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Research review paper

Reverse membrane bioreactor: Introduction to a new technology for biofuel production

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ABSTRACT

The novel concept of reverse membrane bioreactors (rMBR) introduced in this review is a new membrane-assisted cell retention technique benefiting from the advantageous properties of both conventional MBRs and cell encapsulation techniques to tackle issues in bioconversion and fermentation of complex feeds. The rMBR applies high local cell density and membrane separation of cell/feed to the conventional immersed membrane bioreactor (iMBR) set up. Moreover, this new membrane configuration functions on basis of concentration-driven diffusion rather than pressure-driven convection previously used in conventional MBRs. These new features bring along the exceptional ability of rMBRs in aiding complex bioconversion and fermentation feeds containing high concentrations of inhibitory compounds, a variety of sugar sources and high suspended solid content. In the current review, the similarities and differences between the rMBR and conventional MBRs and cell encapsulation regarding advantages, disadvantages, principles and applications for biofuel production are presented and compared. Moreover, the potential of rMBRs in bioconversion of specific complex substrates of interest such as lignocellulosic hydrolysate is thoroughly studied.

Contents

1. Introduction

Membranes and membrane related technologies have now been around for long, attracting the most attention in wastewater treatment and water quality improvement technologies (Lin et al., 2012; Peters,

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2010; Radjenović et al., 2008). The records on industrial scale application of membranes in water treatment goes back to about 1970 and since then membranes have found worldwide acceptance in different engineering processes (Strathmann et al., 2006). Footsteps of membrane technology has been tracked in a wide range of applications from filtration processes to membrane bioreactors (MBR) (Judd and Judd, 2011; Mutamim et al., 2013; Wang et al., 2010; Ylitervo et al., 2013a, 2014). This vast range of membrane applications covers *in situ* product recovery in MBRs (Carstensen et al., 2012; Fernandes et al., 2003), agricultural and industrial wastewater treatment, and desalination processes (Alzahrani and Mohammad, 2014; Mutamim et al., 2013; Petrinić and Hélix-Nielsen, 2014; Quist-Jensen et al., 2015; Subramani and Jacangelo, 2015), metal recovery (Mack et al., 2004), oil-water separation (Padaki et al., 2015), etc.

Due to the increasing demand for alternative renewable fuel sources (Nigam and Singh, 2011) to replace depleting fossil fuels (Brown and Brown, 2013) and also to reduce greenhouse gas emissions, there has been a surge of interest to find applicable biofuel production techniques with a high productivity (Börjesson et al., 2012; Gnansounou, 2010; Naik et al., 2010). In this regard, in a number of biotechnological applications membranes are used to retain cells and/or enzymes inside a bioreactor (Section 1.1). This may occur through immobilization in a membrane matrix or compartmentalization (Carstensen et al., 2012). There are different benefits sought by utilization of membrane bioreactors for biofuel production mainly focused on; the ease of product recovery as a result of high separation efficiency, high product yield and biological conversion rate due to high cell concentration, low energy demand and ease of operation in continuous mode and others. However, there are limitations in the application of conventional MBRs for biological treatment of different feed streams. In brief, handling feed sources containing a high concentration of cell inhibitory compounds or several different prioritized substrate sources by conventional MBR technologies is inefficient. Moreover, feeds with high suspended solid (SS) content are problematic in MBR assisted bioconversions as they deteriorate membrane functionality through exacerbating cake layer formation and membrane fouling. High SS loading also negatively affects cell/medium separation and hinders cell reuse for several batch experiments.

On the other hand, there are cell retention and immobilization techniques such as cell encapsulation that can effectively deal with the issues confronted by conventional MBRs. Through cell encapsulation, a high local cell concentration is provided in a jelly capsule which separates the cells from the main bioreactor medium by a permeable membrane (Westman et al., 2012b). This microenvironment and cell housing configuration gives the cells the ability to tolerate high inhibitor content and also co-utilize different substrates in the feed (Pourbafrani et al., 2007b; Westman et al., 2012a, 2014a). However, this technique also comes with inherent shortcomings. Encapsulating cells is time consuming and laborious and simple flaw in capsule preparation and agitation during application can cause capsule disintegration, rupture and cell escape (Sections 1.2, 2.1 and 2.2) (Ishola et al., 2015a, 2015b; Ylitervo et al., 2011).

The main goal pursued in this review is to introduce the novel promising technology of a reverse membrane bioreactor (rMBR) and its potential application in biotechnological processes. The rMBR is a combinational technique merging conventional MBR and cell encapsulation techniques. In this regard, rMBR provides the opportunity to have a membrane bioreactor system functioning on basis of cell encapsulation principles, benefiting from the advantages of both technologies while simultaneously covering their individual shortcomings and operational limitations. Through this technology, bioconversion of complex feed streams containing inhibitors, multi-substrates and high SS can be efficiently handled in large scale applying a diffusion driven rMBR. The rMBRs are submerged membrane modules housing microorganisms in between membrane layers to provide high local cell density, instead of having them freely suspended in the medium as for the conventional MBRs. rMBRs function on the basis of diffusive mass transfer as for cell encapsulation. High local cell density and the diffusive nature of mass transfer in rMBRs, opens new horizons to biological treatment of complex substrates for biofuel production.

1.1. Conventional MBRs

The centre of focus throughout this review is membrane-assisted cell retention. This technique uses a selective synthetic membrane to retain cells and specific chemical compounds in the bioreactor while allowing some low molecular weight solutes (depending on membrane properties) to diffuse freely through the membrane (Tampion and Tampion, 1987). Membrane applications are generally based on the ability of the membrane to efficiently separate different compounds and/or cells/particles, being selectively permeable to some substances while retaining others. In this context compounds are divided in two groups, i.e. the compounds that pass through the membrane end up in permeate (also called filtrate), the ones that are retained in the retentate. The selective behaviour of different membranes originates from membrane pore size and morphology, and other characteristics such as membrane charge, affinity or hydrophobicity (Judd and Judd, 2011). Membrane separation mainly occurs through application of pressure and/or concentration gradient as the separation driving force over the membrane (Judd and Judd, 2011) (Fig. 1). This is a criterion for categorizing membrane systems on basis of the separation driving force into pressure or diffusion (concentration gradient) driven.

In biological processes where membranes are integrated with the main bioreactor either for filtration, product recovery, or cell separation or retention, the MBR configuration plays a determining role. As mentioned by Judd and Judd (2011), MBR configuration covers both the integration of the membrane with the bioreactor and also the set-up of the membrane module in relation with the bioreactor. In general the configuration of various conventional MBRs sits under one of the two categories of immersed (iMBR), also known as submerged MBR, and side-stream (external loop) sMBR (Fig. 2). The submerged membrane module in iMBRs can be submerged either in the bioreactor or in a separate compartment connected to the main reactor through an external loop (Carstensen et al., 2012; Judd and Judd, 2011). Considering system energy balance, in comparison to sMBRs, iMBRs are more energy-saving as the module is placed in the bioreactor. In contrast, the sMBR set-up requires pumping of great medium volumes through an external membrane module housing in a cross-flow filtration system (Hai et al., 2013; Radjenović et al., 2008). Profound reviews of MBR principles and applications and also the differences between iMBR and sMBR in performance, operation and application are well covered in reviews by Carstensen et al. (2012), Ylitervo et al. (2013a), Judd and Judd (2011) and (Judd, 2008).

Regarding cell positioning in conventional MBRs, in iMBRs cells are kept inside the main bioreactor in a mixture with the feed medium, while in sMBRs cells are pumped through the external membrane module and then recirculated back to the main bioreactor. The ability of MBRs in retaining high cell concentrations in the bioreactor facilitates the *in situ* product recovery in biofuel production (Carstensen et al., 2012; Ylitervo et al., 2013a). Several examples of final cell concentrations (cell biomass) achieved by applying different MBRs for bioethanol production are presented in Table 1.

Conventionally, both sMBR and iMBR processes work based on the application of pressure difference (over-pressure or under-pressure). These pressure driven MBRs have long been in use for a wide range of applications from wastewater treatment to ethanol fermentation (Carstensen et al., 2012; Judd and Judd, 2011; Ylitervo et al., 2013a; Yoon, 2015). In the sMBRs filtration or product recovery happens through pumping the cultivation medium over and parallel to the membrane surface through a membrane compartment/unit, where permeate is withdrawn, set in an external loop to the main bioreactor (Carstensen et al., 2012). On the other hand, iMBRs have the membrane module