Bitlis Eren Üniversitesi Fen Bilimleri Dergisi
BİTLİS EREN UNIVERSITY JOURNAL OF SCIENCE
ISSN: 2147-3129/e-ISSN: 2147-3188
VOLUME: 12 NO: 2 PAGE: 478-484 YEAR: 2023
DOI:10.17798/bitlisfen.1242232

Recycling Wastewater with Membrane Technology and The Case of Singapore

Mikail YENİÇERİ[1*], Kübra TORTUM YENİÇERİ[2]

[1]*Kırşehir Ahi Evran University Graduate School of Natural and Applied Sciences, Kırşehir, Turkey*
[2]*Anadolu University, Public Administration, Eskişehir, Turkey*
(ORCID: 0000-0003-1698-6911) (ORCID: 0000-0002-0436-2119)

Keywords: Membrane Technology, Wastewater, Singapore, NEWater.

Abstract
As a result of the constantly increasing use of water in the world, countries have searched for alternatives to water resources and various studies have been carried out with the available opportunities. One of the studies carried out is the NEWater project on the treatment and reuse of wastewater in Singapore as drinking water. This project has been implemented in the country for 20 years and meets an average of 30% of the country's water needs. With this project, Singapore contributed to its transformation into a global hydroelectric power plant by pioneering innovative water treatment and technologies. However, in this model, the membranes used for wastewater treatment (forward, backward and pressure retarded osmosis and membrane bioreactors) are developed to use advanced oxidation processes, electrochemical methods to directly supply drinking water, especially in countries effort must be made.where water resources are insufficient, or to treat polluted water that causes disease and death. In this study, it is discussed through the NEWater application in Singapore that wastewater can be treated and reused with membrane technology.

1. Introduction

Membrane technologies play an important role in water and energy sustainability. Some are already implemented in large-scale industries. Examples include desalination with reverse osmosis (RO), wastewater treatment with membrane reactors (MBR), lithium-ion batteries, and membrane-based fuel cells. Membrane technologies meet sustainability criteria in terms of environmental impacts, land use, ease of use, flexibility and adaptability, as well as addressing water and energy scarcity. On the other hand, they need to be improved in terms of financial burden, affordability, energy consumption and expertise [12]. method should be given in detail and clearly in terms of reproducibility of the study. The methods used should be supported by previously published references. Changes that contribute to the method in the study should be described in detail [3], [4]. Membrane technology, which has grown greatly in the last decade with the advantages it offers for treatment, offers various options in wastewater treatment [13]. Membrane technology has the potential to bridge the gap between affordability and sustainability, low or no chemical use, and eco-friendliness and easy accessibility. Membrane technology has proven to be a more advantageous option in wastewater treatment processes [14].

Membrane technology, which is not a new technology, has been available since the 18th century and many improvements have been made to make membranes more suitable for many different applications [15]. The changing nature and complexity of wastewater lead to further improvements in efficiency, space requirements, energy, filter quality and technique. Again, there is a continuous modification of membrane modules and elements to reduce membrane fouling, which is a major challenge in membrane processes. The possibility of combining two or more membrane

*Corresponding author: myeniceri@ahievran.edu.tr *Received: 26.01.2023, Accepted: 14.06.2023*

processes with each other or with other forms of technology, such as coagulation or adsorption, in a hybrid fashion, is also being continuously explored, developed and implemented in many wastewater treatment plants [16].

Characteristically, these membranes are classified as isotropic and anisotropic (Figure 1) [12]. Isotropic membranes are identical in composition and physical structure. The permeation fluxes in the microporous case are relatively high compared to the non-porous (dense) case, and their applications are rather limited due to their low permeation fluxes. Isotropic microporous membranes are widely applied in microfiltration membranes. Anisotropic membranes, on the other hand, are not uniform over the membrane area and consist of different layers with different structures and compositions. These membranes have a thin selective layer supported by a thicker and highly permeable layer. It is especially applied in reverse osmosis (RO) processes. [17].

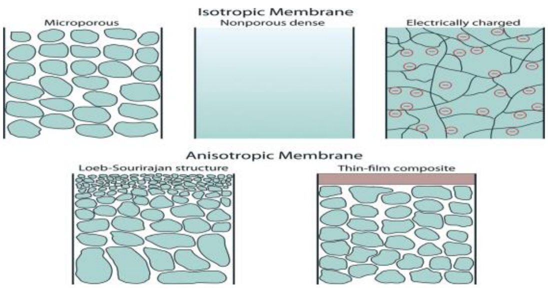

Figure 1. Schematic illustration of various classes of membranes.

In terms of membrane material structure, membranes are classified as organic or inorganic. Organic membranes are made from synthetic organic polymers. Often, membranes for pressure driven separation processes (microfiltration, ultrafiltration, nanofiltration and reverse osmosis) are made from synthetic organic polymers. These include polyethylene (PE), polytetrafluoroethylene (PTFE), polypropylene, and cellulose acetate, among others [18]. Inorganic membranes are made of materials such as ceramic, metal, zeolite or silica. They are chemically and thermally stable and are widely used in industrial applications such as hydrogen separation, ultrafiltration and microfiltration [17]. The structure of the membranes is shown below (Figure 2) [19].

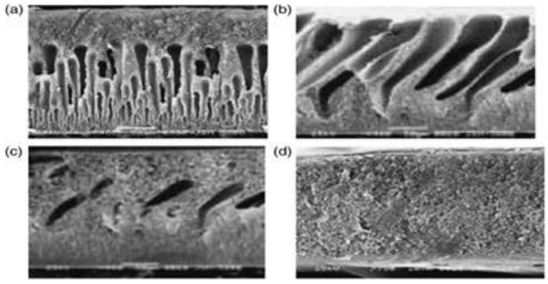

Figure 2. Structure of membrane.

The movement of the medium through the dice is based on different driving forces. There are equilibrium-based membrane processes, non-equilibrium membrane processes, pressure-driven and non-pressure-driven processes [20]. The schematic diagram below (Figure 3) shows a summary of some of these techniques according to their driving forces. These membrane techniques are discussed separately below.

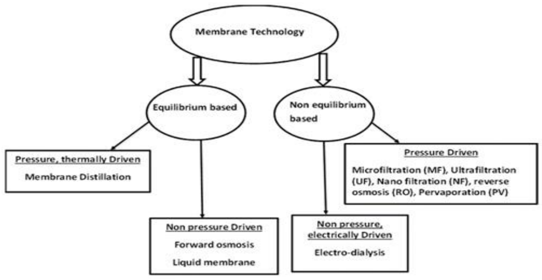

Figure 3. Schematic representation of some membrane processes

Membrane technologies have gained great importance in the advanced treatment and recycling of wastewater in recent years. The reason for this is that water recovery has prevailed in parallel with the increase in water demand and membrane technologies have come to the fore in this regard both in terms of quality and quantity. There are also high-efficiency systems for the removal of primary pollutants such as membrane technologies, endocrine disrupting compounds for the recovery of domestic wastewater and pharmaceutical actives. It is possible to reach the desired output quality by choosing the membrane type in wastewater treatment or recovery. Wastewater treatment systems integrated with membranes have advantages and disadvantages depending on output quality, energy consumption and system complexity factors. In general, membrane systems are used together with physical, chemical and biological processes to provide the most efficient form of regeneration/advanced purification [21].

Membrane technology has started to be used in some areas with significant effects. For example, during the Sydney Olympic Games held in 2000, membrane technology was used in the stormwater recycling system, which used polypropylene hollow fiber microfiltration (MF) membrane as a pre-treatment to remove suspended pollutants and pathogens in rainwater, and then to desalinate with RO technique [22]. Later, the wastewater was chlorinated and used to flush toilets. With excellent processing efficiency, simple apparatus and easy integration with other processing facilities, membrane technology can be promising for emergency water supply. It has been proven that the quality of water treated with membrane technology, unlike conventional treatment methods, can reach or even exceed domestic or drinking water criteria [23]. Membrane bioreactor technology has become a promising technique for wastewater treatment using the use of activated sludge and membrane separation. The membrane bioreactor process has advantages over the traditional activated sludge process and provides stable and high effluent quality [24].

3. Examples of Membrane Technology in the World

Although the water obtained from the recycling of domestic wastewater is mainly used for agricultural irrigation, some technologies allow this water to be used directly or indirectly as a drinking water source. In much of the world, there are more than 450 water recycling facilities in Japan and the USA, and more than 3,300 water recycling facilities in Australia and the European Union [25].

3.1. Example of Sulaibiya, Kuwait

Sulaibiya is a wastewater recovery facility using the world's largest membrane technologies. The daily capacity of the facility is 375,000 m3/day. The water discharged from Sulaibiya is mixed with brackish water and used to improve existing brackish water distribution facilities. Following the biological wastewater treatment plant, the wastewater is treated at a secondary level and the effluent is treated in a recovery plant that includes UF (Ultrafiltration) and RO (Reverse Osmosis) processes. Thanks to the use of UF before RO, the life of RO membranes increases, operating pressures decrease, and chemical wash cycle time increases. The application of UF and RO together creates a quality water supply at drinking and utility water level, as well as the possibility of using water in agriculture and groundwater discharge. The effluent quality obtained from the facility is better than the drinking water standards set by WHO and is also used in agricultural irrigation as an alternative source [26].

3.2. Example of California, USA

Wastewater recovery practices have long been popular in non-water-rich California. In addition, for Orange Country, a wastewater recovery facility was established in this region due to the cost of water supply from Northern California. In this established facility, recovery includes MF (Membrane Filtration), TO and hydrogen peroxide as advanced oxidation and UV (Ultravioye) treatment steps. The daily facility capacity is 270,000 m3/day and thanks to the membrane processes used, pharmaceuticals, pesticides and other harmful substances are removed before they are released into the receiving environment [27].

3.3. Example of Australian

At the facility where 18 million m3 of wastewater is recycled annually, tertiary treated wastewater from three different wastewater treatment plants is processed and recycled. The treated wastewater coming to the facility first comes to a balancing tank and passes through the mechanical filter. Then UF is passed through the membrane and suspended solids, bacteria, viruses, and some of the organic matter are removed. In the next stage, RO membranes are used, and advanced separation is carried out, and the purified water is passed through the decarbonator and then pH adjusted and given to Penrith tea [28].

4. Singapore and NEWater Project

One of the countries working in the field of water recycling is the NEWater project, which purifies the sewage water of Singapore and turns it back into clean drinking water. In this system, the waste water coming out of the sewage system is purified by microfiltration and reverse osmosis methods and brought to drinkable quality. This water is then transported by the municipalities to the cities of the city and to the industries that need clean water at a high rate [29].

Singapore has been using raw water imported from Johor (Malaysia) for many years as its primary water source, which meets around 40% of the country's water needs (250 Mm3 per year). The Singapore government's aim is to minimize the amount of water supplied from this source by 2061 [30].

The second water source of the country is the rain water, which is formed with approximately 2400 mm of precipitation per year. For this purpose, some major urban planning (reconstruction of parts of the city and relocation of houses and industries to improve water collection) has been taken, as well as measures such as water tanks built to harvest rainwater in a large basin. With the addition of some settlements recently, it is aimed to increase the amount of water provided from rain water to 150 Mm3 per year and to collect 90% of the water collection area [31].

Third water source by desalination of sea water. In 2005 and 2013, two purification plants using microfiltration and reverse osmosis were built with a water production capacity of 50 Mm3 and 115 Mm3/year, respectively. These plants, which consume large amounts of energy in the desalination process, are mostly used as backup plants to meet the spikes in demand [32].

The fourth water source is water called NEWater, which consists of water produced by the combination of microfiltration, reverse osmosis and UV treatment of wastewater. Annual production of 110 Mm3 NEWater in 2012 met 18% of the total water needs, while meeting 32% of industrial and commercial needs. 2% of the recovered water is sent to rainwater tanks to be treated in drinking water standards. Urban wastewater (at a rate of 25 Mm3 per year) is reused especially for the petrochemical industry on Jurong Island [33].

Replacing part of the activated sludge process (aeration and post-treatment) and RO pre-treatment process (microfiltration or ultrafiltration) in the NEWater production process with a membrane bioreactor (MBR) will reduce the energy requirement of wastewater treatment. Current research on ways to improve the wastewater system and sludge digestion process are also factors that will help the wastewater sector reduce its energy needs [34].

Within the scope of the NEWater project, water reuse in the country is to meet the water needs of the city by re-purifying the wastewater with membrane systems and to use it as drinking water in the form of bottled water and to reuse the recycled wastewater in industrial processes.With the NEWater project, which was commissioned in 2003, wastewater treatment in effluent quality in accordance with EPA and WHO standards can be realized at a level that can be used both indirectly and for direct use. While the water recovered in indirect use can be used as process water in silicon wafer production, power generation, petrochemical industry and cooling towers, treated water in direct use applications is discharged to reservoirs and rainwater channels and reaches drinking water treatment plants [25].

Utilizing a traction solution to naturally drive the osmotic process in the NEWater project, FO (Forward Osmosis) provides substantially lower energy consumption and contamination tendency compared to RO (Reverse Osmosis); however, the FO product is not NEWater, but a diluted extraction solution that requires secondary treatment. This means that FO and RO may not be mutually exclusive and can be combined for energy optimization with RO concentrate, which is actually used as a draw solution for FO (Figure 4) [11].

When using equations, they should be numbered sequentially. The equation numbers should be enclosed by parentheses and located at the right-hand side of the page [8]. In addition, equations should be prepared with Word or other equation editors and should not be in picture format [9], [10].

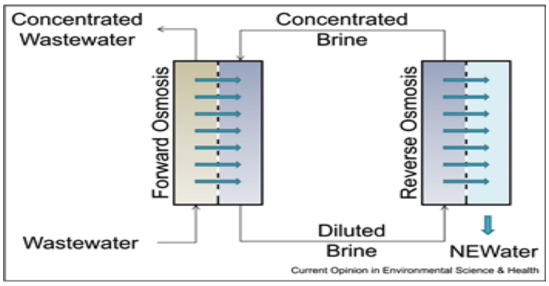

Figure 4. Integrating FO and RO methods for energy optimization. The RO brine would play the role of the draw solution in that NEWater production scheme.

The NEWater product meets the drinking water standard of both the World Health Organization and the US Environmental Protection Agency. The Health Effect Testing Program (HETP) has also shown no health effects from consuming NEWater. In fact, NEWater is cleaner and purer than a raw freshwater source (Figure 5) [35].

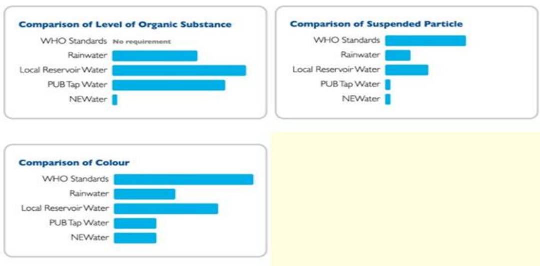

Figure 5. Organic Substance Comparison, Suspended Particle Comparison and Color Comparison.

4.1. NEWater Technology Stage

NEWater production process occurs a few stage. **Stage 1**–The first stage of the NEWater production process is known as Microfiltration (MF). In this process, the treated used water is passed through membranes to filter out and retained on the membrane surface suspended solids, colloidal particles, disease-causing bacteria, some viruses and protozoan cysts.

The filtered water that goes through the membrane contains only dissolved salts and organic molecules. **Stage 2**–Reverse Osmosis The second stage of the NEWater production process is known as Reverse Osmosis (RO). In RO, a semi-permeable membrane is used. The semi-permeable membrane has very small pores which only allow very small molecules like water molecules to pass through. Consequently, undesirable contaminants such as bacteria, viruses, heavy metals, nitrate, chloride, sulphate, disinfection by-products, aromatic hydrocarbons, pesticides etc, cannot pass through the membrane. Hence, NEWater is RO water and is free from viruses, bacteria and contains negligible amount of salts and organic matters. **Stage 3**–UV Disinfection At this stage, the water is already of a high grade water quality. The third stage of the NEWater production process really acts as a further safety back-up to the RO. In this stage, ultraviolet or UV disinfection is used to ensure that all organisms are inactivated and the purity of the product water guaranteed.

Before Storing NEWater in Water Tanks–Balance the pH in NEWater With the addition of some alkaline chemicals to restore the acid-alkali or pH balance, the NEWater is now ready to be piped off to its wide range of applications (Figure 6) [36].

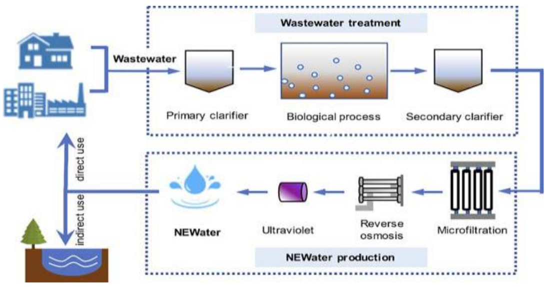

Figure 6. NEWater technology in Singapore

5. Conclusion and Suggestions

Water resources are depleted due to the rapidly increasing need for water in the world and the unconscious use of water in domestic, industrial and agricultural irrigation. It is beneficial in many factors, such as increasing the recycling and reuse of wastewater, reducing water scarcity and pollution, improving soil quality and reducing production costs. For this reason, most of the countries take measures for water and use the water treated in wastewater treatment plants in various areas as drinking water. Membrane technology is a system with significant potential in wastewater treatment. This technology stands out with its advantages over other treatment processes, especially in domestic and industrial wastewater treatment. Membrane systems are systems that can remove organic matter, pathogenic microorganisms and nutrients from wastewater with high efficiency. The number of treatment systems using this technology is increasing. Some of the obstacles to the implementation of these systems, which are advantageous for the treatment of wastewater of small settlements and factories, are the cost of membranes and the resulting operational pollution problems.

The use of wastewater as drinking water with the NEWater application in Singapore is a very important study in terms of preventing a possible water shortage in the world in the future. In addition, membrane technology will still occupy an important position in the future development trend. This article has attempted to summarize some membrane-related areas such as fouling and module structures, along with application examples, advantages and disadvantages. We hope this article will be useful in providing good information for further research on membrane technology applications in wastewater treatment.

Contributions of the Authors

In the study carried out, Author 1 in the formation of the idea, design, and literature review, compilation, and interpretation of the results; Author 2 contributed to the evaluation, presentation, and analysis of the results obtained, in the titles of spelling and checking the article in terms of content.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

There is no need for an ethics committee approval in the prepared article.

References

[1] Koyuncu, B. Zeytuncu, M. E. Pasaoglu, A. Yuksekdag, and B. Kose-Mutlu, “Resource recovery from waste, water and wastewaters with membrane technologies,” *In Proceedings of the International Conference on Civil Infrastructure and Construction* (CIC 2020), Doha, Qatar, pp. 634-639, 2020.

[2] M. F. García-Montoya, S. Gutiérrez-Granados, A. Alatorre-Ordaz, R. Galindo, R. Ornelas, and J. M. Peralta-Hernández, “Application of electrochemical/BDD process for the treatment wastewater effluents containing pharmaceutical compounds,” *J. Ind. Eng. Chem.*, vol. 31, pp. 238–243, 2015.

[3] B. Şahin, “Küresel Bir Sorun: Su Kıtlığı ve Sanal Su Ticareti (Master Thesis, Sosyal Bilimler Enstitüsü)”. 2016.

[4] L. Pintilie, C. M. Torres, C. Teodosiu, and F. Castells, “Urban wastewater reclamation for industrial reuse: An LCA case study,” *J. Clean. Prod.*, vol. 139, pp. 1–14, 2016.

[5] Ö. Demir, M. Yıldız, Ü. Sercan, and C. Ş. Arzum, “*Waste Water Recovery and Reuse*,” pp. 1–14, 2017.

[6] C. F. Bustillo-Lecompte and M. Mehrvar, “Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances,” *J. Environ. Manage.*, vol. 161, pp. 287–302, 2015.

[7] R. Ş. Taşdemir and İ. Koyuncu, “Membran Teknolojileri ile Alternatif Su Temini: Desalinasyon ve Atıksu Geri Kazanımı,” *Sürdürülebilir Çevre Dergisi*, vol. 1, no. 1, pp. 18–30, 2021.

[8] A. F. Santos, P. Alvarenga, L. M. Gando-Ferreira, and M. J. Quina, “Urban wastewater as a source of reclaimed water for irrigation: Barriers and future possibilities,” *Environments*, vol. 10, no. 2, p. 17, 2023.

[9] A. Lee, J. W. Elam, and S. B. Darling, “Membrane materials for water purification: design, development, and application,” *Environ. Sci. (Camb.)*, vol. 2, no. 1, pp. 17–42, 2016.

[10] D. Ghernaout, N. Elboughdiri, and A. Alghamdi, “Direct potable reuse: The Singapore NEWater project as a role model,” *OAlib*, vol. 06, no. 12, pp. 1–10, 2019.

[11] O. Lefebvre, “Beyond NEWater: An insight into Singapore’s water reuse prospects,” *Curr. Opin. Environ. Sci. Health*, vol. 2, pp. 26–31, 2018.

[12] H. Lee and T. P. Tan, “Singapore’s experience with reclaimed water: NEWater,” *Int. J. Water Resour. Dev.*, vol. 32, no. 4, pp. 611–621, 2016.

[13] C. A. Quist-Jensen, F. Macedonio, and E. Drioli, “Membrane technology for water production in agriculture: Desalination and wastewater reuse,” *Desalination*, vol. 364, pp. 17–32, 2015.

[14] N.P. Hankins, R. Singh (Eds.), *Emerging Membrane Technology for Sustainable Water Treatment*, Elsevier, Boston pp.15-52, 2016.

[15] A. G. Fane, R. Wang, and Y. Jia, “Membrane technology: Past, present and future,” in *Membrane and Desalination Technologies*, Totowa, *NJ: Humana Press*, pp. 1–45, 2011

[16] C. Stoquart, P. Servais, P. R. Bérubé, and B. Barbeau, “Hybrid Membrane Processes using activated carbon treatment for drinking water: A review,” *J. Memb. Sci.*, vol. 411–412, pp. 1–12, 2012.

[17] A. K. Pabby, S. S. H. Rizvi, and A. M. S. (Eds.), *Handbook of Membrane Separations: Chemical, Pharmaceutical, Food, and Biotechnological Applications*, (1st ed.). CRC Press, 2015.

[18] U. M. Aliyu, S. Rathilal, and Y. M. Isa, “Membrane desalination technologies in water treatment: A review,” *Water Pract. Technol.*, vol. 13, no. 4, pp. 738–752, 2018.

[19] Lalia, B. S., Kochkodan, V., Hashaikeh, R., & Hilal, N., “A review on membrane fabrication: Structure, properties and performance relationship,” *Desalination*, vol. 326, pp. 77–95, 2013.

[20] Jhaveri, J. H., & Murthy, Z. V. P., “A comprehensive review on anti-fouling nanocomposite membranes for pressure driven membrane separation processes,” *Desalination*, vol. 379, pp. 137–154, 2016.

[21] M. Aslan, Membrane Technologies. *TÜÇEV*, 275 s., 9-13, 2016.

[22] X. Liu, Z. Ren, H. H. Ngo, X. He, P. Desmond, and A. Ding, “Membrane technology for rainwater treatment and reuse: A mini review,” *Water Cycle*, vol. 2, pp. 51–63, 2021.

[23] Z. Wang, J. Ma, C. Y. Tang, K. Kimura, Q. Wang, and X. Han, “Membrane cleaning in membrane bioreactors: A review,” *J. Memb. Sci.*, vol. 468, pp. 276–307, 2014.

[24] A. Tolkou, A. Zouboulis, and P. Samaras, “The incorporation of ceramic membranes in MBR systems for wastewater treatment: Advantages and patented new developments,” *Recent Pat. Eng.*, vol. 8, no. 1, pp. 24–32, 2014.

[25] D. İmer-Köseoğlu, S. Güçlü, and İ. Koyuncu, "Membrane Technologies and Applications in Water/Wastewater Treatment and Recovery," *TÜÇEV*, 2018.

[26] Suez, "Water tech and solutions technical paper Sulaibiya - world's largest membrane water reuse Project". [Online]. Available: https://www.gewater.com/ kcpguest/documents/Technical%20Papers_Cust/Americas/English/TP1030EN.pdf, 2017. [Accessed: Apr. 20, 2023].

[27] A. N. Angelakis and P. Gikas, "Water reuse: Overview of current practices and trends in the world with emphasis on EU states," *Water Utility Journal*, vol. 8, no. 67, 2014.

[28] J. K. Upadhyaya and G. Moore, "Sustainability indicators for wastewater reuse systems and their application to two small systems in rural Victoria, Australia," *Can. J. Civ. Eng*., vol. 39, no. 6, pp. 674–688, 2012.

[29] B. Ekinci, "Example Country Practices for Efficient Use of Water Resources and Applicability of these Studies in Our Country. (Master Thesis, Republic of Turkey Ministry of Agriculture and Forestry)". 2015.

[30] C. Tortajada, Y. K. Joshi, and A. K. Biswas, *The Singapore water story: Sustainable development in an urban city-state*, Routledge, Oxon, 2013.

[31] B. Harley, "Singapore's marina barrage and reservoir-changing mindsets in urban solutions,"*Water Sensitive Cities*, C. Howe and C. Mitchell, Eds. London, England, IWA Publishing, pp. 147–154, 2011.

[32] Global Water Intel. [Online]. Available: https://www.globalwaterintel.com/client_media/uploaded/media/GWI%20Media%20pack%20A4%2013-14%20(2).pdf. [Accessed: Apr. 20, 2023].

[33] V. Lazarova, T. Asano, A. Bahri, and J. Anderson, *Milestones in Water Reuse*. IWA Publishing, 2013.

[34] M. F. Tay, C. Liu, E. R. Cornelissen, B. Wu, and T. H. Chong, "The feasibility of nanofiltration membrane bioreactor (NF-MBR)+ reverse osmosis (RO) process for water reclamation: Comparison with ultrafiltration membrane bioreactor (UF-MBR)+ RO process," *Water research, vol*. 129, pp. 180–189, 2018.

[35] Public Utilities Board. [Online]. Available: https://www.pub.gov.sg/Documents/NEWater%20Technology.pdf. [Accessed: Apr. 20, 2023].

[36] Public Utilities Board. [Online]. Available: https://www.pub.gov.sg/watersupply/waterquality/NEWater. [Accessed: Apr. 20, 2023].