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Numerical evaluation of direct interfacial uptake by a microbial consortium in an airlift bioreactor

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ABSTRACT

Sinkholes, also called *cenotes*, are a common feature in the karst aquifers found along the state Quintana Roo in México. Certain aliphatic and aromatic hydrocarbons have been found in the surface water of these sinkholes resulting in health and environmental hazards. In this study, a mathematical model is evaluated based on its predictive capacity on the biodegradation of oil in an airlift bioreactor (ALB). The model describes the oil uptake at the water-oil interface, whereas the previous modeling approaches focused on oil uptake in emulsified form. Biodegradation of 20 g L^{-1} diesel in an ALB is achieved by using an oil-degrading microbial consortium isolated from a sinkhole located in the urban zone of Playa del Carmen in Quintana Roo. The diesel degraded 83.6% confirming an effective use of ALB for the bioremediation of oil in water. The model is capable of predicting biomass growth and biodegradation by either integrating Monod or Teissier kinetics depending on the inhibitory effect of high concentration of oil on the microbial growth rate. The model is validated against three experimental campaigns performed in ALBs which indicated that it can serve as a valuable tool in the design and scale-up of bioreactors for the biodegradation of oil.

1. Introduction

The geology of Yucatan Peninsula in México, where the state of Quintana Roo is located, is relatively unknown consisting of highly-permeable karst limestone deposits. This is because the rocks of the Peninsula, to depths of more than 500 m, are dominantly limestone and dolomite of Cretaceous and younger ages with significant evaporite lenses but rare siliciclastic units (Fig. 1). Much of what is known about the regional stratigraphy of the Yucatan Peninsula comes from oil exploration (Ward, 1985). The karst surface enables the immediate infiltration of water into the underground system, where karstification (formation of a karst topography) creates interconnected fractures, joints and cavities. Along the Caribbean coast of the Yucatan Peninsula, this underground flooded cave network extends 8–12 km inland providing hydrological conduits that link the inland recharge areas to springs that discharge into the coastal zone (Smart et al., 2006). Sinkholes, also called ‘cenotes’, are common in this karst landscape and provide access into these conduit cave systems. Karst aquifers are extremely vulnerable to pollution and human impacts (Veni, 2002). Underground solution conduits and a little top soil (vadose zone) allow a quick transport microbial and chemical contamination resulting in a significant increase of pollution affecting the ecosystem (van Beynen, 2011).

In recent years, karst aquifers encounter an increased pressure from a variety of activities resulting from comprehensive economic and urban development (Kovačič and Ravbar, 2013). Increased transportation of locals and tourism, are affecting the water in sinkholes along Quintana Roo. Lizardi-Jiménez et al. (2015) reported the presence of aliphatic and aromatic hydrocarbons in the surface water of the sinkholes. The hydrocarbons

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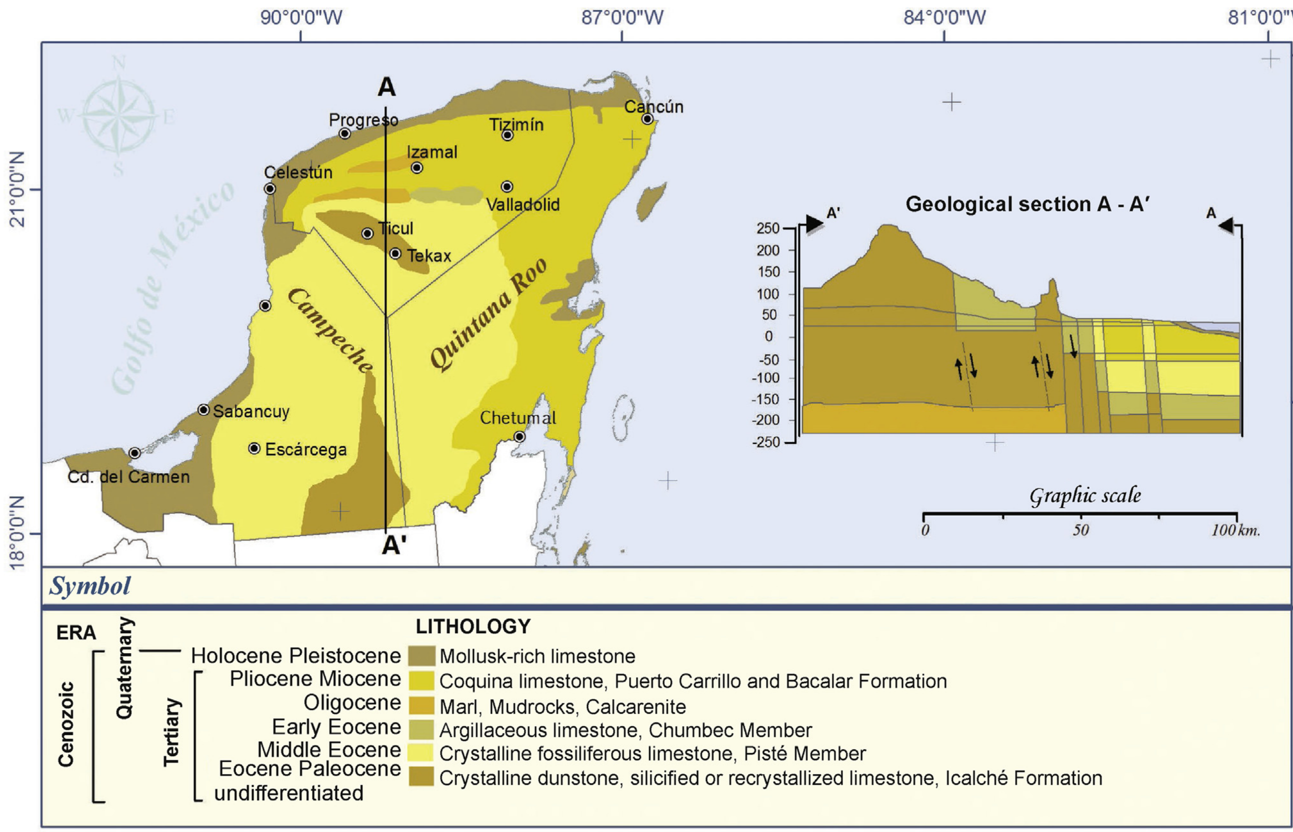

Fig. 1. Geological classification of Yucatan Peninsula (García and González, 2010). Different types of permeable limestone in this area allow water to easily seep down through cracks and react with limestone as it passes through the rock, causing cavity formation.

found were mostly related to combustion fuels and are present due to the run-off of nearby streets and highways. In addition, the concentration of hydrocarbons is related to high and low season (Medina-Moreno et al., 2014). As the flooded cave network rapidly conveys most of the groundwater (0.5–2.5 km day^{-1}), the aliphatic and aromatic hydrocarbons not only contain a risk for non-coastal sites but also for coastal waters and the Meso-American Barrier Reef System (Beddows, 2004). With planned expansion of tourist number and intensive land development in Quintana Roo taken into account, it is crucial to create novel technologies that contribute to the remediation of this pollution (Municipalidad de Solidaridad, 2014). Hydrocarbon-degrading microbial consortia, naturally present in oil-containing environments, play an important role in the biological remediation of oil and oil products in the environment. The bioremediation relies on augmenting the natural biodegradation rate of the hydrocarbons. One method is the use of an airlift bioreactor (ALB) to culture a microbial consortium that only uses hydrocarbons as its carbon and energy source (Kermanshahi-pour et al., 2005; Lizardi-Jiménez et al., 2015). ALB has important advantages over bubble-column and stirred bioreactors such as reduction in cell damage, higher aeration rates, larger mass transfer capacity, higher liquid surface velocity and gas flow, simpler construction and lower energy cost (Chisti and Jauregui-Haza, 2002). In the recent study of Medina-Moreno et al. (2014), hydrocarbon-degrading bacterial cultures were isolated from water and soil samples from hydrocarbon-polluted sinkholes in Quintana Roo. Promising results to degrade diesel in ALB using the indigenous microbial consortium were obtained and suggested that it may be possible to use in future such ex-situ remediation technique in tourism poles. However, they suggested further studies to optimize the biodegradation process consisting of insoluble organic pollutants. The mechanisms of uptake of hydrocarbon-degrading consortia are complex, since petroleum is consisting of innumerable compounds. It is assumed that two different pathways might be responsible: uptake by direct interfacial contact of microorganisms with free forms (macroscopic droplets) and uptake of emulsified forms (microscopic droplets) (Hua and Wang, 2014). A previous study with hexadecane (HXD) and a consortium isolated from a rhizosphere reported a maximum specific HXD uptake rate of the oil-degrading consortium 53 times higher for emulsified HXD than for their free form. This suggests that the consumption of HXD is realized more efficiently by the emulsified form (Medina-Moreno et al., 2013). However, the production of biosurfactants by the microorganisms to generate more emulsified forms is not always necessary to initiate the degradation. Recently, Angeles (2016), working with a hydrocarbon-degrading consortium isolated from a polluted sinkhole located in the urban zone of Playa del Carmen (México) reported a higher consumption of diesel in the absence of emulsifiers (day 0 – day 2 of culture time) than could be explained by the maximum diesel transfer rate. The mass transfer rate was able to explain the maximum quantity of hydrocarbons in their emulsified form, although direct contact uptake was the predominant mechanism in the first two days of the culture time. In addition, direct contact uptake was the primary pathway of diesel uptake. The design and operation of ALB has to aim for a maximum bioavailability of the hydrocarbons for the predominant pathway. Therefore, mathematical models can be used and can gain a better insight in the kinetic processes involved in the biodegradation. Mathematical