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Review

Microbial dynamics in petroleum oilfields and their relationship with physiological properties of petroleum oil reservoirs

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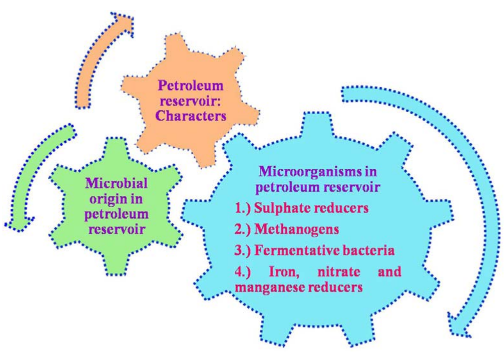
GRAPHICAL ABSTRACT



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ABSTRACT

Petroleum is produced by thermal decay of buried organic material over millions of years. Petroleum oilfield ecosystems represent resource of reduced carbon which favours microbial growth. Therefore, it is obvious that many microorganisms have adapted to harsh environmental conditions of these ecosystems specifically temperature, oxygen availability and pressure. Knowledge of microorganisms present in ecosystems of petroleum oil reservoirs; their physiological and biological properties help in successful exploration of petroleum. Understanding microbiology of petroleum oilfield(s) can be used to enhance oil recovery, as microorganisms in oil reservoirs produce various metabolites *viz.* gases, acids, solvents, biopolymers and biosurfactants. The aim of this review is to discuss characteristics of petroleum oil reservoirs. This review also provides an updated literature on microbial ecology of these extreme ecosystems including microbial origin as well as various types of microorganisms such as methanogens; iron, nitrate and sulphate reducing bacteria, and fermentative microbes present in petroleum oilfield ecosystems.

1. Introduction

A petroleum oilfield reservoir is an extreme environment having high temperature, high pressure, high salinity, and strictly anoxic conditions (Ollivier et al., 1997; Nazina et al., 2007; Li et al., 2010; Li et al., 2013; Lv et al., 2016). Oil reservoirs are large geo-bioreactors rich in wide range of anaerobic microorganisms, including fermentative bacteria, sulphate reducing bacteria (SRB), syntrophic bacteria and methanogens and many more microorganisms (Orphan et al., 2001; Grabowski et al., 2005; Li et al., 2010; Mayumi et al., 2011; Fowler et al., 2012; Bian et al., 2015; Liang et al. 2016; Meckenstock et al., 2016). It also contains large amount of organic substances such as

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different kind of inorganic ions (sulfate, nitrate) and organic compounds (alkanes, alkenes, cycloalkanes, aromatic hydrocarbons etc.) (Vetriani et al., 2004; Cheng et al., 2007; Yang et al., 2016; Varjani, 2017). Sulphate reducing bacteria (SRB) are reported as indigenous to petroleum oilfield ecosystems. First SRB was isolated from production water (Bastin, 1926). Sulfate reducing bacteria have been recognized as contributors to corrosion in water distribution systems, petroleum oilfields, and oil & gas systems as well as reservoir souring (Li et al., 2010; Davidova et al., 2012; Zhao et al., 2016). Major microbial processes prevailing in oil field ecosystems and petroleum hydrocarbon impacted environments are sulfate reduction, fermentation, acetogenesis, and methanogenesis, nitrate reduction, iron and manganese reduction (Dang et al., 1996; Myhr and Torsvik, 2000; Feng et al., 2011; Lv et al., 2016; Zhao et al., 2016).

Crude oil is one of the most important energy sources in the world (Costa et al., 2012; Tiwari et al., 2016; Varjani and Upasani, 2016b). It is used as raw material in various industries (Lucia et al., 2006; Varjani and Upasani, 2017a). Petroleum oil reservoir characteristics play important vital role in survival or growth of microorganisms (Belyaev and Ivanov, 1983; Orphan et al., 2001; Liang et al., 2016). Crude oil and formation water in petroleum oil reservoirs represent an extreme environment of the oilfield with different groups of indigenous microorganisms linked with oil reservoir conditions (Magot et al., 2004; Cheng et al., 2007; Li et al., 2010; Meckenstock et al., 2016). Hence it is important to study petroleum oil reservoir characteristics and its microbial ecology (Davydova-Charakhchyan et al., 1992; Magot et al., 2004; Cheng et al., 2007; Yang et al., 2016).

Microbial activities occurring in crude oil reservoir have significant influence on crude oil's chemical composition and physical-chemical properties (Stetter and Hubber, 1999; Fathepure, 2014; Varjani and Upasani, 2016a). Therefore, it can be said that microbial activities in crude oil reservoirs affect economical value or exploitation conditions of the crude oil (Liamleam and Annachhatre, 2007; Davidova et al., 2012; Tiwari et al., 2016; Varjani and Upasani, 2016b). The influence can be positive (decrease in viscosity of heavy crude oil enhance its exploitation), or negative (drilling equipment corrosion or reservoir souring) (Liamleam and Annachhatre, 2007; Davidova et al., 2012; Nalini and Parthasarathi, 2013; Varjani and Upasani, 2016a; Hussain et al., 2016). Various researchers have reported importance of microbial community dynamics in petroleum oilfield ecosystems (Li et al., 2013; Yang et al., 2016). Microbial community studies of oilfield ecosystems are divided mainly in two parts (a) cultivation dependent (Zhang et al., 2011; Nalini and Parthasarathi, 2013; Varjani and Upasani, 2016c) and (b) cultivation independent (Liang et al., 2009; Sajna et al., 2015; Varjani et al., 2015; Lv et al., 2016; Varjani and Upasani, 2017a).

This review article explores petroleum oilfield reservoir ecosystems characteristics and microbial ecology of these reservoirs including origin of microorganisms in petroleum oil reservoirs and types of microorganisms' *viz.* sulphate reducing bacteria; methanogens; fermentative bacteria; iron, nitrate and manganese reducing bacteria prevailing in these extreme ecosystems.

2. Characteristics of petroleum oil reservoir

Physico-chemical characteristics of ecosystems of petroleum oil reservoirs play vital role in survival or growth of microorganisms in them (Li et al., 2010; Costa et al., 2012). Temperature is one of the important microbial growth limiting factors in these ecosystems (Stetter and Hubber, 1999; Lv et al., 2016; Varjani and Upasani, 2017c). The natural temperature of petroleum oil reservoirs ranges from 10 to 124 °C (Bachmann et al., 2014). Temperature increases with depth at a mean rate of 3 °C/100 m depth, however regional geothermal gradients can be different. Due to this in case of deep oil reservoirs where depths range from 4030 to 4700 m temperature ranges between 130 and 150 °C. Therefore, in such deep oilfield reservoirs (having temperature exceeding 130–150 °C) life cannot sustain. Hence microorganisms cannot sustain as this temperature is considered as the highest theoretical limit for growth due to thermal instability of biological compounds (Stetter et al. 1993a). Presence of microorganisms at maximum temperatures of 80–90 °C has been reported earlier, above this temperature autochthonous bacteria do not survive (Philippi, 1977; Barth 1991; Grassia et al., 1996). Microbial presence has been detected at a depth 3500 m (Stetter and Hubber, 1999). *In situ* petroleum crude biodegradation in reservoirs can be observed at maximum 82 °C (Philippi, 1977). Barth (1991) has collected twenty-two samples of produced formation water from North American oil reservoirs. The samples showed maximum fatty acid concentrations at 80 °C. These results showed that maximum biodegradation occurs below 80 °C, and thermal decarboxylation occurs above 80 °C (Barth, 1991). Hyperthermophilic strains of microorganisms growing at temperatures as high as 80 °C and 102 °C have been isolated from oil reservoirs, the authors suggested that microbial strains represented exogenous bacteria resulting from sea water injections (Stetter et al., 1993b).

Salinity and pH of formation waters play vital role in bacterial activity (Li et al., 2013; Fathepure, 2014; Lv et al., 2016). Li et al. (2013), have reported that for the formation water generally pH ranges from 5 to 8. They have also reported that salinity of formation water ranges from fresh to salt saturated water. The pH is influenced by dissolution of gasses under high pressure, so pH measured at atmospheric pressure is not always identical to *in situ* pH (Varjani and Upasani, 2017a). The *in situ* pH of petroleum oil reservoirs generally ranges from 3 to 7. Salinity and pressure are referred as typical features of oilfield ecosystems such as saline lakes or deep seas (Varjani, 2017). The pressure within oil reservoirs (up to 500 atm) does not hamper development of bacteria *in situ* (Stetter et al., 1993b). In contrast Schwarz et al. (1975), have reported that some petroleum hydrocarbons when reach deep-oceans pollute deep benthic zones. These petroleum hydrocarbons persist for long time i.e. years or decades as they are biodegraded very slowly due to their recalcitrance nature.

Bacterial metabolism within petroleum oil field ecosystems is also influenced by type of electron donors and acceptors available (Barth, 1991; Liamleam and Annachhatre, 2007; Davidova et al., 2012; Lv et al., 2016). These ecosystems are deep subterranean which are isolated from surface waters (Barth, 1991). Oil field ecosystems have very low redox potentials and some electron acceptors are absent *viz.* oxygen, nitrate and ferric iron (Li et al., 2013; Meckenstock et al., 2016). Stratal waters contain different concentrations of sulphate and carbonate (Feng et al., 2011); these factors have led to the assumption that major metabolic processes prevailing in such ecosystems are methanogenesis, sulphate reduction, fermentation and acetogenesis (Feng et al., 2011; Meckenstock et al., 2016; Wilkes et al., 2016; Yang et al., 2016). CO_2, H_2 and some organic molecules are electron donors present in these ecosystems (Yang et al., 2016). Various organic acids acetate, benzoate, butyrate, formate, propionate, naphtenic acids are also present in many crude oil reservoirs (Barth, 1991; Bian et al., 2015; Lv et al., 2016). Crude oil consists of different organic molecules among which aliphatic and aromatic hydrocarbons, nitrogen and sulphur heterocyclics have been degraded by microorganisms (Boll et al., 2014; Varjani et al., 2015; Varjani, 2017). Resins and asphaltenes are heteroatoms of nitrogen, sulphur and oxygen, which are potential source of electron donors for anaerobic metabolism (Varjani, 2017). Their presence is an indication for metabolic activity of strict anaerobes which are using crude oil as a sole carbon and energy source (Meckenstock et al., 2016; Wilkes et al., 2016). Very few research activities pertaining to nitrogen and phosphorous availability in petroleum oil reservoirs have been performed (Li et al., 2010; Feng et al., 2011). Nitrogen gas is assimilated by nitrogen fixing microorganisms. Nitrogen in petroleum oil reservoir is also available as nitrogen heterocyclic compounds (Li et al., 2010). Li et al. (2010), have investigated the abundance, distribution and functional diversity of anammox bacteria in nine high-temperature (55 °C and 75 °C) oil field reservoirs which were having