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Review

Anaerobic membrane bioreactors for biohydrogen production: Recent developments, challenges and perspectives

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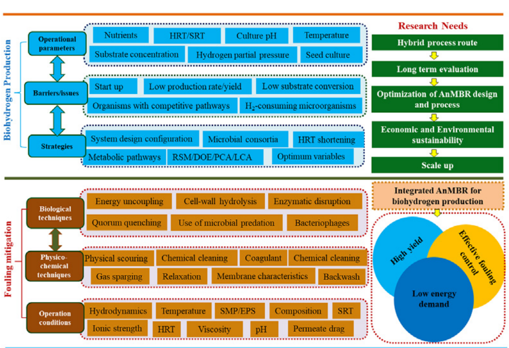
GRAPHICAL ABSTRACT



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ABSTRACT

Biohydrogen as one of the most appealing energy vector for the future represents attractive avenue in alternative energy research. Recently, variety of biohydrogen production pathways has been suggested to improve the key features of the process. Nevertheless, researches are still needed to overcome remaining barriers to practical applications such as low yields and production rates. Considering practicality aspects, this review emphasized on anaerobic membrane bioreactors (AnMBRs) for biological hydrogen production. Recent advances and emerging issues associated with biohydrogen generation in AnMBR technology are critically discussed. Several techniques are highlighted that are aimed at overcoming these barriers. Moreover, environmental and economical potentials along with future research perspectives are addressed to drive biohydrogen technology towards practicality and economical-feasibility.

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1. Introduction

Recent concerns over climate change and depleting fossil fuels are driving to develop alternative biofuels as replacements for non-renewable fossil fuels. The challenges of dwindling fossil fuel reserves and anthropogenic climate change are driving intense research into sustainable energy resources (Bharathiraja et al., 2016; Chawla et al., 2018; Hallenbeck, 2009). Among the various biofuels options, biohydrogen is an attractive future energy carrier due to its potentially higher efficiency of conversion to usable power, high energy density and low generation of pollutants (Gassanova et al., 2006; Ghauri et al., 2011; Hallenbeck and Ghosh, 2009; Nikolaidis and Poullikkas, 2017; Winter, 2009). Recently, variety of technologies for hydrogen production from variable sources has been extensively investigated. Among these, hydrogen production from biomass represents one of the highly attractive options for being a less energy intensive and more economical process (da Silva Veras et al., 2017; Kataoka et al., 1997). Biohydrogen can be produced by several biological ways including photodecomposition of organic compounds by photosynthetic bacteria (photofermentation), biophotolysis of water using algae and cyanobacteria; and fermentative hydrogen production from organic waste streams (Hallenbeck and Benemann, 2002; Show et al., 2011, 2012). However, incomplete substrate conversion and the consequent low yields and generation rates have been the major barriers to the practical applications of biohydrogen technologies.

In recent years, several approaches have been proposed to surpass these drawbacks, such as the construction of more efficient and robust hydrogen producer microorganisms, fermentation optimization and bioreactor design (Boodhun et al., 2017; Guo et al., 2010; Jung et al., 2011). Fermentative bacteria can produce hydrogen gas continuously without any light source in anaerobic wastewater treatment (Kumar et al., 2017; Tao et al., 2007). In addition to hydrogen, such bacteria can produce other products to satisfy their metabolic needs and to further growth, these include organic acids, alcohol and acetone that can be converted into electricity sources, biodegradable plastics and fibers (Hallenbeck, 2005; Khan et al., 2016). Therefore, dark fermentation seems more feasible and there is remarkable progress ongoing toward practicality (Das and Veziroglu, 2008; Hawkes et al., 2007; Kraemer and Bagley, 2007). Conventionally, continuous stirred tank reactors (CSTRs) have been widely used for biohydrogen production by fermentative bacteria (Bartacek et al., 2007; Davila-Vazquez et al., 2008). CSTRs offer simple construction, ease of operation, effective homogeneous mixing and operation under variable conditions of the substrate, pH and hydraulic retention time (HRT) (Kapdan and Kargi, 2006; Wang and Wan, 2009). However, the potential risk of biomass washout has driven investigation and trails of several modified configurations of fermentation systems.

Among bioreactor designs, combining hydrogen fermenters with membrane technology (AnMBR) is one of the most promising solutions. Membranes in AnMBR, compared with CSTR, can prevent biomass loss from the reactor, thus permitting the long solid retention time (SRT) required for efficient treatment while allowing relatively short HRT (Aslam et al., 2014; Charfi et al., 2017b; He et al., 2012; Trad et al., 2015a). In addition, AnMBR produce high quality effluent, reduce plant footprint and produce flexibility in operation (Smith et al., 2014; Stuckey, 2012). Consequently, application of AnMBR has brought significant improvement in biohydrogen production efficiency in dark fermentation processes (Bakonyi et al., 2017, 2014; Lee et al., 2009b, 2007; Noblecourt et al., 2017; Saleem et al., 2018; Singhania et al., 2012; Trad et al., 2015a). However, membrane fouling is still the main barrier in AnMBR applications (Aslam et al., 2017b, 2015; Meng et al., 2017; Spagni et al., 2010). To date, several review papers have been published on membrane fouling and biogas production in AnMBRs (Lin et al., 2013; Ozgun et al., 2013; Shin and Bae, 2018; Smith et al., 2012; Stuckey, 2012; Szentgyörgyi and Bélafi-Bakó, 2010). The potentials of AnMBRs for biohydrogen production were not enlightened. Bakonyi et al. (2014) only reviewed biohydrogen related work done on membrane bioreactors in comparison with conventional CSTR counterparts. The research work related to the potential of biohydrogen production with AnMBR technology has only simply or partially articulated. Recent studies have already proven technical feasibility of AnMBR for biohydrogen extraction from wastewater and other waste streams. Therefore, the technical and economic feasibility study of AnMBR is a promising aspect. Hence, a critical review on recent technical innovations and emerging techniques to improve biohydrogen production is of crucial importance, particularly in AnMBRs.

The present review enlightens promising prospect of AnMBRs for biohydrogen production by reviewing extensive research in the past two decades. This paper deals with recent advances and emerging issues in biohydrogen production with AnMBR technology. A more thorough discussion is carried out with respect to factors affecting biohydrogen production and techniques to improve its yields and generation rates. Finally, environmental and economic potentials are presented along with future research trends in AnMBR technology for biohydrogen production.

2. Basic biohydrogen production technologies and their shortcomings

Biohydrogen can be generated by several biological ways and classified into two major categories: light-dependent and dark fermentative processes. Major light independent process is dark fermentation, whereas light-dependent processes include photofermentation and photolysis. All biohydrogen production pathways depend on either a nitrogenase or hydrogenase for hydrogen evolution. These technologies derive energy either directly from light energy or indirectly via consuming photosynthetically derived carbon compounds. Among these, dark fermentation receives high scientific attention and pilot plants have recently been established (Khan et al., 2010; La Licata et al., 2011; Lin et al., 2011). Although fermentative hydrogen production is undoubtedly promising, intense research is needed to overcome serious technical barriers before it become practical, preferentially by using wastewater and other waste materials (Akinbomi et al., 2015; Lee et al., 2010b; Sinha and Pandey, 2011).

2.1. Direct biophotolysis

In this process, biohydrogen can be produced through the photosynthetic capability of an organism, for example a green algae or cyanobacterium, that uses captured solar energy to drive water splitting process (producing O_2) and reduce ferredoxin - an electron carrier in the chloroplasts. Consequently, electrons are transferred to hydrogenases and/or nitrogenases enzymes (Fig. 1a). Microorganisms release the excess electrons using hydrogenase enzyme under anaerobic or excessive energy conditions, which converts the hydrogen ions to hydrogen gas (Turner et al., 2008). Molecular hydrogen generation occurs, by recombining the electrons and protons extracted from the water splitting reactions, using chloroplast hydrogenase (Hankamer et al., 2007). Photolysis uses water as substrate which is abundant and generates simple products of H_2 and CO_2, as a result it demonstrates promising future prospect. However, there are technical barriers that need to be overcome. Current challenges, such as low light conversion efficiencies, oxygen-sensitive hydrogenase and requirement of expensive hydrogen impermeable photobioreactors; need to be addressed (Hallenbeck and Ghosh, 2009). In addition, Kapdan and Kargi (2006) reported that hydrogen production can be suppressed by generation of oxygen during water splitting process. Major issues with the coproduction of hydrogen and oxygen include co-culture balance, photosynthetic and respiration capacity ratio, concentration and processing of cell biomass (Holladay et al., 2009). Under certain conditions, some microorganisms like algae can directly produce hydrogen. For example, Laurinavichene et al. (2008) revealed that sulfur-deficient green algae