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Application of Forward/Reverse Osmosis Hybrid System for Brackish Water Desalination using El-Salam Canal Water, Sinai, Egypt, Part (2): Pilot Scale Investigation

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Abstract: This paper is the second part of two papers focus on the investigation of a forward osmosis (FO) – reverse osmosis (RO) hybrid process to co-treat brackish water (BW) and El-Salam Canal water in Sinai, Egypt. By using this hybrid process, BW can be diluted before desalination, hence reducing the energy cost of desalination. Simultaneously, contaminants present in the El-Salam Canal water are prevented from migration into the product water through the FO and RO membranes. The main objective of this part is to investigate the performance of the combined FO pretreatment and RO desalination hybrid system on pilot scale and specifically its effects on membrane fouling and overall solute rejection. Firstly, the optimization of the pilot-scale FO process to obtain the most suitable and stable operating conditions for further study in a real site is investigated. Secondly, the pilot-scale RO process performance as a post-treatment to FO process is evaluated in terms of water flux and rejection. The results indicated that up to 60% dilution rate of BW could be reached by application of hybrid system. Finally, the FO/RO system was tested on continuous operation for 15 hrs. and no pollutant was detected neither in BW nor in RO permeate.
Keywords:Forward osmosis, Reverse osmosis, Membrane desalination, Impaired water, Brackish water, El-Salam Canal.

1. Introduction:

Due to the fact that water demand is larger than the conventional supply, the utilization of non-conventional water resources became evident. The Nile River is the main source of fresh water in Egypt, supplying 95 percent of its overall water usage. However, the country is faced with the threat of severe water shortage in the next decade. Egypt experiences an annual water shortfall of 7 billion cubic meters, and domestic water demand in the country is expected to increase by 25 percent in 2025[1]. Accordingly, exploration of novel approaches to increase the country's supply of fresh water in order to meet this constantly rising demands imperative. Currently, Egypt's supply of fresh water relies on exploiting groundwater, reuse of treated wastewater, recycling of irrigation and agricultural drainage water, and desalination, which is the removal of salt from seawater and brackish water to obtain fresh water suitable for agriculture and human consumption. RO has emerged as the leading technology for future desalination facilities because of its relatively low energy consumption and produced water cost compared to thermal desalination technologies[2]. However, the real and perceived costs and energy requirements of its high pressure pumping continue to be a barrier to its implementation[3,4]. FO is an engineered osmotically driven membrane process that uses osmotic pressure of concentrated solutions to extract clean water from diluted solution[5]. In a new approach, FO uses a saline stream (seawater or brackish water) as draw solution to extract water from a source of impaired water[6--9]. The driving force for water flux in FO is the difference in osmotic pressure between two water solutions, the saline water and the impaired water, and not hydrostatic pressure as in RO. As such, the energy cost associated with FO is very low[10]. A combined desalination process using emerging FO technology coupled with RO could potentially reduce the energy consumption of the desalination process, and thus, lower barriers to its implementation.

El-Salam Canal water is a mixture of water from river and agricultural drainage (2.11 billion m^3/y of fresh Nile water mixed with 1.905 billion m^3/y of water from Bahr Hadous and 0.435 billion m^3/y of El-Serw drainage). The ratio of Nile water to drainage water is about 1:1. This ratio is determined to reach total dissolved solids (TDS) not more than 1000– 1200 mg/l to be suitable for cultivated crops. Since the catchment area of Bahr Hadous and Serw drains are located in highly populated area, they are susceptible to pollution from legal and illegal dumping of domestic and industrial wastewater which makes it not acceptable for animals drinking or irrigation purposes[11,12]. This paper is the second part of two papers focus on the investigation of a FO – RO hybrid process to co-treat the brackish water (wells around the canal) and El-Salam Canal water at the same time.

By using this hybrid process, brackish water can be diluted before desalination, hence reducing the energy cost of desalination, and simultaneously, contaminants present in the El-Salam Canal water are prevented from migrating into the product water through two established barriers, the FO membrane and the RO membrane. The main objective of this part is to investigate on pilot scale system the performance of the combined FO pretreatment and RO desalination hybrid system, specifically its effects on membrane fouling and overall solute rejection. Firstly, the optimization of the pilot-scale FO process to obtain the most suitable and stable operating conditions for further study in a real site is investigated. Secondly, the pilot-scale RO process performance as a post-treatment to FO process is evaluated in terms of water flux and rejection.

2. Materials and methods:

2.1. Materials:

2.1.1. Feed and draw solutions:

El-Salam canal water was used as feed solution (FS) in this study for all the experiments. For the draw solutions (DS), NaCland Ammonium bicarbonate (ABC) were used to prepare synthetic brackish water which used as DS with El-Salam Canal water FS.

2.1.2. Membranes:

2.1.2.1. FO membrane:

A spiral wound FO membrane module was used in this study. The spiral wound (SW) membrane module was 4040 FO FS module made up of several flat-sheet cellulose triacetate (CTA) with embedded polyester FO membranes (Hydration Technologies, Albany, OR). The number 4040 refers to the module diameter of 4 inches and the module length of 40 inches. The 4040 FO-FS membrane module has a usable area of 3.2 m^2. The module was operated with the feed water against the active rejection layer and passed through the membrane in the axial direction parallel to the permeate tube. The draw solution faces the porous support layer of the membrane and flows spirally inside the membrane, thus it is diluted by the water extracted from the feed water. The diluted DS is collected in the permeate tube as illustrated in Figure (1). The SW FO element was loaded inside a tubular polyvinyl chloride (PVC) vessel.

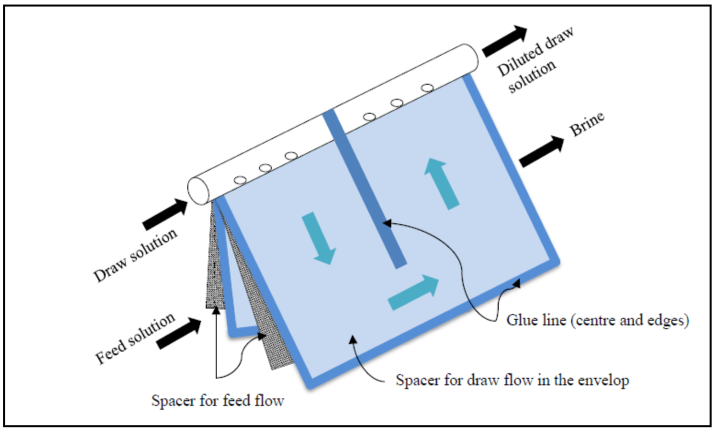

Figure (1): Schematic diagram of a spiral wound forward osmosis (FO) module showing the direction of water in the module.

2.1.2.2. RO membrane module:

The membrane element is Filmtech, Spiral wound; type BW 30-40-40, TFC (Polyamide Composite), Pore size ~ 0.0001 micron, maximum pressure is 16 bar. The effective membrane area is 7.2 m^2, the maximum permeate flow rate is 6 m^3/day, and salt rejection is 99.3 %.

2.2.Experimental set-up:

The schematic diagram of the pilot-scale of the FO-RO system has shown in Figure (2). It was consisted of microfiltration (MF) to minimize the negative effects of the raw feed, the FO process to desalinate using the synthetic salt solution as DS and industrial wastewater as FS, and the RO process to reduce the salt in the final product. Each flow was controlled independently by a pump, and the draw and feed solutions in the FO process flowed in co-current mode in each channel on both sides of the membrane. Figure (3) shows an image of pilot scale unit.

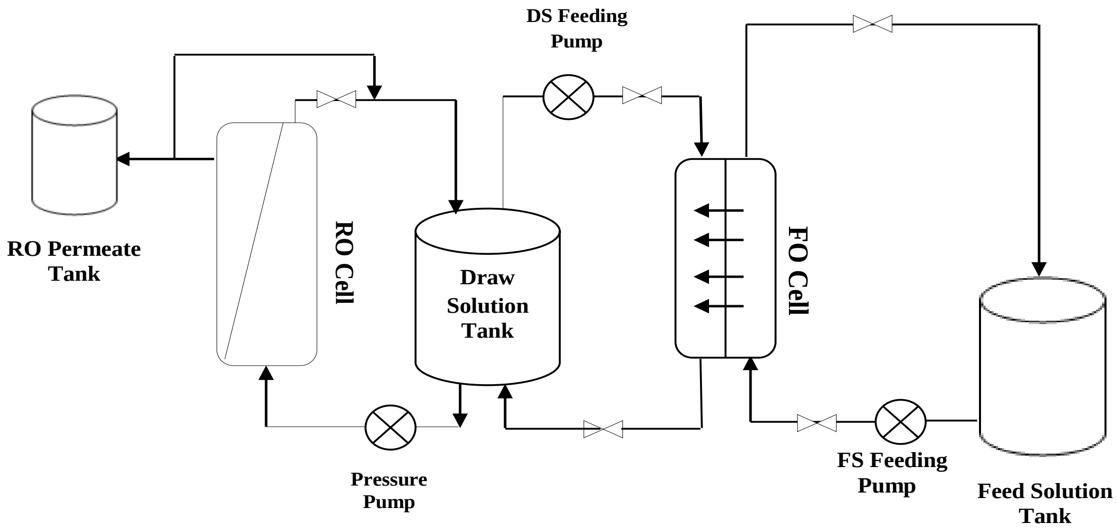

Figure (2): Schematic drawing of the FO/RO experimental setup.

Figure (3): An image of the FO/RO pilot scale

The water flux across the membrane in the FO process was measured by the change in the weight of the DS tank. The conductivity of the feed and draw solutions in the FO process and the permeate flux in the RO process were also collected during the test. The experiments were conducted in a batch mode. Water flux was calculated using the following relationship:

$$Jw = \frac{Change in DS weight\ (L)}{Effecttive membrane area\ (m^2) \times Time\ (h)} \quad (1)$$

The RO process was evaluated as a post treatment for the FO process to achieve a suitable concentration in the final product water. The concentrated solution and the permeate water were recirculated and reused during the pilot-scale RO operation.

The permeate water flux Jw ($Lm^{-2}\ h^{-1}$) was calculated by:

$$Jw = \frac{Volume of water collected\ (L)}{Membrane area\ (m^2) \times Time\ (h)} \quad (2)$$

Furthermore, the salt rejection of the pressure-driven RO membrane was calculated by measuring the total dissolved solid of the feed and permeate (m_S/cm)

$$R\ (\%) = 1 - \frac{permeate}{C_{feed}} \quad (3)$$

2.3. FO-RO pilot experimental procedure:

2.3.1. Batch experimental plan:

In the batch experiments, the application of FO/RO hybrid system in industrial scale was investigated. Figure (4) shows the proposed plant for brackish water desalination using El-Salam canal DS. In the proposed plant, the FO system uses brackish water as DS to extract water from El-Salam canal. The diluted brackish water is then processed through an RO desalination system that provides high salt rejection and dissolved contaminants that may have escaped the FO treatment, hence achieving a multi-barrier treatment system. According to the data obtained from our previous study[13], due to the low driving force between El-Salam canal water and brackish water from the surrounding wells, we add draw solute ammonium bicarbonate on the brackish water to improve the performance of FO process. And hence, ammonium bicarbonate recovery step will be added between FO and RO processes.

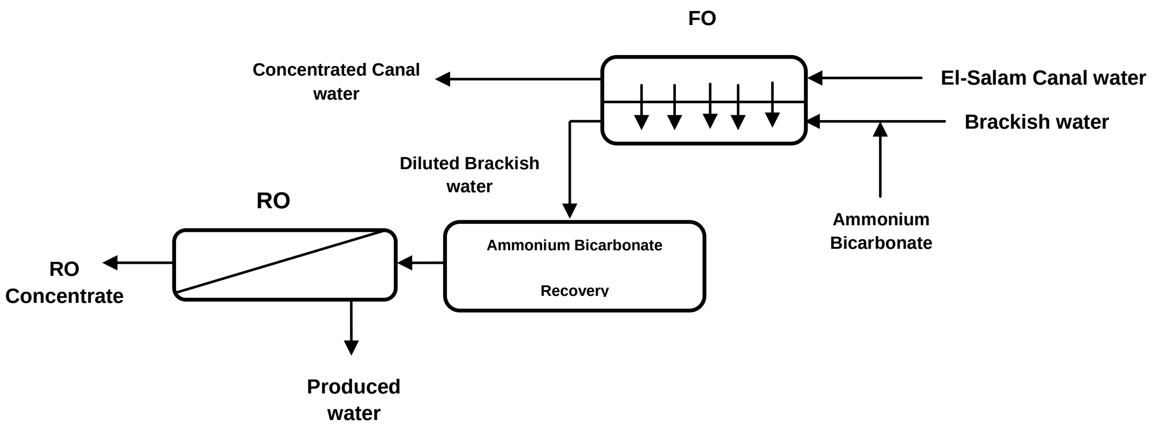

Figure (4): Proposed FO/RO plant for brackish water desalination using El-Salam Canal water.

Each step in the proposed system was tested separately, these include:

a) FO performance:

Water flux, DS dilution, salt rejection and transfer salt flux were measured with time. In addition, transfer of the major contaminant of El-Salam canal (COD) across the FO membrane was tested.

b) RO performance:

The effect of applied pressure on performance of RO with diluted seawater from FO stage was tested. These include measuring of RO permeate water flux, salt rejection and overall water recovery.

2.3.2. Continuous experimental plan:

The continuous operation of FO/RO system was conducted to assess membrane fouling propensity, solute rejection, and any subsequent degradation in performance of the hybrid process, and to investigate rejection of contaminants during the operation of the hybrid process. Diluted DS from the FO membrane cell was returned to the RO feed tank and an RO permeate partial stream (equivalent to the flow rate of water through the FO membrane) was removed from the system. The amount decreased from the feed tank compensated by addition of distilled water.

2.4.Analysis and measurements:

Samples were collected throughout the course of each experiment. For all experiments, 50 ml samples were collected for analysis from the feed and draw solutions.

Based on the results obtained from our previous study[13], no detectable heavy metals contamination was found in the canal water, organic pollution is the major notable contamination that found. Accordingly, we take chemical oxygen demand test (COD) as a measure for organic pollutants.

Analysis of COD at feed and draw solutions for each experiment was determined using spectrophotometer HACH DR2800. TDS for each experiment was determined according to standard method (APHA, AWWA and WEF 2005).

3. Results and discussions:

3.1. Batch experiments results:

3.1.1. FO process performance:

Based on bench scale results[13], the performance of FO process using El-Salam Canal water as FS and brackish water as DS was found to be low due to the lower osmotic driving force between FS and DS. Accordingly, we enhanced the performance by addition of ammonium bicarbonate (ABC) draw solute to the DS to increase the osmotic driving force. It was expected that, the efficiency of FO pilot system may be higher than FO bench scale system (due to higher membrane area of pilot system). So, we investigated the performance of FO process with El-Salam Canal water with and without addition of ABC to BW (TDS: 10000 mg/L).

Figure (5) represents water flux and reverse salt flux as a function of permeation time. It was found that the water flux was increased with time till 4.58 L/m^2hr at 1.5 hr then decreased gradually to 3.96 after 3 hrs. The same trend was found with reverse salt flux, in which it increased by time to 0.02 mol./m^2hr at 1.5 hr then decreased to 0.017 after 3 hrs.

The behavior of flux decline with time was illustrated by Zhao et al.[14] and Grayet al.[15], they demonstrated that coupled adverse effects of internal concentration polarization (ICP) and membrane fouling can reduce the osmotic water flux and increased mass transfer resistance as the feed water became more concentrated due to water permeation from FS to DS and reverse salt diffusion from DS to FS.

Figures (6&7) show the change of DS % dilution, DS TDS and reverse salt flux with time. It is appeared that, after 3 hrs permeation time, the maximum % dilution was about 43%, the DS TDS was decreased from 10000 to 5574 mg/L, while salt rejection was decreased gradually by time from 99.7 at 0.5 hr to 98.1% at 3 hrs.

Table (1) illustrates the analysis of the El-Salam Canal water before and after FO process. The TDS of FS was increased from 2400 to 3760 mg/L, while COD was decreased from 76 to 43 mg/L. No COD was observed in DS after the FO process. As demonstrated in our bench scale study[13], the morphology of used FO membrane showed the presence of organic fouling on the membrane surface. Accordingly, the decrease of COD in FS may be attributed to the adsorption on the membrane surface.

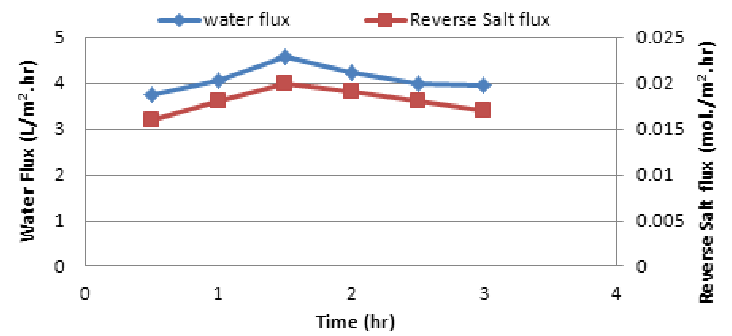

Figure (5): Water & reverse solute fluxes as a function of time.
[El-Salam Canal water (FS) and BW: 10 g/L (DS)]
(FO- Batch Process)

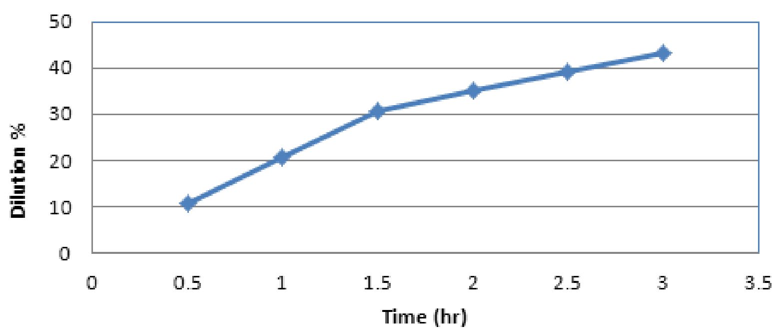

Figure (6): Dilution % as function of time.
[El-Salam Canal water (FS) and BW: 10 g/L (DS)]
(FO- Batch Process)

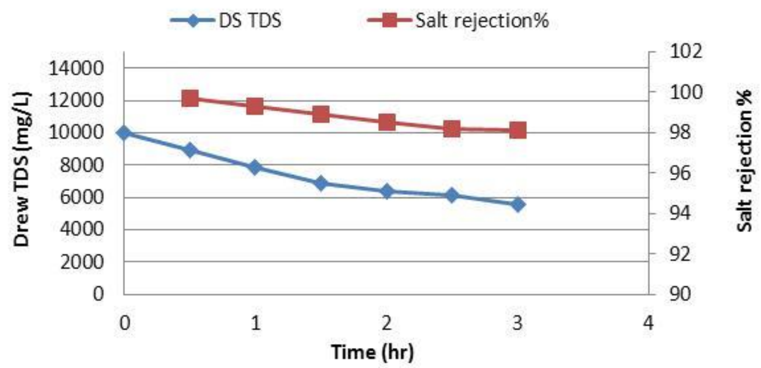

Figure (7): DS salinity and salt rejection % as a function of time.
[El-Salam Canal water (FS) and BW: 10 g/L (DS)]
(FO- Batch Process)

Table (1): Analysis of El-Salam Canal water and synthetic BW before and after FO batch process.

Time (hr) / Parameter	0	3
FS TDS(mg/L)	2400	3760
FS COD (mg/L)	76	43
DS TDS(mg/L)	10000	5574
DS COD (mg/L)	0	0

Figure (8) illustrates the effect of permeation time on water flux and reverse salt flux for FO process with El-Salam Canal water as FS and DS consisted of BW with TDS 10000 mg/L and 20000 mg/L ammonium bicarbonates (ABC). It was clear that, the presence of ABC increased the fluxes values. The maximum water flux obtained after 1 hr was 6.88 L/m^{2}hr, while without addition of ABC was 4.58 after 1.5 hr. In presence of ABC the flux was found to be decreased gradually by time, while it remained almost constant at about 4 L/m^{2}hr in absence of ABC. The same trend was observed for reverse salt flux with and without addition of ABC.

Figures (9 & 10) show the change of DS % dilution, DS TDS and reverse salt flux with time. It is appeared that, the addition of ABC slightly increased the dilution percentfrom 43% to 50% after 3 hrs permeation time, and by duplicated the permeation time to 6 hrs it increased to only 60%.

The DS TDS was decreased from 10000 to 4714 mg/L after 3 hrs, and then decreased to 3722 after 6hrs. The salt rejection was decreased gradually by time from 97.96 at 1 hr to 95.28% at 6 hrs.

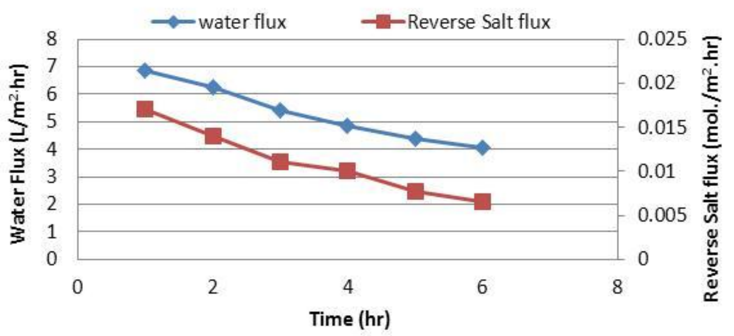

Figure (8): Water & reverse solute fluxes as a function of time [El-Salam Canal water (FS) and BW: 10 g/L + 20 g/L ABC (DS)] (FO- Batch Process)

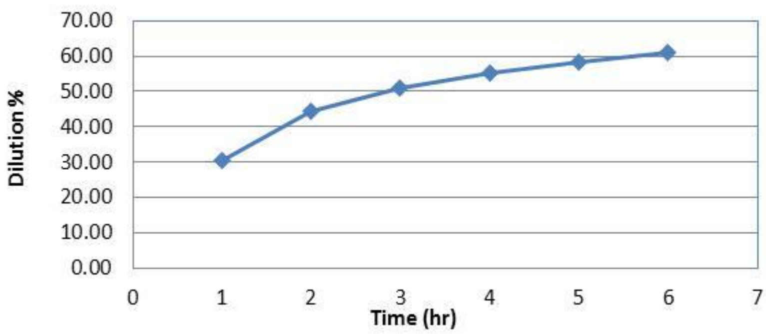

Figure (9): Dilution % as a function time . [El-Salam Canal water (FS) and BW: 10 g/L + 20 g/L ABC (DS)] (FO- Batch Process)

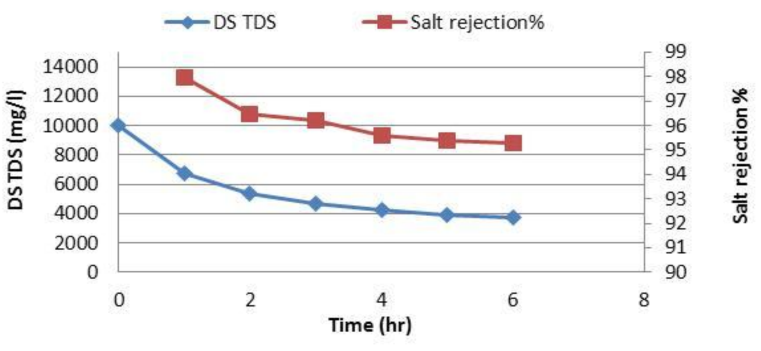

Figure (10): DS salinity and salt rejection % as a function of time.
[El-Salam Canal water (FS) and BW: 10 g/L + 20 g/L ABC (DS)]
(FO- Batch Process)

Table (2) demonstrates the analysis of the El-Salam Canal water before and after FO process with addition of 20 g/L ABC to DS. The TDS of FS was increased from 2400 to 8600 mg/L, while COD was decreased from 76 to 31 mg/L. No COD was observed in DS after the FO process. As clear, the salinity of FS was increased than the salinity of the DS, this is due to the addition of ABC to DS which increased its osmotic pressure and proceeded the permeation time to 6 hrs. Also, as illustrated in the previous section the decrease of COD in FS may be attributed to the adsorption on the membrane surface.

Table (2): Analysis of El-Salam Canal water and synthetic BW before and after FO batch process with addition of 20 g/L ABC to DS.

Parameter \ Time (hr)	0	6
FS TDS (mg/L)	2400	8600
FS COD (mg/L)	76	31
DS TDS (mg/L)	10000	3722
DS COD (mg/L)	0	0

Although, the performance of FO process with El-Salam Canal water with addition of ABC to DS is better than the performance without addition, it was observed that the increase is not big. So, we decided to complete the continuous FO/RO experiment with El-Salam Canal water without addition of ABC to avoid the difficulty of heating step between FO and RO processes in lab. The implementation of ABC addition on large scale for actual application depends on techno-economic evaluation of the process.

3.1.2. RO performance:

The performance of low pressure RO with diluted DS from FO process by using El-Salam Canal water as FS was tested. The diluted DS from FO process without addition of ABC to BW was used directly as feed water for RO process. While, the diluted DS from the FO process by adding ABC to the BW was subjected first to heating to 70°C to break ABC to NH_3 and CO_2 that liberated from the solution.

Figure (11)shows the salinity effect on permeate TDS and water recovery for RO at pressure 15 bar. As expected from literature review [16], the RO performance was found to decrease by increasing of water salinity. With synthetic BW at 10000 mg/L TDS, the permeate TDS was 880 mg/L and water recovery was 21%. With diluted DS at 5574 mg/L TDS (without addition of ABC), the permeate TDS was decreased to 390 mg/L and water recovery was increased to 33.7%. Finally, with diluted DS at salinity of 3722 mg/L (with addition of ABC), permeate TDS was decreased to 208 mg/L and water recovery was increased to 46.15%.

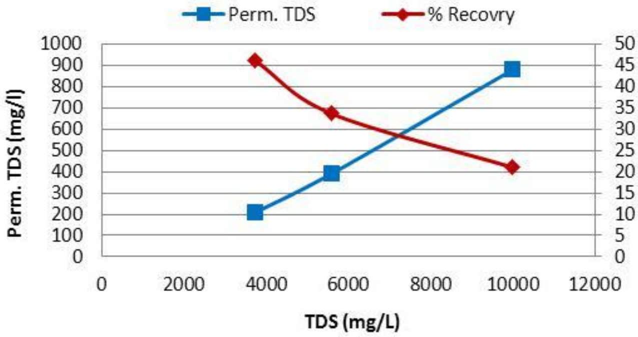

Figure (11): Effect of salinity on water recovery and permeate TDS for RO process at 15 bar with synthetic BW (TDS 10 g/L) and diluted DS from FO process by El-Salam Canal water.

3.2. Continuous experiments results:

Figure (12) demonstrates the effect of FO permeation time on FO water flux and reverse salt flux. It was found that the water flux was constant at 5 L/m^2hr during all operation time, while reverse salt flux decreased gradually by time from 0.054 at 1 hr to 0.031 $mol./m^2hr$ at 15 hrs. The gradual decrease in reverse salt flux may be attributed to the reduction of osmotic driving force by dilution of DS.

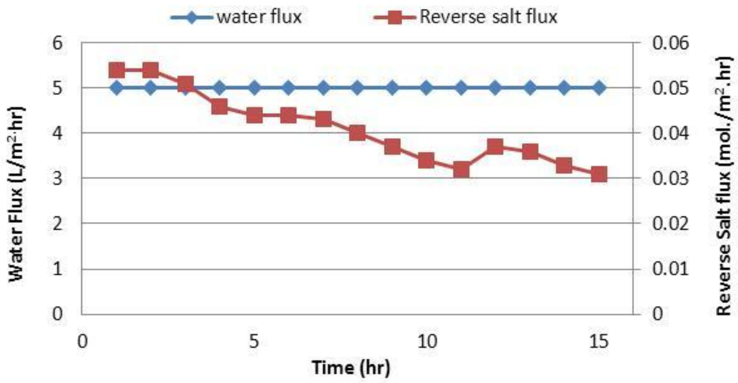

Figure (12): FO water & reverse solute fluxes as a function of time for FO/RO Continuous exp. [El-Salam Canal water (FS) and BW: 10 g/L (DS)]

In spite of the osmotic driving force between DS and FS was gradually decreased due to dilution of DS, it was noticed that the water flux remained constant during all time of continuous operation, this mean that the driving force still enough to proceed water permeation, and no fouling was occurred. In addition, this may be contribute to the fact that El-Salam Canal water did not contain mixtures of heavy metals, organic pollutants is the major contaminant present in it. According to Mi et al.[17]; they demonstrated that fouling in FO was more reversible than in RO. The structure of the organic fouling layer is influenced by the applied hydraulic pressure in RO, resulting in a more compact fouling layer. The more loose and sparse organic fouling layer in FO membrane is weak and easier to break. This may be explained the low tendency of fouling in the continuous experiment with El-Salam canal water due to the weak of organic cake layer which may be formed on the membrane surface beside that El-Salam Canal water only contain 76 mg/L COD.

Figure (13) shows the changes of RO permeate TDS and flux with time, it is clear that the TDS was decreased gradually from 955 mg/L at 1hr to 230 at 15 hrs, while the flux was increased from 21.5 to 30 L/m^2hr; this is due to the dilution of DS by time.

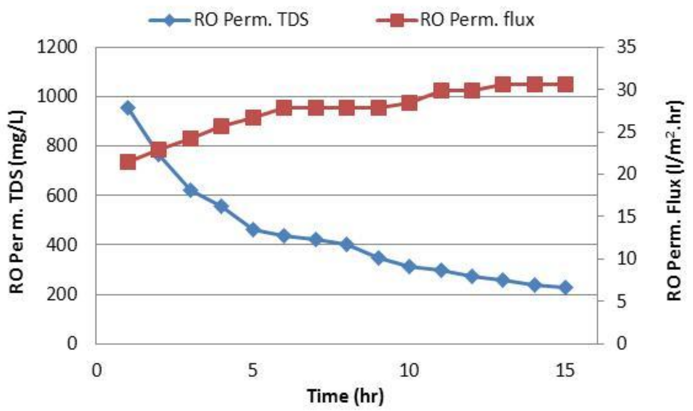

Figure (13): RO perm. and flux as a function of time for FO/RO Continuous exp. [El-Salam Canal water (FS) and BW: 10 g/L (DS)]

Table (3) demonstrates the analysis of the El-Salam Canal water and synthetic BW before and after FO/RO continuous process. The TDS of FS was increased from 2400 to 3360 mg/L, while the TDS of DS was decreased from 10000 to 6600 mg/L. The FS COD was decreased from 76 to 12 mg/L, and no COD was observed in DS after the FO/RO process. As illustrated previously, the decrease of COD in FS may be attributed to the adsorption on the membrane surface.

Table (3): Analysis of El-Salam Canal water and synthetic BW before and after FO/ROcontinuous process.

Time (hr) / Parameter	0	15
FS TDS (mg/L)	2400	3360
FS COD (mg/L)	76	12
DS TDS (mg/L)	10000	6600
DS COD (mg/L)	0	0

4. Conclusion and recommendations:

Finally, it was concluded that, the overall performance of pilot FO/RO process was higher than that obtained in bench scale experiments and the FO membrane can prevent all pollutants in FS from migration to DS. The results demonstrated thatthe dilution rate of BW reached to 43% after 3 hrs FO permeation time,this leading to the reduction of BW salinity from 10000 to 5574 mg/l, while, the addition of 20000 mg/L ammonium bicarbonate slightly increased dilution rate from 43% to 50%, and by duplicated the permeation time to 6 hrs it increased to 60%. The FO/RO system was tested on continuous operation for 15 hrs and no pollutant was detected neither in BW nor in RO permeate at the end of experiment. In addition FO water flux was remained almost constant, while RO permeate flux was increasing by time due to the gradual dilution of DS.

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