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Enhanced recovery of Bonny light crude oil from unconsolidated porous media by two *Pseudomonas* species

Saka Adebayo Balogun[1]*, Obasola Ezekiel Fagade[2], James Adeyemo Adegoke[3], Olusegun Omole[4] and Izuchukwu Michael Akaegobi[5]

[1]Environmental Microbiology and Biotechnology Unit, Dept of Microbiology, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria.
[2]Environmental Microbiology and Biotechnology Unit, Dept of Microbiology, University of Ibadan, Ibadan, Nigeria
[3]Dept of Physics, University of Ibadan, Ibadan, Nigeria.
[4]Dept of Petroleum Engineering, University of Ibadan, Ibadan,Nigeria.
[5]Dept of Geology, University of Ibadan, Ibadan, Nigeria.
Email: balogunsa33@hotmail.com

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ABSTRACT

Aims*: Pseudomonas fluoresens* SL83 and *Pseudomonas mallei* SL63 were employed in tertiary (enhanced) recovery of Bonny light crude oil in unconsolidated porous soil matrix.
Methodology and results: The porous matrix was made from soil of various types and grain sizes [coarse sand (500 µm), fine sand (212 µm) and silt (106 µm) of varying percentage composition]. Porosity of the composite soil matrices were determined to be: 25%, 35% and 40%. Residual oil saturation and irreducible water saturation were determined before the oil recovery test was carried out. The rate of oil recovery after reducing the viscosity of the crude oil showed that *P. fluoresens* had the recovery rate of 33.3%, 23.8% and 20.8% while *P. mallei* had 28.5%, 22.2% and 16.7% at 40%, 35% and 25% porosities respectively.
Conclusion, significance and impact of study: The amount of oil recovered through microbial enhanced oil recovery in this study is quite significant which further confirms the potential of *P. fluoresens and P. mallei* biosurfactants as veritable material for use in enhanced recovery of crude oil.

Keywords: Microbial enhanced oil recovery, *Pseudomonas*, biosurfactant, unconsolidated porous media, porosity, wettability, oil displacement

INTRODUCTION

Crude oil, the world's major source of energy is essentially a mixture of compounds formed from hydrogen and carbon, although they may contain traces of nitrogen, oxygen, sulphur, nickel and vanadium (Okpowasili and Ibiene, 2006). It is one of the main factors that drive the economic development of the world (Youssef *et al.*, 2007). It is non-renewable and hence its exploitation should be optimized and sustainable (Parker, 1998). Despite this vast reserve, global demand for oil always outstrips supply (Alvarado and Manrique, 2010). This had been adduced to increase in the need to provide infrastructure, which goes along with galloping economic growth coupled with improved standard of living. The provision of these infrastructures and amenities require a considerable amount of energy (Burns, 1991).Although other options have been explored, but oil because of its proven record of success coupled with the fact that it is far cheaper than the rest, has given it comparative advantage over the other options (Burns, 1991).

Since a generally positive correlation has been established between oil consumption and economic growth (Burns, 1991; Youssef *et al*., 2007), demand for oil will continue to increase with advancement in science and technology vis a vis the living standard of man. In 2003, global oil reserve stood at 4 trillion barrels, but only 1.4 trillion (about one – third of the reserve) was recoverable (Hall *et al.*, 2003). Hence the need to tap into the large, known resource base of current oil reserves, so as to enhance oil production.

The production of oil from rock formation to the surface is called the recovery process. When it is recovered naturally as a result of pressure in the reservoir, it is referred to as primary recovery (Berger and Anderson, 1992). This natural recovery is followed by enhanced recovery, whereby an external force or energy is used to recover more oil from formation. If the enhanced oil recovery (EOR) process involves the injection of water or

*Corresponding author

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gas, it is called secondary recovery and tertiary if it involves the use of heat, chemical, miscible displacement and microbial products (Green and Wilhite, 1998; Rashedi *et al.*, 2012). Chemical surfactants such as sulphonates, sulphates, polyols, ethers, pyridium among others in EOR have been reported to lead to increase in recovery (Gogarty and Surkalo, 1972; Alvarado and Manrique, 2010), but most of them are toxic, not easily biodegradable and their manufacturing processes and by-products can be hazardous (Maier and Soberon, 2000). Hence, the need for cheaper and environment-friendly oil recovery alternative.

Surface active agents (i.e surfactants) can be produced by microorganisms, most especially bacteria. These agents are referred to as biosurfactants (Coopper and Zajic, 1980; Christofi and Ivshina, 2002; Xu and Lu, 2011). Biosurfactants are amphiphatic and tensio-active molecules capable of reducing the interfacial tension existing between polar and non-polar fluids (Padmariya *et al.*, 2011). Biosurfactants are able to lower the interfacial tension (IFT) that is responsible for trapping oil in the reservoir. This reduction in IFT will lead to tremendous hydrocarbon mobilization and recovery from porous matrix (Austad and Taugbol, 1995; Green and Wilhite, 1998; Crescente *et al*., 2008; de Gusmao *et al*., 2010).

The use of microbial products in EOR is known as microbially enhanced oil recovery (MEOR). Microbially enhanced oil recovery involves the use of whole microorganisms or their metabolites (Xu *et al*., 2009; Nielsen *et al*., 2010). Among the metabolites, biosurfactant had been used extensively in EOR operations around the world with increase in oil production (Maudgalya *et al.*, 2005; Wang *et al.*, 2007; Youssef *et al.*, 2007).

Biosurfactants are biodegradable, environment–friendly (i.e. non–toxic) (Maier and Soberon-Chavez, 2000; McInerney *et al.*, 2005) and can be produced from renewable substrates (Nitschke *et al*., 2004; Sitohy *et al*., 2010). The biosurfactants used in this study, were produced from cane sugar juice and pineapple peel extract (known cheap renewable feedstock). Hence, the objective of the study is to determine the oil recovery potential of *Pseudomonas* sp. in unconsolidated sand columns of different porosities.

MATERIALS AND METHODS

Preparation of crude biosurfactant

Sugar cane (*Saccharum officinarum*) were purchased from Bodija Market, Ibadan, South West, Nigeria. Sugar cane juice (SCJ) was prepared by surface sterilizing the bark of fresh sugar cane stems with 5% sodium hypochlorite solution. It was rinsed repeatedly with plenty of sterile distilled water. The bark was carefully removed with a surface sterilized knife and the inner fleshy part of the sugar cane was chopped into tiny bits. Two hundred, 500 and 1000 g of the sugar cane were measured using a weighing balance. They were milled in a warring blender (Warring Products Division Connecticut, USA.). Prior to use the blender jug was surface sterilized and kept in the oven at 160 °C. Each of the milled materials were dispersed in 500 mL sterile distilled water, sieved and was made up to 1 L.

Seventy-five mililitres of the SCJ were dispensed into 150 mL conical flasks and were inoculated with two loopful of *Pseudomonas mallei* SL63 and *P. fluoresens* SL83. The culture broth were kept on rotary shaker at 180 rpm for 72 h. The crude biosurfactant was purified by removing the bacteria cells by centrifugation at 3500 rpm for 20 min. The supernatant was removed from the cells with a sterile glass Pasteur pipette (Balogun, 2009).

Preparation of sand and packing of the glass column

Sand samples collected from the Dept of Botany and Microbiology, University of Ibadan were collected in clean polythene bags and taken to the laboratory. The samples were washed twice in 0.1 M HCL and rinsed with water sufficiently. This was done to remove organic matter present in the soil (McKenzie and Jacquier, 1997). It was sun dried and thereafter kept in the oven at 180 °C for 3 h. It was allowed to cool and oven sterilized again to constant weight. Using standard ASTM E–II sieves (Fisher Scientific, Ontario, Canada), soil samples were sieved and categorized into 3 different sizes viz: coarse sand, fine sand and silt respectively (500 µm, 212 µm and 106 µm). Three columns containing different combination of the sand sizes were packed. Column I contain: 500 µm, 50%; 212 µm, 30% and 106 µm, 20%. Column II: 500 µm, 30%; 212 µm, 20%; 106 µm, 50%. Column III: 500 µm, 20%; 212 µm, 50% and 106 µm, 30%. The glass columns were of uniform dimension (20 x 5 x 1.1 cm). The essence of varying the soil composition is to be able to have a diverse grain size and hence different porosity. A clean muslin net was used to cover one of the open ends of the glass and was filled with sand. Sand was filled to the 5 cm mark of the glass column. The column was tapped repeatedly with a glass rod until the composite sand is well packed and the 5 cm mark is maintained. After packing the column, the porosity of the sand column was determined prior to use for the oil recovery experiment.

Determination of porosity

Porosity is the ratio of the void space in a rock or sand to the bulk volume of that rock or sand (Frick and Taylor, 1978). The bulk volume, grain volume and ultimately porosity were determined using the imbibition method (Akin and Kovscek, 1999) as modified.

$$\text{Porosity } \Phi = \frac{\text{pore volume}}{\text{Bulk volume}}$$

$$\text{Pore volume} = \text{Bulk volume} - \text{Grain volume}$$

Therefore,

$$\Phi = \frac{\text{Bulk volume} - \text{Grain volume}}{\text{Bulk volume}}$$

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Determination of bulk volume

Soil samples were dried in an oven at 180 °C for 3 h. The sample was allowed to cool. It was dried again in the oven until constant weight at the same temperature and time to kill all living things including microorganisms present in the soil. One millilitre equivalent of the dried sand was measured using a 10 mL measuring cylinder. A thin, long measuring cylinder with a diameter of about 5 mm was used. The cylinder was tapped with a glass rod repeatedly until the sand content gets compacted and maintained a steady volume. The volume was recorded.

Determination of matrix or grain volume

The determination of volume of matrix or grain volume was determined as modified from Akin and Kovscek (1999). A measuring cylinder similar to the one used above, was half-filled with water and the volume was recorded. Three millilitre equivalent of sand as determined above was dispensed into the water. The new volume of the mixture was recorded.

Volume of sand (bulk volume) = A (mL)

Volume of water in the second cylinder = B (mL)

The mixture of A and B = C (mL)

Obviously, (A + B) > C

Volume of pores in the sand = (A + B) – C

Volume of matrix = Bulk volume – volume of pores

= A – {(A + B) – C}

= C – B

Therefore, porosity, $\Phi = \frac{A - (C - B)}{A}$

$= \frac{A + B - C}{A}$

Determination of water saturation and initial oil saturation in sand column

The irreducible water saturation and initial oil saturation in sand column was determined according to the method of Okpowashili and Ibiene (2006). The packed sand column, was flooded with brine (in this case 10% NaCl) until it was saturated. The irreducible water saturation 'S_{iw}' level was determined by materials balance (i.e. the amount of brine trapped in the sand column). Initial oil saturation in sand column was determined by flooding sand column with known volume of Bonny light crude oil, until no water was observed in the effluent discharged. The crude oil sample (i.e Bonny light) used in the experiment was diluted at a ratio of 1:1.5 with kerosene. Initial oil saturation (S_{or}) was determined from the difference in the oil used for flooding and the amount collected back.

Determination of the amount of crude oil recovered by the biosurfactant

Crude oil recovery by the biosurfactant was carried out in a sand column as described by Okpowashili and Ibiene 2006. The oil saturated sand column was flooded with crude biosurfactants produced by *P. mallei* SL63 and *P. fluorescens* SL83. It was flooded at constant fluid head for 20 min. The percentage oil recovery was determined from materials balance of residual oil in the sand column minus the amount of oil displaced from the column. The use of brine is indicative of the secondary oil recovery approach while the use of biosurfactant is the tertiary approach to oil recovery.

RESULTS

The oil recovery ability of *P. mallei* SL63 and *P. fluorescens* SL83 in unconsolidated sand column of different porosity (25%, 35% and 40%) are shown in Figures 1, 2 and 3. Residual oil saturation of the sand columns was determined before the oil displacement experiment. Brine was used to flood the column prior to flooding with biosurfactant from the organisms respectively. Brine flooding or waterflooding was used to simulate secondary oil production approach, while the use of the biosurfactant is an enhanced (tertiary) oil recovery approach. Residual oil saturation values of the packed columns were determined prior to flooding by *P. fluoresens* and *P. mallei* respectively.

At 25% porosity (Figure 1), *P. fluorescens* SL83 and *P. mallei* SL63 recorded the highest oil recovery level of 20.8% and 16.6% respectively. Between 9 min and 16 min, a constant crude oil displacement of 16.8% was recorded for the two Pseudomonads. However, it increased to approximately 21% after 16 min. Oil displacement by the biosurfactant was time dependent. It increased with increase in time.

When the porosity was 35% (Figure 2), residual oil saturation values of 0.7 and 0.3 mL were recorded for the columns flooded with *P. fluorescens* and *P. mallei* biosurfactants respectively. Crude biosurfactant from *P. fluorescens* had the highest oil displacement ability (23.8%) while *P. mallei* biosurfactant recorded the least displacement activity of 22.2% after consistent flooding at constant water head for 20 min. After 10 min of flooding with the biosurfactants, *P. mallei* had oil displacement of 23.8% while *P. fluoresens* had displaced approximately 13%. However, after 20 min *P. fluoresens* had displaced approximately 24% while 22% of the Oil In Place (OIP) was recorded for *P. mallei*. Crude oil displacement increased with time.

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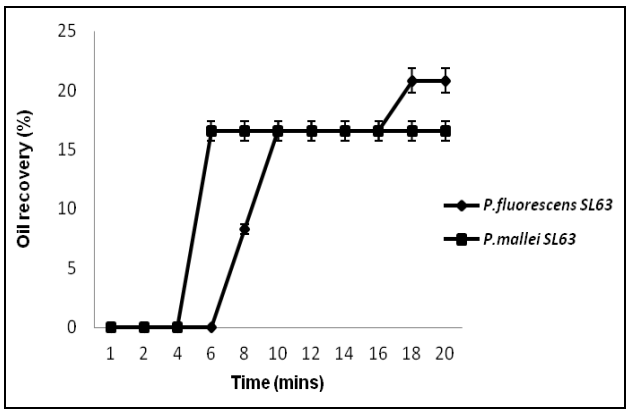

Figure 1: Rate of oil recovery in unconsolidated sand column of 25% porosity.

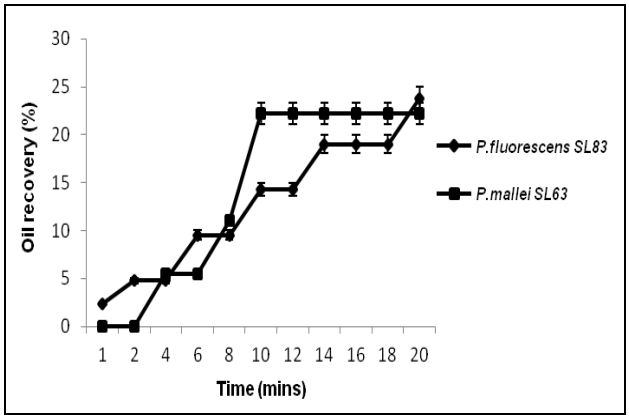

Figure 2: Rate of oil recovery in unconsolidated sand column of 35% porosity.

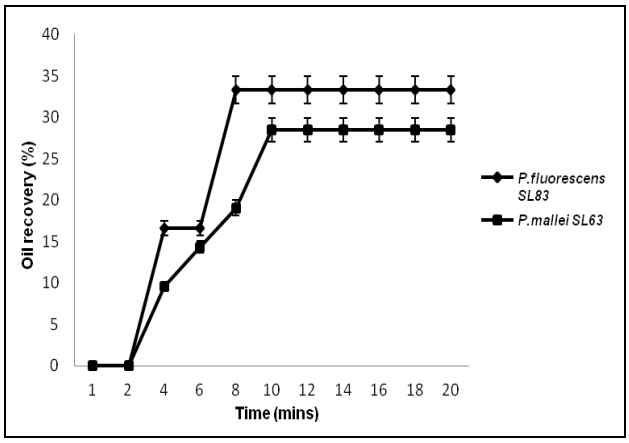

Figure 3: Rate of oil recovery in unconsolidated sand column of 40% porosity**.**

Invariably, pore-spaces increased at 40% porosity of the unconsolidated sand-pack (Figure 3). Oil displacement or sweep increased considerably from 17% to 33.3% for *P. fluoresens* and from 9.2% to 28.5% for *P.mallei* SL 63.

Figure 4 shows the rate of recovery at different porosities by the isolates. At 25% porosity, *P. fluoresens* recorded the highest oil recovery of 20.8% while 17% was recorded for *P. mallei* SL63. When the porosity was at 35%, *P. mallei* was able to displace 22.2% of OIP while 23.8% was displaced by *P. fluoresens.* At the highest porosity of 40%, *P. fluoresens* displaced 33.3% of the residual oil in the column while 28.5% of the OIP was recovered by *P. mallei* SL63.

Comparative oil recovery ability by the Pseudomonads shows that *P. fluoresens* SL83 had the highest oil recovery rate of 20.8%, 23.8% and 33.3% while *P. mallei* SL63 had the lowest rates of 16.6%, 22.2% and 28.5% at 25%, 35% and 40% porosities respectively (Figure 5).

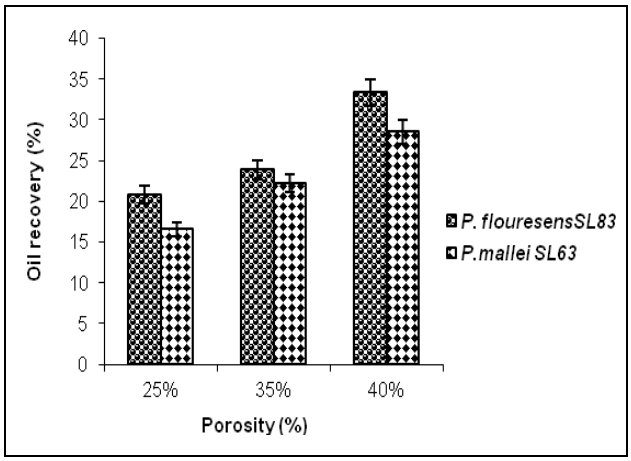

Figure 4: Comparative oil recovery of *Pseudomonas fluoresens* SL83 and *Pseudomonas mallei* SL63.

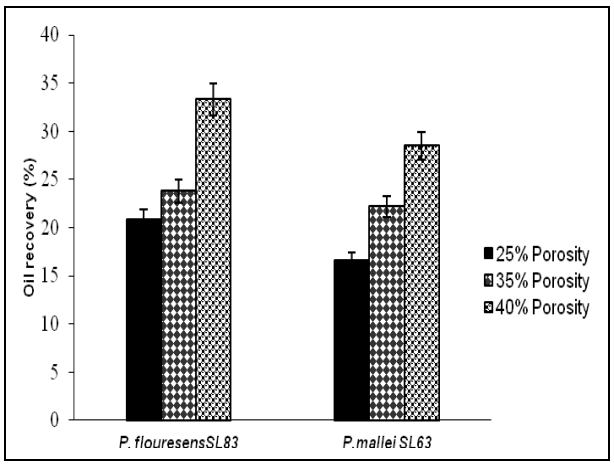

Figure 5: Comparative oil recovery by *P. fluoresens* SL 83 and *P. mallei* SL63 at different porosities.

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DISCUSSION

The residual oil saturation (S_{or}) is the amount of oil trapped in the sand column or sand pack after water flooding and brine flooding. Brine flooding is a simulation of secondary oil production which occurs after the primary production, prior to tertiary production which is equally referred to as enhanced oil recovery. The residual oil left in the sand-pack is the new target of EOR with the aim of contacting a large area of the column and thereby effecting it release from the column (Donaldson *et al*., 1985).

The displacement of 33.3% and 28.5% residual oil by biosurfactants from *P. fluorecens* SL83 and *P. mallei* SL63 recorded in the study is low compared to 52.19% reported by Okpowashili and Ibiene (2006). The displacement of the residual oil in place (OIP) in the sand-pack is attributed to the ability of the biosurfactant to break down the interfacial tension (Afrapoli *et al*., 2010) that may exist between crude oil (a non-polar liquid) and biosurfactant (an amphiphilic liquid). Also, the ability to displace oil in sand-pack by microorganisms especially *Pseudomonas* sp. had been reported by many workers (Okpowashili and Ibiene, 2006; Wang *et al.*, 2007). Also oil displacement trend and values that are similar and close in the two Pseudomonads may be as a result of the fact that the isolates belong to the same phylum, order and genera respectively (Prescott, 2003). This implies that the biosurfactant produced by the isolates may be similar.

High amount of oil recovered in sand column with increase in porosity (Figures 1, 2 and 3) is due to increase in pore space, which can be attributed to the porosity or packing of the soil (Frick and Taylor, 1978). For this study, grain sizes of 106 µm, 212 µm and 500 µm were used to pack the sand column.

The rate of change of oil sweep or displacement increases with time. This agrees with the findings of Okpowashili and Ibiene (2006). The highest amount of displacement of approximately 33% recorded for *P. fluorescens* SL83 at 40% porosity is quite low compared to the findings of Wang *et al.* (2007). This suggests that the crude biosurfactant from this organism was able to mobilize the OIP as a result of increasing the wettability (Morrow and Heller, 1985; Armstrong and Wildenschild, 2012) thereby enhancing the recovery of the hitherto trapped oil from oil reservoirs.

CONCLUSION

The amount of oil recovered through Microbial enhanced oil recovery in this study is quite significant and it is about one-third projection of most EOR work. This study further confirms the potential of *P. fluoresens* and *P. mallei* biosurfactants as veritable materials for use in enhanced recovery of crude oil from Niger Delta, Nigeria.

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