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ENHANCED OIL RECOVERY: A BETTER HYDROCARBON EXPLORATION APPROACH IN LOKAKA FIELD, NIGER DELTA, NIGERIA

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Abstract

Adoption of Enhanced Oil Recovery (EOR) to boost the hydrocarbon saturation (S_h) of reservoirs has caught the interests of many researchers in Geosciences. Evidence from literature shows that both primary and secondary recovery methods have failed to account for about 60% hydrocarbon (HC) that is trapped in the reservoirs and getting to discover large productive new fields has become a herculean task. This study identified the fluid nature and boundaries of reservoirs using some relevant geophysical parameters and reservoir rocks physical features such as shale volume (V_{sh}), permeability (K), water and hydrocarbon saturation (S_w& S_h). Petrophysical data were sourced from the data bank of the Department of Geology, Obafemi Awolowo University, Ile-Ife, Nigeria. Analysis of data was done using the PETREL 2010 and OpendTect 4.6.0 versions for quality checking, delineation of identified reservoirs, fluid contacts demarcation and fluid types' determination. The interpreted data were thereafter loaded into Microsoft Excel environment in order to adopt suitable statistical relations for the estimation of V_{sh}, K, S_w and S_h. Exploration of about 59.4% HC with NaOH, 64.5% HC with KOH, 69.5% HC with NH_4OH and 78.5% HC with LiOH were discovered After EOR. Comparison of the V_{sh}, K, S_w and S_h values before EOR with the values after EOR further showed that the reservoirs produced more HC with EOR. This study concluded that more hydrocarbon saturation can be achieved from reservoirs when EOR is carried out.

Keywords: Enhanced Oil Recovery, Delineation, Shale volume, Geosciences, Geophysical parameters, Permeability, reservoirs.

INTRODUCTION

The vulnerability of Nigeria economy can be traced to its large dependence on proceeds from crude oil (Emediegwu and Okeke, 2017). The sector of oil production in Nigeria has a tremendous impact on the economy even as it represents a very small percentage of the gross domestic product (GDP): about nine percent, as at the year 2020 (Abubakar *et al*., 2016). The year 2021 ranking of the oil producing countries in the world placed Nigeria in the fourteenth position based on the barrels of crude produced per day (bpd) (Akuru and Okoro, 2011). As at the year 2021, findings from existing literatures revealed that Nigeria only produced 1.54 million barrels of crude oil per day (bpd) (Akuru and Okoro, 2011). Records from the Nigerian Upstream Petroleum Commission (NUPRC) showed that this value eventually dropped in 2022 to 1.24 million and the daily consumption of crude per barrel in Nigeria is presently at values existing in hundreds of thousands, particularly 483,000 (Obite *et al*., 2021). The geometric increase in Nigeria population has necessitated an improved way of producing more crude: as the crude produced per day in the country can only sustain the entire citizens for less than three days as about eighty five percent (85%) of the country's oil production is being exported to other countries leaving only 15% for the consumption of the entire citizen (Adepehin *et al*., 2022). This implies that Nigeria has fallen short of the minimum required quota of crude per barrel pegged at 1.80 million bpd for oil producing countries by the Organization Petroleum Exporting Countries (OPEC) (Abayomi *et al*., 2015). It is incumbent on geoscientists in the country to really look into the previously producing reservoirs which are no longer producible and devise means through which trapped hydrocarbon can be recovered, even from other unnatural approaches so as to maximize the production potential of the reservoirs (Abayomi *et al*., 2015). The primary recovery approach is based on the displacement energy which naturally takes place in the reservoirs and the purest form of hydrocarbon which becomes the purest form of fuel after refining is being recovered from this approach (Srivastava *et al*., 2019). The secondary recovery approach keeps the reservoir pressure in place through injection of fluids such as gas and water which were in existence during the drilling procedures into the reservoirs. This is done to cater for the depletion of natural energy which took place in the reservoirs during the primary recovery approach . The trapped hydrocarbons which were not recovered by the primary-natural approach can easily be recovered through the secondary recovery approach Srivastava *et al*., 2019). The viscosity of the crude can be reduced by injecting heat in the form of steam into the reservoirs. This is done in order to increase the movability of hydrocarbon as less viscous fluids have higher speed than the viscous fluids in the reservoirs .This method may however be unsuitable for highly volatile oil deposits as contents may be lost through evaporation (Pedersen and Fredenslund, 1984). Despite the injection of gas and water adopted to recover more volume of hydrocarbon in the reservoirs through the secondary recovery approach, a higher percentage of hydrocarbon has been discovered to still remain trapped in the reservoirs thereby making reservoir engineers and evaluators to underrate producible reservoirs which should have been explored to maximize oil productivity (Druetta *et al*., 2016).

Enhanced oil recovery (EOR) is the practice of introducing fluid into hydrocarbon reservoirs in order to improve the recovery of oil which depends solely on gaseous and water pressure (Deshmukh, 2020). Most of the oil producing companies in the world have shifted focus from natural exploration to unnatural approaches such as the EOR in order to maximize the recovery rate (RR) from available fields and maintain an expected economic status (Farajzadeh *et al*., 2021). This is because of the difficulties involved in discovering oilfields that have not been explored. Prior to the time of the technological advancement that brought EOR in the early seventies, precisely (1970), oilfields in the different parts of the world have been evaluated to produce at an average RR of range (20 to 40%) (Deshmukh, 2020). This is not the case with EOR approaches with an average RR ranging from (60 to 90%) as means are been devised to recovered the trapped oil which could have probably been ignored if the needed technologies and innovations weren't available (Deshmukh, 2020). EOR is however very expensive to carry out but the economic contribution of the additional recovery from EOR will no doubt outweigh its cost implications (Davidson *et al*., 2011). Enhanced oil recovery as a tertiary recovery approach is targeted at recovering the percentage of crude left unexplored after the use of the primary approach which made use of the natural reservoir pressure and the secondary approach which stabilized the reservoir pressure (Boldyrey *et al*., 2022). Rellegdla *et al*., (2018) worked on substituting the polymers with nickel nanoparticles into injection fluid(s) for the purpose of EOR. This is to facilitate increase in the recovery rate (RR) of hydrocarbon and also to determine the extent to which nanoparticles can influence the ability of the injected fluid(s) to easily displace hydrocarbon for possible exploration. The work of Ikpeka *et al*., (2022) based on electro-kinetic EOR done by introducing direct current into the reservoir rocks crevices revealed that electro-kinetic EOR assists in activating the process of EOR and stated that a major setback to this method is the deposition of cathodic salt and gas generation but on the average, EOR can be electrically triggered to facilitate production of more volume of hydrocarbon. Yin and Zhou, (2021) established that oil recovery can be enhanced in fractured reservoirs of low permeability. This was achieved by carefully monitoring the depth profile and performing cyclical controlled water injection so as to facilitate increase in the volume of hydrocarbon. Through these processes, pressure is built up in the reservoir and more hydrocarbons were being produced in the crevices of the reservoir rocks. Injection of fluids into hydrocarbon reservoirs is however accompanied by the challenge of increasing tension at the interface of the water and oil (Li *et al*., 2021). Application of heat to the combination reduces the surface tension and makes the oil recoverable. Apart from heating, detergents can also react to reduce the tension at the oil-water interface, thereby paving way for easy movability of oil from the permeable reservoir rocks (Li *et al*., 2021).It is advisable to have an idea of the type of fluids present in reservoirs before trying to enhance its recovery as some of the bases (alkalines) used as injection chemicals are capable of affecting the future producibility potentials of the reservoirs (Khlaifat *et al*., 2022).

Petrophysical parameters such as the V_{sh}, K, S_w and S_h respond to changes in production capacity of the reservoirs. Reservoirs with very high shale volume most times are characterized by low permeability and those with high permeability are likely to have low shale content or fractured shale deposits [18]. High water saturation is indicative of a low HC saturation and low water saturation is confirming high HC content in the reservoirs (Yin and Zhou, 2021). After a successful EOR approach in a HC reservoir, petrophysical parameters such as V_{sh}, K, S_w and S_h experience changes which increase the potential of HC in the reservoirs (Alam *et al*., 2022). Although several researches have been carried out to maximize hydrocarbon exploration in Nigeria, yet there are still problems of hydrocarbon shortages which are needed to be addressed to facilitate adequate productivity. This research work is aimed at estimating geophysical parameters such as V_{sh}, K, S_w and S_h in Lokaka field using related petrophysical algorithms before EOR, injecting the reservoir fluids with alkaline chemicals through flooding process to enhance hydrocarbon recovery, re-estimating the V_{sh}, K, S_w and S_h after EOR and comparing the parameters before and after EOR in order to arrive at the percentage increase in hydrocarbon recovery after EOR. Findings from this research work is expected to assist reservoirs evaluators, explorationists and engineers to rank hydrocarbon reservoirs for future developmental decisions and to recover more volume of hydrocarbon from reservoirs presumed to be unproductive through enhanced oil recovery (EOR).

Study Area

Lokaka is an onshore field located in the south eastern region of Nigeria (Figure 1). It is a Niger Delta field that is rich in exploitable crude which is capable of sustaining Nigeria economy if well managed [20]. The latitudinal and longitudinal boundaries of the field are respectively ($5^{\circ}49'N$ and $5^{\circ}80'N$) and ($6^{\circ}40'E$ and $6^{\circ}78'E$). The prevailing geologic features of the Niger Delta show a large extensive rift reaching the Gulf of Guinea particularly on the margin of the continent close to the coastal region of the western part of Nigeria (Ejedawe, 1981). There is a long existing link between the Niger Delta and the Equatorial Guinea, Sao Tome and Principe and Cameroon (Ejedawe, 1981). The geology of the subsurface of the area under study is characterized by typical Niger Delta attributes such as high hydrocarbon content and large surface area (Kulke, 1995). The part of Nigeria known as the Niger Delta is the largest or one of the largest petroliferous African basins with many formations of different characteristics Doust and Omatsola, 1990). Around the Niger Delta basin are some other similar basins formed by the same geologic and natural processes. The origin of the Niger Delta formations can be traced to the early drifting away of the African from the South American plates which began at the time of the Jurassic and ended in the Cretaceous (Ejedawe, 1981). At the time of the Paleocene, the Akata formation was the only prevailing formation. This was immediately followed by the Agbada, a formation deposited on top of the Akata at the time of the Eocene. Evamy *et al*., (1978) critically analyzed the Niger Delta stratigraphy and concluded that the formation in Niger Delta referred to as Agbada is an interbedded formation comprising of sand and shale. The Oligocene time is marked by the Benin formation which is the topmost and shallowest of the formations and of age ranging from ancient to late (Evamy *et al*., 1978). Wells bored within the area made it possible to acquire wireline logs used in analyzing some of the parameters considered in this research work.

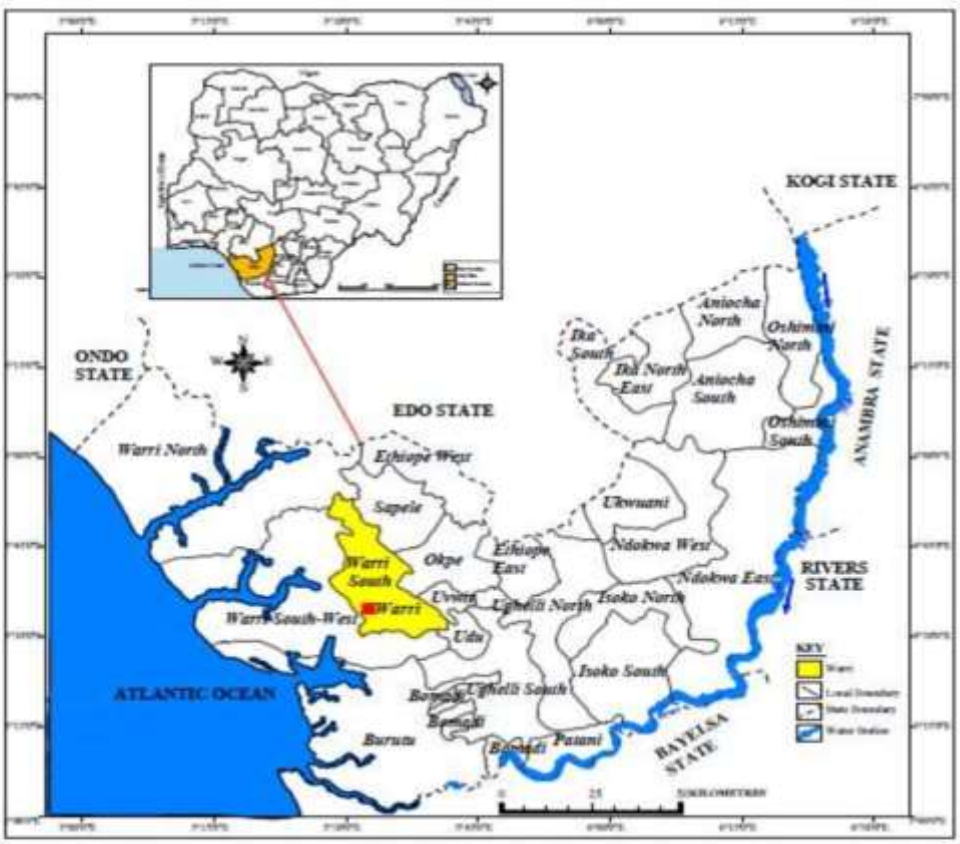

Figure 1: Map of the Study Area (Adapted from Work of Adepehin *et al*., 2022)

MATERIALS AND METHODS

Data Analysis

Data utilized for this research were sourced from the Department of Geology, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria. Analysis of data was done with the Petrel 2010 and OpendTect 4.6.0 versions. The Vsh, K, Sw and S_h were estimated using petrophysical algorithms inputted into version 2015 Microsoft excel environment. The algorithms used for this study include the neutron-density, the Tixier, (1949) and the Archie (1942) petrophysical parameters estimation models. The aforementioned are mathematical relations with which the volume of shale (V_{sh}), permeability (K), water saturation (S_w) and the hydrocarbon saturation (S_h) can be estimated before and after each of the EOR approaches. The reservoir contents such as shale, source rocks, water and hydrocarbon were collected from a well and divided into four different portions. Enhanced oil Recovery was done by injecting each of Sodium hydroxide (NaOH), Potassium hydroxide (KOH), Ammonium hydroxide (NH_4OH) and Lithium hydroxide (LiOH) into the reservoir fluid through flooding process. Alkalis used react with the trapped unexplored hydrocarbon to form surfactants which reduced the tension in the interface of the water and oil. This process triggered additional recovery of hydrocarbon when compared to the primary and secondary recovery methods. The irreducible water saturation (S_{wirr}) and the formation factor (F) are needed to obtain the Tixier, (1949) permeability while the porosity (φ) and resistivity (R) are needed to obtain the S_w from the Archie (1942) model. All these parameters were calculated to enable the estimation of V_{sh}, K, $S_w$and S_h.

Estimation of the Volume of Shale the Neutron-Density Algorithm

The Lokaka field is made up of only effective sand and shale. The neutron-density derived shale volume is only suitable for zones with effective sands and shales just like what is obtainable in the studied zone. The work of Ejieh and Ideozu, (2018) showed that the volume of shale can be calculated from the neutron and density logs with the algorithm below

$$V_{shN-Dderived} = \frac{\varphi_N - \varphi_D}{\varphi_{Nsh} - \varphi_{Dsh}} \quad (1)$$

Where,

φ_N = Neutron log derived porosity in effective sand

φ_D = Density log derived porosity in effective sand

φ_{Nsh} = Neutron log derived porosity in effective adjacent shale

φ_{Dsh} = Density log derived porosity in effective adjacent shale

2.3 Estimation of Permeability

The algorithm proposed by [26] is directly proportional to the porosity in the power of three and inversely proportional to the irreducible Sw. It is actually the product of 250 and the ratio of the cube of porosity to the irreducible water saturation.

$$Tixier_K = \frac{250\varphi^3}{S_{wirr}} \quad (2)$$

Where,

$Tixier_K$= Tixier permeability

φ = Porosity

S_{wirr} = Irreducible S_w

The irreducible S_w can be obtained as a function of the formation factor, F

$$S_{wirr} = (\frac{F}{2000})^{0.5} \quad (3)$$

Where, F is the formation factor

Estimation of the Water Saturation

The S_w can be obtained from the zone invaded by the filtrate mud. The S_w is a direct function of the resistivity of water (R_w) but indirect variation occurs between the S_w and the true resistivity (R_t) (Archie, 1942),

$$S_w = (\frac{a}{\varphi^m})(\frac{R_w}{R_t}) \quad (4)$$

Where,

S_w = Water saturation

φ = Porosity

R_w = resistivity of water

R_t = True resistivity

a = saturation constant

m = cementation exponent

The two resistivity of water Rw and the true resistivity are also related to the Sw as follows:

$$S_w = \sqrt[N]{\frac{R_w}{R_t}} \quad (5)$$

Where,
N is the saturation exponent and every other symbols have the usual meanings.

Estimation of the Hydrocarbon Saturation

The hydrocarbon saturation is a value obtained as a function of the water saturation. The sum of the percentage of water and hydrocarbon in the reservoir is 100[30],

$$\%S_{water} + \%S_{hydrocarbon} = 100 \qquad (6)$$

$$S_h = 1 - S_w \qquad (7)$$

Where,
S_w = Water saturation
S_h = Hydrocarbon Saturation

Estimation of the Percentage Oil Recovery Before and After EOR

The percentage oil recovery was estimated from the primary recovery (PR) and the EOR approaches as follows:
Percentage Recovery from PR and EOR approaches can be estimated from the relations below

$$PR_{percentage} = \frac{OR}{1 - S_w} \times 100\% \qquad (8)$$

Where,
OR = Oil recovered
$1\text{-}S_w = S_h$ = Hydrocarbon saturation

$$EOR_{NaOH} = \frac{OR_{NaOH}}{S_{hNaOH}} \times 100\% \qquad (9)$$

$$EOR_{KOH} = \frac{OR_{KOH}}{S_{hKOH}} \times 100\% \qquad (10)$$

$$EOR_{NH_4OH} = \frac{OR_{NH_4OH}}{S_{hNH_4OH}} \times 100\% \qquad (11)$$

$$EOR_{LiOH} = \frac{OR_{LiOH}}{S_{hLiOH}} \times 100\% \qquad (12)$$

OR_{NaOH}, OR_{KOH}, OR_{NH_4OH} and OR_{LiOH} are respectively oil recovered when different alkaline chemicals NaOH, KOH, NH_4OH and LiOH were injected into the reservoir fluids. EOR_{NaOH}, EOR_{KOH}, EOR_{NH_4OH} and EOR_{LiOH} are respectively the EOR flooding processes using NaOH, KOH, NH_4OH and LiOH chemicals. S_{hNaOH}, S_{hKOH}, S_{hNH_4OH} and S_{hLiOH} are respectively the hydrocarbon saturation recorded after EOR with NaOH, KOH, NH_4OH and LiOH chemicals.

RESULTS AND DISCUSSION

Adequate petrophysical parameters such as the volume of shale, permeability, water saturation and hydrocarbon saturation were determined using statistical relations imputed into Microsoft excel. The shale volume in identified Lokaka reservoirs was obtained using the neutron-density V_{sh} model. The neutron log derived porosity in effective sand, the density log derived porosity in effective sand, the neutron log derived porosity in adjacent shale and the density log derived porosity in adjacent shale were firstly obtained from Microsoft excel spreadsheet. The ratio of the difference between the first two to that of the difference between the last two gives the V_{sh}. The permeability (K) was determined with the Tixier (1949). This model relates the reservoir porosity with the irreducible water saturation in a way in which the K can be determined. The water saturation (S_w) was obtained from the Archie (1942). The relationship between the true and water resistivity and the porosity gives the S_w as shown in equation (4). The hydrocarbon saturation (S_h) showed the remaining reservoir fluid when the water saturation was removed. Figure 2 shows the image of the geophysical well log signatures used for this research work. The most important first step in evaluating petrophysical parameters is the identification of lithology (Asquith and Krygowski, 2004).. This was achieved by converting the obtained digital data to analog form which can effortlessly be understood. These dataset were thereafter imported into the petrel environment. A shale bottom line pegged at 60^o API was employed to distinguish between the shale, water and oil zones in the sequences penetrated by the well. The required petrophysical parameters were thereafter obtained by reorganizing the logs to facilitate their suitability. Intervals demarcated as oil zones were painted green while the water zones were painted blue. Interval painted yellow in Figure 2 represents the shale zones. Reservoir contents made up of shale, source rocks, water and hydrocarbon as obtained from Lokaka field were divided into four portions: PTN U, PTN V, PTN X and PTN Y. NaOH, KOH, NH_4OH and LiOH were then injected into PTN U, PTN V, PTN X and PTN Y respectively. Thereafter the volume of shale, permeability, water saturation and hydrocarbon saturation were all re-estimated and compared to their initial values before EOR.

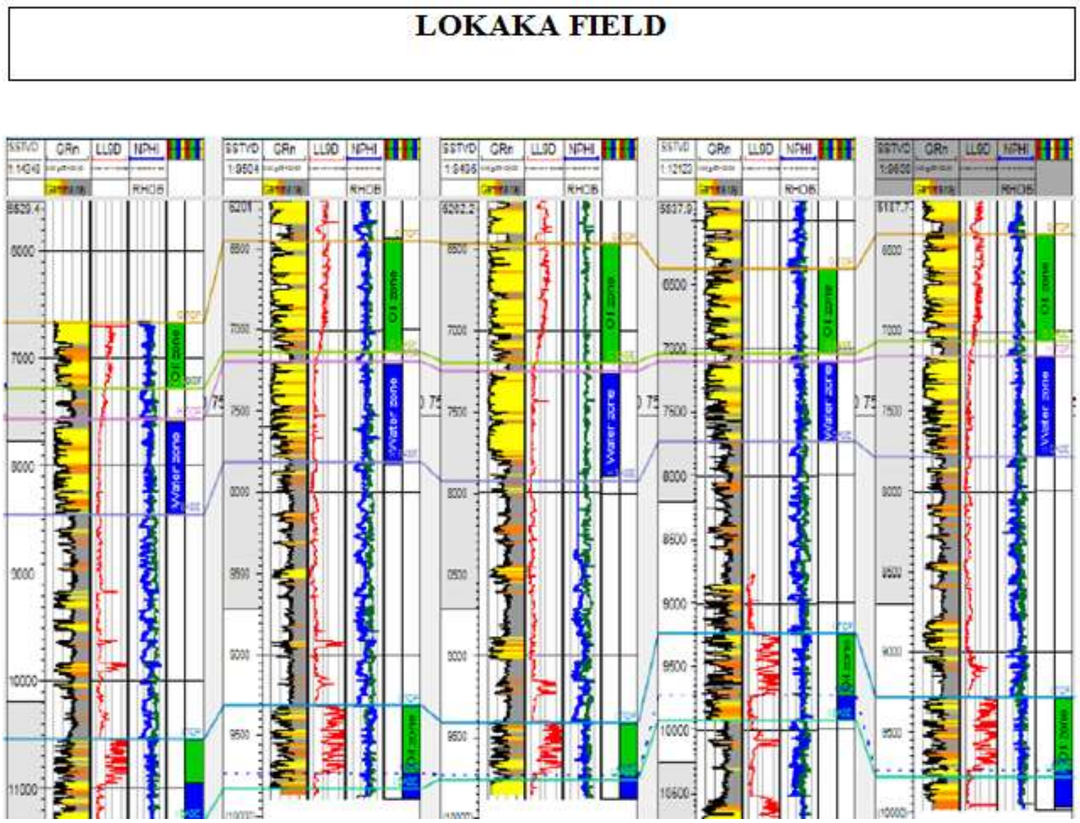

Figure 2: Geophysical well log Obtained from the Petrel and OpendTect Software

Quantitative Evaluation of the Shale Volume

The volume of shale as shown on (Table 1) varied in the four portions PTN U, PTN V, PTN X and PTN Y. There was a slight increase in the volume of shale from PTN U to PTN V. The V_{sh} increased from 0.092 v/v to 0.140 v/v. The value also increased to 0.162 v/v in PTN X and dropped to 0.084 v/v in PTN Y. The volume of shale in Lokaka field is generally observed to witness rises and falls from one portion to another. The 0.080v/v to 0.020 v/v difference in the shale volume may be as a result of the variation in the quantity of the reservoir sands and shale in each of the portion. The EOR carried out with sodium hydroxide (NaOH) chemical altered the V_{sh} as PTN U, PTN V, PTN X and PTN Y respectively recorded V_{sh} values of 0.056 v/v, 0.007 v/v, 0.111 v/v and 0.052 v/v. These values changed to 0.078 v/v, 0.100 v/v, 0.116 v/v and 0.035 v/v when EOR was carried out with potassium hydroxide (KOH). EOR done with ammonium hydroxide (NH_4OH) recorded V_{sh} values of 0.069 v/v, 0.120 v/v, 0.132 v/v and 0.071 v/v for portion PTN U, PTN V, PTN X and PTN Y respectively. When lithium hydroxide (LiOH) chemical was injected into the reservoir content, the values of V_{sh} reduced to 0.091

v/v, 0.130 v/v, 0.153 v/v and 0.060 v/v for PTN U, PTN V, PTN X and PTN Y respectively. A fall in the value of the volume of shale when EOR was carried out is an indication of likely recovery of more hydrocarbon from the reservoir.

Table 1: Recorded Shale Volume Values Before and After EOR (Obtained from Equation 1)

PORTION	*PR V_{sh} (v/v)*	*NaOH(EOR) V_{sh} (v/v)*	*KOH(EOR) V_{sh} (v/v)*	*NH_4OH(EOR) V_{sh} (v/v)*	*LiOH(EOR) V_{sh} (v/v)*
PTN U	0.092	0.056	0.078	0.069	0.091
PTN V	0.140	0.007	0.100	0.120	0.130
PTN X	0.162	0.111	0.116	0.132	0.153
PTN Y	0.084	0.052	0.035	0.071	0.060

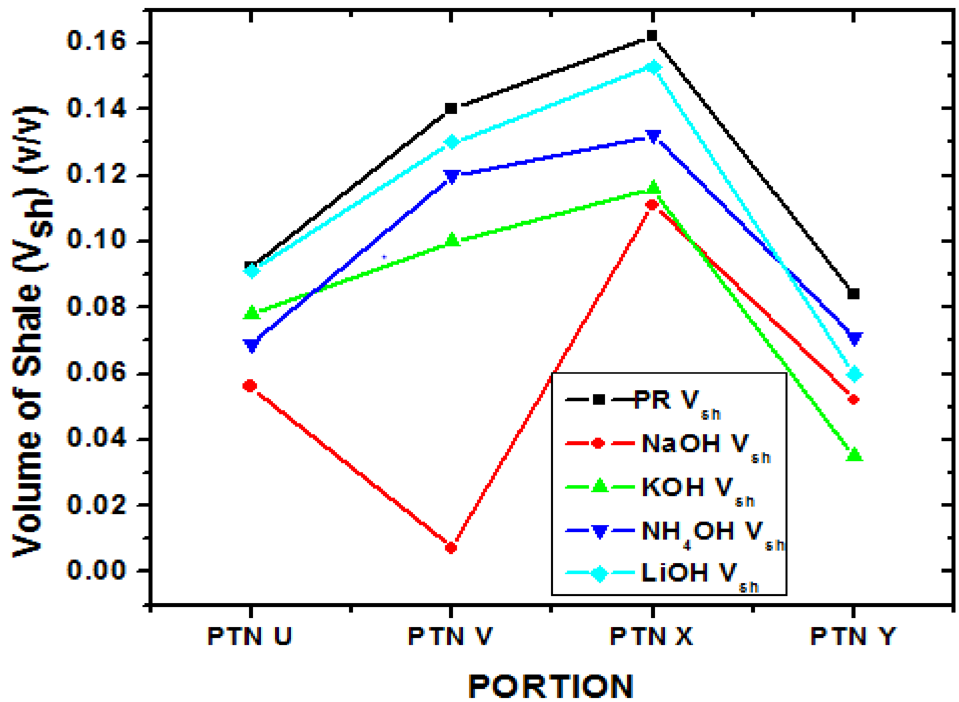

Figure 3: Comparison of the PR V_{sh} and the EOR V_{sh}

The EOR was carried out in two different formations in a bit to increase the hydrocarbon potential. Figure 3 shows that reservoir shale content during the primary recovery is higher than the values recorded during EOR with NaOH, KOH, NH_4OH and LiOH. It is evident from Figure 3 that the average order of increase of the reservoir shale is PR V_{sh}> LiOH V_{sh}> NH_4OH V_{sh}> KOH V_{sh}> NaOH V_{sh}. The introduced alkaline chemicals reduced the previously estimated volume of shale from the PR method. One can say that there exist some percentages of hydrocarbon trapped and unnoticed within the reservoir shale during the convectional PR approach. The trapped hydrocarbon recovered during EOR must have been responsible for the reduction in the volume of shale shown in Figure 3.This implies that more hydrocarbon can be recovered with EOR and the percentage of hydrocarbon that will be recovered depends solely on the type of chemical injected into the reservoir fluids. This is in accordance with the work of Adepehin *et al*., (2022) which stressed that the hydrocarbon saturation increases with a decrease in the shale volume. A similar work of Jiang *et al*., (2014) done to cater for the rising demand for oil in Malaysia showed that the decrease in the shale volume further explain the success recorded in enhancing the recovery of oil in the field as the RR increased from 34% to more promising percentage in the range greater than the target set by the hydrocarbon production companies (Samanta *et al*., 2011). This is similar to the work of Jiang *et al*., (2014) carried out in a bit to flood the reservoir with alkalis so as to examine their interactions with organic acids inherent in crude oil. The physicochemical attributes of the alkaline chemicals were evaluated before the flooding process. This research work also produced results which are in line with that of Samanta *et al*., (2011) in which alkanoic acid functional group was discovered in the crude oil and this reduced the tension in the interface between water and oil and a host of other important petrophysical properties such as the V_{sh} which were employed for EOR. Just like the result of this research, Mayer *et al*., (1983) also examined the ability of alkalis to recover trapped hydrocarbon and discovered that EOR with alkalis yielded more than 15% additional hydrocarbon when compared to the PR approach. A similar research work done by Hendraningrat *et al*., (2013) focused on the use of nanoparticles to aid the performance of water flooding and influence the important petrophysical parameters such as V_{sh} and K concluded that flooding the reservoirs with nanoparticles is another approach capable of yielding surprising increase in hydrocarbon potential and recommended that this approach can be leveraged on by geoscientists as a future yet to be unraveled EOR approach. Similar result was also obtained by Cheraghian *et al*., (2020) who also employed nanoparticles for EOR..

Quantitative Evaluation of the Permeability

Permeability estimated for portion PTN U, PTN V, PTN X and PTN Y shown in Table 2, were observed to be respectively 2885.771 mD, 23.397 mD, 4954.187 mD and 2955.223 mD during primary recovery (PR) approach. These values increased when EOR was carried out. EOR with NaOH chemical respectively recorded 6088.243 mD, 27.597 mD, 5099.140 mD and 4095.464 mD for the aforementioned portions. Similarly, EOR with KOH chemical gave higher permeability values compared to the values obtained from the PR approach. 75419.340 mD, 29.220 mD, 5757.387 mD and 24987.470 mD were recorded for the four portions of the reservoir content. These values change to 16549.890 mD, 57.375 mD, 5460.226 mD and 9091.425 mD when EOR was carried out with NH_4OH chemical. The values however changed to 244055.800 mD, 41.882 mD, 5810.767 mD and 86717.020 mD when LiOH chemical was used for the flooding process. [5] emphasized that an increase in permeability shows a possible increase in reservoirs hydrocarbon contents. EOR with different alkaline chemicals is likely to recover more hydrocarbon from the Lokaka reservoirs when compared to the PR method.

Table 2: Recorded Permeability Values Before and After EOR (Obtained from Equation 2)

PORTION	*PR K (mD)*	*NaOH(EOR) K (mD)*	*KOH(EOR) K (mD)*	*NH_4OH(EOR) K (mD)*	*LiOH(EOR) K (mD*
PTN U	2885.771	6088.243	75419.340	16549.890	244055.800
PTN V	23.397	27.597	29.220	57.375	41.882
PTN X	4954.187	5099.140	5757.387	5460.226	5810.767
PTN Y	2955.223	4095.464	24987.470	9091.425	86717.020

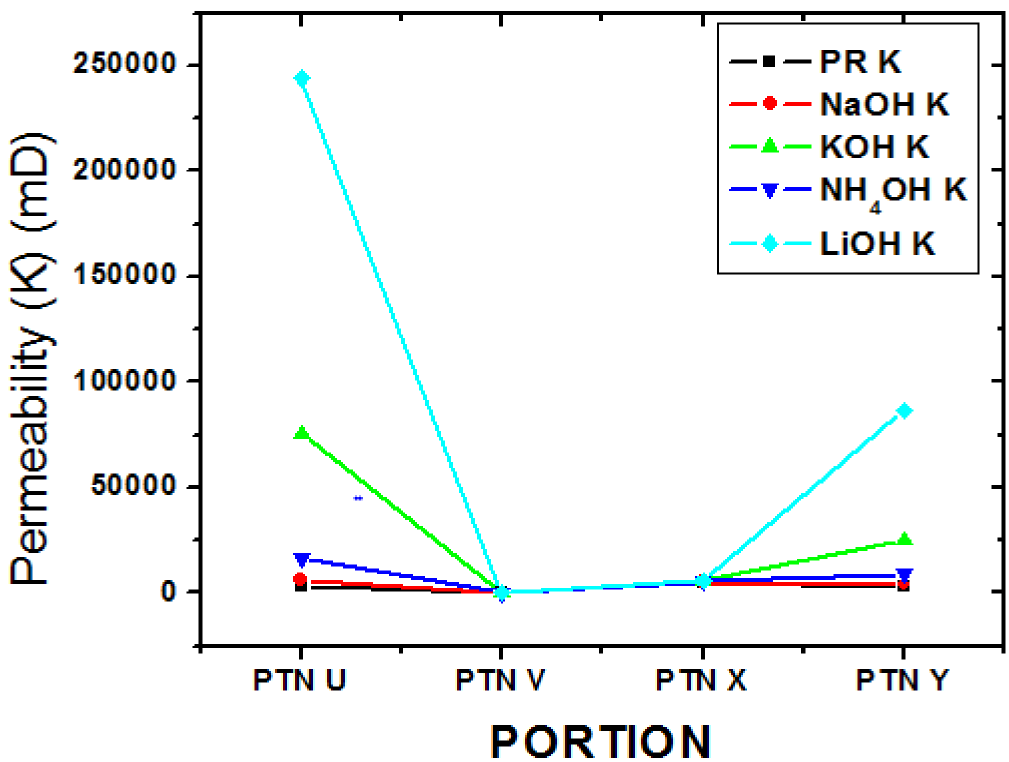

Figure 4: Comparison of the PR K and the EOR K

The estimated permeability of the reservoir when EOR was carried out was compared to the permeability obtained from the PR approach. The EOR recorded more permeability than the primary PR recovery approach. The increase in the estimated permeability during EOR as shown in Figure 4 implies that the initial permeability of the reservoir has been masked by reservoirs heterogeneities (Mode *et al*., (2013). The peculiarity of the reservoir rocks and the nature of the organic acid in the inherent crude provide an enhanced recovery of more hydrocarbon with LiOH due to the increase in the reservoir rocks permeability which respectively ranges from 41.882 mD to 244055.800 mD (Figure 4). The rocks permeability ranges from 29.220 mD to 75419.340 mD, 57.375 mD to 16549.890 mD and 27.597 mD to 6088.243 mD when each of KOH, NH_4OH and NaOH was used to enhance the recovery of oil (Figure 4).This is line with the work of Hendraningrat *et al*., (2013) in which Nitrogen, Carbon IV oxide and an equal ratio mixture of Nitrogen and carbon IV oxide gases were employed to enhance the recovery of oil. The recovery ratios (RR) were examined alongside the recovery time (RT).The highest recovery obtained was with carbon IV oxide gas as the recovery agent. An equal ratio mixture of Nitrogen and carbon IV oxide gases recovered the next highest value of oil while the Nitrogen gas recovered the least volume of oil. This was revealed in the order of increase in the reservoir rocks permeability which is CO_2 K > (N_2 +CO_2) K > N_2 K. Results obtained from this research is similar to that of Zhang *et al*., (2022) based on flooding the reservoir with air foam in order to recover more hydrocarbon from Ganguyi oil field. The used air foam enhanced the volume and the displacement ability of the oil. After a thorough assessment of the reservoir permeability before and after EOR, Zhang *et al*., (2022) discovered that the permeability of the reservoir increased during EOR with air foam in the studied field.

Evaluation of the Water Saturation

The average quantity of water during the PR approach was observed to be more than the one recorded when EOR was carried out. PR approach recorded $S_w$values of 0.781 v/v, 0.962 v/v, 0.843 v/v and 0.954 v/v for portion PTN U, PTN V, PTN X and PTN Y (Table 3). The water saturation values after EOR with NaOH, KOH, NH_4OH and LiOH were observed to have respectively reduced to (0.533 v/v, 0.988 v/v, 0.565 v/v and 0.468 v/v), (0.272 v/v, 0.849 v/v, 0.462 v/v and 0.654 v/v), (0.306 v/v, 0.981 v/v, 0.796 v/v and 0.543 v/v) and (0.167 v/v, 0.782 v/v, 0.506 v/v and 0.124 v/v) for all the aforementioned portions. A fall observed in the water saturation is indicative of a rise in the hydrocarbon saturation (Adepehin *et al*., 2022). This is established in equation 7.

Table 3: Recorded Water Saturation Values Before and After EOR (Obtained from Equation 4)

PORTION	*PR S_w (v/v)*	*NaOH(EOR) S_w (v/v)*	*KOH(EOR) S_w (v/v)*	*NH_4OH(EOR) S_w (v/v)*	*LiOH(EOR) S_w (v/v)*
PTN U	0.781	0.533	0.272	0.306	0.167
PTN V	0.962	0.988	0.849	0.981	0.782
PTN X	0.843	0.565	0.462	0.796	0.506
PTN Y	0.954	0.468	0.654	0.543	0.124

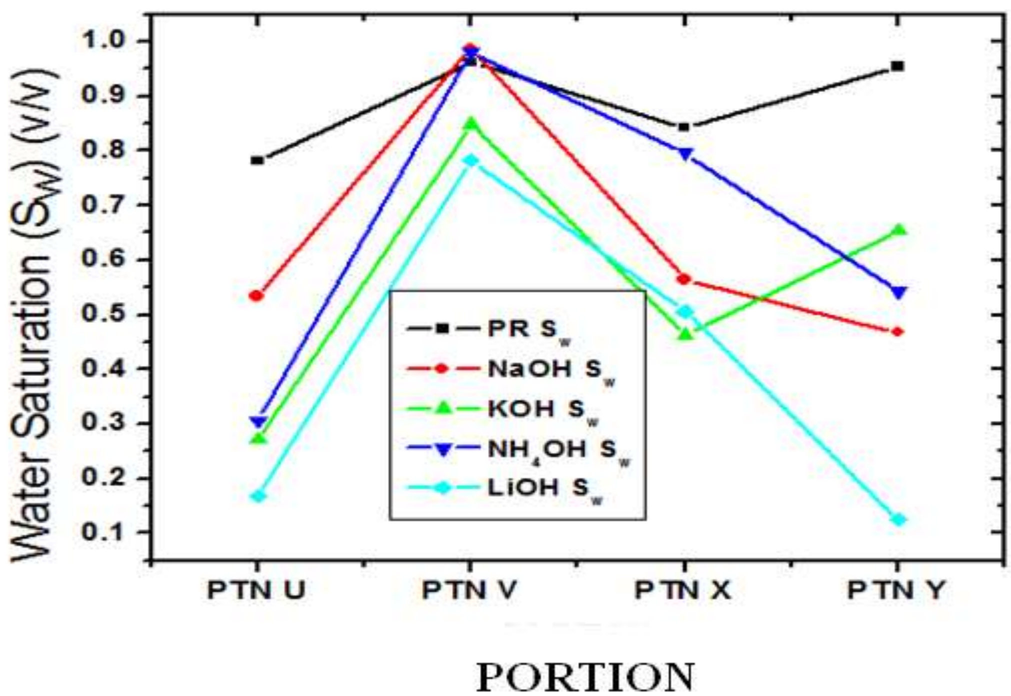

Figure 5: Comparison of the PR S_w and the EOR S_w

The water saturation of Lokaka field reduced when EOR was carried out (Figure 5). The reduction in water saturation serves a pointer to an increase in the hydrocarbon saturation (Adepehin *et al*., 2022). As the alkaline chemicals provide different reservoirs enhancing abilities, the water saturation also changes to suit the recovery percentage. EOR with LiOH records the least S_w while the one with

NaOH and NH_4OH records the highest. One can summarily conclude that EOR reduces the S_w of hydrocarbon reservoir and this gives rise to production of more hydrocarbon during the process, Farad *et al*., (2016) compared oil recovery to the water saturation. The water saturation decreases with increase in the hydrocarbon saturation in the reservoir. Farad *et al*., (2016) concluded that oil recovery from reservoir depends largely on the S_w and that the cores wettability is a function of the recovery time. This agrees with the work of Negin *et al*., (2017) done on the effect of surfactants injection on some petrophysical parameters revealed that the original recovery ability of reservoirs are altered after EOR. The alteration in the wettability of reservoirs was stated by Negin *et al*., (2017) as one of the reasons behind the reduction in water saturation after EOR. Mahmud *et al*., (2019) carried out water flooding with low salt content fluids. The flooding process altered the reservoirs properties such as the water saturation, porosity and permeability. Mahmud *et al*., (2019) emphasized that the effects of these parameters define the basis upon which hydrocarbon can be recovered from reservoirs. The water saturation of the reservoir decreased after EOR just as the one in the findings of this research.

Evaluation of the Hydrocarbon Saturation

The values of the hydrocarbon saturation recorded during the PR process increased when EOR was carried out. PR was able to account for the hydrocarbon saturation of 0.219 v/v, 0.038 v/v, 0.157 v/v and 0.046 v/v for portion PTN U, PTN V, PTN X and PTN Y (Table 4). These values change when EOR was carried out with NaOH, KOH, NH_4OH and LiOH chemicals. EOR with this chemicals respectively recorded hydrocarbon saturation (S_h) values of (0.467 v/v, 0.012 v/v, 0.435 v/v and 0.532 v/v), (0.728 v/v, 0.151 v/v, 0.538 v/v and 0.346 v/v), (0.694 v/v, 0.019 v/v, 0.204 v/v and 0.457 v/v) and (0.833 v/v, 0.218 v/v, 0.494 v/v and 0.876 v/v) for portion PTN U, PTN V, PTN X and PTN Y.

Table 4: Recorded Hydrocarbon Saturation Values Before and After EOR (Obtained from Equation 7)

PORTION	*PR S_h (v/v*	*NaOH(EOR) S_h (v/v)*	*KOH(EOR) S_h (v/v)*	*NH_4OH(EOR) S_h (v/v)*	*LiOH(EOR) S_h (v/v)*
PTN U	0.219	0.467	0.728	0.694	0.833
PTN V	0.038	0.012	0.151	0.019	0.218

PTN X	0.157	0.435	0.538	0.204	0.494
PTN Y	0.046	0.532	0.346	0.457	0.876

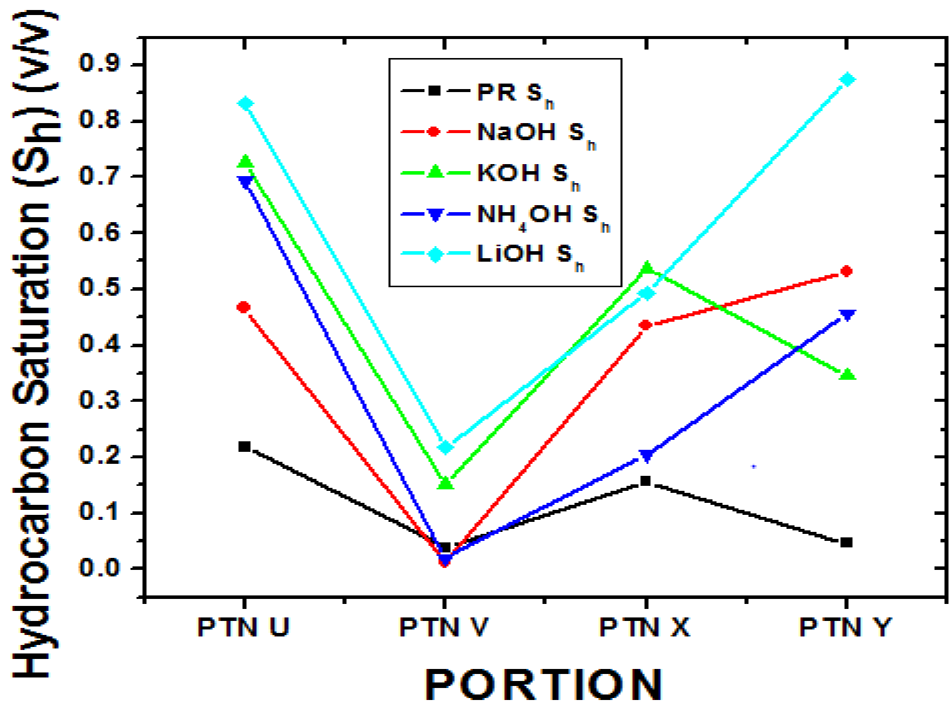

Figure 6: Comparison of the PR S_h and the EOR S_h

The hydrocarbon saturation increases as expected with EOR. Figure 6 shows a decrease in the S_w after EOR and as expected, a decrease in S_w means an increase in S_h. According to Adepehin *et al*., (2022), $S_w + S_h = 1$. The highest recovery rate obtained with EOR results from LiOH. The next highest RR as revealed in Figure 6 occurs when KOH chemical is used as the recovery agent. The use of NaOH and NH_4OHas recovery agents recovered less hydrocarbon than the ones with KOH and LiOH but greater than that of the primary recovery. It is normal to say that EOR increases the hydrocarbon saturation values of reservoirs. This is line with the work of Olabode *et al*., (2021) in which chemical recovery was done to enhance the reservoirs deliverability. Comparison of gas and water injection with the water exchanging gas and foam revealed that more hydrocarbon was recovered with water exchanging gas and foam as recovery agents. Gbadamosi *et al*., (2019) considered the prospect of chemical EOR in an attempt to recover more volume of hydrocarbon from reservoirs. Work done on chemical EOR by Gbadamosi *et al*., (2019) showed that more hydrocarbon saturation values were obtained after EOR.

Evaluation of Percentage Recovery

The percentage recoveries for all the entire portions were evaluated and the average of the calculated percentage values were taken as the percentage of hydrocarbon recovered from the reservoir. This was done during the primary recovery (PR) and after each of the EOR approaches. Table V shows the oil recovery from the PR and the EOR approaches.

Table 5: Oil Recovery (OR) from Lokaka Reservoirs Before and After EOR

PORTION	*PR*	*EOR*			
		NaOH EOR	KOH EOR	NH_4OH EOR	LiOH EOR
PTN U	0.0876	0.2802	0.4805	0.4805	0.6664
PTN V	0.0151	0.0072	0.0982	0.0131	0.1722
PTN X	0.0612	0.2553	0.3443	0.1448	0.3853
PTN Y	0.01771	0.3128	0.2145	0.3108	0.6920

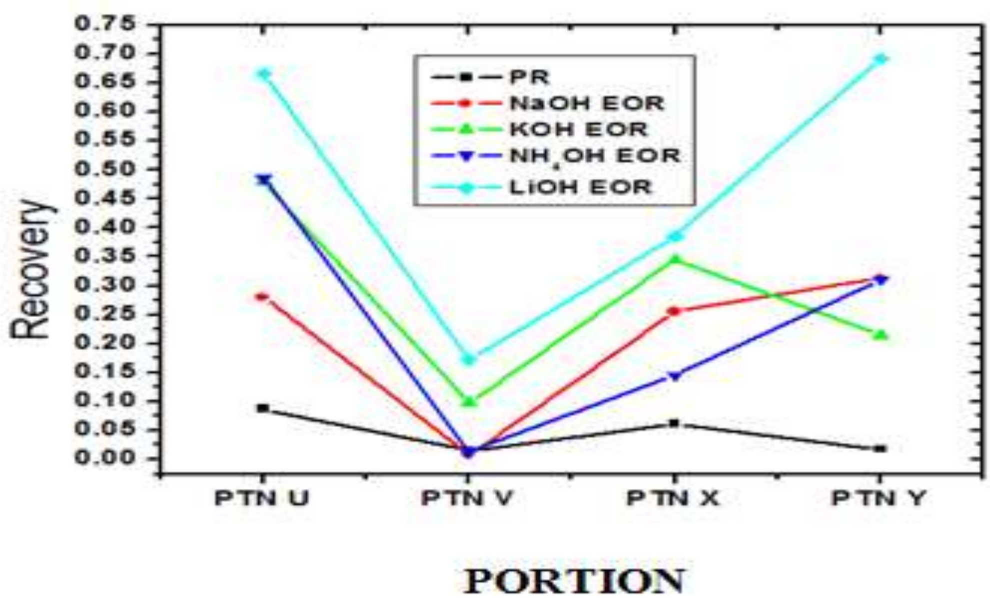

Figure 7: Comparison of the Percentage Recovery from PR and EOR

Figure 7 gives a clearer picture of the effect of EOR on hydrocarbon saturation of reservoirs. Average recovery from each of the four recovery agents (NaOH, KOH, NH_4OH and LiOH) was compared to that of the primary recovery PR from ordinary reservoir pressure. Percentage oil recovered from all the alkaline chemicals is found to be higher than that of the PR. A careful look through the work of Bealessio *et al*., (2021) and Muggeridge *et al*., (2014) revealed that enhance oil recovery, except for unusual reasons will always yield a higher hydrocarbon potential than the original PR. This is because, the reservoirs are being pressure to recovered trapped hydrocarbon which probably may not have been recovered by ordinary reservoirs pressure.

Percentage recovery from PR and EOR approaches were calculated from equations (8 – 12)

Using equation (8), the percentage recovery for all the four portions were calculated before EOR (primary recovery) as follows:

$$PR_{percentage} = \frac{OR}{1-S_w} \times 100\% \quad \text{for PTN U}$$

$$PR_{percentage} = \frac{0.0876}{0.219} \times 100\% = 40\%$$

$$PR_{percentage} = \frac{OR}{1-S_w} \times 100\% \quad \text{for PTN V}$$

$$PR_{percentage} = \frac{0.0151}{0.038} \times 100\% = 39.7\%$$

$$PR_{percentage} = \frac{OR}{1-S_w} \times 100\% \quad \text{for PTN X}$$

$$PR_{percentage} = \frac{0.0612}{0.157} \times 100\% = 38.9\%$$

$$PR_{percentage} = \frac{OR}{1-S_w} \times 100\% \quad \text{for PTN Y}$$

$$PR_{percentage} = \frac{0.01771}{0.046} \times 100\% = 38.5\%$$

$$Average = \frac{40\% + 39.7\% + 38.9\% + 38.5\%}{4} = 39.3\%$$

Only 39.3% of the hydrocarbon was recovered through the primary recovery approach. As this percentage cannot match the consumption rate of the geometrically progressed population of the nation, the EOR were carried out in order to recover more crude. The percentage recovery for each of the EOR approaches was calculated as follows:

Using equation (9), the percentage recovery for all the four portions were calculated after EOR done with NaOH (tertiary recovery) as follows:

$$EOR_{NaOH} = \frac{OR_{NaOH}}{S_{hNaOH}} \times 100\% \quad \text{for PTN U}$$

$$EOR_{NaOH} = \frac{0.2802}{0.467} \times 100\% = 60\%$$

$$EOR_{NaOH} = \frac{OR_{NaOH}}{S_{hNaOH}} \times 100\% \quad \text{for PTN V}$$

$$EOR_{NaOH} = \frac{0.0072}{0.012} \times 100\% = 60\ \%$$

$$EOR_{NaOH} = \frac{OR_{NaOH}}{S_{hNaOH}} \times 100\% \quad \text{for PTN X}$$

$$EOR_{NaOH} = \frac{0.2553}{0.435} \times 100\% = 58.7\%$$

$$EOR_{NaOH} = \frac{OR_{NaOH}}{S_{hNaOH}} \times 100\% \quad \text{for PTN Y}$$

$$EOR_{NaOH} = \frac{0.3128}{0.532} \times 100\% = 58.8\%$$

$$Average = \frac{60\% + 60\% + 58.7\% + 58.8\%}{4} = 59.4\%$$

Injection of NaOH chemical into the reservoir fluids yielded 59.4% recovery from the Lokaka reservoirs. 19.1% more than the percentage recovered from the natural reservoirs pressure.

Using equation (10), the percentage recovery for all the four portions were calculated after EOR done with KOH (tertiary recovery) as follows:

$$EOR_{KOH} = \frac{OR_{KOH}}{S_{hKOH}} \times 100\% \quad \text{for PTN U}$$

$$EOR_{KOH} = \frac{0.4805}{0.728} \times 100\% = 66\%$$

$$EOR_{KOH} = \frac{OR_{KOH}}{S_{hKOH}} \times 100\% \quad \text{for PTN V}$$

$$EOR_{KOH} = \frac{0.0982}{0.151} \times 100\% = 65\%$$

$$EOR_{KOH} = \frac{OR_{KOH}}{S_{hKOH}} \times 100\% \quad \text{for PTN X}$$

$$EOR_{KOH} = \frac{0.3443}{0.538} \times 100\% = 63.9\%$$

$$EOR_{KOH} = \frac{OR_{KOH}}{S_{hKOH}} \times 100\% \quad \text{for PTN Y}$$

$$EOR_{KOH} = \frac{0.2145}{0.346} \times 100\% = 63.1\%$$

$$Average = \frac{66\% + 65\% + 63.9\% + 63.1\%}{4} = 64.5\%$$

Injection of KOH chemical into the reservoir fluids yielded 64.5% recovery from the Lokaka reservoirs. 25.2% more than the percentage recovered from the natural reservoirs pressure.

Using equation (11), the percentage recovery for all the four portions were calculated after EOR done with NH_4OH (tertiary recovery) as follows:

$$EOR_{NH_4OH} = \frac{OR_{NH_4OH}}{S_{hNH_4OH}} \times 100\% \quad \text{for PTN U}$$

$$EOR_{NH_4OH} = \frac{0.4858}{0.694} \times 100\% = 70\%$$

$$EOR_{NH_4OH} = \frac{OR_{NH_4OH}}{S_{hNH_4OH}} \times 100\% \quad \text{for PTN V}$$

$$EOR_{NH_4OH} = \frac{0.0131}{0.019} \times 100\% = 68.9\%$$

$$EOR_{NH_4OH} = \frac{OR_{NH_4OH}}{S_{hNH_4OH}} \times 100\% \quad \text{for PTN X}$$

$$EOR_{NH_4OH} = \frac{0.1448}{0.204} \times 100\% = 70.9\%$$

$$EOR_{NH_4OH} = \frac{OR_{NH_4OH}}{S_{hNH_4OH}} \times 100\% \quad \text{for PTN Y}$$

$$EOR_{NH_4OH} = \frac{0.3108}{0.457} \times 100\% = 68\%$$

$$Average = \frac{70\% + 68.9\% + 70.9\% + 68\%}{4} = 69.5\%$$

Injection of KOH chemical into the reservoir fluids yielded 69.5% recovery from the Lokaka reservoirs. 30.2% more than the percentage recovered from the natural reservoirs pressure.

Using equation (12), the percentage recovery for all the four portions were calculated after EOR done with LiOH (tertiary recovery) as follows:

$$EOR_{LiOH} = \frac{OR_{LiOH}}{S_{hLiOH}} \times 100\% \text{ for PTN U}$$

$$EOR_{LiOH} = \frac{0.6664}{0.833} \times 100\% = 80\%$$

$$EOR_{LiOH} = \frac{OR_{LiOH}}{S_{hLiOH}} \times 100\% \text{ for PTN V}$$

$$EOR_{LiOH} = \frac{0.1722}{0.218} \times 100\% = 78.9\%$$

$$EOR_{LiOH} = \frac{OR_{LiOH}}{S_{hLiOH}} \times 100\% \text{ for PTN X}$$

$$EOR_{LiOH} = \frac{0.3853}{0.494} \times 100\% = 77.9\%$$

$$EOR_{LiOH} = \frac{OR_{LiOH}}{S_{hLiOH}} \times 100\% \text{ for PTN Y}$$

$$EOR_{LiOH} = \frac{0.6920}{0.876} \times 100\% = 78.9\ \%$$

$$Average = \frac{80\% + 78.9\% + 77.9\% + 78.9\%}{4} = 78.9\%$$

Injection of LiOH chemical into the reservoir fluids yielded 78.9% recovery from the Lokaka reservoirs. 39.6% more than the percentage recovered from the natural reservoirs pressure.

CONCLUSION

Critical analysis of results obtained from the primary recovery (PR) and the enhanced oil recovery (EOR) shows that EOR provides hope for reservoir engineers to explore more volume of hydrocarbon from reservoirs that were previously presumed not to be producible. Re-evaluated petrophysical parameters which values determine the hydrocarbon potential give promising estimates with EOR and this can serve as the basis upon which more hydrocarbons can be produced to cater for the high demand of petroleum products in Nigeria. Low shale volume, low water saturation, high permeability and high hydrocarbon saturation estimates recorded with EOR reveal improved recoveries which can be leveraged on by oil companies to produce more volume of crude.

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