

# Heavy Oil Valorization into Lighter Viscous Fuel Using Low-Cost Catalysts

<sup>1\*</sup>Ahmad Galadima, <sup>1</sup>Mubarak Abubakar, <sup>1</sup>Rilwanu Muhammad, <sup>1,2</sup>Uwaisu Yusuf

<sup>1</sup>Department of Chemistry, Federal University Gusau, P.M.B. 1001, Gusau, Nigeria.

<sup>2</sup>Universidad Veracruzana, Boca del Rio 94294, Veracruz, México.

Corresponding Author's E-mail: [agaladima@fugusau.edu.ng](mailto:agaladima@fugusau.edu.ng), [ahmadgldm@yahoo.com](mailto:ahmadgldm@yahoo.com)

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## ABSTRACT

Sequel to the escalations in global energy requirements, different catalysis-based options are under development for the enhanced recovery (i.e. EOR) of the huge heavy and extra-heavy crude oil reserves strategically distributed in key global regions. In line with this trend, the current work investigated the roles of different local catalysts in the aquathermolysis of a heavy crude oil sourced from Ondo State, Nigeria. For the aquathermolysis reactions performed at the conditions 150 cm<sup>3</sup> (total oil-water content, 70/30), 120°C and 0.2g catalyst for 1.5 h, the activity of the various catalytic systems obeyed the pattern C1 (pure carbon) < C2 (CaO-modified) < C3 (MgO-modified < C4 (CaO-MgO modified) < RM (Fe<sub>2</sub>O<sub>3</sub>-rich Red Mud). The results showed the RM material with the highest concentration of basic sites (i.e. 0.50 mmol/g) the best aquathermolysis catalyst followed by the CaO-MgO-modified carbon material formed under constant reaction conditions. The study therefore demonstrated that adequate amount of the basic sites is necessary to actualize the C-S, C-O, C-N and C-C ruptures in bulky heavy oil compounds for successful transformation into lighter more desirable hydrocarbon fuel products. Additionally, the RM catalyst is very prospective for field applications.

**Keywords:** Low-cost catalysts; aquathermolysis; performance; saturates and aromatics; asphaltenes and resins.

## 1.0 INTRODUCTION

The rising population of human beings and associated escalation in industrialization are increasingly accounting for more energy demands around the global regions. Currently, fossil fuels especially the crude oil is providing a greater percentage of the worldwide energy requirements (Ghasemian et al., 2024; Nyasapoh et al., 2026; Rezaee & Silva, 2026). However, although there is an indication the renewables including biofuels with account for a good share of the energy supply (i.e. > 20%) by 2050 and beyond (Sufe, 2026), the fossil fuels will still represent > 80% of the worldwide energy needs. The light crude oil reserves under production on the other have been estimated to be on the serious decline based on the current and steady production rates (Sufe, 2026).

The most acceptable scenario here is that more energy production options are necessary. One of these options being considered is the exploration and production of the over 1.1 trillion proven reserves of heavy and extra-heavy oil. However, these heavy oil reserves are associated with production difficulties due high viscosity, large compositions of asphaltenes and resins as well as low contents of fuel-bearing light hydrocarbons. Therefore, to ensure sustainable and feasible production of heavy oil feeds enhanced recovery (EOR) technologies are certainly required. Several physical, chemical, microbial and thermochemical methods are

under development for the heavy oil EOR (Wang et al., 2026; Zhao et al., 2021). Among these methods, a thermochemical process called catalytic aquathermolysis is increasingly attracting research and industrial attention. The process infers the application of heat (i.e. 200-350°C) and heated steam to degrade the heavy compounds (i.e. asphaltenes and resins) in the heavy oil thereby reducing viscosity and increasing the contents of saturates and light aromatics in the feedstock. This action permits the enhancement of the heavy oil recovery and similarly create a refining feasibility at the later stages. Since the first coining of the process in 1982 by Hyne, different catalytic options are being developed with the view to facilitate the ruptures of C-S, C-O, C-N and C-C bonds in the heavy oil compounds to produce light fuel products. The applications of minerals, metals and their oxides, zeolites, H-donors, surfactants, ionic liquids and many other catalytic materials have been documented. Details about the process chemistry, opportunities and challenges have been provided in some of our earlier publications (Galadima & Muraza, 2017; Muraza & Galadima, 2015). However, the homogeneous of these systems are associated with environmental challenges. On other hand, some of the heterogeneous catalysts posed poor activity-stability properties with consequent corrosion and clogging of reservoir pores. Thus, the search for better catalysts is still under serious consideration. Therefore, the objective of this

investigation is to evaluate the effects of some local catalytic materials as candidates for the catalytic aquathermolysis process. The roles of the catalysts in viscosity reduction as well as upgrading the chemical compositions of the heavy oil were examined under modeled conditions.

## 2.0 EXPERIMENTAL

### 2.1 The Heavy Oil

The heavy crude oil used for the study was a Nigerian grade commodity sourced from Ondo State (OML 53, Omerelu Field; 4.8472°N, 6.9746°E). The sample, without any further treatment, was transported in cleaned and dried plastic containers and kept under laboratory conditions prior to further analysis. This action was performed to evaluate the applicability of any catalyst to the inherent reservoir feeds without deactivation.

### 2.2 Heavy Oil Assessments

The characterization of the virgin and valorized heavy oil feeds was conducted in line with the procedures adopted in various ASTM guidelines for hydrocarbons assessments and quality evaluation. Firstly, the as-received heavy oil feedstock was assessed for its API gravity value based on the guidelines captured in ASTM-D 287. Similar technique was later employed to assess the change in API gravity value for the valorized heavy oil. Other parameters such as viscosity (mPas) and SARA compositions (%) were derived with strict compliance to the principles captured in ASTM-D 445 and ASTM-D 4124, respectively.

### 2.3. Catalysts, Formulations and Physicochemical Properties

The five (5) catalysts used in this study are coded as C1, C2, C3, C4 and RM in line with their compositions. For the C1-C4 systems, a mechanically developed charcoal material C1 from Barakalu Area in Kotorokoshi (latitude 12°8'26" to 12°9'21" N and longitude 6°47'11" to 6°49'19"), was modified with CaO and MgO to form the C2, C3 and C4 mixtures in line with the compositions provided in Table 1. Additionally, the RM sample was red mud material derived from Makurdi in Benue state (7° 44' 34" N for latitude and 8° 31' 19" E for longitude). It was subjected to screening and sieving to remove debris and large metal particles. All the five (5) catalysts were assessed for their compositions and basicity properties using XRF and CO<sub>2</sub>-desorption techniques.

### 2.3 Catalyst Screening for the Aquathermolysis

Aquathermolysis with the designed catalyst systems was conducted under improved lab-scale conditions in line with our earlier works. The glass reactor was charged with heavy oil : water (ratio of 70 : 30, % volume), leading

to a total reactants volume of 150 cm<sup>3</sup>, 2.0g of catalyst and maintained at 120°C for a period of 1.5 h under constant stirring. Exit gases from the process were adequately evacuated to mitigate unwanted pressure development and radical-assisted heavy compounds reversal.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Physicochemical Characteristics:

The results of the compositions and basicity properties of the various catalysts are presented in Tables 1 and 2, respectively. The values depicted in Table 1 are in good agreement with the loadings of the various CaO and MgO on the C2, C3 and C4 samples. The modification was performed to create active sites on the as-prepared charcoal catalyst (i.e. C1 material). The co-modification with both CaO and MgO (5.0 wt.% each) was conducted to establish any possibility of synergy between the two bases and the charcoal support system such that any consequent role in aquathermolysis could be established. The RM catalyst contains mainly Fe<sub>2</sub>O<sub>3</sub> (42.0 wt.%) followed by Al<sub>2</sub>O<sub>3</sub> (22.5 wt.%) and SiO<sub>2</sub> (15.5 wt.%) with Na<sub>2</sub>O and CaO accounting for the balance compositions (i.e. 20.0 wt.%). The basicity of a given catalyst plays a very important role in determining its associated catalytic performance in any reaction of interest (Muraza & Galadima, 2015; Zhou, Li, et al., 2025). Table 2 depicted that the basicity of the catalysts followed the trend C1 < C2 < C3 < C4 < RM, with the RM material exhibiting the largest concentration of basic sites (i.e. 0.50 mmol/g). This unique feature had been attributed to the metal-oxide compositions of the RM material as depicted by the XRF data captured in Table 1.

**Table 1. Chemical compositions of the various catalysts as confirmed from XRF studies**

Catalyst System	Chemical Compositions (wt.%)
Charcoal 1 (C1)	Carbon (100%)
Charcoal 2 (C2)	CaO (5.0%), Carbon (95.0%)
Charcoal 3 (C3)	MgO (5.0%), Carbon (95.0%)
Charcoal 4 (C4)	CaO (5.0%), MgO (5.0%), Carbon (90.0%)
Red Mud (RM)	Fe <sub>2</sub> O <sub>3</sub> (42.0%), Al <sub>2</sub> O <sub>3</sub> (22.5%), SiO <sub>2</sub> (15.5%), Na <sub>2</sub> O (12.0%) and CaO (8.0%)

**Table 2. Basicity characteristics of the various catalysts from CO<sub>2</sub>-TPD studies**

Catalyst System	Basic Sites Content (mmol/g)
Charcoal 1 (C1)	0.05
Charcoal 2 (C2)	0.10
Charcoal 3 (C3)	0.15
Charcoal 4 (C4)	0.23
Red Mud (RM)	0.50

### 3.2 Catalytic Effects on Viscosity

Heavy crude oil feedstock is always associated with high viscosity and low API gravity due to its large compositions of resins and asphaltenes. The virgin heavy oil used for the current study was found to have a viscosity of 5300 mPa.s. However, this viscosity was modified by the action of catalyst depending on the associated catalytic compositions. Specifically, the trend of viscosity reduction was consistent with the concentration of active basic sites in the catalysts. These basic sites participate under the aqua-thermal conditions to trigger the cleavages of heteroatom bonds in the heavy oil feedstock. Therefore, RM catalyst with the highest basic sites produced the most pronounced viscosity reduction from 5300 to only 1500 mPa.s whereas the C1 catalyst relatively exhibited a complete inactivity during the process (see Table 3). The red mud (RM) catalysts have been reported as a very active material in different acidity-basicity dependent reactions (G. Li et al., 2026; Mousavi et al., 2026; Rangappa et al., 2026; Zhang et al., 2026). Therefore, its performance in this study is consistent with these observations.

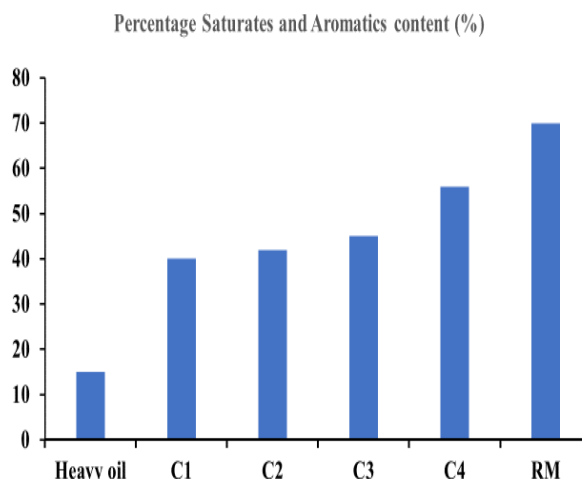
**Table 3. Viscosity reduction properties of various catalysts during the catalytic aquathermolysis process**

Catalyst	Viscosity (mPa.s)
Un-treated Heavy Oil	5300
Charcoal 1 (C1)	5300
Charcoal 2 (C2)	4900
Charcoal 3 (C3)	4000
Charcoal 4 (C4)	2500
Red Mud (RM)	1500

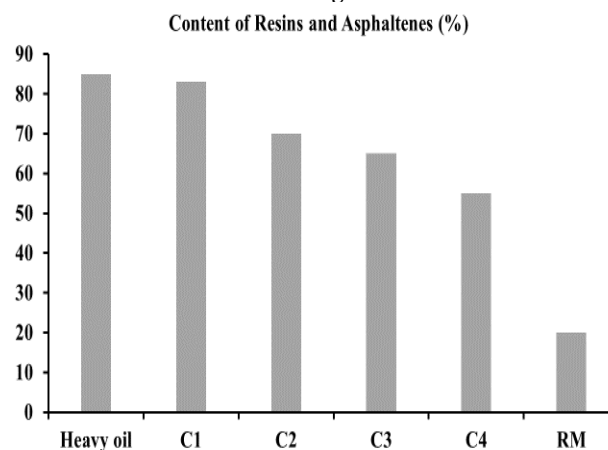
### 3.3 Catalytic Effects on Bond Ruptures

Mechanistically, the aquathermolysis process proceeds with the degradation (i.e. ruptures) of C-S, C-O, C-N and sometimes C-C bonds in the heavy oil compounds to produce lighter hydrocarbon products (J.-j. Li et al., 2025; Thangaraj & Lee, 2024; Zhou, Liu, et al., 2025). This action is triggered by the active basic sites in the

catalyst. Specifically, an active catalyst will reduce the amounts of asphaltenes and resins in the heavy oil feedstock with consequent increased in the contents of the saturates and aromatics. As shown in Figure 1, the degree of bond ruptures followed the pattern  $C1 < C2 < C3 < C4 < RM$ , indicating the RM catalyst as the most active. This specific catalyst produced the highest yields of saturates (i.e. 71.05%). For consistency, the content of asphaltenes and resins found after the reaction is profiled in Figure 2. The trend showed that, for each catalyst, the reduction in these compounds caused an elevation in the yields of saturates and aromatics (see also Figure 1). Overall, the RM material formed the best catalyst due to its larger concentration of basic sites than the other catalysts evaluated.



**Figure 1. The effects of different catalysts on the contents of saturates and light aromatics.**



**Figure 2. The effects of different catalysts on the contents of resins and asphaltenes in the heavy oil.**

## 4.0 CONCLUSION

Heavy crude oil valorization into lighter feedstock for easy production, transportation and refining is one of the

prominent processes under consideration in the field of energy catalysis. Among the various options being considered, the catalytic aquathermolysis is attracting industrial and research interest. This process requires the application of heat, steam and active catalyst to facilitate bonds ruptures and reduce the contents of bulky species in the heavy oil feedstock. Specifically, this study demonstrated that a red mud (RM) catalyst sourced from Makurdi in Benue State, Nigeria can exhibit very good catalytic properties for this application. This catalyst reduced the viscosity of heavy oil from 5300 mPa.s to 1500 mPa.s. Similarly, due to associated high contents of basic sites (i.e. 0.50 mmol/g), the RM material triggered substantial reduction in the levels of bulky species such as resins and asphaltenes with consequent formation of saturates and aromatics. When compared with other carbon-based catalysts modified with CaO and MgO, it was found that the catalytic performance followed the trend  $C1 < C2 < C3 < C4 < RM$ . Therefore, the RM has good prospects for application as an industrial aquathermolysis material.

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