Investigating the effect of different NaCl concentrations as draw solution used to concentrate synthetic municipal wastewater in a Forward Osmosis system

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Abstract

The main bottleneck towards resource and energy valorization of municipal wastewater is the low strength of sewage; characterized by low organic matter and nutrient concentrations. In this study, a bench scale Forward Osmosis (FO) system with a cellulose triacetate membrane (CTA) was used as a pre-treatment system in order to concentrate synthetic municipal wastewater. Increasing concentrations of sodium chloride (NaCl) (0.6, 1.2, 1.7, 2.7 and 3 M) were tested as draw solution (DS), achieving a concentration factor ranging from 1.4 to 4.4. Afterwards, the different concentrated effluents of the FO were anaerobically treated. Based on the results, the most concentrated sewage with the higher water recovery rates yielded higher methane production. The concentration of 1.2 M NaCl (similar concentration to the brine produced in seawater desalination) proves to be the most attractive solution. High water flux (J_w) can be achieved by utilizing the by-product of the reverse osmosis (RO) system as draw solution and closing the loop on the management of two non-conventional water sources.

Keywords: Forward osmosis, synthetic municipal wastewater, water flux, NaCl, draw solution

1. Introduction

In the context of water scarcity management, non-conventional water sources have been identified as fundamental elements for a sustainable water future. Seawater and wastewater are two alternative types of water, which are readily available especially in coastal areas and islands (Tzanakakis et al., 2020). Various technologies have been developed for the production of water suitable for use from these non-conventional water sources, while in recent years the possibility of combining them into one plant is being investigated. The latter is based on the FO process, which is driven by the presence of a high salinity stream. FO is a membrane based process stimulated by the osmotic potential gradient, which triggers water molecules to pass through a semipermeable membrane from a solution of lower concentration (feed solution, FS) to a higher one (DS) (Yang et al., 2019). Compared to traditional membrane processes such as RO, the pressure-free FO is advantageous as it has a lower fouling tendency and decreased energy consumption. Another benefit of this integration is the utilization of the brine stream produced by the desalination plants that apply RO and to date is mainly discharged into the sea without further treatment and/or valorization (Ge et al., 2013). The application of seawater or concentrated brine as a DS candidate is a research challenge, both to reduce the environmental impact and to implement a more circular solution (Yang et al., 2019). By applying municipal wastewater as FS to the FO system, sewage can be converted into a small volume liquid containing a high concentration of organic matter, allowing the subsequent implementation of anaerobic treatment for energy recovery. In the last decade, efforts have been made to implement FO as a pre-concentration system and its combination with the anaerobic process (Ansari et al., 2018). However, key barriers such as the impact of salinity accumulation on the downstream anaerobic treatment remain a challenge.

In this study, the performance of a bench scale FO system was investigated under the application of increasing NaCl concentrations for the pre-treatment of synthetic municipal wastewater. Subsequently, the combined effect of increased organic matter and salts in methane recovery was tested through the anaerobic treatment of concentrated FO effluents.

2. Materials and Methods

2.1. Forward osmosis system

Figure 1 shows the overall layout used in the present study. Specifically, a bench scale FO system (CF042SS-FO, Sterlitech Corporation) was used, which consisted of 2 symmetrical channels with a total effective membrane area equal to 42 cm^2. All experiments were performed with a flat sheet CTA membrane (Fluid Technology Solutions (FTSH2O)), which was oriented facing the FS. Throughout the experiments the flow rate was kept constant and equal to 1.2 L/min, while it was continuously regulated by two flowmeters. In addition, the FS was placed on an electronic balance and its weight changes were constantly recorded online on a computer. As described by Bowden et al. (2012) these data were used to calculate the J_w. In addition, two conductivity meters were placed in both FS and DS. In the latter, the conductivity meter was connected to a controller (SC1000, Hach) and a peristaltic pump so as to control the osmotic pressure. The solutions were recirculated continuously by two pumps (Masterflex, Cole-Parmer 75211-5), while the initial volume of both solutions was 1 L. The synthetic municipal wastewater used in the present study contained the following concentrations: 600 mg/L of $C_8H_5KO_4$, 12 mg/L of NH_4Cl, 12 mg/L $(NH_4)_2SO_4$ and 6 mg/L KH_2PO_4.

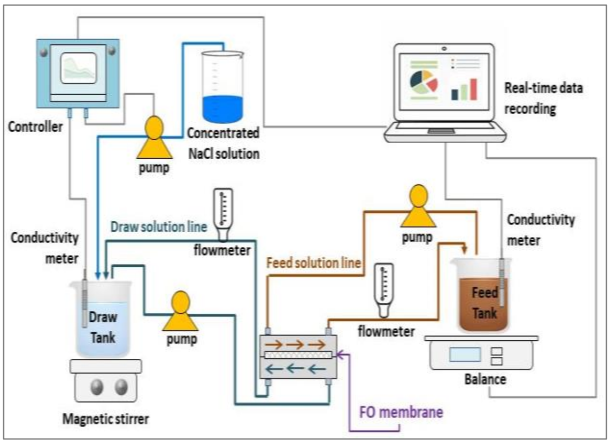

Figure 1. Schematic diagram of the laboratory scale FO system used in this study

2.2. Biochemical methane potential (BMP) apparatus

A BMP apparatus with 16 bottles was purchased from CJC labs and used in this study. The bottles consisted of 0.5 L of anaerobic sludge as inoculum and 0.25 L of different concentrated FO effluent as substrates, while the temperature was kept constant and equal to 35℃. Methane production was continuously recorded through an appropriate data acquisition system.

2.3. Analytical methods

The chemical oxygen demand (COD) concentration was determined using Hach LCK 314 vials, when the chloride concentration was less than 2000 mg/L. In the cases of higher concentrations than the above, TNT 815 vials were used.

3. Results and discussion

3.1. FO performance based on fluxes

The effect of draw solution concentration on the performance of the FO process is illustrated in Figure 2. The J_w increased significantly with the increase of the applied osmotic pressure, recording a percentage increase from the lowest (0.6 M NaCl) to the highest concentration (3 M NaCl) equal to 168%, as the J_w was equal to 5.05 LMH and 13.56 LMH, respectively. This linear correlation between J_w and concentration is also plotted in Figure 3, where the coefficient of determination R^2 was 0.995. As expected, the reverse salt flux (J_s) shows a similar upward trend, in contrast to specific reverse salt flux ($J_{specific}$), which is independent of concentration, giving on average a value equal to 0.7 g/L, similar to that found by Achilli et al. (2010).

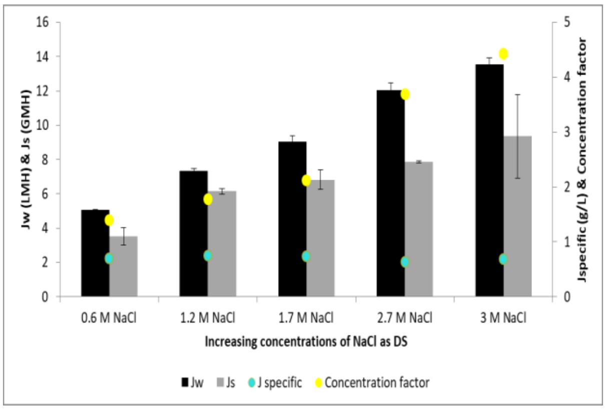

Figure 2. Average J_w, J_s, $J_{specific}$ and concentration factor at increasing concentrations of NaCl. Error bars represent the standard deviation of triplicate experiments

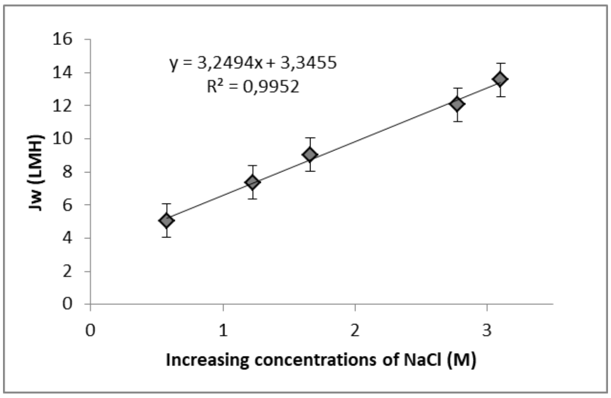

Figure 3. Relationship between J_w and increasing NaCl concentration. Error bars represent the standard deviation of triplicate experiments

3.2. FO performance based on COD concentration

In terms of concentrating efficiency, the highest DS concentrations at the same filtration time (12 hours) achieved a concertation factor of wastewater and COD equal to 4.4 and 2.65, correspondingly. However, at the same concentration (3M NaCl) in COD mass terms, about 43% of the organic matter was lost either on the draw solution side or on the membrane surface and/or the bench scale tubes (Figure 4). Specifically, a trend is observed wherein the higher the osmotic pressure is applied, the greater the percentage of organic matter that is lost.

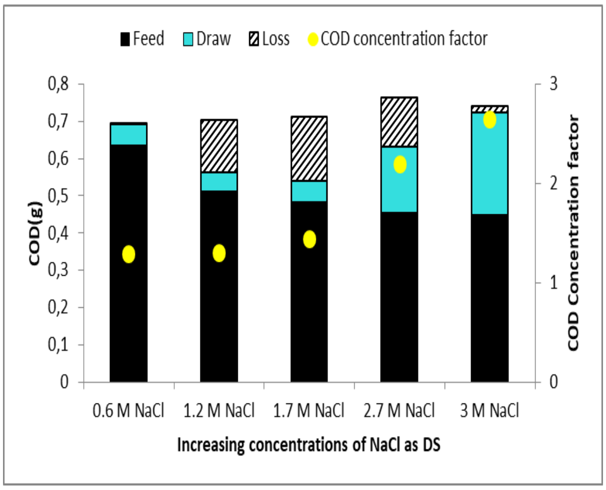

Figure 4. COD mass balance at the end of the experiment and COD concentration factor under increasing concentration of NaCl as DS

As shown in Figures 4 and 5, higher concentrations of organic matter and wastewater recovery can be achieved by applying high osmotic pressure. Lower concentrations require longer filtration time to reach similar yields. In addition, higher concentrations of NaCl as DS usually lead to accelerated fouling of the FO membrane and significantly reduce their lifespan. According to Vinardell et al. (2020), maintaining the wastewater recovery rate of the FO system close to 50% in a circular solution using brine as DS, the overall cost of the process is significantly reduced to 0.81 €/m^3. Therefore, the selected concentration of the DS should maintain a balance between these critical factors, making the concentration of 1.2 M NaCl more preferable.

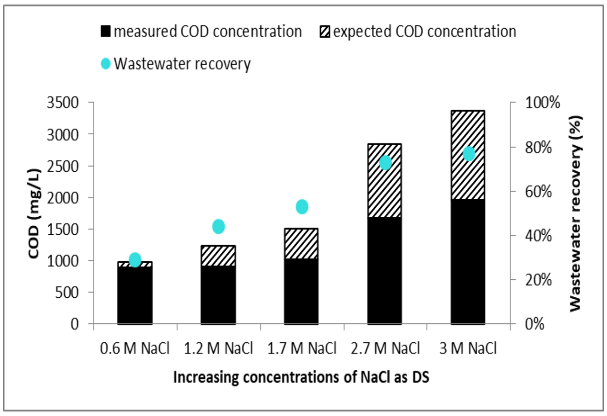

Figure 5. Measured and expected concentrations of COD in the final concentrated effluents of the FO system and wastewater recovery (%) under increasing NaCl concentrations as DS

3.3. Effect of different FO effluents on methane production

For the different DS concentrations, the effluents of the FO system were simulated in a batch anaerobic system based on the resulting concentrations of COD and NaCl. Figure 6 shows that as wastewater recovery rate increases, methane production increases significantly. More specifically, the implementation of the FO as a pre-treatment system has a favorable impact on the subsequent anaerobic process. The presence of a higher organic load boosts the efficiency of the anaerobic treatment. This is clear, as the unconcentrated wastewater with a COD concentration of less than 1 g/L yielded the lowest methane production.

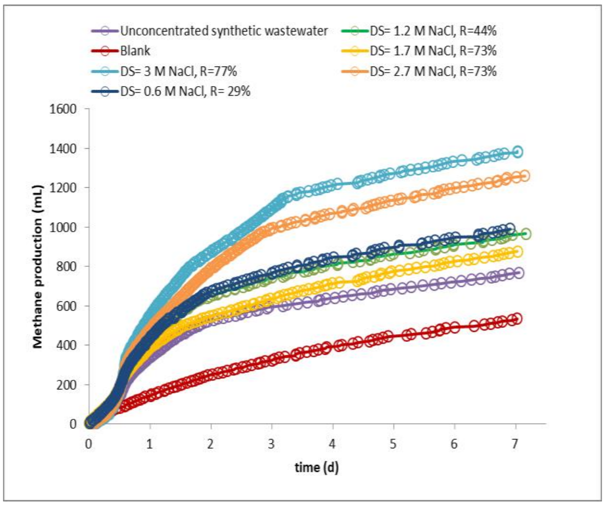

Figure 6. Methane production volumes recorded by the anaerobic treatment of unconcentrated wastewater and concentrated effluents derived from the FO system and resulted after the application of increasing NaCl concentrations as DS

4. Conclusion

The highest concentrations of NaCl used as DS in the laboratory FO system resulted in better performance in terms of J_w, water recovery rate and higher COD concentrations. The latter significantly enhanced the efficiency of the anaerobic process, yielding higher methane production. However, it should not be underestimated that under the application of the highest concentrations the greatest losses of organic mass were observed. Therefore, lower concentrations close to that of brine become more favorable and attractive for the application of a circular solution.

Acknowledgements

This research work was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "1st Call for H.F.R.I. Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment grant" (Project Number: 4008).

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