Water desalination and wastewater reuse using integrated reverse osmosis and forward osmosis system

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Abstract. Rapid industrial growth and urbanization will be the major causes of environmental pollution, wastewater, and water quality deterioration. However, the technological advancement in water purification and the water treatment area will be the breakthrough. In recent ten years, membrane-based technology evolved for wastewater treatment, water desalination and power generation. Integration of technology like reverse osmosis (RO) and forward osmosis (FO) provides ambitious benefits like efficient recovery of osmotic energy from brine, improvement in the tendency of fouling and scaling and less quantity of chemical required for pre-treatment. This study reviews various technology that helps towards the wastewater treatment and water desalination with different integration and configuration. Majorly RO and FO integration gives promising outcome in both the situation and it could be price competitive with reverse osmosis systems when its recovery rate of the system is very high, the membrane flux and the membrane cost of the forward osmosis are like those of the reverse osmosis, and the electricity cost is expensive. The most important thing in commercializing the FO process is enhancing performance by improving flux and increasing recovery. An industrial-scale RO-FO hybrid system will be lucrative with membrane that provides greater flux, high selectivity, better mechanical stability and robustness.

1. Introduction
In past decade, the water sacristy is becoming dangerous to some country and alarming notice to world. Rapid industrialisation and population growth are the major cause for the shortage of fresh water and became the environmental concern [1]. It also affecting the social and economic development. United Nations World Water Development Report (UN WWDR 2020) entitled ‘Water and Climate Change’ shows that in present scenario 4 billion people are directly or indirectly affected by the water scarcity and this number could be increase by 5.7 billion in 2050, which shows the significance of water as a natural and global resource [2]. Figure 1 show the water stress of different country in the world by the year of 2040.

Depletion of various fresh water source leads us towards the threatening level of scarcity, focus on various techniques that treat groundwater, wastewater and seawater leads to ways to meet global water demand. Absorption of such sources like brackish water and wastewater as well as seawater desalination gives abundant opportunity towards the water scarcity [3]. Membrane based technology is the promising future to tackle water issue [4]. From 1960, the reverse osmosis dominating technology in the field of purification and desalination, with highest percentage of market cover in recent years [5]. Around the globe, majority desalination and water purification plant are based on reverse osmosis technology because of simple nature of operation and cost effectiveness.
compare to other thermal based process. The global marketplace for desalination industries is based on reverse osmosis technology, which growing steadily and tends to reach its mature stage. Because of advancement in new technologies in terms of power consumption and membrane innovations, RO becomes the dominating technology in terms of water purification and water desalination [6]. Research and innovation in this type of technology mainly focuses on the reducing the energy consumption, use of renewable type of energy sources and advancement in the membrane. Researcher also focusing to address the various other types of problem like fouling and scaling effect on membrane and try to obtain membrane with suitable high flux [7].

![Water Stress by Country: 2040](image)

Figure 1. Projected water stress of different country by year 2040. [8]

Reliability of reverse osmosis for brackish/ground water and seawater is widely accepted and the technology is most suitable for the low cost operation of sweater desalination and water purification [9]. Feed water characteristics, membrane parameter and operating parameter are the parameter are the factors which affects the whole process efficiency of the reverse osmosis.

Forward osmosis is the process in which flow of two solution with different concentration are differentiated by semipermeable membrane, in which water particles cross from lesser concentration solution to higher concentration solution due to osmotic pressure dissimilarity. This process utilises very low amount of energy for only circulate the solution through the process. The aim of the forward osmosis process in integrated process is to weaken the seawater with incoming wastewater which reduce the pressure for next reverse osmosis process and makes the process energy efficient. Ultimately, the reutilisation of wastewater is advantageous for not only integrated process but also reduce the brine discharge also help to lower the final concentration of the brine.

Various literature has been carried out for FO-RO (Forward Osmosis – Reverse Osmosis) numerical models [10][11] and emphasis that implementation of forward osmosis may reduce the specific energy consumption (SEC) compared to traditional sweater reverse osmosis [12]. Integration of FO-RO can be advantageous in terms of energy and financial terms over the standalone systems.

2. Theoretical Background:

Osmosis is the phenomenon has been known to humankind since many years. It is a natural process, which occurs due to concentration difference (osmotic pressure difference), in which water molecules travel from lesser concentration solution to higher concentration solution through semipermeable membrane shown in figure 2A. Transfer of water molecules can be reversed or stopped using mechanically applied pressure or externally applied pressure. In such case like reversal flow due to externally applied pressure, the external applied pressure overcome the osmotic pressure and water particles are compelled to transfer in the opposite direction of the naturally occurred osmosis. This phenomenon is known as reverse osmosis which is seen in figure 2B. In osmotic equilibrium phenomenon, the water particles are passed through semipermeable membrane and reject the salt. The transfer of water molecules continues till the phase of osmotic equilibrium (figure 2C) where chemical potential becomes equal across the membrane.
Forward osmosis is the phenomenon based on the principle of the osmosis, in which two solution with different concentration is separated with selectively permeable membrane and passed side by side in parallel or in opposite direction. Where, membrane act as selective barrier which allows only water particles to passed and block the other large molecules. Here, on the completion of this process solution with lower concentration (feed solution) is become more concentrated and solution with higher concentration (draw solution) is become diluted. The difference between reverse and forward osmosis is the motive force. The forward osmosis process having numerous applications like wastewater treatment, in food processing industries, brackish/seawater desalination, in biotechnology, power generation using PAFO (pressure assisted forward osmosis) and also in medical applications. It is an alternative process for the treatment of wastewater and high quality water production [15]. The draw solution used in the forward osmosis process having distinct features, which can be reusable after extracting water from it by utilising draw solution regeneration process. Because of this reason forward osmosis is generally coupled with any draw solution regeneration techniques or post treatment step. The use of draw solution is the distinctive feature of forward osmosis system. In forward osmosis system, the feed solution is becoming concentrated and draw solution become diluted, after that draw solution regeneration process is required to recover product water and/or reuse draw solution component. This is the reason why forward osmosis is generally combined with a post step to treat weaken draw solution. Draw solution recovery stage after FO becomes main power consuming system, which makes forward osmosis process less competitive [16]. Therefore, the implementation of forward osmosis technology in actual commercial level depends upon the efficiency of recovery system (draw solution recovery) and effectiveness of overall process.

3. Integrated RO-FO system
Hybridisation is the techniques where various combination is used in single treatment unit while integrated system is where assembly of different water and wastewater treatment process is in sequence. However, both the techniques have different capabilities. Following are some different purposes of hybrid/integrated water treatment system [17],

- Overall, it achieves better performance than any of the single components. Imperfection of any system can be minimised using integrated system.
- To get desired water quality (treated water quality).
- It overcome the trouble to extract water from nonconventional as well as polluted water source, and from untapped wastewater.
- To extend the life of system operation.
- It obeys with the rules and regulation.
- It makes sure that the efficiency of the treatment is good, and it removes various hazardous substance with good recovery of resource (like water as well as nutrients, energy etc.) in wastewater.
- To achieve zero liquid discharge with no liquid discharge to harm or pollute the environment.

3.1 Approach for sustainability and design of advanced integrated systems:
Implementation of integrated wastewater treatment and water desalination system has already progressed around the globe. Innovation in technology tied the research and industrial community together for further advancement in various design-based improvement and sustainable development. The latest is defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs [18]. For the sustainable integrated wastewater treatment, following are several approaches that can be focused,

- Benchmarking the technology for the perspective of sustainability (social, environmental, and economic) and global availability.
- Integration of these techniques with renewable energy sources like solar, wind etc. for better prospect of technology.
- Reduce, reuse, recover and conserve the resources that can be utilised in these techniques.
- Minimise the consumption of chemicals and reduce the secondary waste production.

The motto behind these types of sustainable hybrid/integrated wastewater treatment and water desalination technologies is that to reduce/prevent the depletion of the resources, minimising the environmental impact and preserve the energy while achieving the target aims like provide sufficient and safe drinking water and retrieve and reuse water from the pollute source.

4. Integrated system for wastewater treatment:

Developing interest of drinking water and consciousness of the capability of wastewater (city wastewater) recuperation have drawn out the advancement in wastewater treatment and asset recuperation methods. These arrangements can address the issue of water shortage and natural contamination. Membrane based technologies like reverse osmosis, ultra-filtration, nano filtration etc. can handled the most of dissolved impurities, organic chemical, constituents, natural organic matter and heavy metals. When wastewater is directly pass through the membrane, fouling is expected. For the irreversible type fouling in RO Membrane, Intensive chemical cleaning is required which lessen the lifespan of membrane and escalate the water treatment cost. As well as contrasting and customary water treatment, the activity at raised pressing factors likewise increments both capital and working expenses. Following are some challenges faced by the convention water treatment plants:

- a) Emerging contaminants
- b) Increasingly stringent environmental regulations
- c) Pathogenic microorganisms
- d) Disinfection by-products

Majority of integrated reverse osmosis – forward osmosis system for water reuse and wastewater treatment are generally used forward osmosis technology as a pre-treatment of a first stage of the integrated system. For example, seawater desalination generally used forward osmosis as a first stage of the integrated system. In which wastewater is taken as feed solution and ocean water as a draw solution. Reverse osmosis utilised as posttreatment to extract water from draw solution and restore the draw solution. The utilization of wastewater as the feed solution for forward osmosis measure has given understanding into the idea of utilizing forward osmosis to dodge expensive treatment of effluents by regular treatment measures. Seawater as draw solution is one of the most cost-effective solution for integrated FO-RO system since higher osmotic pressure gives ocean water advantage over the sewage water. The prime objective of forward osmosis in integrated system is to reduction of salinity or waste in stream.

Investigation on hybrid/integrated RO-FO system utilised for wastewater treatment also focuses on the secondary effluents. The schematic shows the integrated seawater desalination process, in which impaired quality water is applied as the feed solution in forward osmosis system while pre-treated seawater is utilised as draw solution in the system. The forward osmosis membrane with high rejection obstruct various suspended and dissolved solid [19]. Numerous examinations have announced that forward osmosis combined with reverse osmosis is found to function as a twofold boundary against those demonstrating pollutants, boron, chemically dynamic mixes, chemicals, and other natural toxins [20]. Utilising municipal effluent (secondary effluent) as the feed of forward osmosis process and
regular/common oceanwater as a draw solution will be resulting the rejection of majority micropollutant in forward osmosis system.

Figure 3. Schematic of integrated SWRO process [21] and FO-RO integration mode for matched volume. [22]

The system rejects majority of hydrophilic micropollutants about to 96 to 99 percentage. Hydrophobic unbiased and hydrophobic impartial mixes removal rate is low compared to the hydrophilic micropollutants [23]. Incorporation with low pressure reverse osmosis (LPRO), the FO-LPRO integrated system had compelling execution in dismissing low-sub-atomic weight micropollutants past 89.1% and other contaminants and mixes can be removed up to 99%. System shown in figure 3 is proposed and implemented by Cath et al. to dilute seawater using two step forward osmosis system with the integration of reverse osmosis system [24]. Which demonstrate the higher removal of natural synthetic compound. Other benefits of this system are the lower specific energy consumption and good recovery with less amount of fouling propensity.

5. Integrated RO-FO systems for water desalination

Seawater/Oceanwater desalination is an encouraging path for addressing the world's water shortage issue. Oceanwater desalination by reverse osmosis measure has been the biggest portion of worldwide desalination limit. Energy consumption in reverse osmosis is a burning issue because of it is operated on pressure driven mechanism [13]. Because of energy intensive nature of sea water reverse osmosis (SWRO), may be the problem turns form water scarcity to energy problem. Energy productivity of the system can address the issue and effort are made towards this direction to improve the desalination process.

Ge et al. established Forward osmosis combined with membrane distillation system which is polyelectrolyte based for the reuse of wastewater and recycle of acid dye. For this type of experimentation high performance polyvinylidene fluoride membrane were utilised to reuse of the draw solute and treat the wastewater [26].The study reveals that, systems still lacks in high performance FO membrane with high flux and high salt rejection and draw solution with high osmotic pressure, which is cost effective and have minimum reverse fluxes [27].

Forward osmosis is process which consume low energy utilising draw solution with sufficiently high osmotic pressure [28]. This is the motivation behind, why forward osmosis is utilized as energy saving cycle option in contrast to other regular reverse osmosis oceanwater desalination.

Various literature shows that the seawater desalination can be done through novel concept of combined forward osmosis and reverse osmosis system, where oceanwater is used as the feed solution and more concentrate non-volatile salt like NaCl, MgCl₂, etc. used as draw solution [29]. The water from the feed side is move alongside the membrane and dilute the draw solution, due to this process majority of the contaminants and salt are removed in forward osmosis process. The clean water is extracted form the draw solution in next step in reverse osmosis. This investigation carried out form bench scale to pilot
scale test. Flux lost by fouling (irreversible) can be re-established by occasional actual cleaning and additionally osmotic discharging in forward osmosis [30].

Figure 4. An integrated Forward osmosis – Reverse Osmosis hybrid systems for direct desalination [29] and Combined reverse osmosis forward osmosis system for indirect water desalination. [31]

Less energy requirement for pre-treatment, longer lifespan of the membrane and reduction in fouling are the major advantages of the periodic cleaning of the system. Theoretical analysis of the integrated forward osmosis – reverse osmosis suggests that high recovery up to 80% can be achieved in integrated FO-SWRO process [28]. A case study of Al Najdah of Oman suggest that combined FO-RO system provide numerous benefits like reduction in OPEX, reduction in ozone harming substance impression and lower consumption of the chemicals compared to conventional SWRO. It is challenge to extract water form draw solution using less energy irrespective to draw used, till the use of low cost energy using renewable energy source or utilisation of waste energy [4]. The integrated system may show the advantage of cost-saving by decreasing labour and upkeek interest for control of fouling and by changing membrane compared to conventional seawater RO system.

Challenges related to reverse draw solute can be overcome by improvement in design of membrane and proper draw solution selection. This is the process with two step including reverse osmosis and forward osmosis for indirect desalination shown in figure 4 [30]. This process used low salinity impaired water as a feed solution which is used to dilute the draws solution (seawater). Finally, this draw solution is supplied to posttreatment reverse osmosis process to extract the fresh water utilising low amount of energy input. The output of this forward osmosis process can be also treated by LPRO (low pressure reverse osmosis) with combination of forward osmosis system with LPRO system. Weakening of seawater by FO with free environmentally friendly energy, less working expenses, different boundaries for water sanitization, limited utilization of synthetic compounds, and decrease of reverse osmosis fouling and scaling is observed in many of investigation [32]. Indirect desalination via integrated reverse osmosis – forward osmosis system is the sore subject of investigation in research community and enlarging this technology from lab scale to the large/industrial level scale is the one of the main challenge. This is the reason to eloborate and provide good understanding towards the process, economic feasibility and environmental impact of the system.

6. Batch Reverse Osmosis System:

Batch reverse osmosis process is a cyclic process which uses the minimum average feed pressure for the purpose of desalination, which minimise the specific energy consumption. The batch reverse osmosis process uses the variation of pressure along the cycle to get higher recovery ratio. In standard continuous RO process the pressure is remains constant during whole cycle.

A proposed batch reverse osmosis configuration by Sandra P. Córdoba et al. is shown in figure 5. The process occurs in following manner. At the initial stage of process, high-pressure pumps feed water to first side (side 1) of the piston in high pressurised tank. This is the process to feed the water in the system. After that, the high-pressure pump uses to feed the water in second side (side 2) and this water is used to displace the water on first side with piston arrangement which is directed to the RO modules with high pressure. Pure water from RO module is collected at particular location and brine/RO reject will be recirculated to the first side of the high-pressurised tank using recirculating pump.
The instant at which the piston arrives at the other end of the high-pressure tank is the sign to complete stage 1 and a purge stage is started. A restriction shuts the recirculation loop, the recirculation pump discharges the salt water in the pipelines and replaces it using feedwater. Then, the high-pressure pump will be started to dispatch the feed water to the reverse osmosis modules and generate clean water in batch mode. At that point, the module purges the salt water/brine into the feed flow loop at high pressure on the other side of piston, where restriction again decrease the pressure to remove the salt water and reintroduce the feed. Later this process the batch RO system is again prepared to produce clean water. The figure 5 shows the different steps for feed, purge and refill the improved batch RO system.

Figure 5. Batch reverse osmosis configuration and Steps in the batch RO configuration [33]

Integration of batch reverse osmosis (BRO) with various other technologies like forward osmosis, electrodialysis, electro coagulation etc. will give numerous amounts of benefit compare to stand alone system. This study focuses on the various application of integrated FO-RO system and lead this study towards the new approach of integrated batch reverse osmosis with other technology.

6.1 Comparison between batch reverse osmosis and convention continuous reverse osmosis

Tianyu Qiu et al. carried out study that compares the various type of reverse osmosis configuration [34]. The carried out this study for single stage, multistage, close circuit, and batch mode reverse osmosis. Figure 6 shows the variation of normalised energy consumption with recovery ratio for all above mentioned mode. Particularly, In Batch RO the specific energy consumption has lowest, which is reduced by 30% compared to close circuit desalination RO at 80 % recovery ratio. Ultimately, batch mode reverse osmosis operation gives higher recovery with less specific energy consumption and at less cost compared to conventional desalination system. During batch or close circuit operation (cyclic operation) pressurisation and depressurisation of fluid occurs on the outer area of the membrane, which affect the stability of the membrane. Fouling and scaling problem in batch reverse osmosis is less due to purging of brine is done using freshwater introduction and these becomes advantageous for the system.

Figure 6. Normalised SEC vs Recovery ratio. [34]
Apart from energy consumption there are several other advantages that benefits the batch reverse osmosis configuration, which are listed below:

- System exhibits maximum recovery batch by batch with simple controls.
- Permeate water quality can be control by stopping the process and improved by total/partial second pass treatment.
- Batch reverse osmosis is flexible system when it changes the feed water quality.
- Cleaning is simple and easily implemented in this type of system.

This technology can potentially used in integration with forward osmosis system will provide benefits in terms of fouling and energy consumption.

7. Challenges and Future trend:

The integrated/hybrid system for water, wastewater treatment and water desalination has helps towards the various challenges related to clean water production, reject management, energy consumption issues as well as environmental pollution related issue. Although, apart from it there are various challenges in front of this technologies like technological maturity in term of membrane development, commercialisation of this technology, operation, and handling of these plants at large scale etc. Another constrain is that some of the integrated system requires pre- and post-treatment to eliminate some of the impurities and achieve zero liquid discharge which is advantage to system as well as the environment, but these technologies are more energy intensive and increase the capital and operation cost of the system. Various literature reported to recover the resources utilising during the process, but few of them were discussing the reutilisation of the resources and making the process more efficient.

Energy consumption is another issue for the integrated/hybrid technologies. As earlier mentioned, that some of the technologies are very energy intensive which increase the overall cost of the system. Integration of renewable energy source with the system leads to the clean energy and lower operating cost. These membrane-based technology needs frequent cleaning to eliminate impurities concentrated on the membrane surface. Generated effluent from this type of processes should be taken care of appropriately before released in to open climate or in channel. Indirectly, this waste management add up the operating cost. This is the issue that can be needs to address with better cleaning techniques or low-cost waste management techniques.

8. Conclusion

Reverse osmosis is most mature and established technology in wastewater treatment and seawater desalination. As well forward osmosis with no applied pressure and with less membrane fouling will be the favourable option for the water treatment processes. The advancement in wastewater treatment and water desalination technologies enables the adaptable combination of different treatment process to meet achievable target like reutilisation of the recovered resource and optimisation of process efficiency with less environmental impact. The integration of pressure driven, and osmotic driven membrane process (like integrated RO-FO) gives benefits of both system with synergetic effect, which makes this type of integration as a system with great potential. Like total energy consumption is reduced by 15% in integrated FO-RO system compare to seawater reverse osmosis system.

The limitation for this type of system is the availability of the membrane for the forward osmosis system, unavailability of ideal draw solution, performance of the system is bounded by the concentration polarisation, draw solute diffusion and membrane fouling. This will limit the economic feasibility of the system. By overcoming these challenges, potentially system can be achieved with great efficiency with minimum losses. Though, in depth studies on sustainable development of this type of technologies has been carried out, but sustainability of hybrid/integrated system have not been widely reported yet. Need to develop more understanding towards the filling the knowledge gap between sustainable development, system design and economic feasibility. The findings from this study will be utilised for the development and experimental investigation of integrated batch reverse osmosis – forward osmosis system.
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