A simple-effective forward osmosis filter water bag designed for producing drinking water during an emergency

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Abstract:

A simple yet effective forward osmosis (FO) water filter bag was designed and tested to produce drinking water from flood water for emergency use. The FO water filter bag operates on the FO process, using flood water as the feed solution and a mixture of sucrose, oresol, and food-grade soda as the draw solution. Experimental results demonstrated that the FO water filter bag, using a mixed draw solution of 6 M sucrose + 2 g oresol + 16 g/l soda, achieved the highest average water flux of 0.68 l/m^2/hours (LMH) during a 5-hour operation. Furthermore, the water produced by the FO water filter bag was of high quality, with removal rates of 98.5, 97.6, and 100% for turbidity, iron, and *E. coli*, respectively. After a 12-hour operation with real flood water as the feed, the FO water filter bag produced 588 ml of water that met both World Health Organisation (WHO) quality standards and Vietnamese technical regulations for drinking water. More importantly, the FO water filter bag exhibited minimal membrane fouling, allowing for reuse and supporting the provision of drinking water in flood and emergency situations.

Keywords: **emergent situations, flood water, forward osmosis, forward osmosis water filter bag, oresol, soda, sucrose.**

Classification numbers: **2.3, 3.6, 5.3**

1. Introduction

Climate change has led to more frequent and severe flooding, causing significant damage in many regions, including Vietnam [1, 2]. During floods, it is crucial to provide clean drinking water, free from pathogens and harmful contaminants, to affected populations [3-5]. Various traditional water treatment methods, such as sedimentation, filtration, disinfection, activated carbon adsorption, advanced oxidation processes (AOPs), and nanofiltration (NF)/reverse osmosis (RO), have been employed to convert flood water into potable water. However, these methods have inherent limitations. For example, sedimentation and filtration require large systems, and they are ineffective at removing dissolved contaminants. Disinfection methods, like chlorination, can eliminate pathogens but may produce harmful by-products. Meanwhile, UV irradiation is safer regarding disinfection by-products but ineffective at removing all pathogens. AOPs and activated carbon adsorption can be expensive and require frequent replacement of carbon materials. While NF/RO processes are considered advanced water treatment technologies and are widely used during floods and emergencies, they are energy-intensive, require extensive pre-treatment, and necessitate frequent membrane replacement [6, 7].

Recently, forward osmosis (FO) has emerged as a promising alternative to NF/RO for floodwater treatment due to its technical and economic advantages [8]. Like NF/RO, FO uses a semi-permeable membrane to separate water from dissolved substances. However, instead of relying on high external hydraulic pressure, FO uses a draw solution with high osmotic pressure to pull clean water from the feed solution through the membrane. The osmotic pressure gradient across the membrane drives water from the low-osmotic-pressure feed solution to the high-osmotic-pressure draw solution. Impurities, including heavy metal ions, bacteria, and organic substances, are retained on the membrane surface due to the tiny pore size (0.37 nm), allowing only clean water to pass through. As

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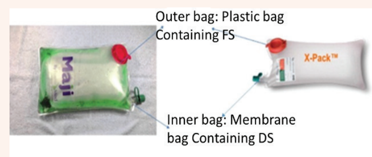
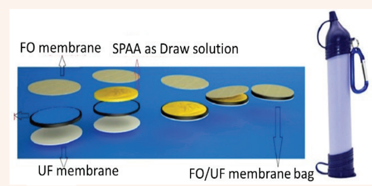
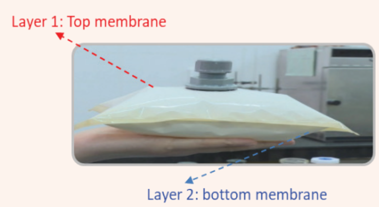
a result, the FO process consumes minimal energy, is less prone to membrane fouling, and requires fewer membrane replacements compared to NF/RO [9-11].

These advantages have led to the development of FO-based applications, including the treatment of contaminated groundwater and wastewater, desalination of brackish and seawater, sludge dewatering, and the concentration of valuable resources, such as juices and pharmaceutical processing water. The FO process has also gained attention for its potential to provide clean drinking water during floods and emergency situations [12-15]. FO water filter bags have been developed as prototypes to quickly produce drinking water during natural disasters.

However, research on FO water filter bags remains limited, and further investigation is required to fully explore these advanced prototypes. For example, HTI developed FO Hydropack bags for producing drinking water, but these bags have a limited membrane area and therefore require long operational times, as they utilise the FO membrane on only one side of the bag [16]. In 2013, M.T. Flynn, et al. (2013) [17] investigated the forward osmosis bag (FOB) for the recovery of potable water from human urine under varying gravity conditions in a National Aeronautics and Space Administration (NASA) study. The FOB used a commercial off-the-shelf device, the X-Pack™, provided by hydration technologies innovations (HTI). This research demonstrated that the FOB could successfully convert contaminated water into potable drinking water [17]. However, a significant disadvantage of the FOB is its complexity and high cost, as outlined in Table 1. The technology involves intricate membrane structures and specialised materials, making it expensive to manufacture. Additionally, FO bags may require frequent maintenance and monitoring to ensure optimal performance, which further increases overall costs.

In 2019, D. Emadzadeh, et al. (2019) [18] developed a membrane bag consisting of multiple layers of FO and ultrafiltration (UF) membranes for water purification. While integrating multiple membrane layers into a single-bag design enhances performance, it also requires sophisticated engineering processes. Furthermore, the complexity of multilayer membrane designs may present challenges related to maintenance, cleaning, and replacement.

Table 1. Disadvantages and advantages of current forward osmosis filter water bags.

Name of production	Configuration of FO bag design	Disadvantages/ Advantages	References
FO Hydropack bag		- The FO membrane area in the bag is limited - Low water permeating and long permeation time - Cannot be reused	[16]
FO X-Pack™ bag		- Water permeating reducing follow time - Long permeation time	[17]
Hybrid FO-UF membrane bag		- Complicated process - Difficult with maintenance, cleaning, and replacement	[18]
FO bag with double FO membrane layer		- Simple design and operation - Large membrane area - Reuseable FO bag	This study

FO: Forward osmosis, UF: Ultrafiltration.

The novel FO water filter bag designed in the present work possesses FO membranes on both sides and can be applied for use in emergency situations in flood-prone areas. This FO water filter bag features a simple operational mechanism, requires no electricity, and is reusable. Additionally, the draw solution (DS) plays a crucial role in the effectiveness of FO bags for emergency water supply. The draw solution is expected to have high osmotic pressure while being both inexpensive and safe for drinking. Therefore, a mixture of sucrose, oresol, and soda was selected as an effective draw solution for FO bags, as it generates not only high osmotic pressure to draw clean water into the bag but also provides essential minerals to enhance the flavour of the beverage.

In this study, various membrane orientations in the FO bag design were evaluated in terms of water flux and membrane fouling using synthetic flood water. The optimal permeation time for the FO bags in real floodwater treatment was then investigated. Water quality was assessed by analysing parameters such as total dissolved solids (TDS), pH, turbidity, iron (Fe), and *E. coli* content.

2. Materials and methods

2.1. Forward osmosis membrane

The FO membrane used in this investigation was composed of cellulose triacetate with an embedded weldable nonwoven support (CTA-NW). These membranes were supplied by hydration technology innovations (HTI, OsMem™ CTA Membrane 130806, Albany, OR, USA). According to the manufacturer, the operational pH range is 3 to 8, and the membrane thickness is approximately 50 µm with a measured contact angle of 60-80°, indicating moderate hydrophilicity. The FO membrane exhibited a water permeation coefficient of 3.06×10-12 $ms^{-1}Pa^{-1}$ and a salt rejection rate of approximately 95-99%. Most FO membranes feature an asymmetric structure consisting of two distinct layers: the active layer (AL), which serves as the dense selective layer, and the support layer (SL), which provides mechanical support due to its porous nature.

2.2. Characteristics of feed solution and draw solution

The feed solution used in the FO bag experiments consisted of synthetic and real flood water, with typical parameters measured as shown in Table 2. The synthetic flood water was prepared by mixing red surface soil with lake water, while real flood water was collected from stream water during heavy rainfall in Dam Rong district, Lam Dong province.

Table 2. The measured parameters of the feed solution.

Parameters	Unit	Synthetic flood water	Real flood water
pH	-	7.2±0.3	6.8±0.5
Turbidity	NTU	209±8	85±5
TDS	mg/l	210±3	110±8
Total iron	mg/l	1.02±0.08	0.42±0.05
Coliform	MPN/100 ml	250±12	620±17

A mixed draw solution, comprising oresol, soda ($NaHCO_3$), and sucrose ($C_{12}H_{22}O_{11}$), was used in the FO bag process. First, sucrose was dissolved in boiling distilled water to reach near saturation concentration (6 M). Next, 2 g/l of oresol was added to the saturated sucrose solution and stirred for 3 hours. Subsequently, baking soda was added to the sucrose/oresol mixture in varying concentrations from 0.4 to 32 g/l, with thorough mixing over 10 hours to ensure complete dissolution.

2.3. Forward osmosis filter water bag fabrication and operation

The FO bag was fabricated using a commercial CTA-NW FO membrane, as illustrated in Fig. 1. Two pieces of FO membrane were cut to dimensions of 16 cm in width and 25 cm in length, providing a total membrane surface area of 800 cm^2. A 21 mm diameter hole was created in the centre of one of the FO membrane pieces to allow the insertion of the draw solution and extraction of clean water. The two membrane pieces were then sealed together using a sealing machine. The FO bag was filled with 40 ml of draw solution and weighed to determine its initial mass. The bag was then

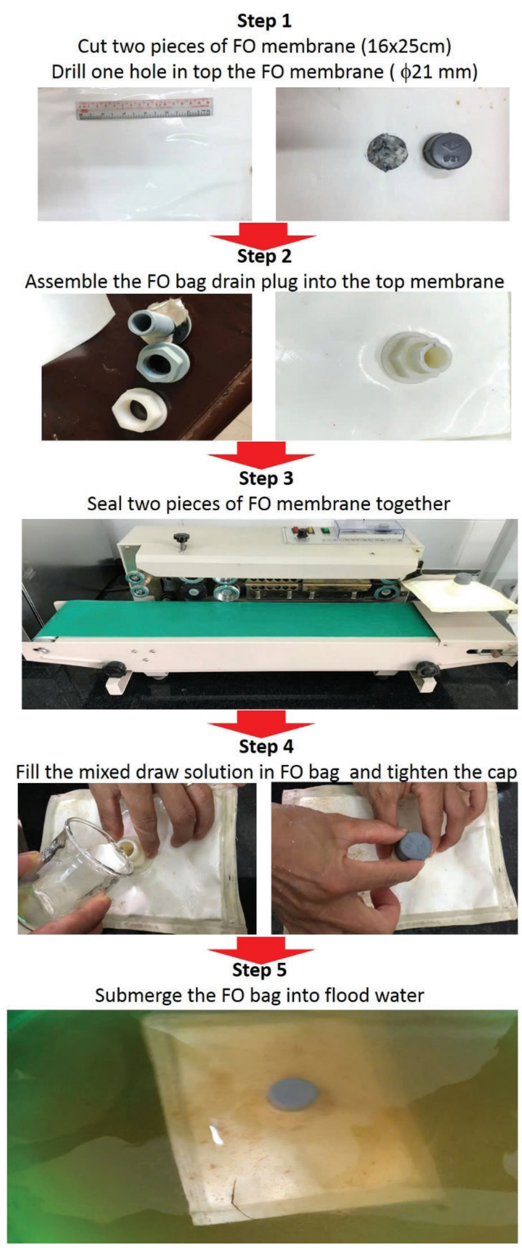


Fig. 1. Forward osmosis filter water bag fabrication.

immersed in a 20 l flood water tank. Over time, clean water permeated from the flood water tank through the FO bag, causing an increase in the bag's mass. After a set period, the FO bag was removed and weighed again, and the water flux and permeate volume were calculated. The quality of the produced water was then compared to the WHO's standards for drinking water.

2.4. The measurement of water flux and reverse salt flux

The change in the feed tank mass over time was used to calculate the experimental water flux, J_w (l/m^2h), as follows:

$$J_W=\frac{\triangle V}{A\triangle t} \quad (1)$$

where A is the effective FO membrane area (m^2) and ΔV is the volume of the permeate flux (l) collected over a predetermined period (Δt(h)).

The contaminant removal efficiency of the FO bag during flood water treatment was calculated by analysing the feed and permeate water quality as follows:

$$R\ (\%)=1-\frac{C_P}{C_F}\ x\ 100\% \quad (2)$$

where R is rejection and C_F and C_P are solute concentrations in the feed solution and production water in FO bag, respectively.

2.5. Analytical methods

Total dissolved solids (TDS) in the water samples were measured using a TDS meter (Hanna HI98301 model). Turbidity and pH were analysed using a turbidimeter (Hach Lange DR 2800) and a pH meter (HI 98129 by HANNA model), respectively. The concentration of iron (Fe) was measured using an ICP-MS instrument. Osmotic pressure was assessed with an osmometer (Model 3320, Advanced Instruments, Inc., USA) based on the freezing-point depression method. *E. coli* content was determined using the most probable number (MPN) method [19] employing an autoclave and incubator (INB-200 32 model).

3. Results and discussion

3.1. Optimum forward osmosis bag design

Most FO bags are designed with one side comprising the FO membrane and the other side made of plastic. This design reduces the effective membrane area, thereby increasing the time required to provide clean water in emergency situations. To address this, a novel FO bag was designed in this study with FO membranes on both sides, each measuring 16 cm in width and 25 cm in length. Additionally, the bag includes a cap to allow the draw solution to be poured in and to extract clean water for reuse purposes, as shown in Fig. 2.

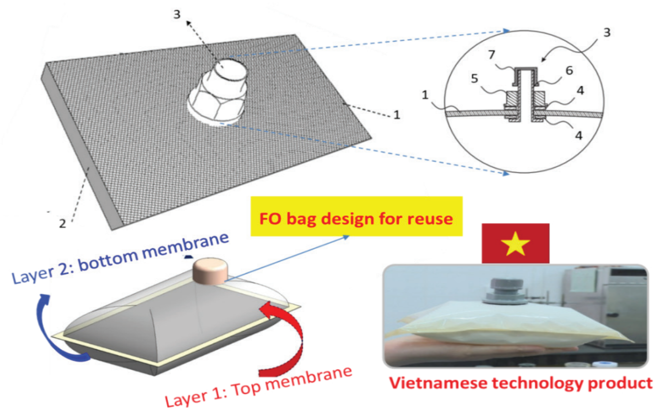


Fig. 2. Forward osmosis bag design for reuse. 1. Top membrane; 2. Bottom membrane; 3. Connecting component for inputting and outputting the solution; 4. Rubber gasket; 5. Bolt; 6. Flange; 7. Cap.

To optimise the FO bag design, different membrane orientations were studied using a 40 ml saturated sucrose solution (6 M) as the draw solution and 20 l of synthetic flood water as the feed solution. The results indicate that water flux in the membrane orientation with the active layer facing the draw solution increased from 0.48 to 0.68 LMH as the operation time increased from 1 to 4 hours (Fig. 3A). Initially, the draw solution volume was small and did not fully contact the FO membrane, resulting in low water flux. After 4 hours, more water permeated through the FO membrane as the bag expanded, allowing uniform contact with the mixed draw solution and leading to the highest water flux. However, the water flux in the active layer-facing draw solution orientation quickly decreased from 0.68 to 0.15 LMH when the operation time was extended from 4 to 10 hours (Fig. 3A). This decline was caused by internal concentration polarisation (ICP), where water from the feed solution permeates the FO membrane, carrying ions into the pores of the support layer (Fig. 3B).

Figure 3C shows that water flux in the membrane orientation with the active layer facing the feed solution increased from 0.46 to 0.66 LMH as the operation time increased from 1 to 5 hours. However, water flux gradually decreased from 0.66 to 0.36 LMH when the operation time was extended from 5 to 10 hours. This reduction in water flux is due to external concentration polarisation (ECP). Nonetheless, the active layer of the FO membrane is smooth and tight, resulting in only a slight effect from ECP (Fig. 3D).

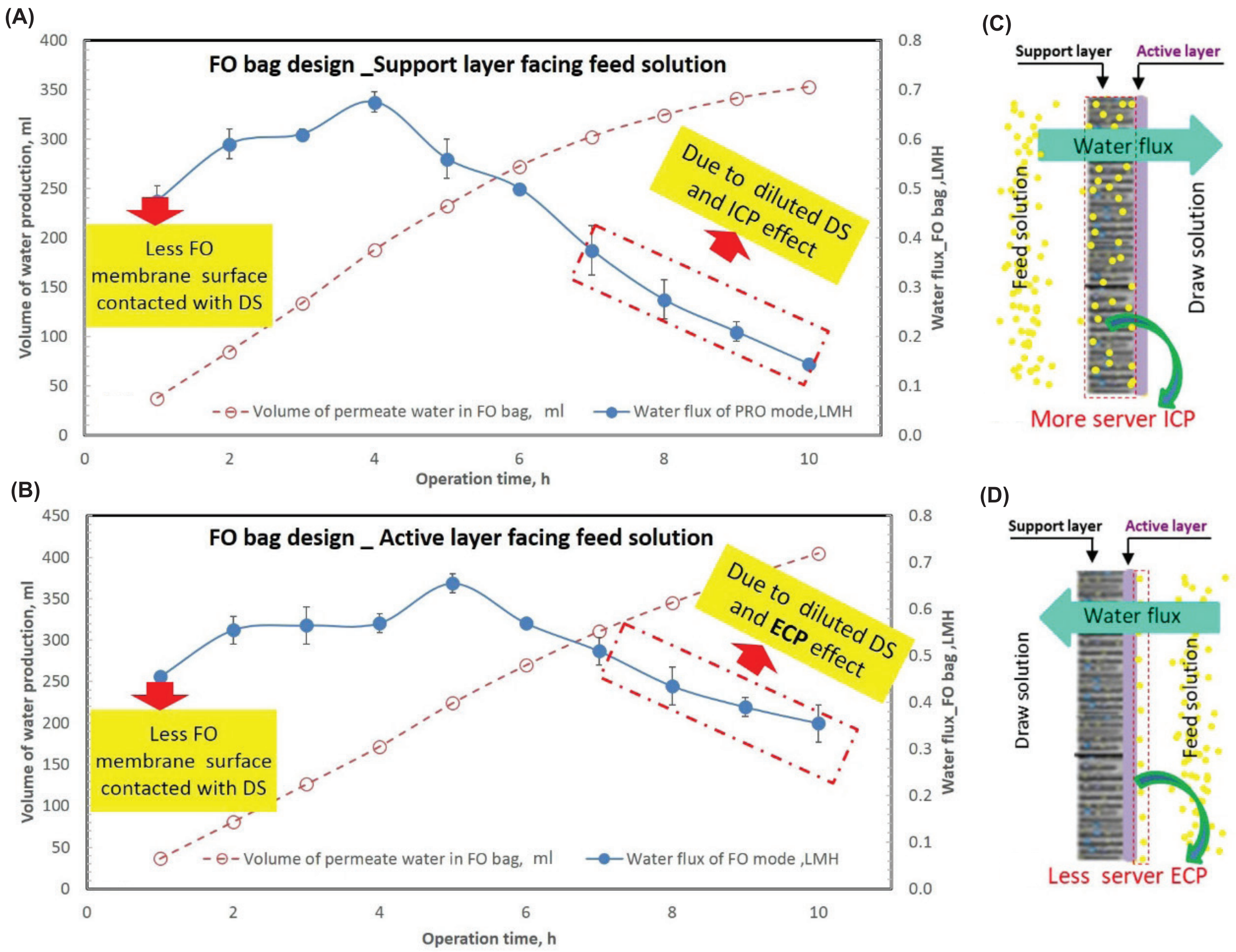


Fig. 3. The effect of membrane orientations on water flux and the volume of water production in forward osmosis bags. **(A)** Forward osmosis bag design following the style of the support layer >< feed solution, **(B)** Fouling serves in membrane orientation of the support layer >< feed solution, **(C)** Forward osmosis bag design following the style of active layer >< feed solution, **(D)** Fouling serves in membrane orientation of active layer >< feed solution.

Figure 3 illustrates that water production from the FO bags increased over time. In the membrane orientation with the active layer facing the draw solution, the water production volume increased from 38 to 353 ml as the operation time increased from 1 to 10 hours. In the membrane orientation with the active layer facing the feed solution, the water production volume increased from 36 to 405 ml over the same period. When compared to the membrane orientation with the active layer facing the draw solution, the total water volume permeating into the FO bag with the active layer facing the feed solution was 12.7% higher due to lower membrane fouling, as shown in Fig. 4. Therefore, the membrane orientation with the active layer facing the feed solution was identified as the optimal design for achieving high water production and low membrane fouling.

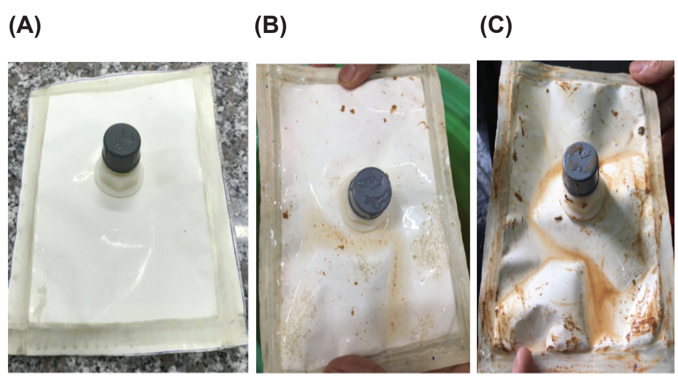


Fig. 4. Membrane fouling of the forward osmosis bag during flood water treatment. **(A)** Original forward osmosis bag, **(B)** Used forward osmosis bag _Support layer facing the feed solution, **(C)** Used forward osmosis bag _Active layer facing the feed solution.

3.2. The effect of draw solutions on forward osmosis bag performance

Selecting a suitable draw solution for FO bags in flood water treatment is crucial, as it must ensure drinking water safety and provide high osmotic pressure. In this study, various safe solutions, including oresol, soda, and sucrose, were tested as draw solutions in FO bags. First, a saturated sucrose draw solution (6 M) was prepared. This was then mixed with 2 g/l of oresol. Finally, soda was added to the 6 M sucrose and 2 g/l oresol mixture in varying concentrations ranging from 0 to 16 g/l.

The results showed that the average water permeate flux over 5 hours for the mixed 6 M sucrose and 2 g/l oresol solution was higher than that of pure sucrose. Fig. 5 illustrates that the average permeate flux for the 6 M pure sucrose solution and the mixed 6 M sucrose and 2 g/l oresol solution was 0.56 and 0.59 LMH, respectively.

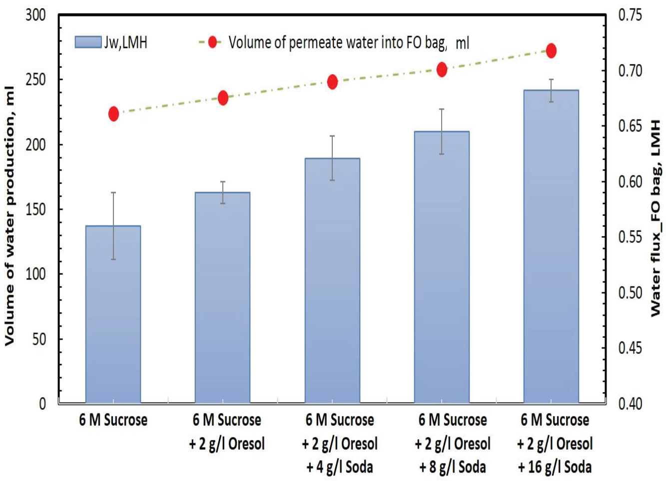


Fig. 5. Water flux and volume of permeate water in forward osmosis bag with different draw solutions.

The increase in total dissolved solid (TDS) for the mixed draw solution of 6 M sucrose and 2 g/l oresol (TDS=120 mg/l), compared to the pure 6 M sucrose solution (TDS=0.45 mg/l), led to an increase in osmotic pressure from 138 to 141 atm, respectively. The rapid increase in TDS for the mixed solution is due to the good solubility of sodium chloride, potassium chloride, and sodium citrate dihydrate in oresol. Furthermore, adding soda to the mixed 6 M sucrose and 2 g/l oresol solution significantly increased water flux. The average water flux increased from 0.59 to 0.68 LMH as the soda concentration in the mixed solution was increased from 0 to 16 g/l. The increase in osmotic pressure, due to the improved solubility of Na^+ and HCO_3^-, explains this.

In addition to increasing the water flux, adding soda to the mixed solution also raised the pH. The pH increased from 7.11 to 7.84 as the soda concentration was increased from 0 to 16 g/l, as shown in Table 3.

Table 3. The characteristic of draw solutions used in forward osmosis bag.

Draw solutions	TDS (mg/l)	pH of draw solution	The pH tolerance value of the FO membrane
6 M Sucrose	0.45	6.45	
6 M Sucrose + 2 g/l Oresol	120	7.11	
6 M Sucrose + 2 g/l Oresol + 4 g/l Soda	434	7.34	
6 M Sucrose + 2 g/l Oresol + 8 g/l Soda	434	7.65	3-8
6 M Sucrose + 2 g/l Oresol + 16 g/l Soda	530	7.84	
6 M Sucrose + 2 g/l Oresol + 32 g/l Soda	593	8.12 (Potential damage to FO membrane)	

However, the pH of the mixed draw solution rose to 8.12 when the soda concentration reached 32 g/l, which exceeds the pH tolerance range of the CTA-FO membrane (pH=3-8). Therefore, the 32 g/l soda concentration was not used to avoid damaging the FO membrane. As seen in Fig. 5, the total volume of permeate water increased gradually from 224 to 273 ml over a 5-hour operation as the soda concentration in the mixed draw solution increased from 0 to 16 g/l. Consequently, the optimum draw solution for FO bag operation was determined to be 6 M sucrose + 2 g/l oresol + 16 g/l soda, achieving both high water flux and a suitable pH.

3.3. Optimal permeation time for forward osmosis bag in real flooding water treatment

To determine the equilibrium point, where water permeation through the FO bag becomes negligible, a mixture of 6 M sucrose + 2 g/l oresol + 16 g/l soda was used as the draw solution, and real flood water from Dam Rong district, Lam Dong province, was used as the feed solution for a 16-hour operation. The FO bag had a rectangular design, with dimensions of 16 cm in width and 25 cm in length, and the membrane orientation had the active layer facing the feed solution. Fig. 6 shows that the permeate water volume increased rapidly from 45 to 588 ml as the operation time increased from 1 to 12 hours. However, after 12 hours, the permeate volume increase was insignificant due to a negligible osmotic pressure gradient between the draw solution and the feed solution, marking the equilibrium point (Fig. 6). The water flux at this stage was less than 0.14 LMH, indicating the balance point for FO bag operation at 12 hours.

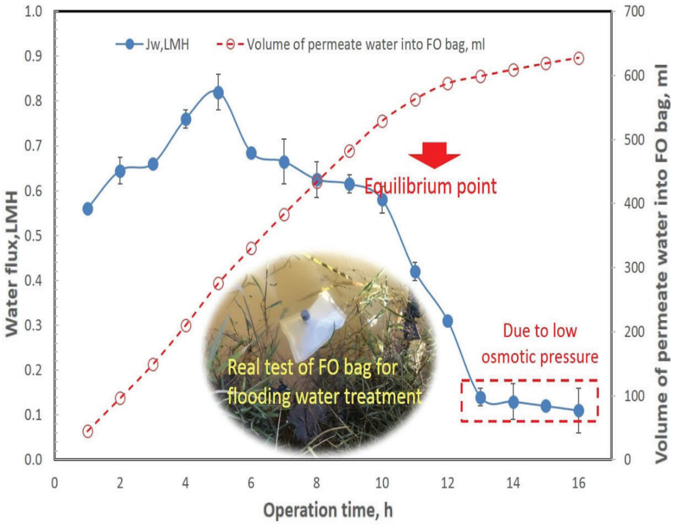


Fig. 6. Forward osmosis bag performance on real flooding water treatment.

To evaluate the reusability of FO bags, the experiment was repeated three times with real flood water and a 12-hour operational period. After the first run, the FO bag was cleaned with deionised (DI) water for 3 minutes and retested. The results showed that the total permeate water volume in the first run was 558±5 ml. The total permeate water volume in the second run decreased by 5% to 559±8 ml, and in the third run, it decreased by 3% to 542±11 ml. While the total permeate water volume decreased slightly in subsequent cycles due to membrane fouling, the reduction was not significant, demonstrating that the FO bags can be reused effectively for flood water treatment.

FO bags operate based on the osmotic pressure gradient between the feed and draw solutions and can be used for up to five years. After each use, the bags should be cleaned on both sides with fresh water and stored in clean water for preservation. Additionally, the water quality produced by the FO bag was suitable for drinking. Over three cycles, the turbidity, iron, and *E. coli* removal rates were consistently high, with turbidity effluent below 1.27 NTU, iron below 0.01 mg/l, and 100% *E. coli* removal. The high selectivity and small pore size of the FO membrane (0.37 nm) were effective in removing microorganisms, metal ions, and macromolecules [20]. The TDS and pH values in the permeate water from the FO bag ranged from 418 to 420 mg/l and 7.71 to 7.86, respectively, across the three cycles. Hence, the water quality met drinking water standards [21] from Vietnamese technical regulations on domestic water quality (QCVN 01-1:2018/BYT), as shown in Table 4.

Table 4. Forward osmosis bag performance over 3 cycles.

Run	Volume of permeate water into forward osmosis bag (ml)	Water quality in forward osmosis bag permeate, mg/l				
		TDS (mg/l)	*Turbidity, NTU*	*pH*	*Fe*	*E. coli*
1	588±5	420±11	1.25±0.04	7.73±0.12	0.01±0.005	0
2	559±8	418±6	1.27±0.01	7.71±0.15	0.01±0.002	0
3	542±11	424±9	1.23±0.03	7.86±0.11	0.01±0.001	0
Standard of WHO		<600	-	6.5-8.5	-	0
QCVN 01:2018/BYT		500	2	6.5-8.5	0.3	<1

4. Conclusions

In this study, FO bags were successfully designed and tested for producing drinking water during emergencies. The experimental results demonstrated that the membrane orientation with the active layer facing the flood water was the optimal design for FO water filter bags, as it minimised membrane fouling. Additionally, the FO bag achieved high pollutant removal rates (almost 100%), attributed to the small pore size of the FO membrane. Over the 12-hour FO process, the total water production volume reached 588 ml, and the filtered water met WHO quality standards for drinking water. However, the water flux of FO bags using the commercial CTA-NW membrane was relatively low. Therefore, further research is recommended to develop new FO membranes that can enhance water flux and reduce the operational time of FO bags in emergency situations.

CRediT author statement

Hau Thi Nguyen: Investigation, Writing original draft, Methodology, Formal analysis, Data curation, Project administration; Nguyen Cong Nguyen: Supervision, Investigation, Conceptualisation, Writing - Reviewing and Editing; Hung Cong Duong: Methodology, Formal analysis, Resources; Shiao-Shing Chen: Supervision, Investigation, Writing - Reviewing and Editing.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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