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Prospect of ionic liquids and deep eutectic solvents as new generation draw solution in forward osmosis process

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ABSTRACT

Forward osmosis (FO) can aptly contribute to increased water reuse at the expense of low energy expenditure. The distinctive feature for FO lies with the exploitation of the natural osmotic pressure gradient generated by a concentrated draw solution for water transport across a semi-permeable membrane. The selection of a suitable draw solution remains to be a grey area of commercial development of FO process. The present review summarizes the importance of ionic liquid (IL) and deep eutectic solvent (DES) with natural product components and their potential as draw solutions in FO and their industrial applications. Various factors affecting performances of ILs and DESs as draw solutions are briefly assessed and critically compared with pertinent literature. Regeneration of IL and DES as spent solution from the process, as well as pure water recovery is discussed with special reference to heat energy optimization. A future pathway for research in IL and DES as draw solute and their economic aspects are also highlighted.

1. Introduction

Forward osmosis (FO), despite being old in its concept, has spurred a renewed interest, both academically and commercially in last two decades. Being natural, clean and ecofriendly process, FO has remarkable potential in substituting or complementing many conventional separation systems. FO finds its increasing applications in the domains of desalination, irrigation, power regeneration, pharmaceutical and protein concentration, water reuse, osmotic membrane bio-reactor and enhanced oil recovery [1,2]. In this process, a semipermeable membrane is positioned in between two solutions of different concentrations (more precisely of different osmotic pressure): a concentrated solution (draw solution) and a dilute solution (feed solution). The concentration difference between the two solutions generates the required osmotic potential which provides the driving force to extract fresh water from a feed solution (such as seawater, brine, or any wastewater, dilute product solution) on the other side of the membrane. As a result the process can concentrate a solution of lower osmotic pressure with that of a higher osmotic pressure. Forward osmosis is endowed with a number of benefits to its credit. These include high salt rejection, less susceptibility to membrane fouling and above all the requirement of less hydraulic pressure compared to their pressure driven counterparts.

The selection of a safe, efficient and inexpensive draw solution plays an important role in the progress of the FO process. A good draw solution should not only be capable of generating high osmotic potential but also be easily recoverable. However, to make FO process commercially competitive with other established separation processes, some of the key issues like low water flux rates, reverse solute flux (RSF), concentration polarization (CP) and energy efficient recovery of draw solutes also need to be addressed adequately. Interestingly, most of the issues related to CP and RSF are dependent on both membrane structure and draw solute properties. There is a strong correlation between the choice of draw solutes and progress of FO membranes research [3]. Synthetic draw solutes with tailor-made properties are being regularly developed and tested for their suitability as draw solutes however the results are met with limited success. Numerous inorganic compounds have been reported and explored in membrane literature as potential candidates for draw solutions [4,5]. Nonetheless, many of these compounds have exhibited a high reverse draw solute flux or are expensive to recycle, leave aside their toxic potency at times. Therefore, the search for a compatible and efficient draw solution assumes paramount importance in view of the wider industrial acceptance of forward osmosis.

Ionic liquids (IL) and deep eutectic solvents (DES) (also referred to as bio ionic liquids) are lately touted as green solvents to be used in a variety of separation processes. These are a few of the latest class of draw solutes which has caught researchers' attention. DES like Choline chloride – Ethylene glycol (Ch-Cl-EG) and Choline chloride – glycerol

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Nomenclature

LLE	Liquid liquid extraction
ED	Extractive distillation
MD	Membrane distillation
UAE	Ultrasound assisted extraction
MBR	Membrane bio-Reactor
Ch-Cl	Choline chloride
EG	Ethylene glycol
MA	Malonic acid
IL	Ionic liquid
DES	Deep eutectic solvent
NADES	Natural deep eutectic solvent
LCST	Lower critical solution temperature
UCST	Upper critical solution temperature

(Ch-Cl-glycerol) has been attempted as potential draw solutes [6]. They have shown to possess high osmotic potential and can be easily recovered rendering better energy efficiency of the overall process. They are also economically competitive and environmentally benign. Although there are quite a good number of reviews on various aspects of FO in recent literature, encompassing membrane development, area specific applications, selection of draw solutions and few more, applicability of IL and DES, in particular, as draw solution have not been surveyed so far. This paper focuses on the amenability of IL and DES as draw solution and critically analyzes their applicability in forward osmosis systems with regard to concepts and key issues. Various physicochemical parameters governing the FO performance, synthesis and recovery of draw solutes and economic aspects are adequately reviewed in the following sections. In spite of limited work reported by researchers in using IL and DES in FO process as draw solute, the impetus for the present review was stimulated firstly by the wide application potential of IL and DES as new generation eco-friendly solvents and secondly to obtain a further insight into the direction of basic and applied research in the area of FO.

2. FO membrane and draw solution

FO membranes, similar to their RO counterparts, generally contain two layers: a selective active thin layer and a porous support layer. The active layer is mainly responsible for salt rejection and the support layer provides the necessary mechanical strength to engineer the module. The two major desirable properties of a successful FO membrane are high solute rejection propensity and high water flux. It is very difficult to provide these two properties at the same time. The other desirable properties include minimal concentration polarization, long term mechanical stability and resistance to various pH environments. Since the pioneering development of modern FO membranes by Hydration Technologies, Inc. (HTI, Albany, OR), a lot of research work on FO has been reported in literature [1]. Cellulose Triacetate (CTA) FO membranes fabricated by HTI, Inc. is credited with high water flux performance but reportedly suffers from high RSF in case of smaller solutes [7]. To mitigate the problem, a thin film composite (TFC) FO membranes, which exhibit reduced RSF without compromising the flux rates [8,9] could be used. Researchers have been working actively in developing TFC membranes for enhancing the performance of FO process further [10].

Draw solution has another dominant role to play in FO processes. A good draw solution should be capable of generating high osmotic pressure [11] and simultaneously be easily recoverable. However, these two requirements are self-conflicting as good osmotic potential needs strong affiliation between the draw solute and water molecules, e.g., via hydration or ionization, which subsequently makes recovery process difficult [5]. On the other hand, it should also have essential solvent characteristics like wide availability, high solubility, minimal toxicity, non-reactivity and above all low cost. Search for an ideal draw solution constitutes a major focus of FO research. Considering the diversity of feed streams to be treated, it may not be possible for a single universal draw solution to become a panacea to treat all type of feed streams.

Draw solutes are broadly classified into two groups; compounds that are commercially available and structurally modified synthetic compounds (Fig. 1). The commercially available compounds include inorganic salts like NaCl, $MgSO_4$, $NaHCO_3$, $KHCO_3$, K_2SO_4, $(NH_4)_2SO_4$, Na_2SO_4 etc., organic salts like sodium acetate, sodium formate, magnesium acetate, sodium propionate, etc.; volatile compounds like NH_3-CO_2 gas mixture, SO_2 etc.; nutrient compounds like glucose and

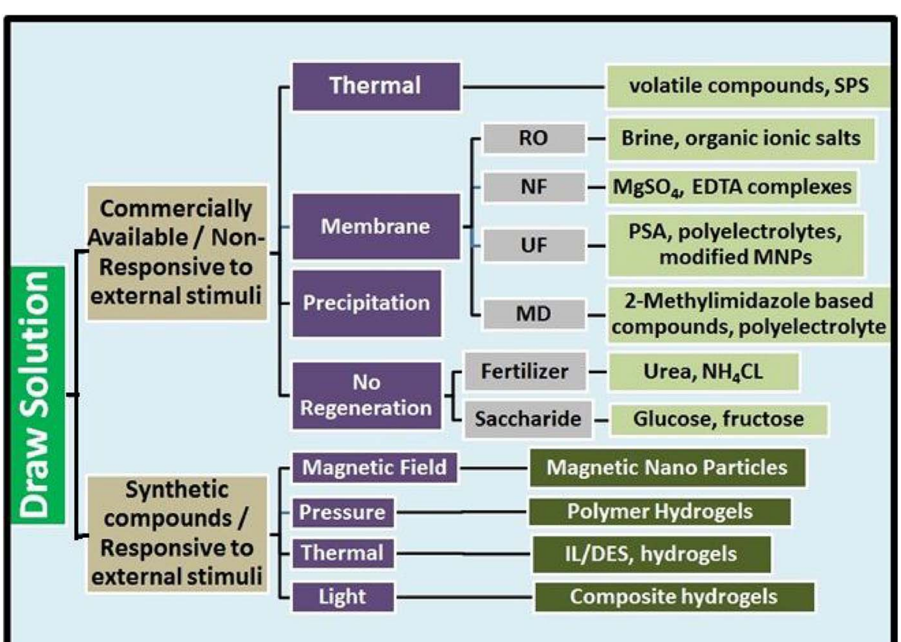

Fig. 1. Classification of draw solutes [3–5,27].