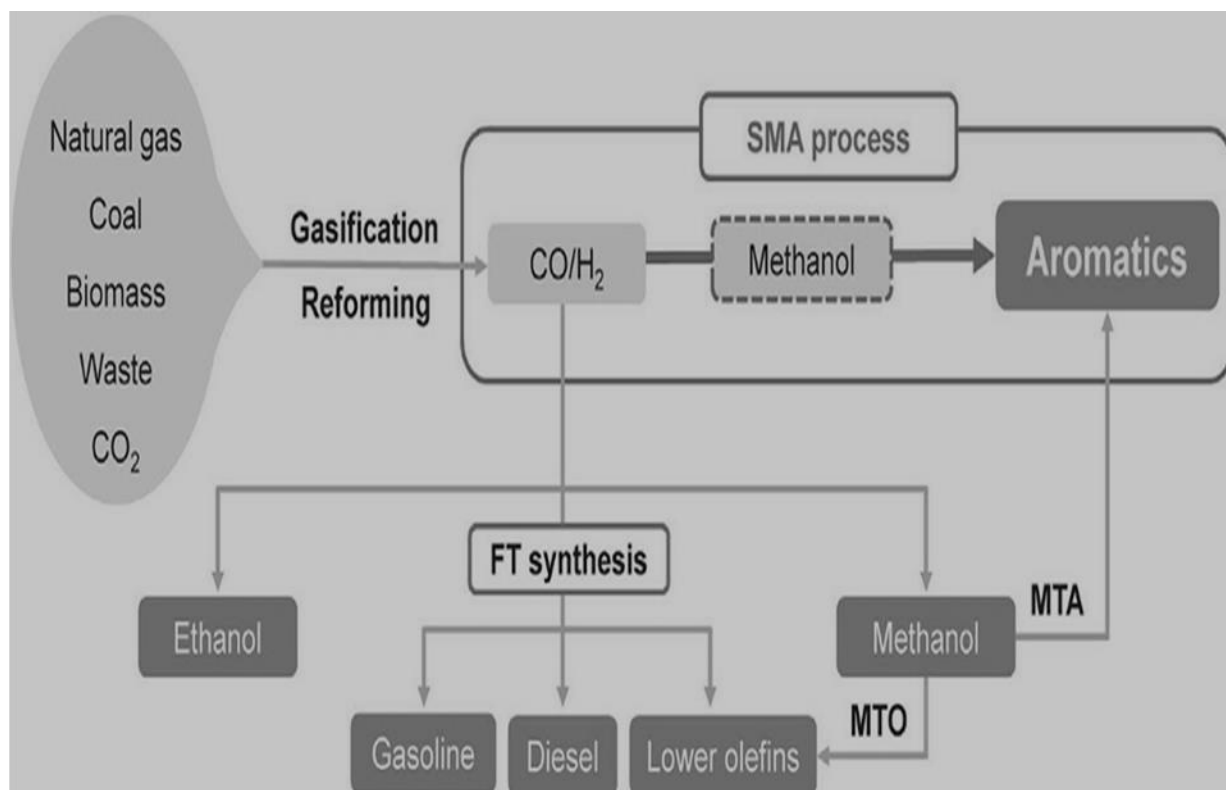


Figure 5. Selected catalytic routes for the transformation of fossil fuels, bioass and wastes into valuable fuels and chemicals (See also Vedrine, 2019)

4.0 CONCLUSION AND RESEARCH PERSPECTIVES

There is no any iota of doubt, the paper substantially demonstrated that energy production in Nigeria is limited due to poor harnessing and production strategies. Similarly, plans for proper utilization of abundant resources as catalysts for energy production are yet to be prioritized. Industrial activities ranging from coal processing, cement manufacture to rock exploitations and biomass upgrading are associated with production of large quantities of waste products including fly ash, solids, char and other allied materials. While these wastes are currently disposed as pollutants, new scientific results indicated substantial possibilities of their conversions into oxides, zeolites and other forms of heterogeneous catalysts that are strongly relevant for energy production. The paper thus highlighted how the derived catalysts could be used for catalyzing the various crude oil refining processes, aquathermolysis of heavy oil, biomass valorization (into energy fuels like hydrogen,

biodiesel, biogas and bioalcohols), dry and steam reforming of natural gas and other industry-based technologies for energy production. For the interest of research expansion in this direction, the following are recommended:

- i. **Coal Fly Ash for Zeolites:** fly ash and other wastes from coal manufacture should be frequently characterized and modified for upgrading into zeolite substances. Feasible acidification, basicification and post-synthesis treatment procedures are abundant for deriving very efficient industrial catalysts. Thus, new researches must consider these options with seriousness. The activities of the derived catalysts should be compared with those of existing industrial systems for identifying best activity-enhancement strategies to be applied.
- ii. **Oxides from Cement Manufacture:** cement production process generates waste substances that require only slight modifications to form catalytic oxides with varying degree of active sites. The latter

materials that could be both acidic and basic in nature could further be modified to fit reactions of interest (including petroleum refining reactions, aquathermolysis and biomass upgrading). This represents a giant opportunity that requires research prioritization. Careful post-modification characterization of the wastes before identifying suitable application option (s) is inevitable in this perspective.

- iii. **Biochar from Biomass Processing:** Biochar and other solid residues from biomass pyrolysis and/or gasification are good candidates for catalyzing a range of industrial reactions. This is also similar to the modified carbonized-biomass feedstock. In both cases active sites could be developed via simple physico-chemical approaches. Therefore, shifting a research in this direction will be very beneficial in the direction of proper energy planning model.
- iv. **Other Catalyst Resources:** Nigeria is a rocky-nation with all forms of igneous, sedimentary and metamorphic rocks strategically distributed in the regions of the country. Many of these rocks contained zeolitic precursors and oxide analogues that could be transformed into very active catalysts via feasible modifications. Thus, further research in this direction is inevitably required.

5.0 ACKNOWLEDGEMENT

The author is thankful to Tertiary Education Trust Fund (TETFUND, Nigeria) for a supportive research funding under the IBR scheme (2018-2021, Merged Intervention to FUGUS).

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