FACTORS AFFECT CLEAN WATER PRODUCTION PERFORMANCE: A REVIEW ON ULTRAFILTRATION MEMBRANE

Shahidul, M.I. and Michael A.B.

Faculty of Engineering, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia

Corresponding Author; Shahidul Islam, Email: mislam@unimas.my, shahid.buet1986@gmail.com

ABSTRACT: *This study aims to reveal factors that affect the performance of Ultrafilter membranes (UFM) in producing clean water. This study was designed to unlock the influence of feedwater quality, feedwater pre-treatment efficiency, energy consumption rate of UFM, and operating costs in producing clean water. Nearly a hundred journal articles related to the performance of UFM, published from 2000 to 2022, were reviewed. The outcome of the review revealed that factors such as feedwater pre-treatment, higher feedwater pressure, chemically enhanced backwash, and osmotic pressure are positively associated with the performance of the UFM. Additionally, feedwater quality such as low pH, TSS, turbidity, and COD are the sources of cake layer that affect energy consumption and operating cost in producing clean water by the UFM. This study concludes that UFM is an effective water treatment technology but its performance depends on feedwater quality and mode plant operations. This study also suggests further research on the UFM to discover optimum operating conditions to optimize the energy consumption rate and water production cost for contributing to achieving sustainable development goal 6(SDG 6).*

Keywords: Water Sustainability, Membrane technology, Clean Water, Production Performance, Energy consumption. Water production Cost.

1.0 BACKGROUND OF THE STUDY

This study aims to reveal the research findings conducted on factors that affect the performance of UFM in producing clean water from feedwater streams. This review focuses on feedwater quality, the performance of the feedwater pre-treatment, and the mode of the plant machinery operations that affect the overall performance of UFM in producing the desired water quality.

The UFM is getting a choice in the water purification industry due to its higher performance in separating suspended total solids (TSS), colloids, proteins, and bacteria from feedwater [1, 2]. The economic benefits of using this membrane are ease in plant operation and maintenance, a small footprint for plant installation, and less project implementation time. Additionally, simple design, less energy consumption rate, and capital investment are the potential benefits of UFM [2, 3].

The application of UFM in clean water production is sometimes limited by some factors; and to address this issue, extensive research has been carried out by researchers to understand the factors that affect the performance of this membrane. Among many, the potential factor is membrane fouling, which causes less water productivity, a higher energy consumption rate, and water production cost [4–6]. Indeed, the membrane fouling depends on the concentration of TSS, turbidity, NOM, bacteria, and colloidal materials in the feedwater [7, 8].

All these factors are associated with energy consumption, plant maintenance frequency, the life cycle of UFM modules, and water production cost. Indeed optimizing the overall performance requires understanding all these factors [9, 10]. With this background, this study is designed for reviewing relevant research reports to reveal the optimum operating conditions of UFM to achieve sustainable performance by reducing energy consumption and the cost of plant operation for producing clean water at an affordable cost.

2.0 Introduction to the Ultrafiltration Membrane in Producing Clean Water

This study aims to reveal the research findings conducted on factors that affect the performance of UFM in producing clean water from feedwater streams. UFM is a low-pressure driven process widely used in water treatment for power plants, chemical industries, food processing, electronic and pharmaceutical industry. Traditionally, this membrane has been installed at the secondary and tertiary levels in the water treatment process [11, 12].

Several indicators have been used to measure the performance of UFM. Efficiency in reducing COD, BOD, and pollutants from feed water has been used as an indicator for measuring the UFM's performance. Other potential indicators are reliability, energy consumption, and water production cost [13–15]. A series of research and development (R&D) activities have been conducted to optimize the performance of UFM. The research findings demonstrate that the potential advantages of using the UFM in water treatment are low energy consumption [kWh(m3-water)$^{-1}$] and low operating costs. It has been observed that the UFM systems require around 70% less space than typical media filtration systems [16, 17]. Additionally, the UFM system has been distinguished as low energy consumption, economically sustainable and environmentally friendly water treatment process [18,19]. However, problems such as membrane fouling and concentration polarization are the barriers to its use because fouling is responsible for permeate flux, membrane life, efficiency, increases energy consumption, and operating cost. These factors affect the overall UFM performance [20].

This study has been divided into two parts that address the factors and performance of UFM. Firstly, the indicators relating to the measurement of UFM performance in producing clean water. Secondly, the factors affecting the performance of UFM in producing clean water.

3.0 Indicators to Measure the Performance of UFM

A few indicators have been used to measure the performance of UFM in producing clean water. The indicators are the efficiency of permeate flux, productivity in water production, energy consumption rate [kWh(m3)$^{-1}$], and cost of water production per liter. The input-output model of producing clean water has been used by a few researchers to analyses the performance of UFM which is present by Figure 1.0 [21–24].

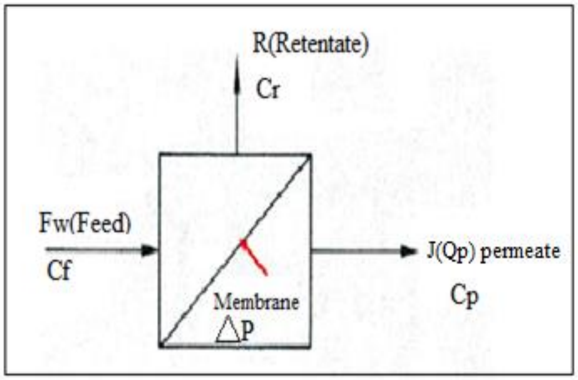

Figure 1.0

Here, F_w is the feed water. C_f presents the concentration (TSS, TDS and etc.) of feedwater. P stands for permeate flux (clean water). Cp is the mass concentration in permeate (TSS and TDS). R is retentate with diameters higher than the membrane pore. Cr is the concentration (TSS and TDS and bacteria) in the retentate. And, J is the flux of permeate. Equation 1.0 presents the model of permeate flux a measure of UFM performance [21-23, 25]

$$J = K\frac{\Delta P}{t} \qquad \text{Eq (1.0)}$$

Here, J is the permeate flux. ΔP *is* the pressure difference across the membrane. "t" is the membrane thickness. K is the factor of efficiency. Water input-output model has been used by Singh and Hankins, [25], and Ghidossi and Daorelle, [19] to measure the performance of UFM. Review on UFM performance concludes that efficiency, productivity, energy consumption rate and water production cost are the effective indicators of in clean water production performance.

4.0 Effect of Operating Parameters on the Performance of Ultrafiltration Membrane

Factors related to the feed water quality and operating parameters have been used to evaluate the performance of UFM. The feedwater quality was employed to measure its effect on the performance of UFM, which are as follows: suspended solids (TSS), pH, Chemical oxygen demand (COD), oxygen demand (BOD), feed water temperature, and water-born bacteria. The operating paraments of UFM used to evaluate the performance are: Operating time, feed water pressure, membrane backwash frequency, feed water flow rate, and process control system. The morphology of UFM was also used to evaluate the performance in clean water production.

4.1 **The effect of Pore Size on the Performance in Permeate Yield**

In water treatment, the membrane has been used to remove impurities from a feedwater stream. The common impurities in water streams are TSS, NOM, total dissolved solids (TDS), and bacteria [21]. According to Zirehpour *et al.*, UFM is a porous media used to separate impurities from the feedwater by the molecular sieving process [21]. The pore size distribution of the membrane family presents in Figure 2.0.

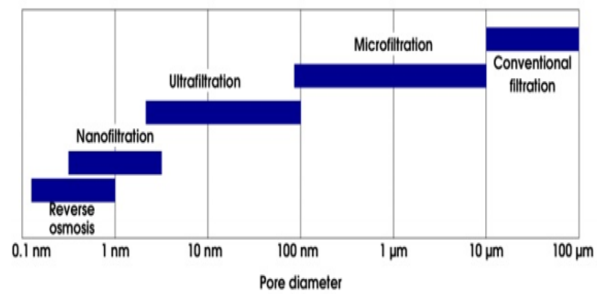

Figure 2.0: Pore Size Diameter of Membrane [26]

Figure 2.0 demonstrates that the pore size (Ø) of UFM ranges from 0.004 to 0.1 µm [27]. The rate of cake layer thickness development in membrane depends on the concentration of the feedwater impurities (TSS, NOM and turbidity) and membrane pore size. The research reports demonstrate that the rate of cake layer formation in smaller pore size membrane is faster than the higher pore size membrane and increase the down time of plant operations. The performance of smaller pore sized UFM in permeate yield and energy consumption is also higher compared to the larger sized membrane [28]–[30]. These findings indicate that the pore size of UFM has a significant role in the performance.

4.2. Effect of Feed Water TSS on the Performance of Ultrafiltration Membrane

Falsanis et al., 2010 [31] and Illueca et al., 2008 [32] discovered that TSS in feed water is positively associated with fouling formation rate in UFM and the overall performance of the membrane. The research report demonstrated that an increase of the TSS in feed water causes a fast cake layer formation and clogging the membrane pores resulting in increased of resistance to water flow. Additionally, overcoming resistance requires high-pressure pump, which consumes energy and increase operating cost of UFM. To address this issue, Bourgeous *et al*., [33], Kabsch-Korbutowicz *et al.*, [34] and Carroll *et al.*, [35] have used feedwater pre-treatment and chemical enhanced clean system.

4.3 Effect of Water Born Bacteria on the Performance of Ultrafilter Membrane Dialynas & Diamadopoulos [43], Arévalo *et al.*, [44], and Gómez *et al.*, [45] discovered during research with UFM that the coliform removal performance from water varied from 4.54 to 5.92 log (from 99.99715% to 99.99988%) [36–38]. In this regard, Collivignarelli *et al* and Jamalinezhad *et al*. reported that UFM is an effective means for producing acceptable quality water, despite (the disadvantages of these methods) several aspects limit the use of UFM technology [15, 39].

4.4 Effects of Pre-treatment Efficiency on the Performance of Ultrafilter Membrane

Various research reports demonstrated that TSS, NOM, turbidity, BOD, and COD are responsible for a cake layer formation on the UFM surface, which affects the performance of this membrane. Bourgeois *et al.*, [33], Carroll *et al.*, [35], and Kabsch *et al.*, [34] conducted experiments to investigate the effects of feedwater pre-treatment on the performance of UFM. Research findings disclosed that the efficiency of pre-treatment is positively associated with the fouling formation rate, permeate flux yield, and energy consumption rate. It was also reported that the effective feedwater pre-treatment process for achieving desired performance from the UFM are sedimentation, aeration, media filtration, and microfiltration [40–43]. To remove NOM from feedwater, Bolton *et al.*, [44] and Humbert *et al.*, [45] used anion exchange resin, which reduces cake layer formation.

Park *et al.*, [46] and Choi *et al.*, [47] used a coagulation process for feedwater pre-treatment to reduce turbidity and larger-sized organic particles responsible for COD. Research findings demonstrated that this process was effective to reduce (≥ 80%) COD from the feedwater. Similar research was conducted by

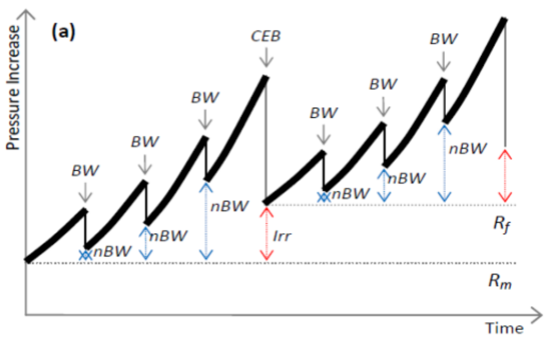

Figure 3.0: Effect of Backwash on UFM cleaning.

Falsanisi *et al.*, [31], Melgarejo *et al.*, [48], and Nader & Bastaki, [49] and found that the coagulation process is effective pre-treatment in reducing COD from the feedwater.

Jack, [50] and Azmi *et al*., [51] discovered that biomass in feed water is a source of membrane fouling. To address this problem, Shahidul *et al*., [52] conducted an experiment with biomass-enriched feedwater and discovered that pre-treatment with an aeration system and granular media was an effective pre-treatment in reducing fouling rate. This section of review concludes that feedwater pre-treatment efficiency affects UFM performance.

4.5 Effect of Feed Water pH on the Performance of Ultrafilter Membrane (24/10/2022)

A few experiments discovered that feed water with lower pH played a vital role in UFM performance. For example, Dong *et al*., [53] investigated the effect of pH on membrane fouling. The findings demonstrated that the pH reduction in feed water could decrease the molecular size of NOM and enhance the adsorption onto the membrane resulting in significant fouling. Dong *et al.*, [53] and Yitian *et al.*, [54] revealed that feed water pre-treatment with coagulation at the lower pH enhanced NOM removal from feed water, resulting in mitigating of fouling. Dong *et al*., [53], Yitian *et al*., [54], and Due *et al*., [55] concluded that fouling could occur in UFM at a lower feed water pH; and result in reducing permeate yield. Furthermore, Gao *et al*., [56] and Bogati, [57] disclosed that when UFM membranes operate with the lower pH feed water, the fouling rate increase and resulting in the increasing of energy consumption and operating costs. The conclusion is the effect of feedwater pH on membrane fouling depends on membrane charge characteristics because the fouling process is an outcome of interaction between UFM and foulant. Feed water with lower pH (<6), the fouling rate increase resulting in the increasing of energy consumption and operating costs. On the other hand, an alkaline feed pH (≥ 7.1), offers lesser fouling and operating cost is also lower.

4.6 Effect of Membrane Cleaning on the Performance Ultrafilter Membrane

The aims of the membrane cleaning is to restore original permeate flux rate. Falsanisi et aland Xu *et al.* revealed that the backwash period has a significant (p-Valve<0.05) effect on the removal of foulants accumulated on the membrane surface [31, 58]. In this aspect, Arévalo *et al*., found that membrane cleaning by water and chemical enhanced process has a significant effect on reducing cake layer that formed due to water born bacteria (bio-film) and NOM [37]. Want *et al.*, [59], Shi *et al*., [59], and Levitsky *et al*., [60] stated that membrane cleaning is a process that removes the deposited substances from membrane. Nguyen & Roddick) [61] and Levitsky *et al*., [60] pointed out that the common procedure of UFM cleaning are backwash by clean water (BW) and chemically enhanced backwash (CEB). The CEB is conducted by the alkaline (pH≥ 12) and acidic (pH≤5) solutions. The effect of membrane cleaning by BW and CEB is presented by Figure 3.0 [61, 62]. The figure demonstrates the effect of (BW) and CEB on UFM cleaning. The findings conclude that effect of CEB much higher than that of BW. The CEB is capable to restore (90%) of designed permeate flux.

4.7 Effect of Transmembrane Pressure on UFM Performance

According to Rosdianah & Nurmin, , [22], the net driving pressure or transmembrane pressure (TMP) is a measure of the actual driving pressure require to push the feed water through the membrane. Generally, permeate flux is associated with the TMP; the TMP can be estimated by the equation 6.0. [63].

$$TMP = \frac{P_f + P_c}{2} - P_p \qquad \text{Eq (6.0)}$$

Here, the measurement unit of TMP is kPa or psi, $\boldsymbol{P_p}$ is permeate pressure (kPa in psi), $\boldsymbol{P_f}$ is feed pressure (kPa in psi, $\boldsymbol{P_c}$) is concentrate pressure (kPa in psi). Rosdianah & Nurmin, [22], Li *et al*., [64], Xia *et al*., [65] discovered that permeate flus is increased with TMP up to the optimum level of pressure. After optimum level of flux, permeate flow rate starts to decline with feed pressure. In this regard, a few researches reported that the permeate flux decreases due to increase the cake layer on the membrane surface [66, 67]. It was also reported that hydrophobic nature of membrane materials is responsible for higher rate of cake layer formation and thereby lower flux rate [68, 69].

4.8 Effect of Feedwater Pressure on the Performance of Ultrafilter Membrane

A few research reports demonstrated that feedwater pressure affect the permeate yield. In this regard, Wahab *et al.* [70], Khairul *et al*., [71], and Wu *et al*., [72] discovered that the permeate flux in UFM increased with feed pressure to the optimum level, and then started to reduce. In this regard, Vishali & Kavitha and Wagner & Eng observed that feed water pressure has a positive impact on the clean water production performance of UFM [73, 74]. Figure 4.0 presents the effect of feed pressure on the permeate flux of UFM.

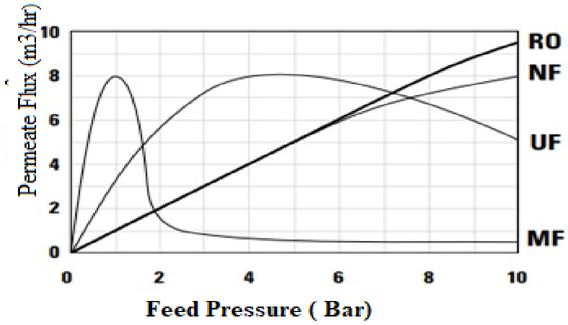

Figure 4.0: The effect of feed pressure on permeate flux of UFM [73]

Figure 4.0 demonstrates that permeate flux of UFM has increased with feed pressure. The optimum level is 4.0 bar and 8.0 m^3/hr. After 4.0 bar feed pressure, the flux rate tents to reduce. Zambujo, [33]; Yunos *et al*., [71] and Tansel *et al*., [75] have also found that feed water pressure has a positive effect on permeate flux and TSS separation of UFM.

4.9 Effect of Operating Time on the Performance (Permeate Flux) of Ultrafilter Membrane

Continuous plant operations without membrane cleaning are positively associated with the performance of UFM [69, 76].Wong *et al*., [24], and Kumar *et al.*, [77], reported that the operating hours of UFM have an effect on Permeate flux, cake layer thickness, and TMP. It was also pointed out that cake layer thickness is an outcome of membrane fouling, which creates resistance to water flow resulting in reduced permeate flux. Figure 5.0 presents the effect of filtration time on the cake layer thickness and feed water pressure.

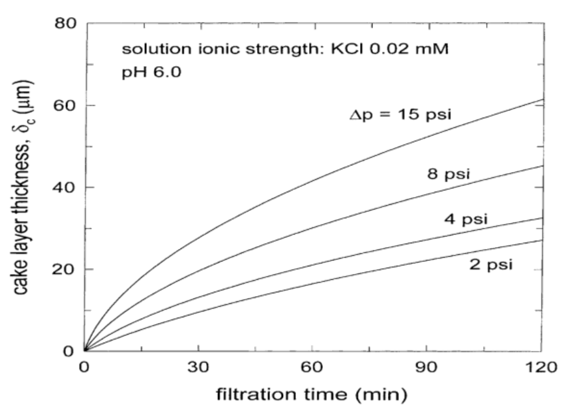

Figure 5.0: Effect of Filtration time on Cake Layer Thickness [20, 78, 79]

Figure 5.0 demonstrates that the cake layer thickness and feed pressure increased with the operating time (length) hour infiltration of UFM. In this regard, Beckmann *et al*., discovered that energy consumption in UFM is increased gradually with plant operating time due to increase cake layer thickness [20]. Figure 4.0 shows that after optimum level, the permeate flux reduced with feedwater pressure. This operating properties of UFM are supported by Beckmann *et al*., [20] and Myung *et al*., [78]. The conclusion of these finds is the higher length of UFM plant operations will increase cake layer thickness which would contribute to increase energy consumption and reduction of permeate flux.

4.10 Effect of Feedwater Temperature on the Performance of UFM

Lower feedwater temperature tends to reduce the permeate yield. Xu *et al*., [80] and Praneeth *et al.,* [81] had conducted research with UFM to evaluate the effect of feedwater temperature on permeate flux and discovered that at the low feedwater temperature affect the permeate flux of UFM. The research statement demonstrated that permeate flux could be dropped by 20% for feed water temperature drop from 30 to 18˚C. A similar research had conducted by Sheying *et al*., discovered that at the feedwater temperature less than 20˚C, the energy content of water molecules reduces, which decrease the velocity of water molecule and lost its ability to move through the membrane pores [34]. In this regard, Shengji *et al.*, [82] and Benítez *et al*., [83] disclosed that the higher temperature ($\geq 35^0$C) of feed water does not necessarily increase the permeate flux. The conclusion is feedwater temperature ($\leq 20^0$C) is sensitive to the permeate flux yield of UFM.

4.11 Effect of Process Control System on the Performance of Ultrafilter Membrane

Huang *et al*., [84],Paulen & Fikar, [85], and Bernhard & Uwe, [86] conducted experiments with the UFM to access the effect of real-time monitoring process control devices on membrane performance. The research reports demonstrate that the real-time monitoring and control system can limit the TSS, bacteria, colloidal particles, and turbidity in product water. A similar experiment has conducted by Huang *et al*., and Gilbert and the research findings demonstrated that the process control system in UFM plant operations was an effective tool to eliminate bacteria, colloids materials, suspended particles, and turbidity from feedwater [85, 87]**.** In the optimization aspect, Tomei *et al*., [88] suggesting using appropriate mathematical models and software to operate process control devices and UFM to optimize process performance. Appels *et al.*, [89] use a process control device and UFM to optimize the permeate flux and energy consumption, the research finding reported that the process control system is an effective tool to optimize the energy consumption rate [kWh(m3)$^{-1}$]. Thus, real-time monitoring process control device has appeared to be an effective tool in UFM plant operations in optimizing energy consumption and operating cost.

4.12 Effect of UFM Operating Parameters on Energy Consumption

The energy consumption rate is directly associated with the mode of UFM plant operation. Ghidossi *et al.* and Zambujo conducted experiments with UFM to determine the energy consumption rate in producing clean water from a feedwater stream [19, 90]. The research findings demonstrated that the energy consumption of feed pumps is positively associated with the feedwater pressure of the pump required to overcome membrane resistance. Ana *et al*., [91] and Li *et al*., [92] estimate the energy consumption of UFM, which presents by equation 7.0:

$$P(\frac{kW}{m^3}) = \frac{Q\Delta P}{\eta_{pump}} \qquad \text{Eq (7.0)}$$

Here *P* is the power consumed by pumps. *Q* (m^3h^{-1}) is the feed flow rate passing a membrane. Δp (bar) is the pressure loss during water flow through the UFM. Regarding optimizing the UFM energy consumption, Aditya et al.,2020 [10], Chang et al.,2019 [93], and Chon et al,.2012 [2] suggested to installing an efficient pre-treatment using macro and microfiltration system for removing fouling elements responsible membrane resistance due higher cake layer and TMP. The conclusion is energy consumption rate by UFM is increased with the higher level of TSS, TDS, and turbidity of feedwater [33]. It was also demonstrated that the energy consumption rate in UFM is Interswitch the cake layer thickness [56].

5.0 Literature Review Findings and Conclusion

This study aims to reveal factors that affect the performance of UFM in producing clean water. This research was designed to unlock the information on the clean water production efficiency, mode of plant operations, and maintenance that affect productivity, energy consumption and water production costs. This study has reviewed about 100 research publications and revealed that the overall performance of UFM has been measured with efficiency, productivity, energy consumption rate [$kWh(m^3)^{-1}$] , and the cost of water production per liter [$\$(Liter)^{-1}$].

Various research reports demonstrate that a few potential factors highly affect the performance of UFM. The factors are feed water flow rate, pH of feed water, the concentration of TSS, COD, BOD, and particulates of NOM in the feed water, the effectiveness of pre-treatment, feed water pressure, thickness of the cake layer developed on the membrane surface and membrane backwash efficiency.

The performance of UFM also depends on feedwater pressure, length of plant operating time, and pore size of UFM. Furthermore, feedwater quality and feed water pre-treatment efficiency in removing pollutants are positively associated with the UFM's performance. Additionally, the TSS, BOD, COD, NOM, and water-born bacteria are responsible for developing a cake layer on the membrane that affects the performance of UFM in producing clean water. Various researchers reported that higher feed water temperatures ($\geq 30^oC$) membrane is thermally stable, but at low-temperature ($20^oC\leq$) affects permeate flux of UFM. Permeate flux could reduce by 20% for feed water temperature drop from 30 ˚C to 18˚C. It was also reported that feedwater with lower pH($pH\leq 5.5$) is responsible for developing a higher rate of cake layer. The factors of poor feedwater pretreatment, the higher operating time of UFM with poor quality feedwater, poor cleaning performance affect the performance of UFM and resulting in a higher rate of energy consumption and higher water production cost.

Addressing the problems relating to the poor performance of UFM, various researchers have installed efficient pre-treatment with an aeration system to reduce fouling elements from feedwater. Additionally, the chemical-enhanced membrane cleaning with water backwash (both the top and bottom part of the membrane) have been used for reducing cake thickness aiming to decrease the energy consumption rate in water production. A few researchers have also installed process control devices in the UFM plant for monitoring and controlling the limit of TSS, bacteria, colloidal particles, and turbidity for optimizing the performance of the UFM. The process control system has appeared as an effective means for optimizing permeate flux, energy consumption rate, and water production cost. The findings of this study would useful for consultants and policymakers involved in clean water production. This study recommends further research to develop a model to optimize factors that affect the performance of UFM in producing clean water at the minimum energy and affordable cost for contributing to achieving sustainable water supply (SDG 6).

6.0 Acknowledgment

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