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Evaluation on suitability of osmotic dewatering through forward osmosis (FO) for xylose concentration

David Inhyuk Kim[a,b], Jongmoon Choi[a], Seungkwan Hong[a,*]

[a] School of Civil, Environmental & Architectural Engineering, Korea University, 145, Anam-ro, Seongbuk-Gu, Seoul 02841, Republic of Korea
[b] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology, Sydney (UTS), NSW 2007, Australia

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ABSTRACT

Forward osmosis (FO) has great potential for sustainable osmotic dewatering, which can attain several goals including low energy use, high water recovery, and low membrane fouling. However, this technology still involves critical issues that should be explored to achieve successful functioning of osmotic dehydration process, such as feed characteristics, FO membrane performance, and draw solution selection. In this study, the effectiveness of FO for osmotic dehydration was demonstrated by adopting xylose solution as model feed. Aside from current energy intensive evaporation methods, this widely used sweetener needs an advanced and energy-efficient concentration method such as FO. The stable performance showed xylose can be sustainably concentrated with a consistently high dewatering rate, whereas the recovery rate using a pressure-driven membrane system was constrained by the bursting pressure of nanofiltration membrane. Lastly, high-quality of concentrated product can be obtained by selecting a suitable draw solution of which its reversely diffused salts barely affect the xylose solution or are used to enhance the xylose quality. Employing Poly (aspartic acid) sodium salt or sugar-based solutes as draw help to preserve the purity of enriched xylose. These results suggest that FO can provide a feasible solution for food processing which requires product concentration through dewatering while preserving and improving its quality.

1. Introduction

Liquid foods are highly nutritive as they are naturally enriched with minerals, vitamins and other favorable constituents required for human health and nutrition. Since the liquid food such as fruit juices and sugar solutions are primarily composed of water, which contributes to microbial growth, the food industry's focus on dewatering has been essential to the effort to increase product stability, improve shelf-life, and reduce preservation and transportation costs [1]. However, the thermal-based process, the most widely employed technology in dehydration of liquid foods, has several negative impacts on sensory and nutritional values of the concentrated product [2]. Furthermore, the intensive energy use, necessary for the evaporative process has led to the need to develop a new technology for energy-efficient food processing, and thus, non-thermal technologies for the food industry have been explored as an alternative [3,4].

For the past few decades, reverse osmosis (RO) has been acknowledged as the most promising technology to replace the conventional thermal-based process for dewatering [5]. However, the pressure-driven membrane process constrained by several operational drawbacks such as its need for high hydraulic pressure, limited maximum attainable concentration factor, and irreversible membrane fouling [6]. Lower cost demand as well as improved performance can be anticipated by replacing RO to nanofiltration (NF). Several studies of NF used for food processing suggested that sustainable concentration of food liquid products could be facilitated by selecting a suitable NF membrane of which the molecular weight cut-off ranges from 150 to 1000 Da, and by establishing proper operating conditions [4,7].

In recent times, forward osmosis (FO) which uses the difference of osmotic pressure across the membrane as a driving force for water permeation has been regarded as an advanced and energy-efficient osmotic dewatering process [1,2]. The use of FO as an osmotic concentration process is expected to (i) spend less energy for applying hydraulic pressure, (ii) keep food components from thermal degradation attributing to low processing temperature, and (iii) attain a high recovery rate and small amount of brine disposal [1,2]. This emerging osmotically-driven membrane technology has been widely studied as a means of concentrating a variety of food products such as sugar solutions, and natural colorants [6,8–13]. These previous works have shown great promises of FO attaining high recovery and rejection, and

* Corresponding author.
E-mail address: skhong21@korea.ac.kr (S. Hong).

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low membrane fouling. However, the very low water flux presented in most former studies constrained the efficiency of osmotic dehydration, and thus developing a high performance FO membrane has been the major challenging issue to overcome for its practical application [6,8–12].

The development of high performance thin-film composite (TFC) FO membranes with reduced internal concentration polarization (CP) and increased water permeability has brought progress in the application of FO to osmotic dehydration [14,15]. The water permeability of the newly-fabricated membranes has been significantly improved, whereas their salt permeability has remained to be low. Given the progress of membrane manufacturing technologies, perhaps the practical application of FO technology for osmotic dewatering with high concentrating rate and low fouling may not be no far off.

Nonetheless, verifying the suitability of FO dewatering is still a major challenge. Besides the performance of FO membrane, there are several more concerns which need to be further examined for real application. First, the physiochemical properties of feed solution should be characterized. Since viscosity and osmotic pressure, as well as the fouling potential of feed solution significantly affect the FO performance, such as water flux and recovery, a thorough understanding of the feed features is required to achieve effective osmotic dewatering. For instance, a viscous and hypertonic liquid would be hardly concentrated by the FO system. Furthermore, it should be noted that reverse solute flux is as important as high osmotic pressure in selecting a suitable draw solute. Using a high molecular weight draw solute or mixing different types of draw solutions may be used to lower reverse diffusion [16,17]. In addition, such salts reversely diffused from the draw solution could be used as nutrient compounds in concentrated products. After selecting the type of draw solute, its concentration should be determined to achieve both high osmotic pressure and substantially low reverse salt diffusion to prevent degradation of concentrated feed quality.

Xylitol has been widely utilized as an ideal sweetener in several products due to its dental health benefits for reducing caries and remineralization [18]. However, since extracting xylitol from natural sources is a complex and costly process, it has been obtained by biological means from xylose. The synthesis of xylitol from xylose incorporates fermentative and biocatalytic processes in bacteria, fungi, and yeast cells [19]. The yeasts utilized in xylitol production are *Candida guilliermondii* and *Candida tropicalis* with 75–100 g/L of xylose. Xylose itself, which can be hydrolyzed from xylan-rich substances such as corn stalk, wheat straw and flax straw, is also useful in a wide variety of ways, including sugar source for diabetic patients, a non-nutritive sweetener in pharmaceutical industry, an additive in color photography, a brightener in zinc electroplating, and ethanol production during the fermentation process [20]. However, the current evaporation concentration method has been shown to be energy intensive, so there is a crucial need to develop an advanced and efficient concentration method. Only a few studies have been conducted for xylose concentration by utilizing pressure-driven and osmotic membrane technologies as potential alternative dewatering processes as shown in Fig. 1 [20–22]. Both of NF and RO exhibited good water flux but limited recovery rate during xylose enrichment [20,21], whereas FO showed contrasting results that are high recovery rate but very low dewatering rate [22].

In our work, the suitability of FO using a high performance TFC-FO membrane for dewatering xylose was systematically explored to possibly replace the conventional xylose separation/concentration process, such as an evaporative concentration, without compromising xylose quality (Fig. 2). To clarify the characteristics of xylose and verify its suitability as a target feed solute in FO, we first analyzed the chemical features of xylose, such as osmotic pressure and viscosity. Then, the promises of FO dehydration were critically examined through assessing its performance (i.e., permeate water flux and feed solute rejection) and comparing with NF process during xylose concentration. Lastly, the ideal type of draw solute exhibiting high water flux and low reverse salt flux was delineated by conducting the evaluation of various draw solutions.

2. Experimental

2.1. Xylose as feed solution and its characterization

The model feed solute, xylose, was provided by Sigma-Aldrich (St. Louis, MO). The molecular weight of xylose is 150.13 and its reported solubility in water, according to the manufacturer, is 1 M. Its viscosity and osmolality were quantified under varied solution concentrations using SV-10 Vibro Viscometer (A & D Company LTd., Japan) and Osmomat030 (GOnotec GmbH, Germany), respectively.

2.2. FO and NF membranes

The FO tests were carried out using a thin film composite (TFC) osmotic membrane provided by Porifera, Inc. (Hayward, CA). This membrane was chosen due to its stable performance exhibiting high water and low solute permeability. The membrane samples were received as a flat sheet and stored in deionized (DI) water at 4 °C. Both membrane orientation modes were employed in this study: the active layer facing feed solution (AL-FS) mode and the active layer facing draw solution (AL-DS) mode.

A widely used commercial NF 90 membrane was selected for the NF runs. The molecular weight cut-off (MWCO) of the membrane was acknowledged to be tighter than 200 Da that can successfully retain the model xylose solution. This TFC polyamide membrane was provided by DOW Filmtec (Edina, MN), and was received as spiral wound modules with 10.1 cm in diameter and 101.6 cm in length. The NF membrane modules were disassembled in the laboratory, and then stored in DI water.

2.3. FO and NF experimental setups

The FO and NF experiments were performed with a same lab-scale cross-flow system as described in our previous study [23]. The dimensions of the symmetric feed and draw/permeate channels of the test cell were 7.7 cm in length, 2.6 cm in width, and 0.3 cm in height, providing an effective membrane area of 20.02 cm^2. Fine mesh spacers were employed in both the feed and draw/permeate channels to ensure mechanical stability against hydraulic pressure, and to improve mass transport [24,25]. A high pressure pump (Hydracell, Minneapolis, MN) was used for the feed solution recirculation in both FO and NF runs, whereas the draw solution during the FO runs was recirculated using a variable-speed gear pump (Cole-Palmer, Vernon Hills, IL). The temperature of each solution in both FO and NF experiments was maintained at 20.0 ± 1.0 °C. The weight changes of draw solution in FO and of permeate water in NF were calculated using a digital balance

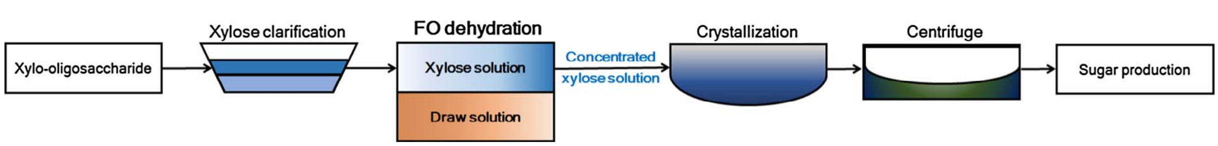

Fig. 1. Possible application of FO in an integrated xylose concentration process. The FO integrated xylose concentration process includes clarification, FO dehydration, crystallization, and centrifuge.