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Microbial Enhanced Oil Recovery in Upper Assam Oil Reservoirs: A Screening Framework for Success

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Abstract
Majority of oil fields in Upper Assam, India, are depleted and brownfields, and also most of them are producing under waterflooding operations. So to assist waterflooding processes, microbial enhanced oil recovery (MEOR) method can be employed in oil wells under waterflooding operations. Past implementation of the MEOR method in Upper Assam oil fields had several complications, and the results of oil recovery were not significant due to various factors like fluid injectivity issues, absorption/adsorption, reduction in permeability, etc. The main objective of this work is to perform screening of rock properties of Upper Assam Oil fields and see if MEOR can be implemented. This paper presents the effects/impacts of rock properties that can influence the performance of MEOR in subsurface. A series of laboratory experiments were carried out on subsurface sandstone cores of different formations and depths to determine their petrophysical properties, wettability, pore throat, petrographic analysis, and clay minerals. The experimental results from the present study showed an average porosity of 22.8%, permeability of 27.08 mD, and rock wettability that was mostly water-wet. Results also demonstrated an average pore throat diameter of 4.9 µm in all the sandstone cores. Clay minerals mostly present were kaolinite, illite, chlorite, and montmorillonite. In terms of mineralogy, quartz is the most dominant mineral found in all samples. This article concludes that Upper Assam oil fields can be good candidates for MEOR with a better understanding of rock characteristics, which can help in designing more effective MEOR strategies for recovering additional oil from reservoirs.
Keywords: *Enhanced oil recovery. Sandstone core. Rock properties. Upper Assam Oil Fields. Microbes. Waterflooding operation.*

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I. INTRODUCTION

Every oil reservoir, considering its age is a candidate for enhanced oil recovery (EOR) (Bryant and Lockhart 2002). This is due to the fact that even after conventional, primary, and secondary recovery operations, reservoirs still hold sizable amounts of oil. The economic situation, the state of the technology, and operator priorities all influence how many candidates become project (Bryant and Lockhart 2002). In order to mobilize residual oil, microorganisms and their metabolites, such as biosurfactants, biopolymers, biogenic acids, enzymes, solvents, and biogases, are used in the important tertiary oil recovery technique known as microbial enhanced oil recovery (MEOR) (Youssef, Elshahed, McInerney 2009; Banat 1995 and Lazar et al. 1991). In order to improve the mobilization of residual oil, MEOR involves adding extra or native microorganisms to an oil reservoir or boosting the native microbial population. Microorganisms can be used to metabolize metabolites with cheap raw materials, such as molasses, corn syrup, and other agricultural byproducts, as well as agricultural organic waste. MEOR products have the advantage of cost independent of crude oil prices compared to other petroleum based chemicals used in EOR (Sen 2008; Al-Bahry et al. 2013). For an extensive analysis of MEOR and the mechanisms involved, we refer to (Youssef, Elshahed, and McInerney 2009).

1.1 Parameters affecting MEOR

It might be difficult to select the reservoir for MEOR processes, particularly when dealing with mature or marginal assets. A multitude of factors must be taken into account when selecting candidates for MEOR operations to be executed properly. When it comes to established assets, in-situ MEOR mostly targets the residual oil left over after primary production and secondary recovery techniques. After undergoing several production cycles and processes, mature assets need a thorough analysis of numerous parameters that may have changed over time. Globally, producing fields are experiencing indications of maturity, such as declining pressure and increased water and gas production. Because of this situation, the operators must figure out how to prolong the field life in addition to using primary and secondary recovery techniques. Before applying MEOR to a particular reservoir, the following common parameters must be taken into account. From reservoir to reservoir, these parameters might differ significantly, and before MEOR is put into practice, new parameters can occasionally be taken into considerations. The main parameters are (1) Rock lithology; (2) Microbial community; (3) Subsurface environment; (4) Reservoir rock properties, such as pore size, porosity & permeability, wettability, etc.; and reservoir conditions. The main parameters affecting MEOR are pictorially represented in Figure 1.

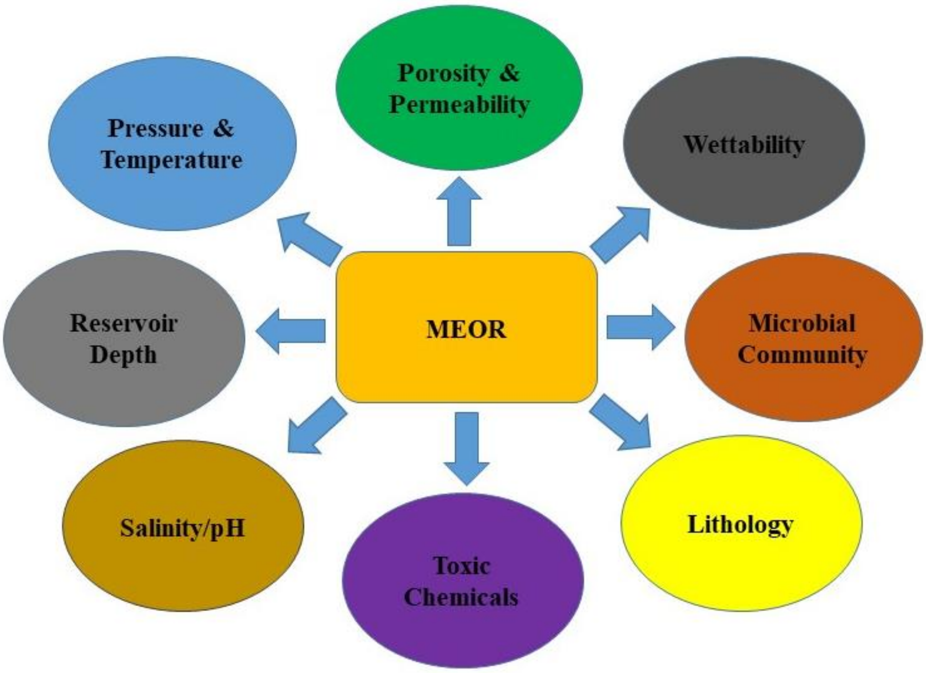


Fig.1: Parameters affecting microbial enhanced oil recovery processes.

1.1.1 Rock Lithology

The adsorption behavior of metabolites, i.e., surfactants, and the presence of native microorganisms are controlled by the physical properties of rocks. Depending on their presence in the reservoir rock and how they contribute to the biogenic weathering of the reservoirs, microorganisms are classified. Endolithic microorganisms reside within the spaces of rocks or between mineral grains, whereas epiliths are firmly attached to the surface of the rock. Chasmoendoliths build up in crevices in the rock or in excavated formations. Euendoliths generate the borings by active digging and accumulate on carbonate surfaces by dissolving them into rock layers (Hoppert et al. 2004). The amount of biosurfactant required to extract oil depends on the rock surface's adsorption capability. The absorption values of different rock formations vary a lot. In general, sandstone may absorb 0.1–1 mg of surfactant/g of rock; however, this also relies on the surfactant's initial concentration (Abbas et al., 2022). Due to the high adsorption capacity of carbonates, the anionic surfactant flooding in sandstone reservoirs is more effective than in carbonate reservoirs (Nikolova and Gutierrez 2020).

1.1.2 Microbial community

The choice of microbe species is essential for MEOR. They must produce the necessary bio-products and meet the requirements of the reservoir. The only microorganisms that have been suggested for methods of enhanced oil recovery are bacteria. They are tiny, grow rapidly, and produce a variety of metabolic products, including gases, acids, surfactants, and polymers. Additionally, bacteria can survive in harsh conditions like high water salinity, high pressure, and high temperatures (Omoniyi 2015). Bacterial strains have varying capacities for adaptation, the choice of bacteria is dependent upon reservoir characteristics and fluid parameters. The ecology of reservoirs serves as the foundation for bacteria's beneficial response. Particular consideration must also be given to bacterial colonization in pores and the products that result from this colonization. In other words, testing on cores and meticulous laboratory analysis are the only ways to identify the most appropriate strain of bacteria. Although MEOR contains a wide variety of microorganisms, they may be classified into two main categories (Youssef et al., 2009): 1) Native or autochthonous microbes that are already residing in oil reservoirs; and, 2) microorganisms that are developed especially to be injected into reservoirs, either exogenous or allochthonous. Table 1 presents the list of microbes used in MEOR and their produced bio-products along with the applications in oil recovery (Mclnerney et al., 2002).

Table 1. Microorganisms, bioproducts and their applications in oil recovery

Bio-Products	Microorganisms	Applications
Bio-surfactants	Acinetobacter calcoaceticus, Arthrobacter paraffineus, Bacillus sp., Clostridium sp., Pseudomonas sp.	Emulsification, interfacial tension reduction, viscosity reduction
Biopolymers	Bacillus polymyxa, Brevibacterium viscogenes, Leuconostoc mesenteroides, Xanthomonas campestris, Enterobacter sp.	Injectivity profile modification, mobility control, viscosity modification
Biomass	Bacillus licheniformis, Leuconostoc mesenteroides, Xanthomonas campestris	Selective plugging, viscosity reduction, oil degradation, wettability alteration
Bio-solvents	Clostridium acetobutylicum, Clostridium pasteurianum, Zymomonas mobilis	Emulsification, viscosity reduction
Biogases	Clostridium sp., Enterobacter aerogenes, Methanobacterium sp.	Increased pressure, oil swelling, interfacial tension reduction, viscosity reduction, permeability increase
Bio-acids	Clostridium sp., Enterobacter aerogenes	Permeability increase, emulsification

Three primary categories may be used to categorize microbes based on how much oxygen they take in: aerobes, whose development depends on an abundant supply of oxygen to produce cellular energy. On the other hand, strictly anaerobes, which are found in deep oil reservoirs, have responses to even low concentrations of oxygen. These anaerobes lack the proper balance of enzymes required for development in an aerobic environment (Pommerville 2005). (Lazar 1987) discovered that non-spore-forming bacilli were present in shallow reservoirs whereas spore-forming cocci and bacilli were detected in deep reservoirs (Ramsay 1987). Facultative microorganisms are the third category of bacteria and may proliferate in both low and high-oxygen environments (Pommerville 2005). Most effective field experiments made use of anaerobic microorganisms (Maudgalya et al., 2007). Bacteria can grow at low nutrient concentrations because the surface can enrich the nutrients (Zobell 1943). Bacterial species that should be considered for MEOR can be isolated from a variety of sources. (Lazar et al., 1991) recommended four primary sources for bacterial isolation for MEOR operations. These include formation waters, sludge from biogas operations, sediments from purification facilities (collecting stations), and effluents from sugar refineries. Soil that has been contaminated by oil may be a useful source of isolated microorganisms for MEOR (Sarkar et al., 1994). The molecular fingerprint technique, which primarily uses 16S rDNA and is significant but beyond the purview of petroleum engineers, offered a new means of connecting bacteria that could not be cultivated in harsh conditions. Thus, MEOR requires contributions from multidisciplinary fields like petroleum engineering, geology, biotechnology etc. The microbial community of Upper Assam oil fields was performed using metagenomics sequencing of formation water sample was reported and based on that the beneficial microbial strains were identified are Pseudomonas Aeruginosa, Pseudomonas Putida, Bacillus Subtilis and Bacillus Liceniformis (Bhattacharjee et al., 2023).

1.1.3 Subsurface environment

The reservoirs' depth distribution is quite varied. While depth alone has little effect on microbial growth, depth-dependent variables such as pressure and temperature can have an impact on microbial growth and metabolic activity. As long as the reservoir temperature is kept within acceptable bounds, the depth of the reservoir will not hinder microbial flooding (Sheng 2013). Microbes can be categorized according to the temperature ranges in which they can live and grow: The highest temperature at which psychrophiles may tolerate is 25 ◦C; mesophiles can endure between 25 and 45 ◦C; and thermophiles can endure between 45 and 60 ◦C. In most commercial sub-surface reservoirs, thermophiles are necessary for survival. There is a temperature at which microbiological growth is most favorable, and beyond this limit has negative effects (Chen et al. 2001). Temperature also has an impact on the biosurfactant's composition (Roy 2017). Oil reservoir pressure normally ranges between 10 and 100 MPa. Because increased pressure in natural habitats is associated with temperature variations, the effects of pressure on microorganisms are likewise consistently correlated with temperature (Marshall 2008). Thus, microbial survival and metabolite synthesis are likewise impacted by pressure. The pressure and exposure duration have an impact on the rate of microbial decomposition also (Jeong et al. 2021). The reservoir temperatures of Upper Assam oil fields ranged from 60 to 120 ◦C, which shows these oil fields are susceptible to microbial growth (Oil India Limited 2013).

The surface charge and enzyme activity of the microorganisms are influenced by the pH of the aqueous formation fluids that contain them (Marshall 2008). The pH of the transport fluid greatly influences how much the proteins in a microbe's cell wall are ionized. The pH of the formation fluid is typically a determining factor for the enzyme activities involved in microbial respiration. Different microorganisms have different ideal pH values, ranging from 2 to 9.5. The acids produced by microbial metabolism can affect the fluid's pH sustainability, which is necessary for the microbes' long-term existence (Marshall 2008).

1.1.4 Toxic chemicals

(Silvestro and Desmarais 1980) have identified other compounds that are known to be toxic to microorganisms and that may be present in some reservoirs. Many of these substances are utilized in different chemical EOR processes, such as cosurfactants, surfactants, biocides, ethlyenediaminitetracetate, and toluene. Numerous of these substances have been shown to be hazardous to certain strains of microorganisms as well as the microbial community in soil by (Grula and Grula 1983).

1.1.5 Reservoir Rock Properties

For the exploration and production of oil and gas, reservoir rock characteristics are crucial. The subsurface reservoirs characteristics, including its capacity to store and transmit fluids like oil and gas, are determined by these properties. Depending on their composition, structure, and geological history, reservoir rocks have different characteristics. Sandstone and carbonate are the two main types of sedimentary rocks found in reservoir systems along with limestone and dolomite. Because they are more porous than the majority of igneous and metamorphic rocks, which can also store oil, sedimentary rocks are known as common reservoir rocks (Amyx et al., 1960).

The majority of the Upper Assam basin's oil and gas fields are located in the southeast on a concealed high basement. The northeastern corner of the Indian subcontinent is formed by the alluvium-covered foreland shelf zone of Upper Assam, which is a part of the larger Assam-Arakan basin. The majority of the hydrocarbons found in the area thus far have been found in the sandstone reservoirs of the Miocene Tipam formation, the Oligocene Barail sandstone reservoirs, and the Paleocene/Eocene Lakadong + Therrias / Langpar. In certain regions of the Upper Assam basin, newer Girujan-clay strata dating from the Upper Miocene have also been shown to contain producible oil or gas. Tipam formations is mostly in arenaceous range made up of medium-grained, salt-and-pepper colored sandstone with blue and bluish grey shale streaks. In the middle and lower Tipam, there are some coal streaks. The origin of the Tipam sands is fluvial in nature. The Tipam sandstones are characterized petrographically as lithic-arkosic arenites with fine- to medium-grained, occasionally coarse-grained, and conglomeratic grains. The Upper Tipams have smectite and smectite-chlorite, while the Lower Tipams have kaolinite as the primary clay type. Tipam formation have values of porosities 18-21%, up to 25% and permeability: 1-400 mD. The two stages of development of Barail formation are often referred to as argillaceous and arenaceous. The Barail formation of argillaceous range is primarily composed of blue-grey mudstone interspersed with thin coal streaks and bands of fine-grained sandstone. There are well-developed additional bands of fine-grained sandstone ranges in several places. The calcareous mudstone, bluish grey shale, and fine to medium grained sandstone, with sporadic coal streaks, make up the arenaceous range. The environment in which the Barail sands were deposited was deltaic. The majority of the quartz lithic arenites found in the Barail sandstones are fine or fine-medium-grained and moderately well-sorted. Although some mudrock is present, metamorphic schists make up the majority of the lithic fragments. Widespread cement with changing local minor to considerable abundance is denoted as siderite. Locally, there are overgrowths of ankerite and quartz, and the most common clay mineral is kaolinite. Barail formation have typical values of porosities 20-23%, up to 30% and permeability: 1-500 mD. Lakadong + Terria formation development stages includes glauconitic sandstone, fine- to coarse-grained saccharoidal to calcareous sandstone, bluish grey shale, and carbonaceous shale with light grey to dark grey splintery shale. Mostly found in the middle and lower part are thin strings of coal, white, and brownish charts. The formation has values of porosities 15-18% and permeability: 100 - 4000 mD. Langpar is mostly composed of arkosic sandstone with medium to coarse grains and streaks of bluish shale. Langpar formation has values of porosities 13-20% and permeability: 100 – 2000 mD.

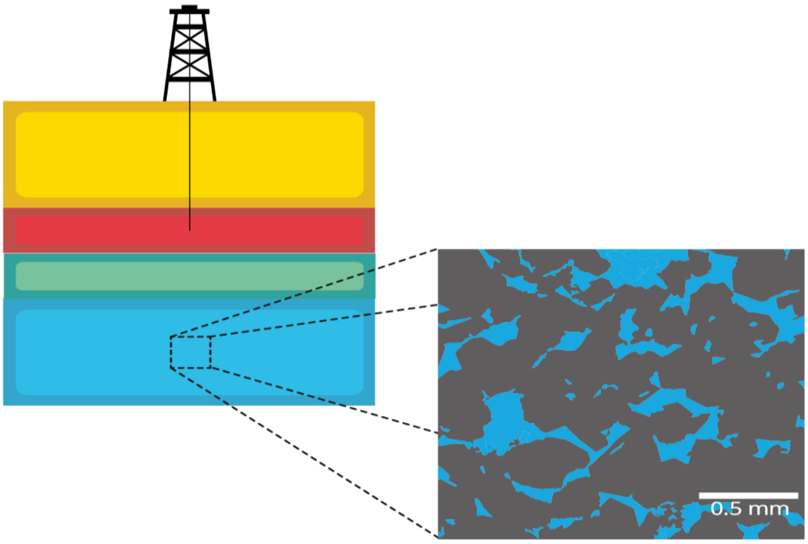


Fig.2: Schematic of a large reservoir field showing the pore spaces at micro-scale in a reservoir rock. The blue color represents the water while the black color represents the rock matrix. Source (Ganat 2019).

The large surface area of porous media within the reservoir (a cubic foot of rock can have the same surface area as several football fields) can also influence bacterial growth and metabolism. Any enhanced oil recovery technique must always meet the criteria of porosity and permeability. The effect of rock porosity on the MEOR process is highly dependent on the pore spaces that are available for microbial colonization. In addition to allowing for the storage and flow of fluids, the presence of pore spaces in rock also creates a habitat for microorganisms that can be used for MEOR applications. The ability of microorganisms to enter the rock matrix and colonize the reservoir is influenced by the porosity of the rock. Larger pore spaces found in high porosity rocks are conducive to the transport of microorganisms and MEOR agents into the deep reservoir. The following colonization and growth of these microorganisms has the potential to increase oil recovery. This may result in better nutrient and microorganism distribution throughout the reservoir, potentially increasing the effectiveness of MEOR strategies. Obviously, the only factors that must be considered are interconnected pores and the corresponding effective porosity. Because of the generally homogeneous structure of sandstone rock formations, there are typically very few variations in their effective porosities (Manger 1963). After primary and secondary recovery techniques have been exhausted, determining the porosity of the reservoir rock in terms of MEOR or any other EOR methods will probably help determine how much oil is still present in the pore spaces of the rocks. MEOR, a tertiary enhanced oil recovery technique, requires some residual oil in order for the bacteria and the metabolic products produced by the bacteria to function. Although porosity has no direct impact on the effectiveness of MEOR, it undoubtedly aids in understanding pore size and fluid saturation. The movement of microorganisms in porous media is directly impacted by a rock's permeability, which is defined as its capacity to transmit fluids through interconnected pore spaces. The ease with which microorganisms can pass through the matrix of the rock and colonize the reservoir depends on the permeability of the rock. Understanding how microbes and nutrients are transported into deep reservoirs is the main impact of reservoir permeability on MEOR. High permeability rocks allow for greater fluid flow and transport of MEOR agents. Microorganisms may encounter difficulties in low permeability rocks when trying to colonize them and get access to the nutrients and energy sources they need to grow. As a result, consideration for the reservoir rock's permeability is necessary when choosing MEOR agents and strategies. To achieve effective MEOR in these kinds of reservoirs, it might be necessary, for instance, to use microorganisms that are better able to move through rocks with low permeability. Bacteria can clog rock pores, reducing the permeability of the rock, which is occasionally undesirable as it can result in decreased permeability during water flooding operations. The MEOR process can be impacted by permeability heterogeneity because all reservoir rocks are known to be highly heterogeneous in terms of porosity and permeability. Figure 2 & 3 shows the schematic of porosity and permeability at micro scale cross section of reservoir rock. Rock types and clay minerals can have the effect of retaining microbial cells and nutrients within the pore spaces of rocks. (Jang et al. 1983) have shown that clostridium spores and synthetic microspheres (1.0 mm in diameter) are less adsorbed when they flow into oil saturated sandstone in comparison to carbonate rocks. Environmental as well as geological reservoir characteristics, such as lithological composition, rock properties, reservoir temperature, crude oil gravity, and fluid attributes, have an impact on the activity of the microbes. These factors directly or indirectly control microbial growth, movement, and metabolism and will help to produce bio-products which will aid in oil recovery (Dhanarajan et al. 2017; H. Al-Sulaimani et al. 2011;Hanaa Al-Sulaimani et al. 2012). In comparison to high permeability reservoirs, low permeability reservoirs are predicted to have decreasing production. Therefore, it is anticipated that increased permeability will lead to better transportations of nutrients and bacterial cells into the reservoir which will help for better oil reclamation in MEOR operations. Majority of past and recent research in MEOR is mostly focused on the production of biosurfactants and their role in reducing the interfacial tension hence mobilizing the residual oil. Despite all the laboratory and core scale studies about MEOR there is hardly any positive outcome in terms of oil recovery in field applications.

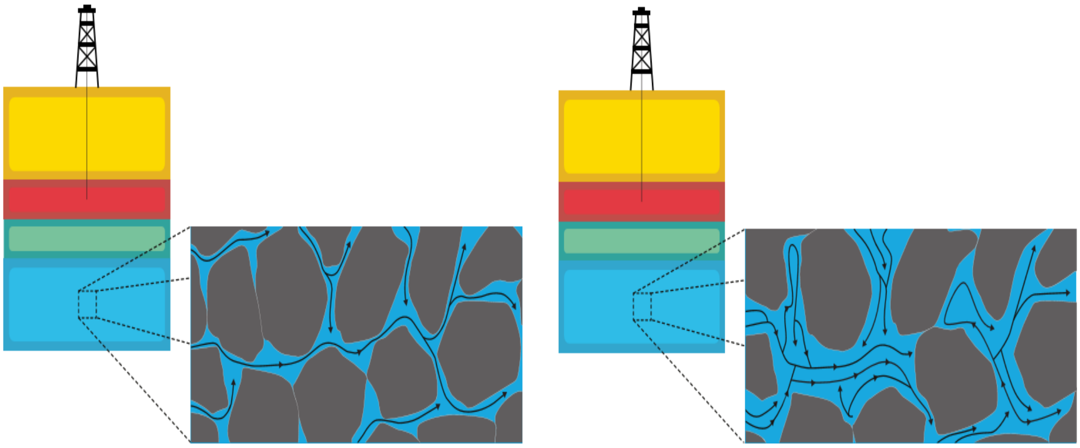


Fig.3: Schematic showing the reservoir cross section at micro-scale (a) low permeability rock and (b) high permeability rock. Reservoir fluids can flow much easier in rock (b) in comparison to rock (a). Source (Ganat 2019).

One major issue affecting oil recovery is the reservoir rock wettability. When the rock is oil wet, water has a harder time adhering to the reservoir rocks, which lowers sweep and displacement efficiencies and reduces oil productivity. Increasing the reservoir rocks water wetness will increase oil recovery (Lazar et.al.2007 and Sen 2008). The wettability of the rock determines the extent to which it is water-wet or oil-wet, which in turn affects the distribution and transport of fluids and microorganisms in the reservoir rocks. In water-wet reservoirs like the Upper Assam reservoir rocks, water has a higher affinity for the rock surface, and it can displace oil more efficiently. In contrast, in oil-wet reservoirs, oil has a higher affinity for the rock surface, and it can be difficult to displace using water based MEOR agents. MEOR agents may also experience reduced mobility in oil-wet systems due to oil blocking the flow paths. Therefore, the wettability of the reservoir rock is an essential consideration in designing MEOR strategies. Changing the wettability of the rock surface can improve the displacement of oil by water and enhance the mobility of MEOR agents. This can be achieved through various methods, such as the use of surfactants or by altering the mineralogy of the rock surface. In terms of MEOR, we measure the wettability of reservoir rocks to plan a strategy for biosurfactant production and its role in altering the wettability of oil-wet rocks to water-wet rocks. The addition of surfactants or the stimulation of the microbes that adhere directly to reservoir rocks are the two techniques for wettability alteration from oil-wet to water-wet that increase oil recovery by increasing water and oil mixing. In the MEOR process, biosurfactants and biofilm formation are used to change the reservoir rocks wettability towards water-wet. By making the reservoir rock wet with water, a microbe's production of surface altering products aids in improved oil recovery. Altering the wettability of the rock surface is a practical way to increase oil recovery in the MEOR process, regardless of whether the production of such bio-products takes place in situ or ex situ (Patel et al. 2015). However, the transition from an oil-to-water-wet state known as wettability alteration plays a more significant role in oil recovery in carbonate reservoirs, because the oils in carbonate rocks are concentrated in larger pores that are easily accessible after flooding, a water-wet condition is somewhat advantageous for better oil recovery (Kowalewski et al. 2006). Figure 4 represents the wettability process like water-wet, oil-wet and mixed-wet in reservoir rocks. Bacterial transport can be impacted by the permeability, porosity, wettability, and pore size of a rock. These techniques increase oil recovery by improving sweep and displacement efficiencies. Many other difficulties, such as understanding rock properties, remain research topics for MEOR applications, in addition to reservoir environments that may affect bacterial growth, such as pH, temperature, and pressure.

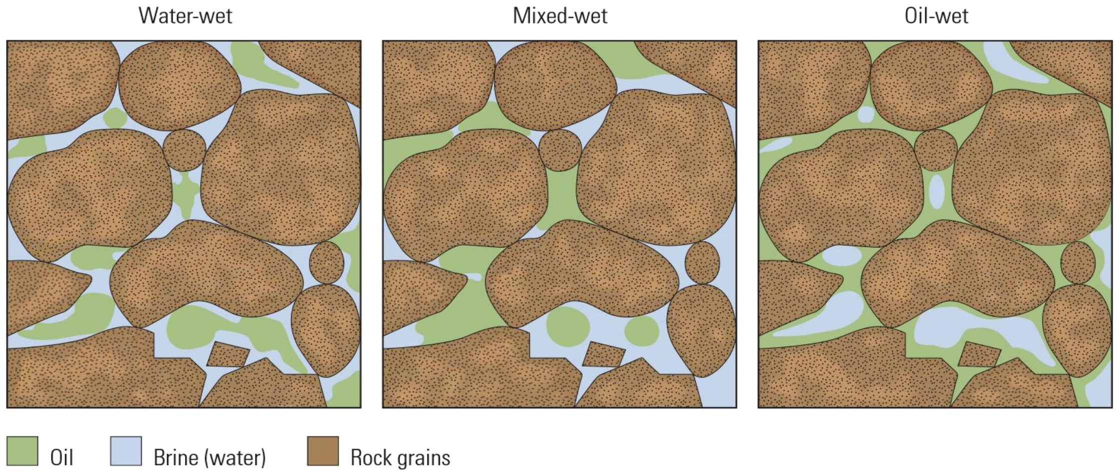


Fig.4: Oil remains in the center of the pores (left) water-wet case. Water remains in the center of the pores (right) oil-wet case. In mixed-wet case (middle) oil still remains in the center of the pores. Source (Abdallah Wael et al., 2007)

The main barriers to effective oil recovery are addressed by these techniques, including the low permeability of some reservoirs, high crude oil viscosity, and high oil water interfacial tensions that may lead to high capillary forces holding oil in reservoir rock pores (Makkar, Cameotra, and Banat 2011). However, because of other events that take place concurrently in the field, evaluating the improved oil recovery (IOR) effects caused by MEOR is frequently a challenging task. Similar issues frequently arise when microbial core flood interpretation is concerned. The MEOR technique's implementation is influenced by a number of intrinsic and extrinsic factors, including the type of reservoirs, rock properties, appropriate screening of potential microbial communities, the viability of the microbes in the internal reservoir environment, the amount of metabolites produced, mobilizing residual oil, and cost-effective factors (Desouky et al. 1996). There are field cases (Nagase et al. 2001), as well as laboratory experiments (Patel et al. 2015), where no effects of oil recovery using bacteria have been observed. The mechanisms underlying oil mobilization remain poorly understood despite all of this testing of MEOR processes and descriptions of bacterial growth and the production of metabolites that result from it (Kowalewski et al. 2006). MEOR method has already been developed and implemented in oil fields of Upper Assam but the results are not encouraging. Formation water of oil fields was used to isolate bacteria, which have been cultured in laboratories for various parameters, including pathogenicity (Oil India Limited 2022). Although there are several complications that hinder the process of MEOR like transporting MEOR agents in deep reservoirs, injectivity issues caused by Sulphate Reducing Bacteria (SRB) and other suspended solids in deep disposal wells in the Upper Assam area, etc. (Oil India Limited 2016).

2 Field Application

2.1 Screening Criteria for MEOR Projects

The conditions of the reservoir, including temperature, permeability, porosity, pressure, mineralization, pH, and viscosity of the crude oil, are critical to the effectiveness of MEOR. The reservoir's temperature is the most crucial factor that has a significant impact on the development and metabolism of microorganisms. Extremely high or low temperatures will hinder the synthesis of microbial products by causing microorganisms to develop slowly or possibly die. Excessive pressure will hinder the growth of microorganisms, making it a crucial aspect of the MEOR process. Variable pressure also affects reservoir gas solubility, which alters crude oil viscosity and may have an impact on oil displacement efficiency. High mineralization tends to produce precipitate with other chemicals and cause blockage in addition to influencing the growth of microorganisms (Gao 2018). The performance of biosurfactants is influenced by pH in addition to microorganisms' metabolic activities. Biosurfactants, which are frequently employed in research for the crude purification of surfactants produced by microorganisms, will aggregate and sediment at low pH levels (Pereira et al., 2013; Safdel et al., 2017). Microbial movement is influenced by the reservoir's permeability and porosity; the process of microbial migration is more resistant to small pore radius (Sen 2008). The parameters used to screen reservoirs for MEOR technology vary significantly because of the huge variations in technology and reservoir conditions across various nations and regions. Reservoir screening criteria are listed in Table 2 which includes the US Department of Energy, CNPC (China National Petroleum Corporation), and the Institute of Reservoir Research.

Table 2: Reservoir Screening Criteria for MEOR Projects.

Parameters	**CNPC (Guo et al., 2015)**	**IRS (Patel et al., 2015)**	**US DOE (Patel et al., 2015)**
Type of formation	Sandstone	Sandstone	Sandstone
Temperature, °C	30-60	<90	<71
Pressure, kg/cm2	-	<300	-
Salinity, g/L	<100	<10	<10
pH value	-	6-9	-
Permeability, mD	>150	>50	>100
Porosity, %	17-25	-	-
Viscosity, cp	30-150	<20	-
°API gravity	-	>20	-
Water cut, %	60-85	30-90	-
Depth, ft. (m)	-	<8000	<10000
Wax content, %	>7	-	-
Oil saturation, %	-	>25	>25

2.2 Field trials

Numerous MEOR field trials have been conducted globally over the past few decades, with varying degrees of success. Global field test statistics show that over 90% of MEOR field trials result in beneficial outcomes (Safdel et al., 2017). The United States was one of the first nations to carry out MEOR field trials. In 1954, the Lisbon oil field in Arkansas hosted a field trial employing methods including gases, acids, and biosurfactants for the activation of Clostridium acetobutylicum by injecting molasses (Lazar et al., 2007; Safdel et al., 2017). In a field experiment conducted in Oklahoma's North Burbank unit, the growth of native microorganisms was encouraged by the injection of nutrients, which successfully blocked high-permeability regions and reduced effective permeability by 33% (Jenneman et al., 1996). A biosurfactant concentration nine times lower than the required minimum was also observed in a field trial of biosurfactant in-situ for the Bacillus strain in the Oklahoma Bebee field, and crude oil recovery was enhanced (Youssef et al., 2007).

Several oil fields in China, including Daqing, Changqing, Xinjiang, Liaohe, Shengli, Qinghai, and Jilin have seen field implementation and applications carried out by MEOR. According to incomplete statistics indicate that the majority of MEOR field applications in China are for microbial wax removal; 11 fields and total of 1739 wells have been evaluated (Wang 2012). China possesses a total of 678 CMR (Cycle Microbial Recovery) wells spread throughout 12 fields, including the oil fields of Jilin, Shengli, Zhongyuan, and Daqing. Microbial huff and puff method was done in 1640 wells at Shengli Oilfield, improving production by 219,000 tonnes of crude oil; in 10 blocks at Daqing Oilfield, microbial huff and puff was done in 518 wells, increasing production by 64,000 tonnes of crude oil. Compared to CMR, fewer MFR (Microbial Flooding Recovery) field experiments have been conducted. Daqing Oilfield completed on-site microbial flooding operations in 45 injection wells over 11 blocks by the end of 2012, accumulating 56,837 tonnes of crude oil in total (Gao 2018). As a result of MEOR's recent and effective implementation in China, the country is actually among the leaders in this field in terms of oil recovery.

Several oil fields in Romania underwent field testing on MFR and CMR applications, resulting in an average 100% and 200% increase in oil production (Safdel et al., 2017). In the Piedras Coloradas oil field in Argentina, the average production of the six production wells increases by 66% and the viscosity of the produced crude oil significantly decreased after injecting hydrocarbon degrading and anaerobic fermentation bacteria for a 12-month period (Maure et al., 1999). Endogenous microorganisms were triggered in the first step of nutrient infusion in endogenous microbial flooding studies carried out in the Saskatchewan oil field in Canada. The experiments' outcomes revealed a 10% decrease in water content. The next phase of the MFR test was administered based on the information above. Following a three-week test period, the output of crude oil rose from 10.18 m^3 /d to 16.7 m^3 /d (Town et al., 2010). In India, some field trials using huff and puff were carried out by the Oil and Natural Gas Corporation (ONGC) Limited in association with The Energy and Resources Institute (TERI, New Delhi) and the Institute of Reservoir Studies (IRS), Ahmedabad.12 wells in 4 fields were used in these field studies, which were based on strict anaerobic microbial population isolated from the reservoir. The results revealed a threefold increase in crude oil production and a notable decrease in water cut (Sen 2008). Bokor field was chosen to be the first in Malaysia to apply MEOR technology, which uses microorganisms to produce biochemicals like biosurfactant, solvents, gases, and weak acids, thereby facilitating, increasing, or extending oil production from reservoirs. The low oil specific gravity of 20 °API and high viscosity crude (4 to 10 cp) of the field led to its selection. This could result in a poor recovery factor in significant reservoirs, which can vary from 19% to 25% of the original oil in place. The production increase can be attributed to three factors: a decrease in emulsion stability, a reduction in watercut, or a high gross production (PI improvement). 5 months after MEOR, the total average net oil gain is 270 bbl/d (47% oil incremental) (Ghazali et al., 2001).

Upper Assam oil fields are in declining stage of production, and most of the oil fields are producing under depletion driving mechanisms and assisted by waterflooding operations. So implementing a method that is cost effective and can also assist waterflooding operations is good choice for these oil fields. To implement MEOR method more efficiently in depleted reservoirs of Upper Assam, it requires more specific strategies and a thorough understanding of reservoir properties. This has led to the motivation for this work to study the critical reservoir rock properties and their role in transporting MEOR agents in deep reservoirs of Upper Assam oil fields. The main objective of this work is to understand the limitations of reservoir rock properties for successful implementation of the MEOR method in Upper Assam oil fields. MEOR is a really a challenging topic and many operators with waterflood assets trying to assess the microbial EOR as a way to improve oil recovery. Based on the literature and records, many were unsuccessful either due to improper screening or implementation. This manuscript has the potential to improve the understandings of rock properties and screening criteria. In this study we have performed experiments on sandstone core samples of different oil fields and formations from various depth from 2300 to 3400 meters, measuring different properties and used the pre-existing screening criteria for MEOR process to see if there is a chance for implementation of MEOR method in Upper Assam oil fields. Also in this study we have tried to understand the role of clay minerals and pore throat as a screening criteria for MEOR operations. The findings in this paper could be used to support MEOR research on a larger scale, especially in the oil fields of Upper Assam, such as that conducted in the sand pack or microbial core flooding prior to field application.

II. MATERIALS AND METHODS

3.1 Materials

3.1.1 Core Samples and Source of Microorganisms

Upper Assam oil fields were used as the source for the reservoir core samples in this study. Also, the rock samples were from different formations, like Barail Main Sand and Tipam Sand, and all of them are from different depths. Table 3 provides a detailed description of the core samples used in this study. Biosurfactant producing microbes such as Bacillus were used in this study to analyze their morphological structures and their relation with pore throat size. The Bacillus sp. MTCC 297 strain was procured from the Microbial Type Culture Collection (MTCC) at the Institute of Microbial Technology, Chandigarh, India, for this study.

Table 3: Core samples description of Upper Assam Oil fields.

Core Samples ID	Formation	Depth (meters)
Core Sample 1	Barail Main Sand	3377.0
Core Sample 2	Barail Main Sand	3312.0
Core Sample 3	Tipam Sand	2329.6

3.2 Methods

3.2.1 Core Plug Preparation

For core analysis, conventional cores of Upper Assam oil fields from various depths were cut into 1.5-inch cylindrical core plugs that were 3–8 cm long. Prior to determining their petrophysical properties, the core plugs had to be cleaned with solvents such as toluene and methanol in a soxhlet apparatus. The core plugs had to be thoroughly cleaned of all interstitial fluids and dried in an oven to achieve constant dry weights.

3.2.2 Measurements of Rock Properties (Porosity, Permeability & Wettability)

Porosity of core samples of Upper Assam oil fields was measured using Helium Porosimeter (Make: Coretest Systems, Inc., USA; model: TPI-219) which is based on the Boyle’s Law double cell method. In this study, porosity has been measured by grain volume measurement. The grain volume can be calculated using the Boyle's Law Double-Cell Method, the dry weight of the core plugs, and the density of the sand grains are required (Amyx et al., 1960). Permeability of core samples is measured by passing a fluid with known viscosity, such as nitrogen, through a core plug and measuring the flow rate and pressure drop across the core plug, permeability is calculated using the famous Darcy's equation (Ahmed 2010). In this study, gas permeability has been measured with Gas Permeameter (Make: Coretest Systems, Inc., USA, and Model: TKA-209). It is found that the permeability obtained by flowing a liquid is lower than the permeability measured by flowing gas. Klinkenberg proposed that the higher value was caused by gas slippage at the surface of the sand grain and a higher gas flow rate at a given ΔP (Klinkenberg 2012). Applying the klinkenberg principle, the measured gas permeability values were used to calculate the equivalent liquid permeability. To determine a surface's wettability, numerous experimental methods have been developed. These techniques include: (a) contact angle measurements, (b) Amott (Amott-Harvey) method, (c) United States Bureau of Mines (USBM) method, (d) Rise in core (RIC) method (Teklu et al. 2015; Anderson 1986; Abdallah Wael et.al 2007). To determine the wettability of rock samples in this study, contact angle measurements was done using the sessile drop method which is used for all types of contact angle measurements on a laboratory scale (Kyowa Interface Science Co. 2018). The contact angle measurements were taken with an apparatus equipped with a high resolution camera and digital processing software (Make: Kyowa Interface Science Co., Ltd, Model: Contact Angle Meter DMe-211 Plus). The main principle behind contact angle measurements is the Young equation which is described on Figure 6. Figure 5 shows the prepared core discs/slices measure roughly 2 cm by 2 cm and have a 0.5 cm thickness, for wettability measurements.

Fig.5: Core slices/discs saturated with brine and aged with crude oil of Upper Assam Oil field.

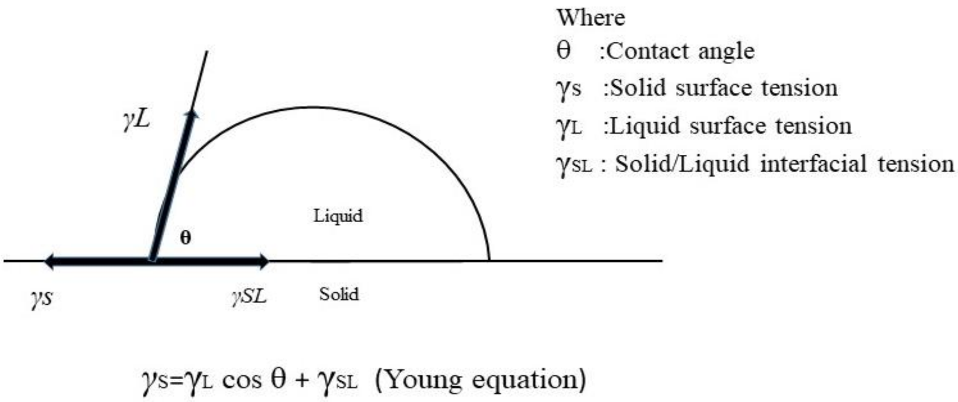


Fig.6: The contact angle is a result of the above-mentioned interface/surface tension between the liquid, air, and solid, which is well known as the Young equation. Modified after (Kyowa Interface Science Co. 2018).

3.2.3 Identification of clay minerals

Upper Assam oil field samples were used in this study for XRD (X-Ray Diffraction) to identify clay minerals. Powder XRD of the rock sample was carried out in a 9 KW Powder X-Ray Diffraction, (Make: Rigaku Technologies, Japan, Model: Smartlab) system to characterize the reservoir rock and assess its mineralogy and clay content. It is well known that XRD is a crucial tool for determining the reservoir rocks mineralogical makeup (Al-Bazzaz and Gupta 2007). An X-ray diffractometer's geometry is such that the sample rotates at an angle θ in the path of the collimated X-ray beam, and the X-ray detector rotates at an angle of 2θ to collect the diffracted X-rays. A goniometer is the device used to hold the angle and rotate the sample. For typical powder patterns, data is gathered at preset angles 2θ in the X-ray scan, ranging from to ~5° to 70° (Barbara L Dutrow). Thin-section analysis typically includes measurements of the mineral content, grain and sediment provenance, fabric studies, and the order of digenetic events. An integral part of any integrated characterization of sedimentary reservoirs has long been the conduct of petrological studies on thin sections (Tucker 1988). In this study, the format of the thin-section slices was 25×45mm.The thin sections were examined under the (Make: Leica Microscope, Model: DMLP).

3.2.4 Pore Morphology Measurement using FESEM Images

The primary goal of FESEM analysis in the investigation of Upper Assam reservoir rock samples is to characterize the reservoir's pore and grain morphology, which is important for determining the reservoir's porosity, permeability, and pore throat radius. Being able to study elements that are too small for a binocular microscope or too delicate for making thin sections is one of the benefits of FESEM (Tucker 1988). FESEM images were analyzed under the (Make: Zeiss, Model: Sigma 300). The resolution of the rock image was 100 µm due to the specification of magnification in this range. The area of these features is scanned in the following step using digital image analysis software, which can precisely measure and report a number of morphological parameters of any feature as specified by the examiner (Schindelin et al. 2012). This study mainly focused on two aspects of the image: pore space and pore throat.

III. RESULTS AND DISCUSSION

4.1 Screening of Rock Porosity & Permeability

In this study, the porosity and permeability of three sandstone core samples collected from Oil fields of Upper Assam at different depths has been measured. Table 4 presents the petrophysical data in more details and shows the porosity and permeability values of three core samples, which clearly indicate average porosity of 22.8% and permeability of 27.08 mD. The equivalent liquid permeability values obtained by plotting mean pressure vs. gas permeability are shown in Figure 7. Barail Main Sand and Tipam Sand rock formations are both source rocks, but their grain size, depositional environment, texture, and sorting are dissimilar, which leads to varying petrophysical values in Upper Assam oil fields (Oil India Limited 2013).

Table 4: Showing the porosity and permeability values of different formation with varying depths

Core Sample ID	Formation	Depth (m)	Porosity (%)	Permeability (mD)
CP1	Barail	3377.0	16.86	11.02
CP2	Barail	3312.0	25.73	32.12
CP3	Tipam	2329.6	25.77	38.09

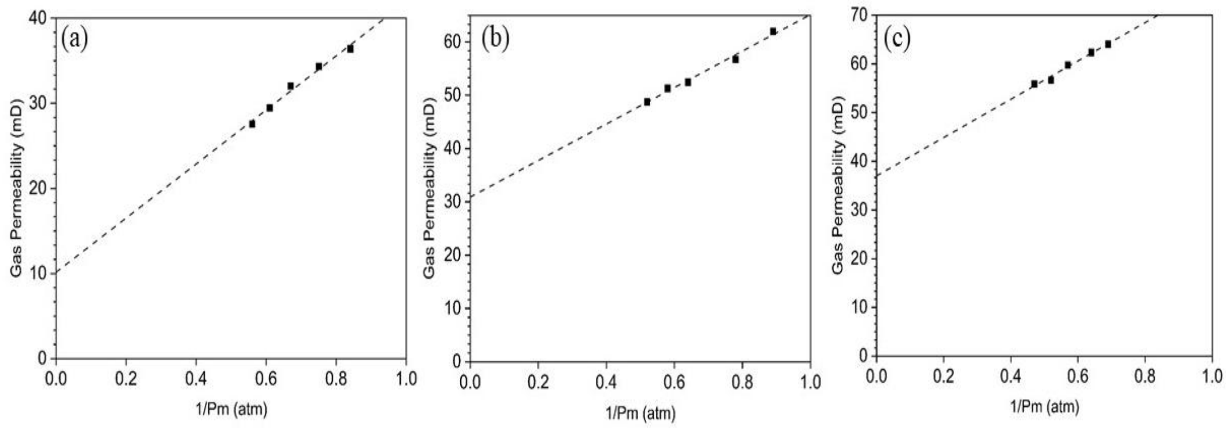


Fig.7: Determination of Liquid Permeability of three samples: (a) Core plug 1 (b) Core plug 2 (c) Core plug 3 from the Gas Permeability values using klinkenberg Method.

For the MEOR process, a residual oil level greater than 25% is desirable (Patel et al., 2015). Past screening criteria for MEOR also suggest that a porosity value of >15% is needed for microorganisms and their agents to work efficiently for oil recovery (Sheng 2013). The permeability data in the Upper Assam Oil fields, it indicates low permeability for an efficient MEOR process, which could also be the cause of injectivity issues found in these oil fields before. Permeability values of >50 mD are desirable for successful implementation of the MEOR process. Although there have been successful trials on sandstone reservoirs with permeabilities ranging from 10-75 mD (Maudgalya, Knapp, and McInerney 2007). According to previous analytical, numerical, and experimental findings, early nutrient, microbial, and biosurfactant breakthroughs leave negligible concentrations in their respective fronts at very low reservoir porosity (about 10%), which are not enough for the recovery of the trapped oil. Additionally, nutrients, microbes, and biosurfactants are lost as porosity increases to around 30% and above due to higher dispersion during their movement within the reservoir. Therefore, the overall MEOR process is significantly more effective in sandstone formations, with an intermediate effective porosity value of about 20% (Chakraborty, Govindarajan, and Gummadi 2020). Previous studies in sandstone cores of Upper Assam with low permeability has also resulted in increasing oil recovery due to microbial flooding (Bhattacharjee et al., 2023). Bokor field in Malaysia has also similar range of porosity and permeability values like Upper Assam where MEOR method was successfully implemented (Ghazali et al., 2001). It is crucial to keep in mind that the impact of porosity on MEOR can be complicated and may depend on a range of parameters, including the mineralogy of the rock, the temperature of the reservoir, and the particular microorganisms and MEOR agents employed. Therefore, more investigation is required to fully comprehend the role of porosity in MEOR and to create practical plans for improving oil recovery through microbial processes. The success or failure of MEOR processes is significantly influenced by the pore size and permeability of the rock by (Jensen and Esbjerg 2014). All this information about Upper Assam oil field's permeability values suggests that evaluation of pore throat size distribution and its relation to the selection of bacterial strains based on permeability values is critical. Based on the screening for porosity and permeability values of Upper Assam oil fields, it should be stated that these reservoirs can be candidate for MEOR process. Designing effective MEOR strategies requires a thorough understanding of how rock porosity and permeability affects microbial transport in porous media.

4.3 Screening of Rock Wettability

The wettability of reservoir rocks of Upper Assam Oil fields was measured using the sessile drop method. Upper Assam reservoir rocks were mostly water wet rocks, which aid in the enhanced oil recovery process. The contact angle values of three rock samples were given in detail on Table 5, and images of measurement were depicted on Figure 9. From Table 5, we can understand that core plug 1 & 3 are highly water-wet in comparison to core plug 2. The reason it is because of rock grains texture and their uniformity throughout. Figure 8 is the schematic image showing the wettability ranges of oil-rock system.

Table 5: Contact Angle values of all three samples in study.

Core Sample ID	Salinity, ppm	Contact Angle, θ, in degrees	Volume of oil droplets, µl
CP1		68	6.5
CP2	3000	83.7	2.3
CP3		65.2	1.7

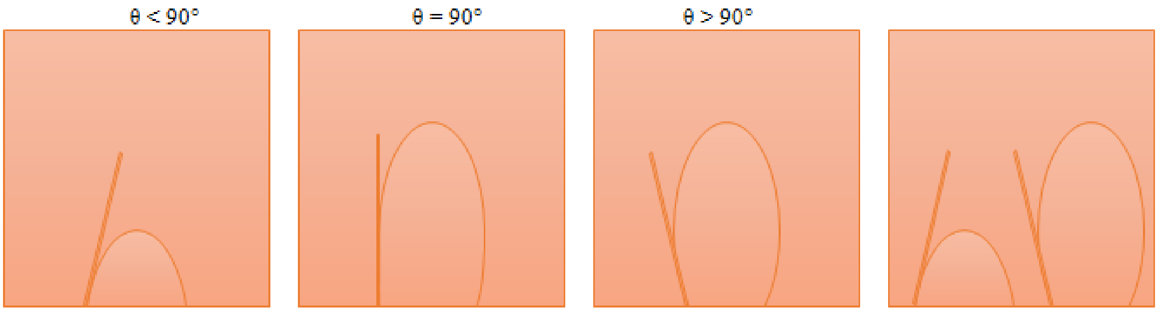
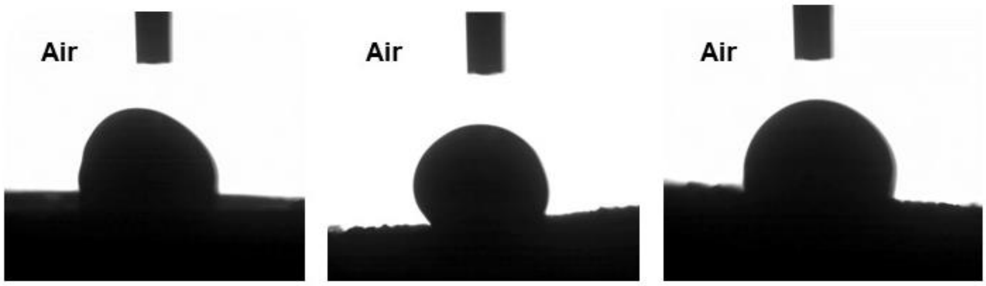


Fig.8: Schematic showing the wettability values of fluid-solid system.

Water-Wet (a) Intermediate-Wet (b) Oil-Wet (c) Mixed-Wet (d)



(a) (b) (c)

Fig.9: Images of wettability measurement of rock-oil system with respect to air.

In the Upper Assam oil fields, results of wettability suggest water-wet rocks, so the use of biosurfactants in this type of reservoir will be more viable as compared to oil-wet rocks. Research on the impact of wettability on microbial fluid flow in reservoir rocks is ongoing, and further studies are required to fully understand the relationship between wettability and the performance of MEOR strategies. Overall, understanding the wettability of the reservoir rock can help in selecting appropriate MEOR agents and designing effective strategies for enhanced oil recovery. (Karimi et al., 2012) presented the findings of a study looking into the change in wettability at the pore scale. To simulate different wetting conditions, the trials were carried out on substrates that had been aged with crude oil. The surface wettability was seen to vary from an oil or mixed-wet to a water-wet state. (Afrapoli et al., 2012) conducted another investigation utilizing Rhodococcus sp. 094 as the bacterium to examine the impact of wettability on microscopic two-phase flow displacement mechanisms of bacterial flooding. In comparison to the oil-wet micromodel, the residual oil saturation reduction in the water-wet micromodel was greater. Previous research has demonstrated the significance of the wettability modification in MEOR. In terms of screening wettability of reservoir rocks of Upper Assam oil fields, for the implementation of MEOR, this rocks are mostly water wet which will be helpful in terms of oil recovery processes and can be good candidate for MEOR operations using biosurfactant as metabolite.

3.4 Screening of Rock Mineralogy

In order to conduct an XRD analysis, three samples from the Upper Assam oil fields were chosen. The minerals and clays identified by the XRD scans on these 3 samples are shown in Figure 10. Chlorites, kaolinites, illites, and montmorillonite are the four main clay groups that are commonly found in the Upper Assam oil fields (Oil India Limited 2013). There is also a significant amount of quartz mineral present in all three samples in the study.

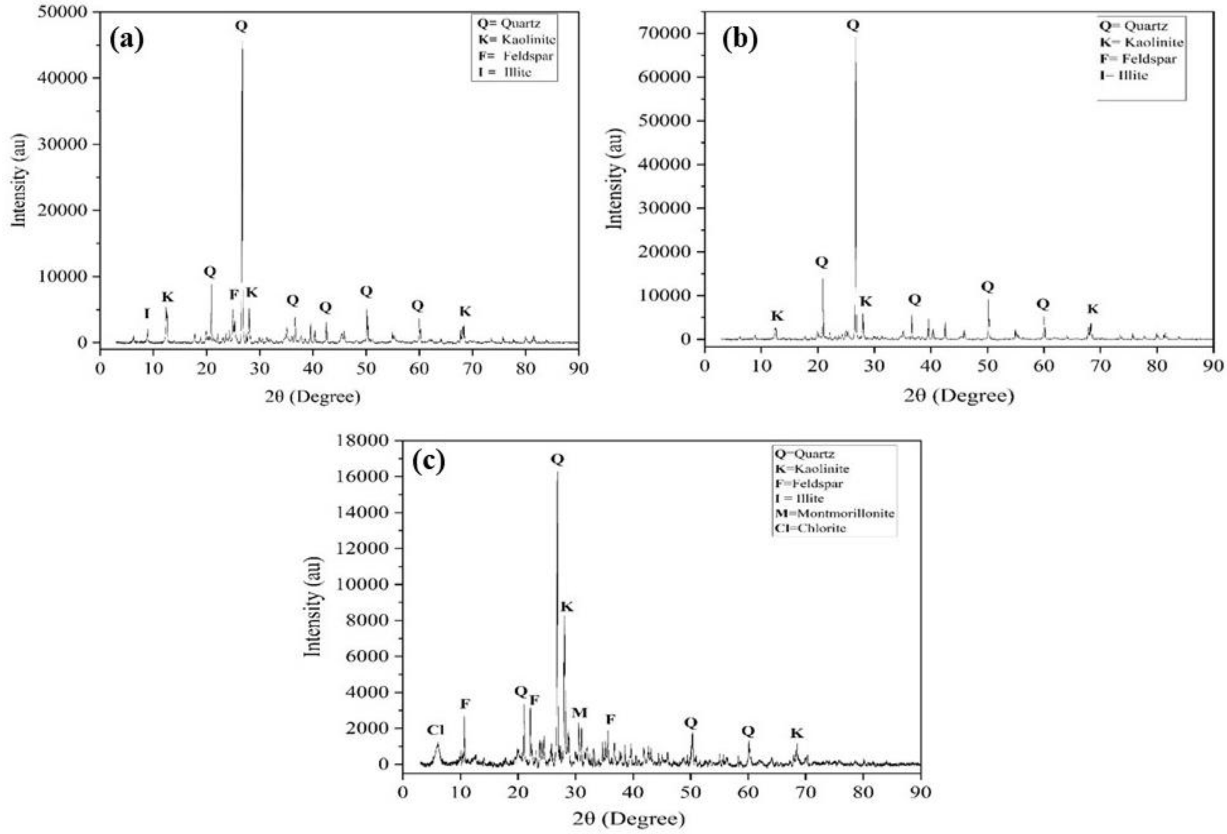


Fig 10: X-Ray Diffraction Pattern for identification of clay minerals (a) Sample 1, (b) Sample 2, and (c) Sample 3.

The mineralogy composition of Figures 10 (a) & (b) is similar as they are both from the same formation, i.e., Barail Main Sand, and are at an almost similar depth. Quartz mineral predominates in these oil fields, with very little percentage of kaolinite and illite. Figure 10 (c), which is from a different formation Tipam Sand and depth, also demonstrates the presence of quartz in a significant amount. Clays like kaolinite are predominant in this sample, and there is also a small amount of chlorite and montmorillonite in comparison to the other two samples. Figure 12 presents the thin-section slides of core samples 1 and 2 show the presence of minerals like plagioclase feldspar, quartz, mica, muscovite, and rock fragments, while core Sample 3 shows the presence of clay minerals like chlorite, kaolinite, etc. A thin-section analysis is performed to understand the composition of the rock sample and validate the XRD results.

The mineralogy of the reservoir rock can have a significant impact on the performance of microbial enhanced oil recovery (MEOR) techniques. The growth and activity of microorganisms can be either promoted or inhibited by specific minerals or clays, which can have an impact on the efficacy of MEOR strategies. The major effect of mineralogy on the MEOR process is the adsorption of microbial cells and nutrients (El-Masry et al., 2023). Biological processes can be hampered mostly by the adsorptive capacity of clays as well as certain minerals found in porous rock, even though silicates and carbonates barely restrict microbial activity. Injectivity issues related to the transportation of MEOR agents in Upper Assam oil fields could be due to the presence of clay minerals, which is shown in FESEM images in Figure 11.

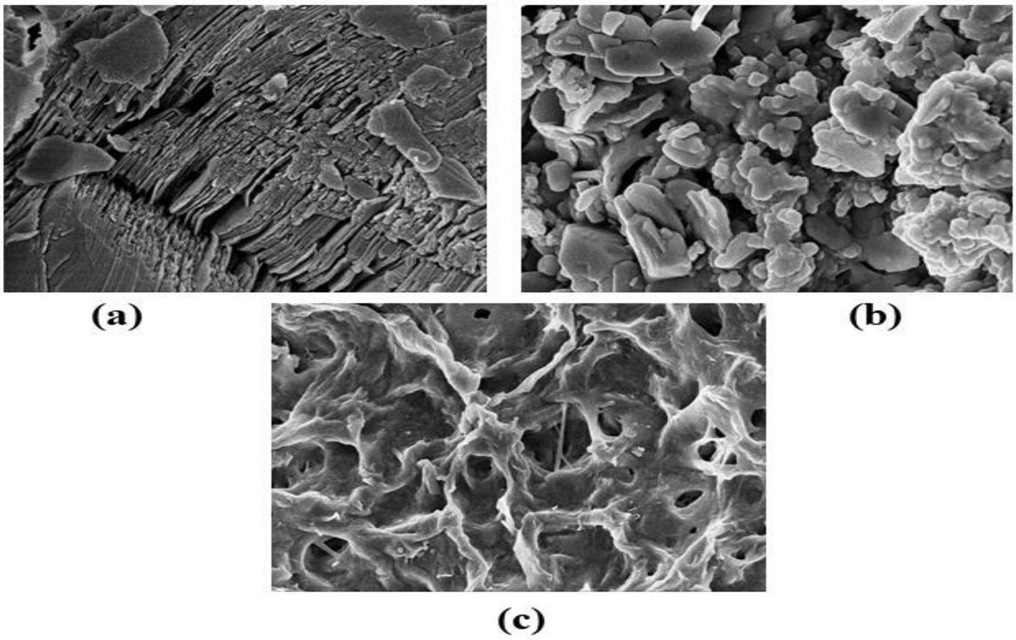


Fig.11: FESEM micrographs of showing the presence of clays. (a) Sample 1 (b) Sample 2 (c) Sample 3.

Clays and rocks have charges on their surfaces that act to adsorb bacteria and prevent their migration through the porous medium when pH and ionic strength are in the right combination. The highest ion exchange capacity is found in montmorillonite clays, whereas kaolinites are the least adsorptive. Illites have a moderate capacity for exchange. The chlorites are commonly found in sedimentary rocks on the surfaces of calcite grains or near a porous feature. The presence of chlorite restricts pore throats and consequently reduces permeability. Clays have the ability to absorb water, causing them to swell, which limits the movement of microbes through the rock mass. The salts (NaCl, KCl, and others) present in most reservoir brines reduce this swelling. Clays can also make the aqueous phase more viscous and prevent the diffusion of nutrients and gases necessary for microbial metabolism (Jenneman et.al. 1989). Although the XRD results have not shown any significant presence of smectite clays, their presence is inevitable in these types of depleted oil reservoirs. The swelling impact between smectite and its mixed minerals in low-permeability reservoirs is a bottleneck problem that directly leads to a decrease in reservoir porosity, permeability, and oil recovery (Cui et al. 2022) . The results from screening of mineralogy especially clay minerals suggest that these oil fields will have issues of injectivity due to presence of clay minerals. Based on the potential damage from the clays present and the low permeability rock, pore throat studies are necessary to understand the limitations of the Upper Assam oil fields in terms of the application of MEOR.

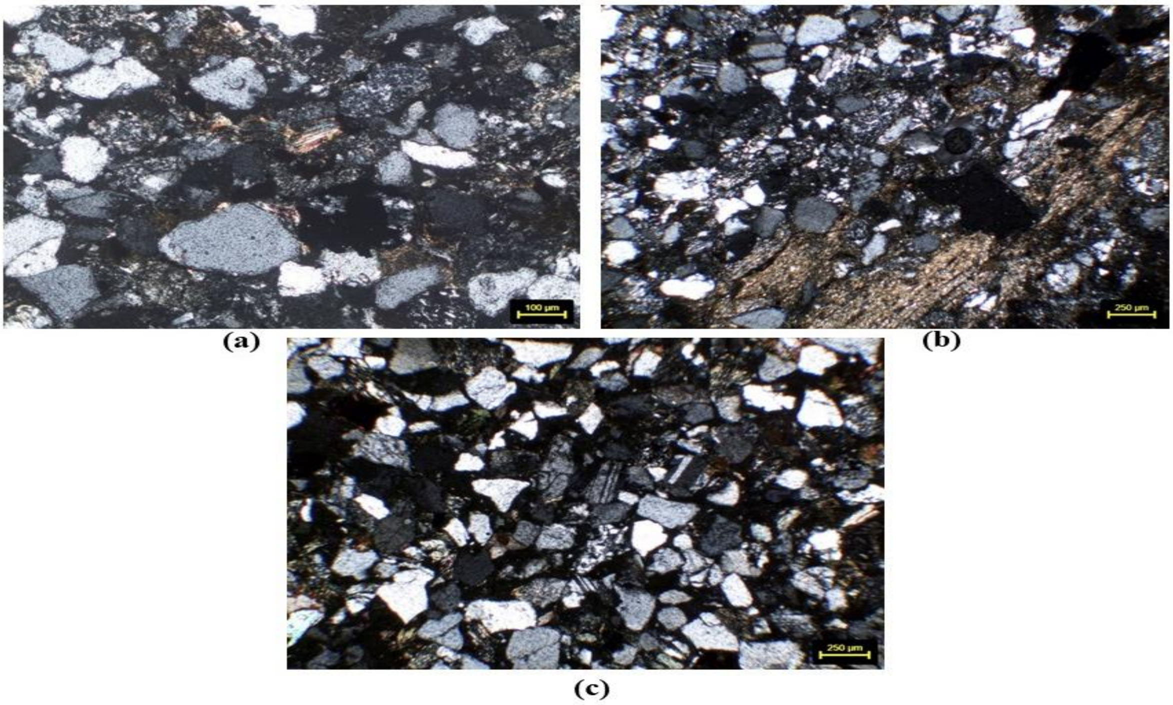


Fig.12: Thin Sections images of (a) Sample 1 (b) Sample 2 (c) Sample 3 showing the presence of Quartz, Feldspar, Mica, and Muscovite.

3.5 Screening of Pore Throat

Three samples were selected for FESEM analysis to represent the polished surface of the rock sample. Pore area and pore throat studies play a vital role in MEOR operations; they also give an idea about the selection of microbial strains.

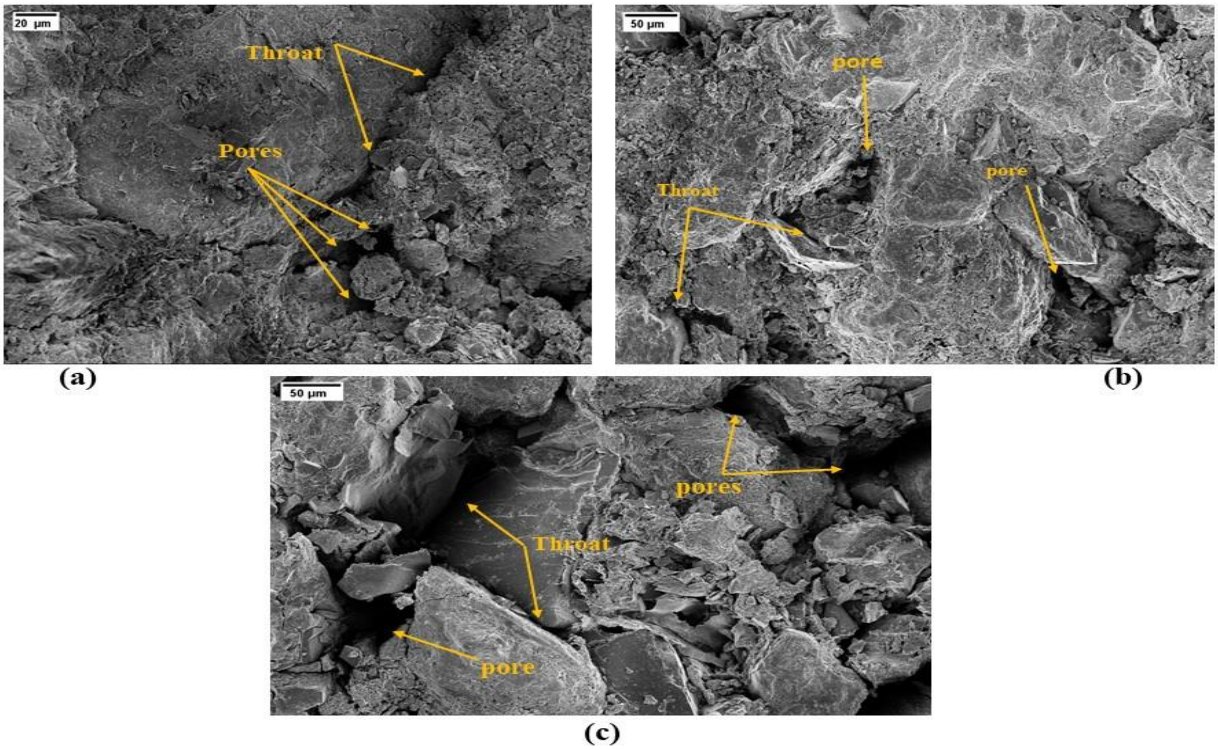


Fig.13: FESEM images showing the actual pores and pore throat (a) Sample 1 (b) Sample 2 (c) Sample 3.

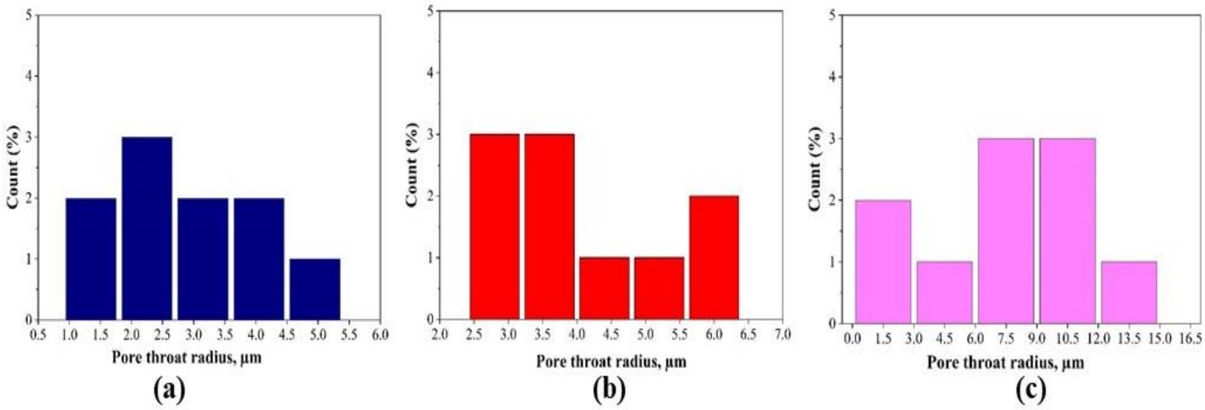


Fig.14: Distribution of Pore Throat radius of rock samples measured from FESEM Images.

In the image space, the software counts all possible pore areas and pore throat radii, their frequencies of occurrence, perimeters, and their shape and roundness. For example, image analysis for Sample 1 is depicted in Figure 13 (a), which shows the respective pores and pore throat scattered inside the image. From Figure 13 (a), it was found that Sample 1 has an average pore throat radius of 2.8 µm which reflects its low porosity and low permeability values in that field. It was also observed that Sample 2, which is from the same formation and similar depth, has an average pore throat radius of 4 µm respectively (Figure 13 (b)). Sample 3 belongs to a lower depth, and it also has high porosity and permeability values as compared to other samples, the average pore throat radius measured was 7.8 µm for sample 3. Figure 13 (c) shows the larger pores and pore throat in comparison to other samples. The actual pores and pore throats of all the samples found in FESEM images and their distribution have been given in Figure 14. The effectiveness of MEOR techniques can be significantly impacted by the pore throat radius of the reservoir rock. The size of the openings or channels between the rock grains, known as the "pore throat radius," affects how fluids move through the rock. The potential for MEOR success is generally increased by larger pore throat sizes, which can improve the movement of fluids and microorganisms through the rock. Pore throat analysis of the Upper Assam Oil fields suggests that Sample 3, which is from Tipam Sand, has the most ideal properties in terms of implementations of the MEOR method. Sample 3 will also have fewer injectivity issues in comparison to other samples due to its larger pore throat radius.

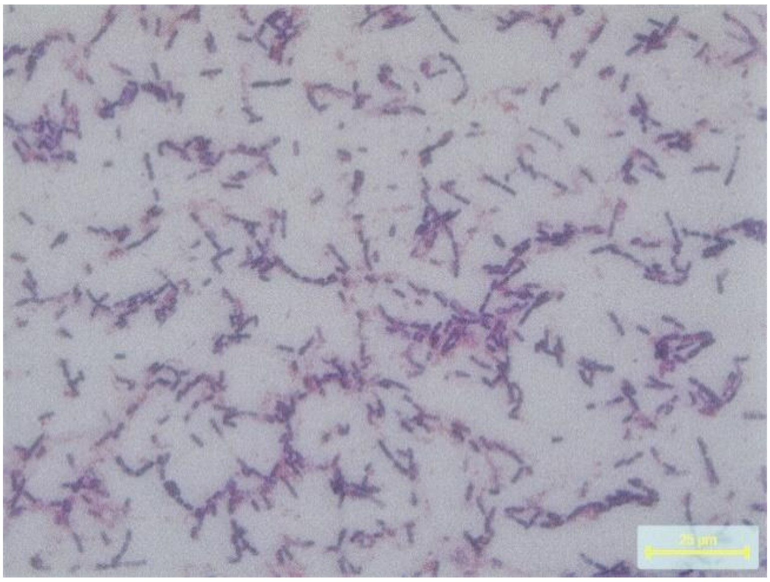


Fig.15: Bacillus strain and its morphology.

For microorganisms to penetrate the rock and get to the oil, the pore throat must be a specific size. Microorganisms may be unable to pass through pore throats that are too small, which would limit their activity and lessen the effectiveness of MEOR. Because different bacterial morphologies (e.g., rods, cocci, curved rods, tetrads, chains, etc.) have dimensions of 0.5–10.0 µm length and 0.5–2.0 µm width, the pore size of the rock matrix is a crucial factor in bacterial transportation (Li et al., 2023). When the pore size is less than 0.5 µm, it means that the movement of bacteria through porous media is severely constrained (Updegraff D.M. 1983). For cocci or short bacilli to move through the matrix of rocks, the pore size needs to be greater than twice the size of the cell. For our better understanding of bacterial morphologies, we have shown an image of a Bacillus sp. strain and its morphology Figure 15, which was generated by a gram staining experiment in the laboratory. A list of measured of rock properties for all three core samples is given in detail on Table 6. The authors have also done microbial flooding on these core samples and the results are highly positive in terms of oil recovery (Bhattacharjee et al., 2023).

Table 6: Details of Rock properties of all three samples of Upper Assam Oil Fields.

Rock Properties	Core sample 1	Core sample 2	Core sample 3
Porosity (%)	16.86	25.73	25.77
Permeability (mD)	11	32	37
Depth (m)	3377.0	3312.0	2329.6
Rock Type	Barail	Barail	Tipam
Contact Angle (Degree)	68	83.7	65.2
Clay Minerals	Kaolinite, Illites	Kaolinite, Illites	Kaolinite, Illites, Montmorillonite & Chlorites
Average Pore throat size (µm)	2.8	4	7.8

IV. CONCLUSIONS

In this study, the rock properties of Upper Assam oil fields were characterized, and their screening for implementation of microbial enhanced oil recovery were determined. Three core samples from different fields and various depths were used in this study. Such limited selection is usually not acceptable to represent a large reservoir, but this is a result of the limited sample availability. Upper Assam Oil fields are in declining stages of production, so the employment of an economic oil recovery method is a good choice, as is one that can assist waterflooding operations undergoing in these depleted reservoirs. Conventional core samples of reservoir rocks from different oil fields and also from different depths have been used for the characterization of rock properties in this study. Rock properties such as porosity, permeability, wettability, clay and mineral identification, and pore throat studies were examined in relation to the MEOR screening process (Martyushev et al., 2023). The permeability values of rock samples were low but it will not hinder any microbial movement. Contact Angle results showed that reservoir rocks are water-wet, which would be beneficial in terms of biosurfactant production and its relation to reducing interfacial tension between oil and water. Overall, after screening the rock properties of the Upper Assam oil fields, it sums up that MEOR can be implemented in these types of reservoirs after careful consideration of reservoir lithology, formation water analysis, microbe selection and interactions of rock-fluids.

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Data Availability Enquiries about data availability should be directed to the authors.

Ethics Declarations

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