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Bioreactors for oil sands process-affected water (OSPW) treatment: A critical review

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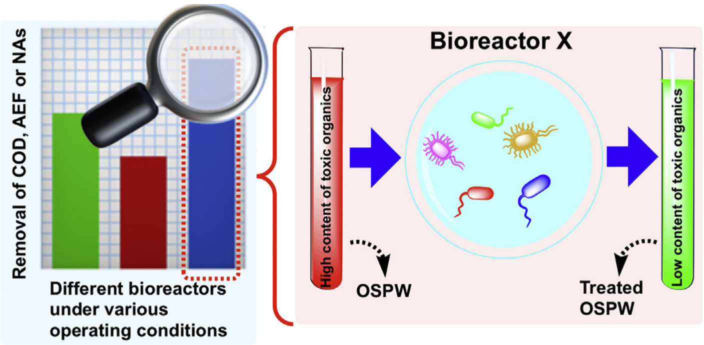
HIGHLIGHTS

- Biodegradation is competent for OSPW treatment.
- Biofilms have more resilient microbial community structures.
- Biofilms and elevated suspended biomass are beneficial to degradation of OSPW.
- Incorporation of biofilms in membrane bioreactor is promising.

GRAPHICAL ABSTRACT



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ABSTRACT

Canada has the world's largest oil sands reservoirs. Surface mining and subsequent caustic hot water extraction of bitumen lead to an enormous quantity of tailings (volumetric ratio bitumen:water = 9:1). Due to the zero-discharge approach and the persistency of the complex matrix, oil producers are storing oil sands tailings in vast ponds in Northern Alberta. Oil sands tailings are comprised of sand, clay and process-affected water (OSPW). OSPW contains an extremely complex matrix of organic contaminants (e.g., naphthenic acids (NAs), residual bitumen, and polycyclic aromatic hydrocarbons (PAHs)), which has proven to be toxic to a variety of aquatic species. Biodegradation, among a variety of examined methods, is believed to be one of the most cost effective and practical to treat OSPW. A number of studies have been published on the removal of oil sands related contaminants using biodegradation-based practices. This review focuses on the treatment of OSPW using various bioreactors, comparing bioreactor configurations, operating conditions, performance evaluation and microbial community dynamics. Effort is made to identify the governing biotic and abiotic factors in engineered biological systems receiving OSPW. Generally, biofilms and elevated suspended biomass are beneficial to the resilience and degradation performance of a bioreactor. The review therefore suggests that a hybridization of biofilms and membrane technology (to ensure higher suspended microbial biomass) is a more promising option to remove OSPW organic constituents.

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Contents

1. Introduction

As the global energy demand grows, the exploitation of unconventional oil resources, such as oil sands mining in Canada and shale oil production in the USA, is becoming more important to the global economy (Armstrong et al., 2009; Hughes, 2013). Due to the modified Clarke caustic hot water extraction process, the oil sands exploitation in Canada has been generating enormous quantities of process water termed tailings water or oil sands process-affected water (OSPW). Because of zero discharge approach maintained by the regulatory framework, the oil sands producers use vast tailings ponds to store OSPW (Allen, 2008a; Government of Alberta, 2015). Up to 2013, the tailings ponds had covered >220 km^2 and contained ~1 trillion liters of contaminated water (Government of Alberta, 2017). OSPW consists of water, clay, heavy metals, salts, naphtha diluents, residual bitumen, naphthenic acids (NAs), polycyclic aromatic hydrocarbons (PAHs), and other organic compounds (Allen, 2008a; Li et al., 2017; Mahaffey and Dubé, 2016; Pramanik, 2016; Xu et al., 2017). The increasingly stringent constraint on tailings pond expansion and aggressive timeline on OSPW reclamation set by the jurisdiction compel the industry to seek more efficacious OSPW treatment approaches to efficiently reuse and/or safely discharge OSPW to the environment.

Among all the contaminants contained in OSPW, organic compounds are considered the most problematic, particularly NAs. Various techniques have been used for quantification of the organic content in OSPW, such as chemical oxygen demand (COD) (Huang et al., 2015), Fourier transform infrared spectroscopy (FTIR) (Gamal El-Din et al., 2011; Rogers et al., 2002), gas chromatography coupled with mass spectrometry (GC/MS) (Scott et al., 2008), ultra-performance liquid chromatography coupled with high resolution mass spectrometry (UPLC/HRMS) (Martin et al., 2010; Sun et al., 2014), Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS) (Ajaero et al., 2017), etc. Detailed reviews on different characterization methods for OSPW could be found elsewhere (Brown and Ulrich, 2015; Clemente and Fedorak, 2005; Headley et al., 2009; Hughes et al., 2017; Sun et al., 2014). Due to the high complexity of the organic matrix in OSPW, there is no current technique that is able to fully discern all individual compounds existing in OSPW. Thus, the characterization of OSPW is indeed a topic of profound significance to a better understanding and the resolution of the issue.

NAs are defined as a group of aliphatic and alicyclic, alkyl-substituted carboxylic acids with a generalized formula of $C_nH_{2n+Z}O_x$. Z is either zero or a negative even integer, indicating hydrogen deficiency caused by the presence of ring structure or double bond equivalents (DBE). The oxygen atom number x signals whether the species is classical NA ($x = 2$) or oxidized NA (oxy-NA) ($x \geq 3$) (Huang et al., 2018; Meshref et al., 2017). OSPW usually contains classical NAs within a range of 20–120 mg/L (Toor et al., 2013b), which usually amount to ~50% of the acid extractable fraction (AEF) in OSPW (Grewer et al., 2010). Classical (O2), O3 and O4 NAs are arguably the dominant species in OSPW, with O2 species being distinctly the primary group (Ajaero et al., 2017; Huang et al., 2017a; Xue et al., 2017). O3 and O4 NAs are likely the oxidation products of classical NAs through biological processes (Ajaero et al., 2017). In addition, heteroatoms, such as S and N, may be contained in NA molecules, which are therefore termed heteroatomic NAs (Headley et al., 2009; Islam et al., 2015; Meshref et al., 2017; Yue et al., 2016).

As the major contributor to the OSPW toxicity to aquatic and terrestrial lives, NAs are attracting particular attention. In addition, with an estimated in-situ half-life of ~13 years in tailings ponds (Han et al., 2009), NAs are tremendously recalcitrant. Thus, it is of profound environmental and public-health significance to find an economical way to effectively degrade NAs from OSPW. A wide variety of techniques have been examined for the degradation of OSPW NAs, including physical (e.g., filtration, adsorption and membrane separation), chemical (e.g., advanced oxidation processes (AOPs)), and biological methods (e.g., microbial biodegradation) (Brown and Ulrich, 2015; Pramanik, 2016). In addition, PAHs have recently been identified and investigated in OSPW (Mahaffey and Dubé, 2016; Zhang et al., 2015). PAHs and aromatic NAs may contribute significantly to the toxicity of OSPW despite their relatively low abundance (Rowland et al., 2011; Scarlett et al., 2013).

Among all the examined potential solutions, biodegradation is believed to be the major pathway of the natural degradation/dissipation of NAs in tailings ponds (Quagraine et al., 2005). It is thus crucial to engineer biological processes to accelerate the biodegradation of OSPW NAs. Back to early 1980s, Wyndham and Costerton (1981) reported the capability of hydrocarbon degradation of microorganisms within the Athabasca oil sands deposit. Herman et al. (1994) first observed in the laboratory that the acidic extract of OSPW was markedly degraded by indigenous microorganisms sourced from oil sands tailings ponds. In addition, the researchers demonstrated that commercial NA mixtures were compositionally different and less recalcitrant than OSPW indigenous AEF. Since then, with the rapid growth of oil sands production, the evolvement of detecting techniques and more elevated public awareness of the OSPW-induced environmental issues, increasingly more studies have been published on the biological treatment of OSPW (*c.f.* Fig. 1). To date, a wide variety of bioreactors, including batch and continuous, bench- and pilot-scale setups, have been investigated for either OSPW organic content (i.e., NAs, AEF, PAHs, etc.) or commercial NAs/