Article 9

Biotechnology and the Future of the Petrochemical Industry: Legacy and Prospects

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Despite progress in the production of different types of renewable energy, this is anticipated to cover only a minor fraction of the global energy demand in the near future, thus rendering petroleum (crude oil) the major energy source in the coming decades (International Energy Agency, 2023, Organization of the Petroleum Exporting Countries, 2023). Accordingly, petroleum recovery and refining operations have been expanding in oil-producing countries to satisfy the growing worldwide demand for cleaner fuels and petrochemicals. Unfortunately, recovery and production of fossil fuels and petrochemicals are associated with large-scale environmental pollution issues, particularly climate change and global warming due to emission of hazardous gases and oil spills (deliberate or accidental) (Philp et al., 2005; Jafarinejad, 2017; European Environment Agency, 2023). Moreover, the conventional technologies for oil production and refining are very costly, technically challenging, and themselves generate secondary pollution (Bachmann et al., 2014; Ismail et al., 2022a). Those shortcomings are exacerbated due to depletion of the light crude oil reserves and shift of the refinery feed to unconventional heavy and extra-heavy crude oil reserves which require unconventional technologies for production, transport, and refining (Speight and El-Gendy, 2018; Ismail et al., 2022a). Therefore, there is increasing interest in the development of green, sustainable, and economic technologies that can: i) mitigate environmental pollution and climate change consequences, and ii) enable the oil industry to meet the growing market demand for cleaner fuels and comply with strict environmental regulations. One of the promising approaches deals with the applications of biotechnology in the petroleum industry, namely, Petroleum Biotechnology or Hydrocarbon Biotechnology (Speight and El-Gendy, 2018).

Petroleum biotechnology is a sub-domain of environmental biotechnology, which exploits the unique metabolic and physiological traits of some microorganisms, including bacteria, fungi, and microalgae (Morales et al., 2010; Ismail et al., 2022a; b). These microbes are commonly found in close contact with oil in reservoirs and in oil-polluted aquatic and terrestrial environments where they can have a direct impact on the quality of the crude oil, which consists of a heterogeneous mixture of organic and inorganic components that can be utilized by some microorganisms as carbon and energy source (Speight and El-Gendy, 2018; Ismail et al., 2022b). In addition, petroleum contains sulfur, nitrogen, and some metals which are essential for microbial growth and reproduction. Hence, petroleum-degrading microorganisms are endowed with unique metabolic machinery that enables them to catalyze many biochemical reactions

or biocatalytic transformations using the different oil components as substrates (Ramírez-Corredores and Borole, 2006; Bachmann et al., 2014). The origin of petroleum biotechnology dates back to the beginning of the 20th century where theories on the role of microorganisms in petroleum formation had permeated the literature (Dake, 1913). In 1946, Claude E. ZoBell published a landmark review, Action of Microorganisms on Hydrocarbons (Zobell, 1946), with 182 citations including Miyoshi's observations in 1895 of Botrytis cinerea penetrating thin layers of paraffin. ZoBell's review discussed a wide range of relevant topics like hydrocarbon-containing culture media and effects of growth conditions; types, hydrocarbon substrates and ecology of hydrocarbonoclastic microorganisms, activities of these organisms on petroleum, as well as the use of microorganisms as indicators of oil deposits. Further exploration of those themes continued, thanks to microbiologists interested in hydrocarbon biotechnology, to better understand the microbial physiology and ecology of hydrocarbon-metabolizing microorganisms and to reveal how those microorganisms may be exploited to the benefit of the world.

Microbial interaction with crude oil can lead to either complete degradation or mineralization of the oil or just specific biotransformations of one or more components. These principles can be adopted in different approaches to develop various useful applications in the petroleum industry. Biotechnology has been historically applied for oil spill bioremediation and reclamation of oil-polluted soil, which is the classical application of petroleum biotechnology in the environment/oil industry. However, biotechnology can be potentially applied throughout the value chain of the oil industry, starting with exploration and recovery all the way through transportation, refining as well as waste treatment/valorization. For instance, biodesulfurization/biodenitrogenation of diesel, biocatalytic upgrading of heavy crudes, and bioconversion of crude oil to chemicals/fuels, are examples of potential applications that await in-depth investigations (Ismail et al., 2022b). Moreover, conversion of residual hydrocarbons in depleted oil reservoirs into methane can potentially promote the recoverable fraction of energy (Kilbane, 2016). Hence, these prospective applications represent virgin fields for further research and development efforts both in academia and the oil industry, which can contribute to capacity building and training of junior scientists and petroleum engineers. Initially, research efforts should focus on better understanding of the science at work, which shall pave the way towards development of commercially viable bioprocesses for specific applications in the petroleum industry. Being a multidisciplinary field, petroleum biotechnology is an ideal research area for graduate students and junior scientists from various backgrounds including microbiology, molecular biology, biochemistry, chemistry, chemical/biochemical engineering, geology, petroleum engineering, bioinformatics, etc. However, to ensure success within a reasonable timeline, it is crucial to capitalize on strong collaboration between academia and the petrochemical industry by developing problem-based or problem-oriented joint megaprojects managed by dedicated

multidisciplinary teams. Considering the global environmental issues and climate change crisis, petroleum biotechnology can be instrumental in the achievement of sustainable development goals and implementation of circular economy towards decarbonization of the petrochemical industry and a sustainable environment.

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