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An initial study and potential application of maltodextrin as draw solution in forward osmosis process for desalination

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ABSTRACT

Forward osmosis (FO) has been considered as one of the most promising technologies for desalination with the advantages of low energy cost, high rejection of many pollutants and low membrane fouling in comparison with the other membrane processes. In this study, maltodextrin was investigated as a draw solution in the FO process. Various parameters such as the total dissolved solids, electrical conductivity, water flux, reverse salt flux, and recovery efficiency of draw solution were studied. The results show that the highest water flux was 11.5 LMH reported in 1.00 M of maltodextrin concentration. In addition, the maltodextrin draw solution can be easily recovered using the NF90-400 membrane (95.61%), which provides a new promising method for future applications in producing freshwater using FO systems with lower energy consumption. It is fully expected to meet the demands of clean water for people living in coastal areas and saline pollutant areas in Vietnam as well as other countries in the world.

Keywords: Desalination; Maltodextrin; Forward osmosis

1. Introduction

Water plays many important and essential roles in our body, for life and most activities of humans for economic and social development [1]. Among the growth of population in the world, demand for clean water is significantly rising, especially, in the saline pollutant areas [2]. Saline water pollution is considered a type of groundwater contamination mainly caused by climate changes and human activities such as using marine water for shrimp farming and exploitation of groundwater in the coastal areas [3,4]. This will cause water shortages over the next years. Lack of accessibility the clean water is one of the global water challenge issues of the 21st century [5]. The scarcity of water might be limiting economic development, affecting human health, and leads to ecological and environmental degradation, etc [6]. Thus, it is important to find out the alternative resources of freshwater to respond to the development worldwide.

Desalination is considered as a solution producing freshwater from seawater, brackish water, and inland water, which increases the availability of fresh water in the coastal areas [6,7]. There were two main categories of the desalination process, obtaining both thermal process and membrane process with different types, in which reverse osmosis (RO), multi-stage flash and multi-effect distillation were the most applied desalination technologies with the installed desalination capacity over the world was 65%, 22% and 8%, respectively [6,8]. In addition, the other

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desalination processes were also used including electrodialysis (ED) and electrodialysis reversal [8]. However, these processes require a high cost of capacity as well as a large amount of energy for operation, whereas the future trends are priority applied and developed technologies that use less energy [9,10].

Forward osmosis (FO) has been considered as one of the most promising technologies for desalination with the advantages of low energy cost, high rejection of many pollutants and low membrane fouling in comparison with the other membrane processes such as RO, nanofiltration (NF), ultrafiltration (UF), and microfiltration [11,12]. This technology utilizes the natural phenomenon of osmosis which was generated by different pressures between feed solution and draw solution in two sides of the semi-permeable membrane to produce fresh water. A followed process was conducted to reconcentrate the diluted draw solution and produce clean water. In the FO process, the draw solution plays a pivotal role to attract water from the feed solution. A numerous of draw solutions was studied for FO process such as ammonium bicarbonate [13], fertilizer [14], and magnetic nanoparticles [15], EDTA sodium salts [12], 2-methylimidazole-based compounds [16], polyacrylic acid sodium salts [17], sodium lignin sulfonate (NaLS) [18], etc. The study and select a suitable draw solute can greatly influence the efficiency and sustainability of FO operations. According to Luo et al. [11] and Tian et al. [19], the properties of an ideal draw solute in FO were high osmotic pressure, minimal reverse solute diffusion, ease to recovery from the diluted draw solution, non-toxic, low cost, reusability, and compatibility with FO membranes.

Maltodextrin is a polysaccharide produced from the enzymatic hydrolysis or the acidic of starch, which is considered as a polymer of D-glucose chains linked by glycosidic α-(1-4) and α-(1-6) bonds, and is formed by linear (amylase) and branched (amylopectin) carbohydrates with different equivalents of dextrose [20]. Maltodextrin was a nontoxic material which used widely in the cosmetic domain [21], food industries [20,22], and the pharmaceutical industry [23]. However, no reports were studied maltodextrin as a draw solution in the FO process.

In this study, we investigated the function of maltodextrin as a draw solution in the FO system via the change of various parameters such as total dissolved solids (TDS), electrical conductivity (EC), salt concentration, water flux, salt reserve flux, the efficiency of water production, and the recovery of maltodextrin. Exploration of suitable concentration of maltodextrin used as a draw solution in the FO process will be contributed to produce freshwater serving for people living in the coastal and saline water pollution areas.

2. Materials and methods

2.1. Materials

Maltodextrin ($C_{6n}H_{(10n+2)}O_{(5n+1)}$) (>98%) was purchased from Sigma-Aldrich Corporation (Germany). Maltodextrin material and its chemical structure are provided in Fig. 1. The commercial thin-film composite forward osmosis membrane (305 mm × 305 mm) was bought from Sterlitech Corporation (USA). An ultrapure water system (PURELAB flex 3, ELGA, UK) was used to produce deionized water, which was utilized to prepare the different concentrations of all solutions for experiments.

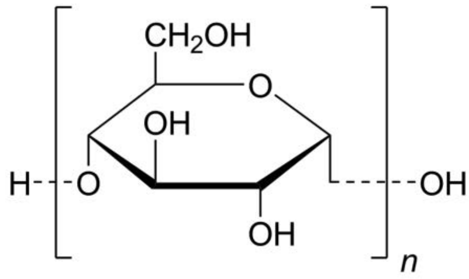

Fig. 1. Structure of maltodextrin.

2.2. Characterizations of maltodextrin and FO membrane

The morphology of the maltodextrin and FO membrane was observed by scanning electron microscopy (SEM) (JEOL JSM-5600, Japan). The characterizations of maltodextrin solutions were determined via TDS, EC and salt concentrations using Laqua F-74 sensor (Horiba, Japan). The FO membrane was a thin-film composite membrane and can be used in conditions of pH range from 2 to 11 and 5–75 psi of pressure.

2.3. Forward osmosis setup

Experiments were carried out on a laboratory scale in the Center for Research and Transfer of Technology (CRETECH) – Vietnam Academy of Science and Technology (VAST), Hanoi, Vietnam. FO membrane was immersed into the DI for 24 h before use to ensure the porous support layer of the membrane is fully saturated with water.

The experiments were conducted in three replications with two stages as below:

- *The first stage*: A rectangular cross-flow permeation cell (8 cm in length, 4 cm in width and 0.5 cm in height) was designed in a plate and frame configuration to hold the flat FO membrane for experiments (Fig. 2). The experiment was set up with the active layer of FO membrane oriented to face the feed solution, whereas the support layer of the membrane facing the draw solution. The pumps with a flow rate of 1.2 L/min, the maximum outlet pressure of 125 psi, the voltage of 24 VDC and an amp of 0.24 A were separate used to re-circulate the feed and draw solutions on both sides of the FO membrane.

DI water was used as feed solution, whereas draw solutions were prepared from maltodextrin in DI water. An amount of 500 and 300 mL was the initial volumes of feed solutions and draw solutions, respectively. A digital scale balance (Sartorius, Goettingen, Germany) was used to determine the changes in the weight and volume of feed solution while the Laqua F-74 sensor was utilized to monitor any changes in TDS, EC and salt concentration of the feed solutions and draw solutions periodically 15 min during experiments. Different concentrations of draw solution (1%, 5%, 10%, 15% and 30%) were investigated to find the optimized concentration use for the complete FO membrane system in the next stage of the experiments.

- *The second stage*: The most suitable concentration of draw solution was used in the complete system of the FO process in combination with the nanofiltration using DOW FILMTEC NF90-400 membrane to produce fresh water and recover the draw solution. The schematic diagram of the complete FO system is shown in Fig. 3.

2.4. Measurement of water flux and reserve salt flux

The water flux and reserve salt flux across the FO membrane were determined via the volume exchange of feed solution using the equations as below:

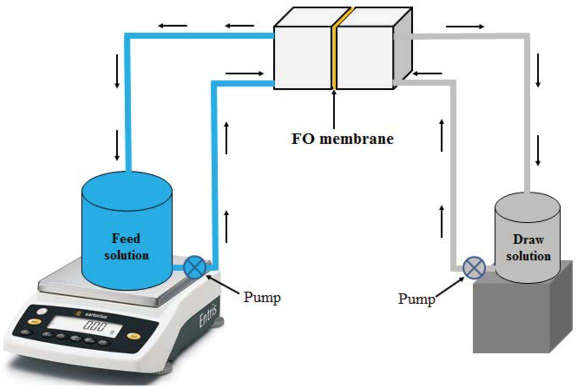

Fig. 2. Schematic diagram of FO system to test the efficiency of draw solution.

$$F = \frac{V_i - V_o}{A(T_i - T_o)}(*) \quad \text{RF} = \frac{C_i V_i - C_o V_o}{A(V_i - V_o)}(**) \tag{1}$$

where F is the water flux across the FO membrane (LMH); RF is the reserve salt flux across the FO membrane (LMH); A is the surface area of the FO membrane (cm²); C_o is the initial concentrations of the feed solution (g/L); C_i is the concentration of the feed solution measured at a time of T_i (g/L); V_o is the initial volume of feed solution used for experiments (mL); V_i is the volume of feed solution determined at a time of T_i (mL).

3. Results and discussion

3.1. Properties of maltodextrin and FO membrane

The SEM of the thin-film composite forward osmosis membrane is shown in Fig. 4 with the surface of the active layer has a uniform network structure, whereas the porous support layer is formed by dip coating followed by cross-linking. The pore diameters of the support layer membrane were approximately 2 µm and the average thickness of the membrane was 110 ± 15 µm, which allowed the separation of water molecules and removal of salts in the desalination process.

Fig. 5 presents the SEM of maltodextrin material with the multi-face structure, which increases the surface area contact to the solutions in its application processes. In addition, this material possesses high hydrophilic properties increasing the ability to bind and absorb water molecules which generate the driven force of water molecules via the FO membrane.

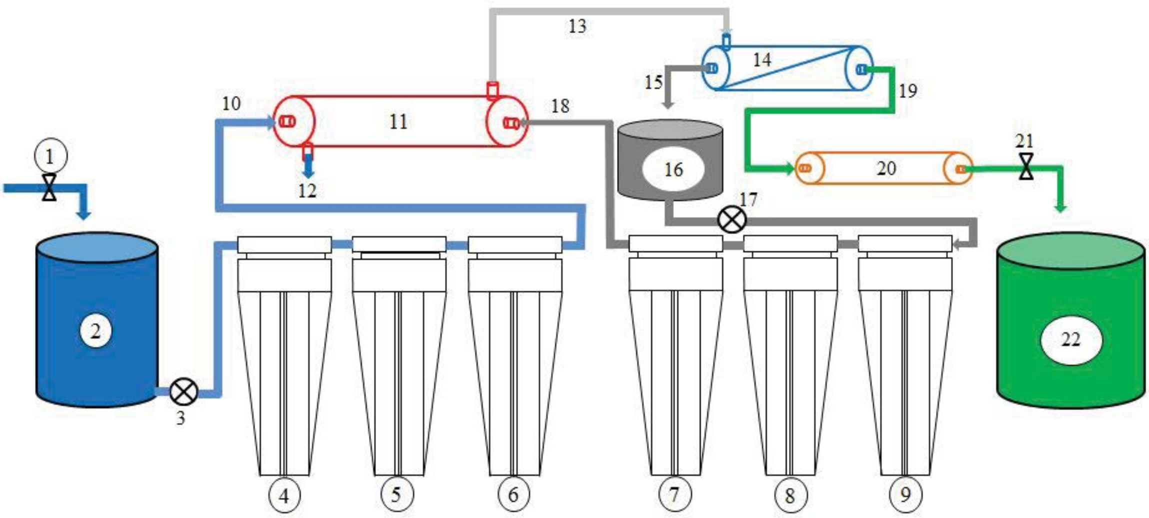

Fig. 3. Schematic diagram of the complete FO system in combination with nanofiltration to produce fresh water. (1) Valve of feed solution; (2) Tank of feed solution; (3) Pump; (4) Raw filter column with hole diameter <5 µm; (5) Activated carbon filter column; (6) Fine filter column with hole diameter <1 µm; (7) Fine filter column with hole diameter <1 µm; (8) Activated carbon filter column; (9) Raw filter column with hole diameter <5 µm; (10) The feed solution after pre-treatment; (11) FO membrane column; (12) The concentrated feed solution; (13) The diluted draw solution; (14) Nanofiltration column; (15) The diluted draw solution; (16) Tank of draw solution; (17) Pump; (18) The draw solution after pre-treatment; (19) Freshwater after nanofiltration; (20) Silver nanofiltration column; (21) Valve; (22) Tank of freshwater.

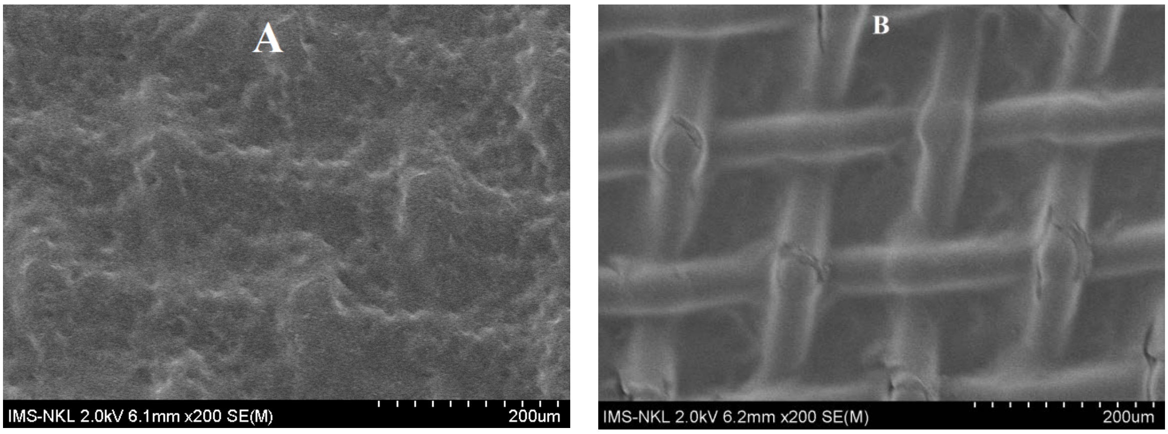

Fig. 4. SEM of forward osmosis membrane used in the experiments (A and B are the active layer and the support layer of the FO membrane).

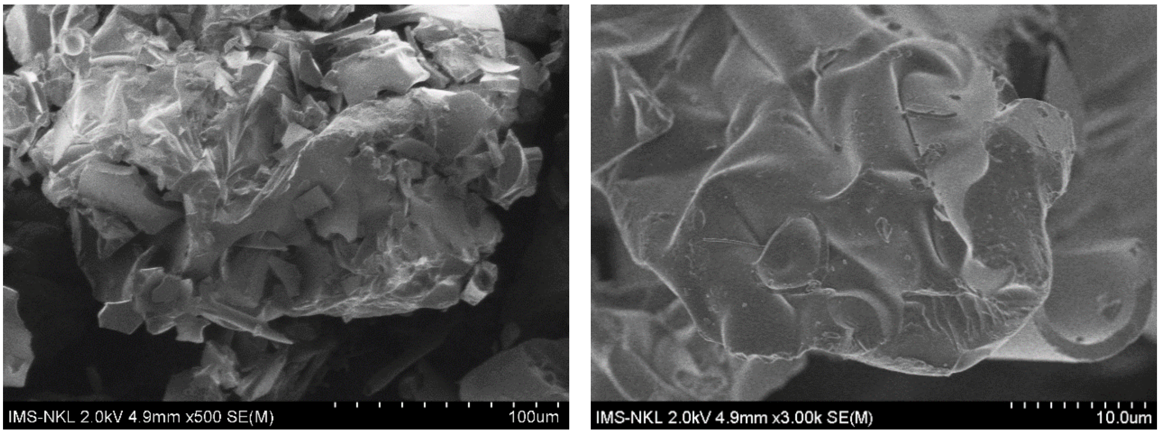

Fig. 5. SEM of maltodextrin used as a draw solution in the FO system.

3.2. FO performance

The performance of the draw solution was studied via the water permeation flux (LMH) and the reverse solute flux (GMH) using a cross-flow FO cell at a laboratory scale. DI water was used as the feed solution which was faced with the active layer of the membrane in the experiments. Different concentrations of draw solutions were used, including 0.05, 0.20, 0.50 and 1.00 M, respectively. A comparison between these concentrations was performed to select the suitable concentration of draw solution for the FO process. In addition, 1.6 M NH_4HCO_3 [24] was chosen as a benchmark draw solution in comparison with maltodextrin concentrations. The change of the water permeation flux and the reverse solute flux of the experimental draw solutions are presented in Fig. 6. The different water fluxes were reported between the different concentrations of maltodextrin and NH_4HCO_3 draw solutions. The highest water flux was found at 11.5 LMH in the draw solution of 1.00 M maltodextrin. The second and third positions of water flux were determined at 9.8 and 9.2 LMH in the concentrations of maltodextrin at 0.50 and 0.20 M, respectively. The water flux of the draw solution of 0.05 M maltodextrin was 8.9 LMH, which was similar to the water flux of NH_4HCO_3 draw solution with 8.8 LMH. The studied results obtained 38.0 mL of water volume in the 1.00 M maltodextrin group, which was higher than the 0.50 M (32.5 mL), 0.20 M (30 mL), 0.05 M (28.5 mL) maltodextrin groups and NH_4HCO_3 draw solution (27.6 mL). It is in agreement with the previous studies of Nguyen et al. [25] that the higher water flux might generate the higher osmotic driven force in the transportation of water through the membrane. In addition, NH_4HCO_3 was used as a draw solution in the forward osmosis process [24,26]. This indicated that the potential application of maltodextrin as the draw solution of the FO process in desalination. However, the highest reverse salt flux was 2.3 GMH in the 1.00 M maltodextrin draw solution, followed by the 0.50 and 0.20 M maltodextrin concentrations at 1.65 and 0.75 GMH, respectively, then was the 0.05 M maltodextrin at 0.52 GMH, and the lowest was 0.45 GMH at the control group. These data illustrated that the higher the water flux, the greater the reverse salt flux permeating via the FO membrane. In addition, the study suggested that 1.00 M maltodextrin was the preferable concentration in this study to obtain high water flux in the FO process. This concentration of maltodextrin was then applied to the followed experiments in evaluating the efficiency of the desalination process using the FO system.

3.3. Change of TDS and conductivity of draw solution in the FO process

Fig. 7 shows the change of TDS and conductivity of draw solution in the FO process using deionized water as feed solution during the experiments in 60 min. Generally speaking, the conductivity and TDS of the draw solution were significant decreased among the increase in the experimental time. It is interesting to note that, the conductivity was decreased to 95.4% after 15 min in comparison with its initial value. This parameter was continuously decreased to 93.10% and 90.8% at the experimental time of 30 and 45 min, respectively. The figure of the conductivity was then decreased to 89.1% after 60 min of the experiments. A similar trend was found in the TDS parameter of the draw solution in the FO process. The TDS was decreased to 95.8% after 15 min operating the FO system. This value was continuously decreased to 91.7% and was then decreased to 88.3% after the experimental time of 30 and 45 min, respectively. Research results showed that the TDS of the FO process was decreased by 85.8% after 60 min of the total time of the experiments. These data illustrated that the draw solution of the FO system was diluted by the water transporting from the feed solution via membrane during the experiment. It demonstrates that the potential application of maltodextrin as the draw solution in the FO process, needs further study to develop and apply this solute in the production of freshwater from marine water sources. It is fully expected to produce freshwater serving for people live in the sea sides' areas were always lacking clean water for their daily and production.

3.4. Efficiency of water production and the recovery of maltodextrin via NF

In the FO process, two steps are conducted, including the concentrate draw solution is diluted by the water from the feed solution and the diluted draw solution is regenerated to the initial state, respectively. Draw solution recovery is considered as one of the major challenges in FO applications which draw the attention of scientists over the world [27,28]. Numerous draw solutions were investigated to apply in FO systems among with their specific recovery methods such as using reverse osmosis, heating, UF, membrane distillation (MD), and magnetic separation processes… [19,24,27,29,30]. However, the drawback of these DS recovery methods is high reverse salt flux, irreversible membrane fouling and high operating costs, which make them impractical in FO processes. To increase efficiency with minimal salt leakage and decrease the energy costs for operation, nanofiltration process is used for recovery of draw solution, which was reported with great potential applying in the industries of chemical, pharmaceutical synthesis, water treatment, wastewater treatment, food processing, and desalination… [31–36]. In this study, the DOW FILMTEC NF90-400 membrane was studied to recover the draw solution in the FO system. Table 1 shows the variations in the TDS permeate and removal efficiency achieved using the maltodextrin draw solution. The data indicated that the removal efficiency of the draw solution was 95.61% at low operating pressure. It illustrated that most of the draw solutes did not permeate via the NF90-400 membrane and was reused in the FO process again. This result is in agreement with the previous studies of Hau et al. [12], who reported that 91% of 0.05 M EDTA-2Na and 95% of 0.05 M EDTA-2Na coupled with 15 mM NP7 draw solutions were removed by the NF-TS80 membrane. In another study, Ge et al. [33] indicated that the NF process could reject more than 90% of ferric and cobaltous hydro-acid complexes draw solutes in the FO process. These data demonstrated that the maltodextrin draw solution can be easily recovered using the NF90-400 membrane, which provides a new promising method for future applications in producing freshwater using FO systems.

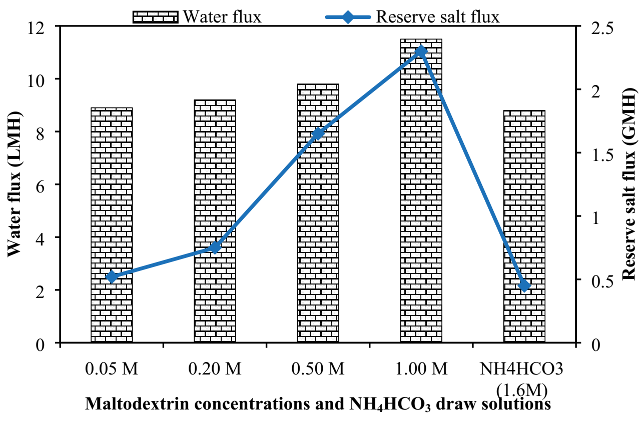

Fig. 6. The water permeation flux and the reverse salt flux of draw solutions (The concentrations of maltodextrin were 0.05, 0.20, 0.50 and 1.00 M).

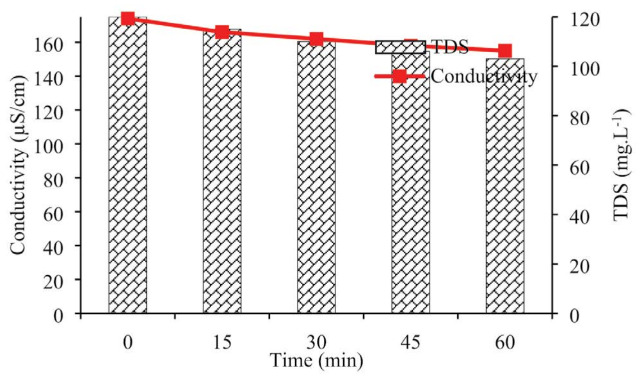

Fig. 7. The change of TDS and conductivity of draw solution in the FO process.

Table 1
Recovery efficient of draw solution using NF membrane

TDS input (mg/L)	120 ± 1.52
TDS permeate (mg/L)	4.8 ± 0.64
Removal efficiency (%)	95.61 ± 0.01

3.5. Energy consumption and efficiency of FO system

Energy consumption is a key factor affecting the freshwater production cost in desalination technologies [37]. In this study, the power consumption of the FO system is mainly attributed to the circulation pumps, which were calculated following the Ohm's Law equation of $P = V \times I$. Where P is the power in W, I is the current in Amp and V is the voltage in V. Therefore, the energy consumption of two pumps was P = 24 VDC × 0.24 A × 2 = 11.52 W ≈ 0.01 152 kW. In addition, the study reported that the highest water flux of the FO system was 11.5 LMH, which means that there was 11.5 L of freshwater transported through the FO membrane and used electricity of 0.01152 kW/h. On the other hand, the removal efficiency of NF was reported at 95.61%. Therefore, the performance efficiency of the FO-NF integrated system in producing freshwater in an hour is calculated as 11.5 L × 95.61% = 10.995 L. Hence, it is estimated to produce a freshwater volume of 1,000 L (~1 m^3) it will be needed to use electricity of 1.048 kW for operating the FO system. According to Yangali-Quintanilla et al. [38], the performance of FO combined with low-pressure reverse osmosis (LPRO) for the desalination of the red seawater consumed an estimated energy range of 1.3–1.5 kWh/m^3, and that of the standard high-pressure standalone seawater reverse osmosis (SWRO) process used an approximate power of 2.5–4.0 kWh/m^3. In addition, freshwater drawn from the groundwater source requires 0.14–0.24 kWh/m^3 for a pumping head of 100–200 ft and the conventional treatment of surface waters to potable quality requires 0.36 kWh/m^3 [39,40]. The data illustrated that the energy consumption to produce freshwater by the FO-NF integrated system in our study was 2.91 times higher than that of the conventional treatment of surface waters, but it was 1.24–1.43 times lower than that of the desalination process using the LPRO system and was 2.39–3.92 times lower than that of the SWRO process. This demonstrated that the potential application of the FO system using the maltodextrin draw solution in desalination, which could be considered to apply to produce freshwater serve human life activities in coastal areas and saline pollutant areas over the world.

4. Conclusion

In summary, different concentrations of maltodextrin were studied as draw solutes in the FO process. The highest water flux was 11.5 LMH reported in 1.00 M of the maltodextrin concentration. In addition, maltodextrin draw solution can be easily recovered using the NF90-400 membrane, which provides a new promising method for future applications in producing freshwater using FO systems. It is fully expected to meet the demands of clean water for people living in coastal areas and saline pollutant areas in Vietnam as well as other countries in the world.

Acknowledgments

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