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Research review paper

Recent advances in membrane technologies for biorefining and bioenergy production

Yi He [a], David M. Bagley [b], Kam Tin Leung [c], Steven N. Liss [d], Bao-Qiang Liao [a,*]

[a] Department of Chemical Engineering, Lakehead University, 955 Oliver Road, Thunder Bay, ON, Canada P7B 5E1
[b] Department of Chemical and Petroleum Engineering, University of Wyoming, Laramie, WY 82071, USA
[c] Department of Biology, Lakehead University, 955 Oliver Road, Thunder Bay, ON, Canada P7B 5E1
[d] School of Environmental Studies and Department of Chemical Engineering, Queen's University, Kingston, ON, Canada K7L 3N6

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ABSTRACT

The bioeconomy, and in particular, biorefining and bioenergy production, have received considerable attention in recent years as a shift to renewable bioresources to produce similar energy and chemicals derived from fossil energy sources, represents a more sustainable path. Membrane technologies have been shown to play a key role in process intensification and products recovery and purification in biorefining and bioenergy production processes. Among the various separation technologies used, membrane technologies provide excellent fractionation and separation capabilities, low chemical consumption, and reduced energy requirements. This article presents a state-of-the-art review on membrane technologies related to various processes of biorefining and bioenergy production, including: (i) separation and purification of individual molecules from biomass, (ii) removal of fermentation inhibitors, (iii) enzyme recovery from hydrolysis processes, (iv) membrane bioreactors for bioenergy and chemical production, such as bioethanol, biogas and acetic acid, (v) bioethanol dehydration, (vi) bio-oil and biodiesel production, and (vii) algae harvesting. The advantages and limitations of membrane technologies for these applications are discussed and new membrane-based integrated processes are proposed. Finally, challenges and opportunities of membrane technologies for biorefining and bioenergy production in the coming years are addressed.

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* Corresponding author. Tel.: +1 807 3438437; fax: +1 807 3438928.
E-mail address: bliao@lakeheadu.ca (B.-Q. Liao).

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1. Introduction

The global economy has evolved within a paradigm reliant on fossil energy sources (coal, oil, natural gas) which provide the majority of the feedstock used to produce fuels and chemicals. However, the long-term utilization of these depletable resources is unsustainable due to their limited reservoirs and non-renewable nature (Uihlein and Schebek, 2009). According to the estimates of the Oil and Gas Journal (O&GJ) released at December 6, 2010, the worldwide reserves of oil and natural gas were 1.47 trillion barrels and 6.6 quadrillion cubic feet, respectively (Radler, 2010). At the current consumption rates of around 84 million barrels per day of oil and 284.5 billion cubic feet per day of natural gas (BP, 2010), the reserves correspond to 48 years of oil supply and 64 years of natural gas supply.

Biomass represents an alternative source of chemical feedstock and energy, and biorefining biomass is analogous to petroleum refining (Octave and Thomas, 2009). The National Renewable Energy Laboratory (NREL) defined the concept of a biorefinery as "a facility that integrates conversion biomass processes and equipment to produce fuels, power, and chemicals from biomass" (National Renewable Energy Laboratory, 2009). Additionally, bioenergy derived from biological sources has been long thought to be an important source of energy that will reduce dependency on fossil resources (Ruane et al., 2010). Currently, a great number of countries have established targets for increasing the percentages of biofuels to be incorporated into transport fuel. For example, Europe aims to reach a biofuel percentage of 5.75% for automotive fuel in 2020, according to the draft directive for renewable energy, while IEA (International Energy Agency) and IPCC (Intergovernmental Panel on Climate Change) expect biofuels to make a significant contribution to reducing dependence on petroleum-based fuel for the transportation market by 2030 (10–20%) (Cherubini and Ulgiati, 2010).

The biorefinery concept is often considered for the production of fuels from biomass feedstocks. A typical bioprocess for the production of 1st generation biofuels is illustrated in Fig. 1. In this biorefining process, lignocellulosic feedstocks are converted to ethanol. The biomass is first pre-treated to remove lignin and hemicelluloses. The remaining cellulose is hydrolyzed to produce sugars which are fermented to produce ethanol. Finally, the ethanol is recovered and purified for commercial application. Separation technologies have been incorporated into the process, including ion exchange resins that have been used for the detoxification of fermentation hydrolyzates, distillation in the recovery of ethanol and ethanol dehydration, and membrane separation has been utilized in the removal of water from ethanol solution (Huang et al., 2008). First generation biofuels, include bioalcohols, biodiesels, biogas and biosyngas are typically derived from sugar, starch, and vegetable oil (Demirbas, 2011). Advances based on different biomass options have led to 2nd and 3rd generation biofuels (Singh et al., 2011). Biofuels from agriforesty wastes including the stalks of wheat, corn, wood, and dedicated non-food based bioenergy feedstocks (e.g. miscanthus, willow and poplar) form the basis of 2nd generation biofuels (Sims et al., 2010). Third (3rd) generation biofuels are derived from algae (Costa and de Morais, 2011). Optimization of processes for effective and efficient biomass conversion for 1st, 2nd and 3rd generation biofuels and for true integration in a biorefinery will require appropriate separation technologies. Compared to other separation technologies, the low energy consumption, greater separation efficiency, reduced number of processing steps, and high quality of the final product are the main attractions of membrane separation processes in biorefining and bioenergy production (de Morais Coutinho et al., 2009).

A number of specific membrane processes are of particular value for biorefining and bioenergy production: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), pervaporation (PV), membrane distillation (MD), and diafiltration (DF). The MF, UF and NF processes use porous membranes and are driven by hydrostatic pressure, PV uses nonporous membranes and is driven by a chemical potential gradient, while MD uses porous hydrophobic membranes and is driven by a thermal gradient. The properties and applications of membrane processes for biorefining and bioenergy production are summarized in Table 1.

This review aims to present a state-of-the-art review on applications of membrane technologies for biorefining and bioenergy production, with specific emphasis on the recovery of valuable constituents from biomass, intensification and optimization of bioprocesses, membrane bioreactors for biorefining and bioenergy production, dehydration of bioethanol, bio-oil and biodiesel production, and algae harvesting. Current knowledge regarding application of

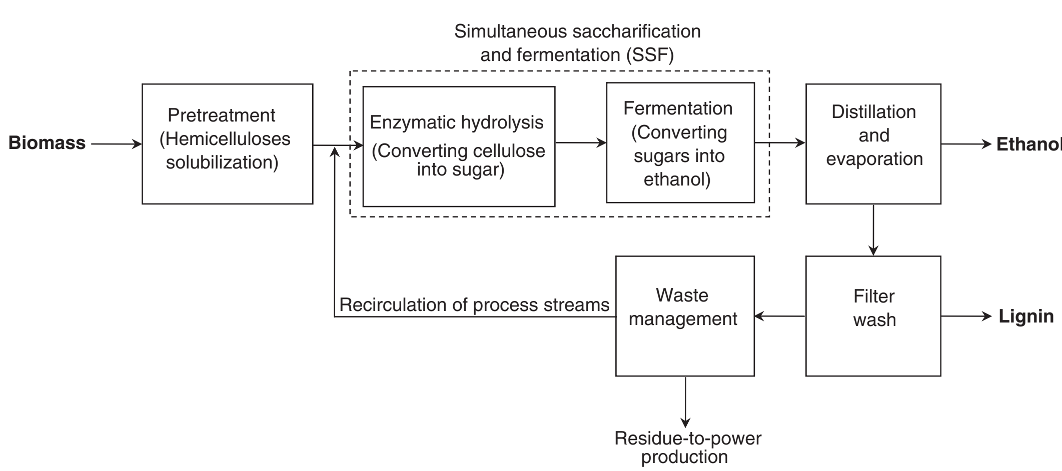

Fig. 1. Schematic flowsheet for the bioprocessing of biomass to ethanol (Hahn-Hägerdal et al., 2006).