Communication in Physical Sciences 2020, 6(1): 726-737

Review of Reverse Osmosis as Green Technology against Water Supply: Challenges and the way Forward

Ahamefula A. Ahuchaogu* **and Chukwuemeka T. Adu**

Received 19 September 2020/Accepted 02 October 2020/Published online: 04 October 2020

Abstract *Contaminated water can be treated and be re-used but where portable water supply is not available, implementation of reverse osmosis technology is capable of increasing the volume of water supply. This paper reviewed the technology behind reverse osmosis, their proportional utilization, methods classification, expected technical problems and solutions that are connected with its operation. Desalination is admitted as one of the major application areas of reverse osmosis program. The review acknowledges fouling, scale formation and corrosion as the major challenges that can hinder the operation of reverse osmosis plants and recommended precautional methods during design, testing and implementation of reverse osmosis plants.*

Key Words: *Water supply, shortage, challenges, reverse osmosis*

Ahamefula A. Ahuchaogu
Department of Pure and Industry Chemistry,
Abia state University, Uturu. Abia State, Nigeria
Email: ahuchaogua@gmail.com
Orcid id:0000-0002-6412-7487

Chukwuemeka T. Adu
Department of Pure and Industry Chemistry
Abia state University, Uturu. Abia State, Nigeria
Email: aduchukas@gmail.com

1.0 Introduction

Water scarcity in most settlement in the world has attracted research attention on the establishment and implementation of innovative, reliable and ecofriendly technologies that can be harnessed as sources of sustainable solutions to water crisis. Impart of **c**limate change on the pattern and distribution of rainfall patterns and drought in some parts of the world has significantly contributed to the global problem of water shortage. According to Mekonnen and Hoekstra (2016), estimated population of 4 billion people are affected by water shortage for at least 1 month every year while the figure is expected to multiply in the coming decades, if adequate remediation procedures are not implemented. Availability of portable water has also been limited by population growth, industrialization, contamination of freshwater resources, and climate change. Also, knowledge of enormous societal and ecological benefits of adequate water resources, economic vitality, public health, national security, and ecosystem friendly have received wider acceptability and is facilitating the search for technological solution to water shortages. Therefore, there is need to implement factors and policies that can alleviate the impact of water shortage. These may include water conservation, repair of infrastructure, and improved supply and distribution systems. However, while these measures are important, they can only improve the use of existing water resources rather than increasing their supply. Membrane-based filtration/ desalination has been recognized as one of the promising approaches to resolve the global water challenges (Shannon *et al*., 2008). Desalination, a technology that converts saline water into clean water offers a seemingly unlimited, steady supply of high-quality water, without impairing natural freshwater ecosystems. Desalination is assumed to be the most feasible water purification technology amongst others towards increasing global freshwater to millions across the world solutions. Expanding interest in desalination as an attractive solution is increasing because sea water desalination has great potential of increasing global freshwater supplies considering the vast amount of continental seawater bodies spanning the earth surface (Hameeteman.,2013).

There has been rapid growth in the installation of seawater desalination facilities in the past decade as a means to augment water supply in countries that are facing water stress (Elimelech and

Phillip.,2011). A great deal can be achieved by improving the effectiveness and efficiency of water purification technology, to produce clean water and protect the environment in a sustainable manner, is considered by many as perhaps the main challenge of the 21st century (Elimelech.,2006).Therefore, research interests on desalination are currently expanding towards optimum status with the aim of averting increasing global challenges in water supply in some countries.

In recent years, reverse osmosis (RO) is a leading technology that has guaranteed future hope towards increasing the supply of clean water through the purification of nontraditional water sources such as seawater, brackish, and wastewater (Baker., 2004)). It is a process that is practically simple to design and operate compared to some traditional separation processes such as extraction, distillation, ion exchange, and adsorption. Therefore, RO is the simplest and most efficient technology for seawater desalination purposes (Rao *et al*.,.1997). According to Fritzmann *et* al. (2007), membrane-based desalination accounts for about 44 % of the installed capacity of water desalination globally (Fritzmann *et al*.,2007). Reverse osmosis is a pressure-driven membrane-based process, where the membrane (almost always polymers) serves as the engine of the process in separating the undesired constituents from feed water source to obtain the desired pure product. The schematic representation of reverse osmosis process is shown in Fig.1. An RO membrane functions as a semi-permeable barrier that allows selective transport of a particular species (solvent, usually water) while partially or completely blocking other species (solutes, such as salt). The separation characteristics depend upon the properties of the membrane which in turn depend on the chemical structure of the membrane material. The fast-growing application of reverse osmosis processes in sea and brackish water desalination, and wastewater purification is attributed to the development of more sustainable membrane technologies that have lowered the cost of membrane modules and produced higher quality filtrate (Matin *et al*.,2011).

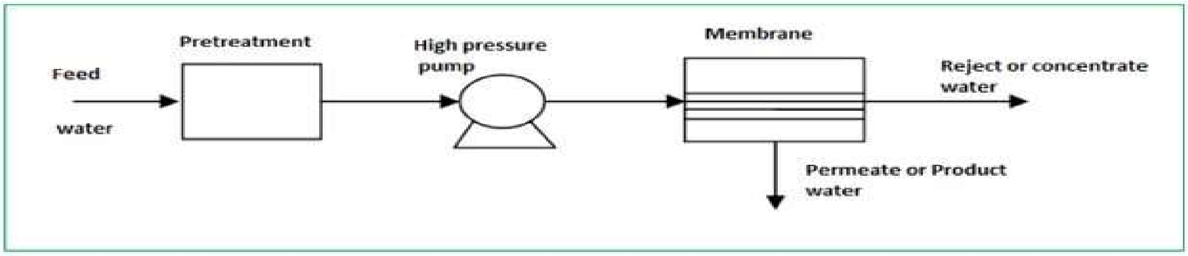

Fig. 1: Schematic representation of reverse osmosis process (Ahuchaogu *et al*.,2018)

2.0 Desalination

Desalination is one of the most feasible strategy amongst others towards increasing global freshwater supply via desalination of seawater The major desalination technologies currently in use are based on membrane separation via RO and thermal distillation (multistage flash and effect distillation), with RO accounting for over 50% of the installed capacity (Zhou and Tol.,2005; Veerapaneni *et al*.,2007).Thermal desalination is a process of boiling and evaporating salt water and condensing the resulting vapor. Two of the commonly used thermal processes are multistage flash distillation (MSF) and multiple effect distillation (MED). Both processes work in a way similar to the evaporation process: the saline water passes through a series of chambers, with each successive chamber operating at a progressively lower pressure.

Thermal desalination (i.e. MED, MSF,) are mainly applied in oil-rich countries of the Middle East. However, conventional thermal desalination processes are inefficient in utilization of energy and the installations often suffer from corrosion and scaling which have the potential of degrading the operation facilities (Bourounia *et al*.,2001). Proportional utilization of the different methods (in percentage) is shown in Fig. 2 which indicated that the RO is currently the dominant seawater desalination technology and is widely applied for both drinking and industrial water production. The rapid growth of the application of RO desalination technology in recent years is not only driven by the steady increase in water demand, but also by the declining RO water production cost (Lattemann *et al*.,2010).

Seawater desalination by RO is taken into account to be more energy efficient, more compact, and more flexible (modular) compared to other desalination processes. The present water cost of RO desalination is usually cheaper than thermal desalination processes (GWI.,2007). The cost may further decrease if a more efficient and/or extra-large RO systems is installed in the near future the past decade, particularly due to the event of more (Kurihara,and Hanakawa.,2013). For large-scale desalination, RO has advanced significantly within robust membranes and really efficient energy recovery systems. As a result, the reduction in energy consumption of RO desalination has been remarkable (Alonitis *et al*., 2003; Seacord *et al*.,2006).

.

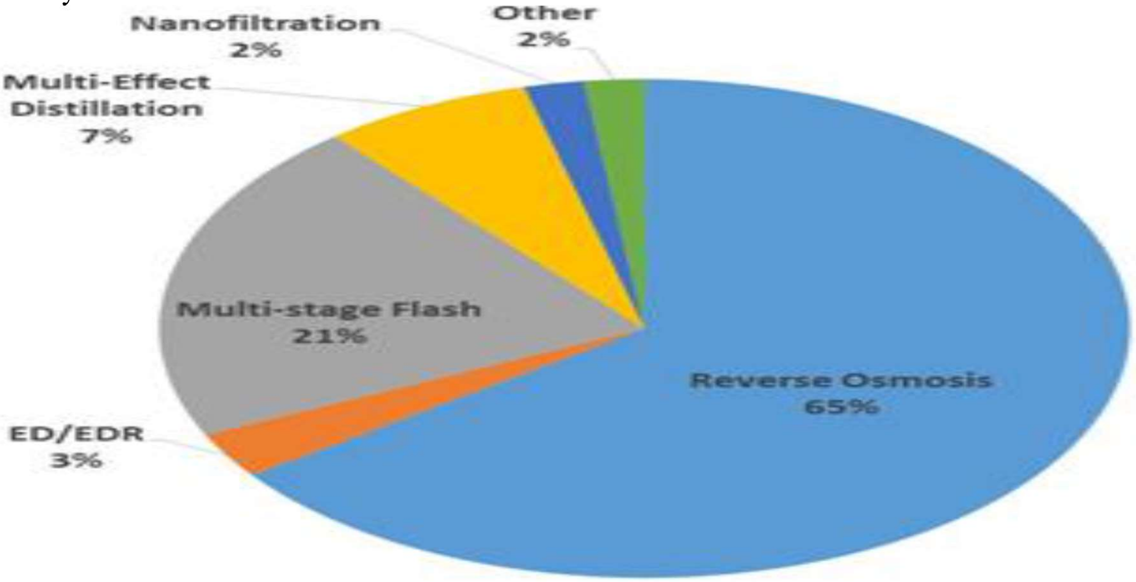

Fig. 2: Desalination methods and their percentage utilization (Source: Cohen *et al*.,2007)

2.1 Membrane fouling

Membrane fouling is a big threat to smooth operation of RO desalination plants, which cannot be fully prevented, even if effective pre-treatment of RO feed water is conducted. Fouling is the deposition, accumulation, and/or adsorption of particulate and organic materials from feed water and bio foulants on the surface of membrane and/or within the membrane pores, which can cause the basic membrane functions to deteriorate over filtration time, including permeate flow, solute removal efficiency, and pressure drop across the membrane (Jiang *et al*.,2017). As RO membranes does not have detectable pores compared to microporous membranes, the main fouling mechanism in RO membranes is usually related to surface fouling on the polyamide (PA) layer of thin film composite membrane (Piyadasa *et al*.,2017).

Membrane fouling has been observed as a significant factor that can affects the efficiency of RO plants due to clogging and poor effluent quality of the pre-treatment system which eventually forced the shutdown of various desalination plants. RO membrane foulants can be classified as biological fouling, organic fouling, inorganic and colloidal fouling (Matin *et al*.,2011). However, without consideration of the threat posed by membrane fouling effect on RO facilities compared to other membrane filtration processes, the phenomenon of membrane fouling is a major problem that affects the performance and efficiency of RO systems. This is because, it leads to permeate flux decline, through the formation of a cake/gel layer on the membrane surface or the blocking of the inside membrane pores especially polyamide (PA) layer. Generally, it results in decrease in salt rejection, increase chemical consumption/cost due to additional chemical pre-treatment (e.g. coagulation) and frequent chemical cleaning of the membrane, Poor quality of product water due to increased pressure passage through the membrane. Permeate flux decline, not excluding deformation of membrane (Aende *et al*.,2020).

Fouling of membrane may be affected by the following factors, (i) nature of membrane of membrane material and its physiochemical properties (ii) the feed water quality (iii) the effects of operating or processing parameter such transmembrane pressure and temperature (Zhao.,2000)

2.2 Microbial fouling

Microbial fouling is caused by microorganisms in the source water which leads to the attachment and development of biofilms on the surface of RO membrane. Unlike the inorganic fouling and colloidal fouling that occur mainly at specific element in an RO facility, biological fouling can take place at any stage during desalination process and is generally agreed to contribute the most to RO membrane fouling (Valavala *et al*.,2011; Armstrong *et al*., 2009).

Micro-organisms are present in various water bodies and are capable of colonizing some surface (Baker and Dudley1998). In most cases, the adsorbed microorganisms multiply rapidly through the formation of biologi, cal film (biofilm) at the expense of nutrients in the source water. A biofilm is an assemblage of surface-associated microbial cells that is irreversibly associated (not removed by gentle rinsing) with a surface and enclosed in a matrix of extracellular polymeric substances. Among the bacteria that have the potential to impact negatively on RO membranes are Mycobacterium, Flavobacterium, *Pseudomonas* and a host of other species (Knoell *et al*., 1999;Sadr-Ghayeni *et al*.,1998; Chen *et al*., 2004).

Also, microbial fouling can not only reduced membrane efficiency (due to clogging caused by organism in the feed water) but can also biodegrades the PA selective layer through hydrolysis. They tend to appear and grow mainly at the expense of nutrients accumulated from the water phase. The attached micro-organisms excrete extracellular polymeric substances (EPS), in which they are embedded, and form biofilms. Biofilms are composed majorly of microbial cells and EPS, which accounts for 50–90 % of the total organic carbon (TOC) of biofilms and can be considered the primary matrix material of the biofilm. EPS may vary in chemical and physical properties, but consists primarily of polysaccharides, proteins, glycoproteins, lipoproteins and other macromolecules of microbial origin ((Matin *et al*.,2011; Ahimou *et al*.,2007)

There are several stages in the development of biofilm on the RO membrane surface as shown in Fig. 4. The first stage involves the preconditioning of the membrane surface by the adsorption of macromolecules (such as protein, polysaccharide), and smaller molecules (such as fatty acid and polyaromatic hydrocarbons). Combination and synergistic adsorption of these materials may create a nutrient-enriched surface that is ideal for bacterial adhesion. The second stage is the development of biofilm in areas behind the feed spacers (i.e., filament crossings) and in the spiral wound RO element that provides a shielded environment for it to further propagate on the membrane surface (Vrouwenvelder *et al*., 2009). Strong adhesion is established if the bacteria produces proteinaceous cell appendages that encourage better association with polymeric surface (Piyadasa *et al*., 2017). However, the adherent bacteria grow into colonies and a confluent biofilm by consuming the nutrients present in the source water, this causes the polarization layer to become more concentrated. The third stage of biofilm formation, the dispersion of cells occurs when the detached cells (from the matured biofilm) is capable of initiating new sites for further proliferation (Romeo *et.al.,* 2006). Ridgway (1998) reported some negative effects of the biofilm formation on the RO membrane surface and its declining effects in water production and rate of salt removal. He observed that mechanism of flux reduction usually exhibits two phases, including, an initial rapid decline followed by a more gradual decay. The initial rapid decline is typically correlated with the early attachment and propagation of microorganisms on the membrane surface. The slow decline (plateau) phase results from establishment of an equilibrium condition during which biofilm growth and EPS production are balanced by biofilm loss, caused by hydrodynamic shear at the solution–biofilm interface (Matin *et al*., 2011).

In addition to flux deterioration, available literature has revealed that the increase in salt passage in the permeate of RO membrane fouled with bacterial cells (Herzberg and Herzberg.,2007; Murphy *et al*., 2001). However, the reduction in flux may be rapid or more gradual, depending on the physicochemical and microbiological properties of the feed water, membrane polymer, and biofilm in most cases, the system pressure is going to be increased by a rise of the pump performance so as to compensate the flux decline due to the biofilm.

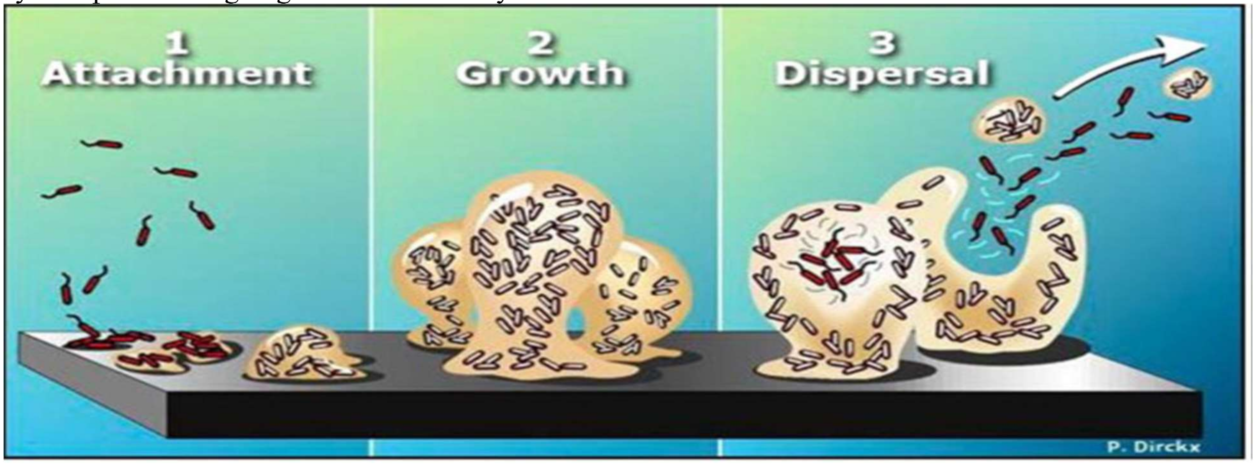

Fig. 3: Schematic illustration of Stages of Biofilm development on RO Membranes (Source: Matin *et al*.,2011)

2.3 Inorganic Fouling

Fouling of membrane by inorganic foulant is a major setback to implementation of water treatment technologies, including the dominant desalination processes, seawater reverse osmosis (Swaminathan *et al*., 2018; Rezaei *et al*., 2017). Inorganic scaling occurs when the concentration of sparingly soluble salts such as calcium sulfate, barium sulfate, and calcium carbonate in the feed water exceeds their solubility (supersaturation) at high product water recovery and, as a result, precipitation of these salts on the membrane surface, which are responsible to the flux decline and surface blockage of the RO membranes (Mi and Elimelech .,2013). Among the various scalants, calcium sulfate dihydrate (gypsum) and silica are the most common in seawater or brackish water desalination (Mi and Elimelech., 2010, 2013). Also, one of the major factors that leads to scale formation is the availability of nucleation sites. Upon the nucleation and formation of microcrystals that develop with time, the membrane surface is adsorbed with the mineral scales that damage the selective layer and deteriorate the water transport. The scale formed on RO surface membranes can be classified based on the properties of alkaline, non-alkaline, and silica based. Calcium carbonate, which can exist in the form of calcium and bicarbonate ions in industrial water, brackish water, and seawater, is the most common type of alkaline-based scalant in RO membranes (Piyadasa *et al*.,2017). The degree of scaling largely depends on the hardness of calcium and alkalinity of bicarbonate, as well as the pH, temperature, and total dissolved solid (TDS) composition of the feed water. (Goh *et al*., 2018). Some sparingly soluble inorganic salts associated with membrane fouling and their solubility at 25 °C are listed in Table 1. $CaCO_3$ and $CaSO_4$ are the most common inorganic foulants in desalination system (Comstock *et al*., 2011, Jawor and Hoek, 2009, Yang, 2005). Over the years, some of the known approaches that have been explored to mitigate inorganic fouling and improve membrane performance include, reducing supersaturation through pretreatment, flushing the membrane with acid, pH adjustment and most importantly the use of antiscalant. The most usually used antiscalant includes surfactants, organic phosphates and polymers organic in nature (Shenv *et al.,* 2015).

2.4 Organic Fouling

Organic fouling is the deposition or adsorption of organic substances (which includes natural organic matters and/or exopolymer particles) on the surface of RO membrane or inside the membrane pores (Jiang *et al*.,2017). The presence of natural organic molecules such as fulvic and humic acids in the seawater is due to the biodegradation and decomposition of living organisms, whereas transparent exopolymer particles are mostly made up of long-chain polymers of amino-sugars or mucopolysaccharides that are formed from organic matters released by aquatic organisms. These organic compounds usually consist of humic substances, polysaccharides, proteins, lipids, nucleic acids and amino acids, and organic acids, (Cho *et al*., 1999; Jeong *et al*., 2016). For surface water or seawater, natural organic matter (NOM) is usually used while for wastewater effluent organic matter (EfOM) is usually adopted (Kim and Dempsey, 2013).

Table 1. Some sparingly soluble inorganic salts associated with membrane fouling and their solubility at 25 °C calculated with PHREEQC

Salt reduced	Name	Solubility [g/L]	Solubility Product *K*	Solubility
$CaCO_3$	Calcium carbonate (calcite)	0.24	3.3×10^{-9}	High pH, high temperature
$CaSO_4 \cdot 2H_2O$	Calcium sulfate dehydrate (gypsum)	2.0 (as $CaSO_4$)	2.6×10^{-5}	High temperature (>60 ^{o}C)
SiO_2	Amorphous silica	0.12	1.9×10^{-3}	Low temperature

(Source: Warsinger *et al.,* 2018)

In wastewater treatment, organic fouling is a serious problem in RO treatment because the EfOM concentration (10–20 ppm) is much higher compared to the concentration of natural organic matters in surface waters (2–5 ppm) (Malaeb and Ayoub, 2011). Generally, different organic substances on RO membrane could vary in different situations, with one kind of organic matter being the dominant foulant in one situation but replaced by another organic contaminant in another situation. Therefore, it is imperative to state that feed water constituents, foulant-surface interactions as well as foulant–foulant interactions are three important factors affecting organic fouling. Organic fouling could cause a decline in flux and deterioration of RO membranes and it is hard to eliminate in the complex structures formed by dissolved organic matters together with other substance (Ding *et al.,* 2016; Naidu *et al*., 2014; Shen and Schafer, 2015). The relative molecular mass of organic matters is another important factor for membrane fouling (Teixeira and Sousa, 2013). Also, organic molecules with a low molecular weight are more difficult to be removed through conventional pretreatment technologies such as coagulation compared to high molecular weight organic matters (Fabris *et al*., 2008). Lee *et al*. (2008) found that the initial stage of fouling was caused by medium to low molecular weight components of organic matters, while the majority of fouling was caused by very high molecular weight organic matters. Adsorption of Organic debris on RO membrane is shown on Fig. 4.

Fig 4: Adsorbed organic substances on RO membrane surface (Source: Maqbool *et al*., 2019)

2.5 Colloidal fouling

Colloidal formation on RO membrane can be inorganic foulants or organic matters, The main inorganic foulants in natural water include aluminum silicate minerals, silica, iron oxides/hydroxides while the organic macromolecules within the water mainly contains materials like polysaccharides, proteins, also as some natural organic matters and exopolymer particles (TEPs) (Tang *et al*., 2011). Therefore, colloids are fine suspended particles, with sizes ranging from few nanometer to micrometers. A number of factors can influence the fouling rate by colloids which includes, size of particle, ionic charges, large size colloids do not get adsorbed to membrane's surface in cross flow velocity mode.

Foulant–ion and membrane–ion specific interactions can affect the membrane fouling. For example, the cations such as calcium and magnesium have more probability to clog polyamide membranes (Sim *et al*.,2017; Wang *et al*., 2014). The deposition of colloids on the RO membrane surface, inform of cake layer, could lead to an additional hydraulic resistance and a serious concentration polarization, which could cause reduction of permeate flux and high of operational pressure (Ang and Elimelech., 2007). Similar to other categories of fouling, the formation of a colloidal cake layer could also be impacted by feed water chemistry such as the concentrations of the foulants and the physiochemical characteristics, nature of membranes as well as operational conditions (Ju and Hong, 2014; Kim *et al*., 2014; Motsa *et al*., 2017; Ning *et al*., 2005).

3.0 Pretreatment

This treatment technique has been widely used process before all RO desalination system to reinforce the standard of feed water and performance efficiency of RO membrane by reducing scaling, precipitation and other categories of fouling in RO systems. It has the advantage of ensuring reliable RO operation and also prolong membrane life. the tactic and complexity of the pretreatment technique adopted, however does not depend upon raw feed water quality, efficiency of RO membrane process alone but also varies with the location of the plant, the intake system and cost of establishment of such facility (Goh.,2018). Consequently, the pretreatment processes for RO membrane desalination facilities must be ready to tackle the subsequent inevitable challenges of RO membrane system:

(a) Microbial fouling caused by bacteria and biofilm
(b) Organic fouling caused by organic substances.
(c) RO membrane inorganic fouling resulting from scaling and other insoluble salts.
(d) Colloidal fouling.

Some chemical compounds that are currently in use in the traditional pretreatment process of the raw feed water before RO membrane desalination are often classified into coagulant/flocculants, scale inhibitor, acid, and oxidant. Coagulant and flocculants are mainly used to improve the settlement of suspended particles within the feed water to realize higher removal rates. The addition of scale inhibitor is to extend the solubility of dissolved salts like carbonate and sulfate. In recent times, UF, coagulation/flocculation and MF are the three technologies that are most studied by researchers as RO pretreatment methods. Fig.5 Shows the flow chart of RO pretreatment processes with their effects in removing foulants from water. Conventional treatment involves, physical pre-treatment and the chemical treatment. The latter is liable for mechanical filtration through screening, cartridge filters, sand filters or membrane filtration. Chemical pretreatment includes the addition of scale inhibitors, coagulants, disinfectants and polyelectrolyte (Migliorini and Luzzo.,2004). However, most reverse osmosis facilities practice conventional pre-treatment, which is defined as chemical and physical pre-treatment without the utilization of membrane technologies. Conventional pretreatment generally uses coagulation, flocculation, chlorination, sand filtration and cartridge filtration as physical pre-treatment. With reference to product water quality, conventional pretreatment does not address the major problems of concern, which is complete removal of foulants, thus membrane filtration (non-conventional) is being considered as an alternate to standard pretreatment (Wolf and Siverns.,2004 ; Vial and Doussau.,2002; Wilf and Schierach.,2001) Micro- and ultrafiltration membranes are the foremost modern, cost effective and more efficient sort of pretreatment. Particulate, colloidal inorganic, and a few of the solid and colloidal organic foulants contained within the saline source water are often removed easily using MF or UF membrane pretreatment. Although at the present about 10% of all existing desalination plants worldwide have UF or MF pretreatment, application of membrane filtration for saline water pretreatment is gaining more and more attention (Busch *et al.*, 2010; Lazaredes and Broom.,2011).

‘

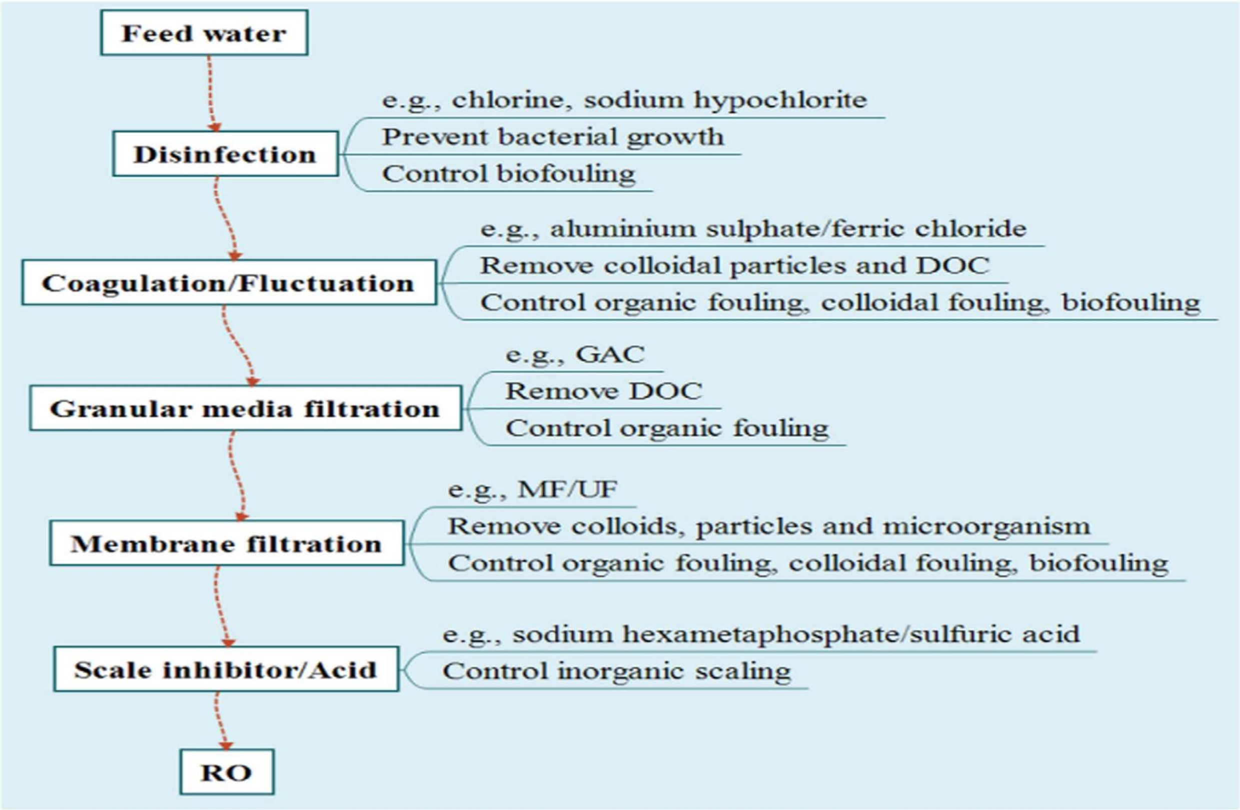

Fig. 5: Schematic presentation of the steps involves in pretreatment processes on RO membrane (Source: Jiang *et al.*, 2017)

4.0 Conclusion

Reverse osmosis technology is a fast-growing process that has the capacity of providing significant water supply in several parts of the global society. It is regarded as one of the best technologies for water treatment and desalination However, implementation of RO technology may involves huge challenges that should be resolves in order to obtain optimum production process. Depending on feed water qualities, operation conditions and membrane characteristics, depending, fouling may occur to some degree in all RO facilities. There are several types of foulants, including inorganic foulants (colloids an precipitates) and organic foulants (dissolved organics) and microbial foulants. Although several types of foulants may have different forming processes, sometimes there are not any distinct boundaries between these foulants and their connectivity or synergistic effects remains unclear. The most important key factor for the cost-effective operation of the RO system is the existence of an appropriate pretreatment technology. Therefore, for effective operation and optimum efficiency of RO facilities, pre-treatment or other controlled methods should form part of the system designed and operations

5.0 References

Aende A., Gardy.J & assanpour.A.(2020)Seawater Desalination: A Review of Forward OsmosisTechnique, Its Challenges, and Future Prospects, *Processes* 8, 901, pp 1-35.

Ahimou, F., Semmens, M. J., Haugstad, G. & Novak, P. J. (2007). Effect of protein, polysaccharide, and oxygen concentration profiles on biofilm cohesiveness, *Application of Environmental Microbiology,* 73, pp. 2905-2910.

Ahuchaogu, A. A., Chukwu, O. J., Obike, A. I., Igara, C. E., Nnorom, I. C. & Echeme, J. B. O. (2018) Reverse Osmosis Technology, its Applications and Nano-Enabled Membrane. *International Journal of Advanced Research in Chemical Science* 5, 2, pp. 20-26.

Alonitis, S. A., Kouroumbas, K. & Vlachakis, N. (2003). Energy consumption and membrane replacement cost for seawater RO desalination plants. *Desalination,* 157, pp. 151–158.

Ang, W.S. & Elimelech, M., (2007). Protein (BSA) fouling of reverse osmosis membranes: implications for wastewater reclamation. *Journal of Membrane Science*, 296, pp. 83-92.

Armstrong, N. W., Gallego, S. &Chesters, S. P. (2009). *Removing biofilm from membranes – A practical approach*, Genesys International Limited, 3A Aston Way, Middlewich, Cheshire, CW10 0HS, UK

Baker, R. W. (2004). *Membrane technology and applications*, 2nd ed. John Wiley & Sons, removal from natural waters in Tanzania by nanofiltration/reverse osmosis. Science of *Research Technology*. AQUA 55 3.

Baker, J. S. & Dudley, L. Y. (1998) Biofouling in membrane systems- a review. *Desalination*,118, pp. 81-90

Bourounia, K., Chaibib, M. T. & Tadrist, L. (2001). Water desalination by humidification and dehumidification of air: state of the art. *Desalination* 137, pp. 167–176

Busch, M., Chu, R. & Rosenberg, S. (2010) Novel trends in dual membrane systems for seawater desalination: minimum primary pretreatment and low environmental impact treatment schemes. *IDA Journal of Desalination and Water Reuse*, 2,1, pp. 56-71.

Chen, C. L., Liu, W. T., Chong, M. L.,Wong, M. T. & Ong, S. L. Seah, H. & Ng, W. G. (2004) Community structure of microbial biofilms associated with membrane-based water purification processes as revealed using a polyphasic approach, *Application of Microbiological. Biotechnology,* 63, 4, pp. 466–473

Cho, J., Amy, G. & Pellegrino, J. (1999). Membrane filtration of natural organic matter: initial comparison of rejection and flux decline characteristics with ultrafiltration and nanofiltration membranes. *Water Research*, 33, pp. 2517–2526.

Cohen, Y., Semiat, R. & Rahardianto, A (2017). A perspective on reverse osmosis water desalination: Quest for sustainability. *AIChE Journal*, 63, 6, pp. 1771-1784.

Comstock, S. E. H., Boyer, T. H. & Graf, K. C. (2011). Treatment of nanofiltration and reverse osmosis concentrates: comparison of precipitative softening, coagulation, and anion exchange. *Water Research*, 45, 16, pp. 4855–65.

Ding, S., Yang, Y., Li, C., Huang, H. & Hou, L. A. (2016). The effects of organic fouling on the removal of radionuclides by reverse osmosis membranes. *Water Research*, 95, pp. 174-184.

Eddy, N. O., Ekwumengbo, P. A. & Mamza, P. A. P. (2009). Ethanol extract of *Terminalia catappa* as a green inhibitor for the corrosion of mild steel in H_2SO_4. *Green Chemistry Letters and Review* ,2, 4, pp. 223-231.

Eddy, N. O., Ameh, P., Gimba, C. E. & Ebenso, E. E. (2011). GCMS studies on *Anogessus leocarpus* (AL) gum and their corrosion inhibition potentials for mild steel in 0.1 M HCl. *International Journal of Electrochemical Sciences,* 6, pp. 5815-5829.

Elimelech, M. (2006) The global challenge for adequate and safe water, *Journal of Water Supply Research. Technology*. AQUA 55 3

Elimelech, M. & Phillip, W. A. (2011). The Future of Seawater Desalination: *Energy, Technology, and the Environment Science* ,333, I6043, pp. 712-717.

Fabris, R.., Chow, C. W. K., Drikas, M. & Eikebrokk, B. (2008). Comparison of NOM character in for seawater desalination. *Journal of American Water Works Asso*ciation, 99, pp. 95-106.

Fritzmann, ., Löwenberg, J., Wintgens, T. & Melin, T. (2007). State-of-the-art of reverse osmosis desalination, *Desalination* 216, pp. 1-76.

GWI, Desalination Markets (2007). A *Global Industry Forecast (CD ROM),* Global Water Intelligence, Media Analytics Ltd, Oxford, UK,

2007. Available from Global Publications, Anaheim, California.

Goh, P. S., Lau, W. J., Othman, M. H. & D. Ismail, A. F. (2018) Membrane fouling in desalination and its mitigation strategies. *Desalination, 425*, pp. 130-155

Hameeteman, E. (2013). *Future water.* In Security: Facts, Figures and Predictions; GlobalWater Institute: Columbus, OH, USA,

Herzberg, M. & Elimelech, M. (2007). Biofouling of reverse osmosis membranes: role of biofilm-enhanced osmotic pressure, *Journal of Membrane Science*. 295, pp. 11-20.

Jawor, A. & Hoek, E. M. (2009). Effects of feed water temperature on inorganic fouling of brackish water RO membranes. *Desalination*, 235, 1-3, pp. 44–57.

Jeong, S., Naidu, G., Vollprecht, R., Leiknes, T.O. & Vigneswaran, S., (2016). In-depth analyses of organic matters in a full-scale seawater desalination plant and an autopsy of reverse osmosis membrane. *Separation Purification. Technology,* 162, pp. 171-179. http://dx.doi.org/10.1016/j.seppur.2016.02.029

Jiang, S., Li, Y. & Ladewig, B. P. (2017). A review of reverse osmosis membrane fouling and control strategies. *Science of the Total Environment*, 595, 1, pp. 567-583.

Ju, Y.& Hong, S., (2014). Nano-colloidal fouling mechanisms in seawater reverse osmosis process evaluated by cake resistance simulator-modified fouling index nanofiltration. *Desalination* 343, pp. 88–96.

Kim, H. C. & Dempsey, B. A., (2013). Membrane fouling due to alginate, SMP, EfOM, humic acid, and NOM. *Journal of Membrane Science,* 428, pp. 190-197.

Kim, Y., Elimelech, M., Shon, H. K.& Hong, S.,(2014). Combined organic and colloidal fouling in forward osmosis: fouling reversibility and the role of applied pressure. *Journal of Membrane Science*, 460, pp. 206-212. http://dx.doi.org/10.1016/j.memsci.2014.02.038.

Knoell,T., J. Safarik., T.Cormack., R.Riley., S.W. Lin., &H.F. Ridgway, (1999) Biofouling potentials of microporous polysulfone membranes containing a sulfonated polyether hersulfone.polyethersulfone block copolymer: correlation of membrane surface properties with bacterial attachment, *Journal of Membrane. Science*. 157, pp.111-121

Kurihara, M. & Hanakawa, M. (2013). Mega-ton Water System: Japanese national research and development project on seawater desalination and waste *Desalination,* 308, pp. 131-137.

Lattemann, S., Kennedy, M. D., Schippers, J. C. & Amy, G. (2010). Global desalination situation, in: I.C. Escobar, A.I. Scha¨fer (Eds.), Sustainable Water for the Future: *Water Recycling versus Desalination, Sustainability Science and Engineering*, 2, pp. 7–39.

Lazaredes, H. & Broom, G. (2011). *Review of the pretreatment selection/design for Australia's big six desalination projects*. In Proceedings of IDA World Congress, Perth, Australia

Lee, E. K., Chen, V. & Fane, A.G., (2008). Natural organic matter (NOM) fouling in low pressure membrane filtration - effect of membranes and operation modes. *Desalination*, 218, pp. 257-270.

Malaeb, L & Ayoub, G. M., (2011). Reverse osmosis technology for water treatment: state of the art review. *Desalination,* 267, pp.1-8. http://dx.doi.org/10.1016/j.desal.2010.09.001

Maqbool N., Saleem, Z and Jamal,Y (2019)A Short Review on Reverse Osmosis Membranes: Fouling and Control, *Journal of Waste Manage Xenobiotic*,2,2 pp 1-10 doi: 10.23880/oajwx-16000122

Matin, A. Khan, Z., Zaidi, S. M. J. & Boyce, M. C. (2011). Biofouling in reverse osmosis membranes for seawater desalination: phenomena and prevention, *Desalination*, 281, pp. 1–16,

Mekonnen, M. M. & Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science. Advances*, 2, 2, pp. 1-6:e1500323. doi: 10.1126/sciadv.1500323

Mi, B. & Elimelech, M. (2013). Silica scaling and scaling reversibility in forward osmosis. *Desalination*, 312, pp. 75–81.

Mi, B. & Elimelech, M.(2010). Gypsum scaling and cleaning in forward osmosis: Measurements and mechanisms. *Environmental. Science. Technology,* 44, pp. 2022-2028.

Migliorini, G. & Luzzo, E. (2004). Seawater reverse osmosis plant using the pressure exchanger for energy recovery: a calculation model, *Desalination*, 165, pp. 289–298.

Motsa, M. M., Mamba, B. B., Thwala, J. M. & Verliefde, A. R., (2017). Osmotic backwash of fouled FO membranes: cleaning mechanisms and membrane surface properties after cleaning. *Desalination,* 402, pp. 62-71. http://dx.doi.org/10.1016/j.desal.2016.09.018.

Murphy, A. P., Moody, C. D., Riley, R. L., Wai, S., Murugaverl, B. & Rusin, P. (2001) Microbiological damage of cellulose acetate RO membranes, *Journal of Membrane. Science*, 193, pp. 111–121

Naidu, G., Jeong, S., Kim, S.J., Kim, I.S., Vigneswaran, S., (2014). Organic fouling behavior in nanofiltration membranes. *Water Research*, 33, pp. 2517–2526.

Ning, R.Y., Troyer, T. L. & Tominello, R.S., (2005). Chemical control of colloidal fouling of reverse osmosis systems. *Desalination* 172, pp. 1–6.

Piyadasa, C., Ridgway, H. F., Yeager, T. R., Stewart, M. B., Pelekani, C., Gray, S. R. & Orbella, J. D. (2017) The application of electromagnetic fields to the control of the scaling and biofouling of reverse osmosis membranes - a review, *Desalination,* 418, pp. 19–34.

Rao, A. P., Desai, N. V. & Rangarajan, R. (1997). Interfacially synthesized thin film composite RO membrane for seawater desalination, *Journal of Membrane. Sciencce*. 124, pp. 263-272

Rezaei, M., Warsinger, D. M., Lienhard, J. H. & Samhaber, W. M. (2017). Wetting prevention in membrane distillation through superhydrophobicity and recharging an air layer on the membrane surface. *Journal of Membrane Science*, 530, pp. 42-52.

.Ridgway, H. F. (1998). *Microbial adhesion and biofouling of reverse osmosis membranes*, in: B.S. Parekh (Ed.), Reverse Osmosis Technology, Marcel Dekker, New York, pp. 429-481.

Romeo .T, (2006) When the party is over: a signal for dispersal of Pseudomonas Aeruginosa biofilms, *Journal of Bacteriology*. 188, pp. 7325–7327

Sadr-Ghayeni, S. B., Beatson, P. J., Schneider, R. P. & Fane, A. G. (1998) Water reclamation from municipal wastewater using combined microfiltration-reverse osmosis (MFRO):preliminary performance data and microbiological aspects of system operation, *Desalination* 116, pp. 65-80..

Seacord, T. F., Coker, S. D. & MacHarg, J. (2006). *Affordable desalination collaboration 2005 results. In International Desalination and Water Reuse Quarterly* (Green Global Publications, Anaheim, California

Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G. Marinas, B. J. & Mayes, A. M. (2008). Science and technology for water purification in the coming decades. *Nature*, 452, pp. 301-310. oi:10.1038/nature06599

Shen, J. & Schafer, A. I. (2015). Factors affecting fluoride and natural organic matter (NOM)removal from natural waters in Tanzania by nanofiltration/reverse osmosis. *Science of Total Environment.* 527,528, pp. 520–529.

Shenvi S. S, Isloor A. M . & Ismail, A. (2015) A review on RO membrane technology: Developments and challenges. Desalination 368: pp. 10-26.

Sim, L. N., Chong, T. H., Taheri, A. H., Sim, S. T. V., Lai, L., Krantz, W. B. & Fane, A. G. (2017). A review of fouling indices and monitoring techniques for reverse osmosis. *Desalination,* 434, pp. 169-188.

Swaminathan., J. H. & Lienhard V, (2018) Inorganic fouling mitigation by salinity cycling in batch reverse osmosis. *Water Research* 137, pp. 384-394

Teixeira, M. R. & Sousa, V.S., (2013). Fouling of nanofiltration membrane: effects of NOM molecular weight and microcystins. *Desalination* 315, pp. 149–155

Veerapaneni, S., Long, B., Freeman, S. & Bond, R. (2007) Reducing energy consumption for seawater desalination. *Journal of American. Water Works Association*, 99, pp. 95–106

Vial, D. & Doussau, G. (2002). The use of microfiltration membranes for seawater pre-treatment prior to reverse osmosis membranes, *Desalination*, 153, pp. 141-147

Vrouwenvelder, J. S., Picioreanu, C., Kruithof, J. C. & Van Loosdrecht, M. C. M. (2010). Biofouling in spiral wound membrane systems: three-dimensional CFD model-based evaluation of experimental data, *Journal of Membrane. Science,* 346, pp. 71-85.

Wang, J., Mo, Y., Mahendra, S. & Hoek, E.M.V., (2014). Effects of water chemistry on structure and performance of polyamide composite membranes. *Journal of Membrane Science,* 452, pp. 415-425

Warsinger, D. M., Tow, E. W., Maswadeh, L. A., Connors, G., Swaminathan, J. & Lienhard, J. H. (2018). Inorganic fouling mitigation by salinity cycling in batch reverse osmosis. *Water Research,* 137, pp. 384-394

Wilf, M & Schierach, (2001). Improved performance and cost reduction of RO seawa.ter systems using UF pretreatment. *Desalination,* 135, pp. 61-68.

Wolf, P. H. & Siverns, S. (2004). *The new generation for reliable RO pre-treatment*, International Conference on Desalination Costing, Limassol.

Yang, N. (2005). *Physical conditioning for scale prevention during desalination by reverse osmosis*. *Master Degree Thesis:* Chalmers Institute of Technology, Goteborg, Sweden

Zhao, Y. J., Wu, K. F., Wang, Z. J., Zhao, L. & Li, S. S. (2000) Fouling and cleaning of membrane—A literature review. *Journal of Water Process Engineering*,12, pp. 241–251.

Zhou, Y., & R. S. J. Tol (2005), Evaluating the costs of desalination and water transport, *Water Resource and Research*, 41, pp. 1-10.