Membrane Technologies For Sustainable Water Management

The idea of a green, sustainable future has sparked interest in developing membrane technologies globally, conserving energy and achieving non-discharge and waste minimisation (Le et al., 2016). To mobilise this vision, membrane technology advancements and their numerous applications are crucial. Concurrently, the invention of membranes dates back to the 18th century. Since then, there have been numerous advancements to improve the suitability of membranes for a variety of applications (Fane et al., 2011). From drinking water applications to industrial separation and wastewater recovery and reuse applications, the reporting of membrane technology uses steadily increased throughout the 1990s.

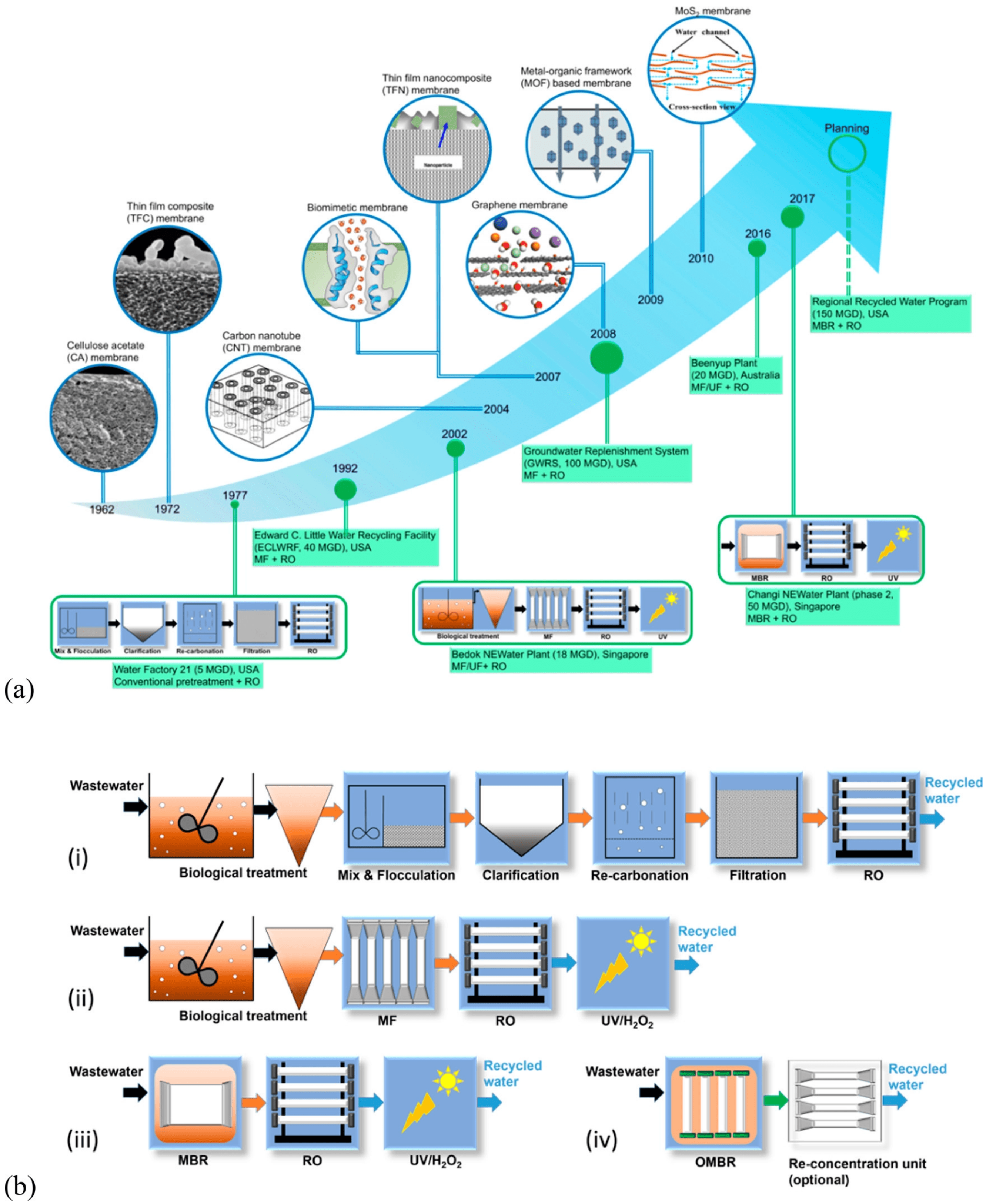
Since the beginning of this new millennium, a diversity of industries operating in the domains of computer/chip, renewable energy, pharmaceuticals, power plants, biotechnology, food and beverage have paid great attention to this form of technology (Kislik, 2010).

What are membrane technologies?

Basically, membrane technologies are a physical separation method for dividing material mixtures that use membranes as their main process element. This is in comparison to traditional separation techniques, typically thought to be more effective (Yalcinkaya et al., 2020). It is one of the most effective and practical efforts to address the global concerns we are currently facing. Unfortunately, in many regions of the world, the depletion of water resources, poor water quality, a changing climate, rising food demand, and health issues have presented a major challenge for climate adaptation (VA Tzanakakis, 2020).

Membrane technology is the most efficient membrane process, and it offers the best future prospects in wastewater treatment when compared to coagulation-flocculation, traditional filtering, and biochemical treatment systems (Elorm et al., 2020).

In fact, compared to traditional treatment systems, membrane filtering systems typically save a lot of space and chemical use (Judd, 2016; Sanghyun et al., 2017). Additionally, the filtration of membrane removal differs from that of conventional and biochemical approaches. This is because the former can ultimately have an impact on the dosages, locations, and types of coagulants used (Sanghyun et al., 2017).



Developments of membrane-based wastewater reuse.

Source: ACS Publications

Types of Membrane Technologies

Semi-permeable membranes with a porous support layer and a thin, dense layer on top are typically used. (Calabr et al., 2011). In turn, this filter acts as a barrier between the two phases, preventing the selective passage of various components through it (Takht et al., 2009). Additionally, membranes are divided into four classes based on their structural characteristics.

1. **Symmetric**
2. **Asymmetric**
3. **Homogeneous**
4. **Heterogeneous**

It is important to note that membranes are divided into organic (polymeric) and inorganic types according to their synthesis material.

Properties	Polymeric Membranes	Inorganic Membranes
Material	Rubbery or glassy type membranes based on the operating temperature	Inorganic materials i.e., glass, ceramic, silica, etc
Characteristic	Rigid in glassy form and flexible in rubbery state	Chemically and thermally stable, mechanically robust, operational under harsh feed condition
Advantages	Cost-effectiveness, good selectivity, easy processability	Withstand harsh chemical cleaning, ability to be sterilized and autoclaved, high temperature (up to 500 °C) and wear resistance, well-defined and stable pore structure, high chemical stability, long life time
Disadvantages	Fouling, chemically nonresistant, limited operating temperature and pressure, short life time	Fragile, rigid

Scientific characteristics have advantages and disadvantages.
Source: MDPI

According to Zorpas (2014), managing water resources sustainably involves being able to fulfil rising water demands without jeopardising them. In turn, we can encourage the ability of future generations to do the same. The primary solution (if we want to preserve the steady growth of society, the economy, and the ecological balance) is addressing key concerns about the global lack of water. Future generations face a serious threat from rapid industrial development, population increase, water limitations, and rising demands. Additionally, the global agriculture industry impacts water constraints (Tsangas et al., 2020; Economidou et al., 2021). According to Dos Santos et al. (2021), there is a significant increase in the demand for freshwater to meet needs in urban, rural, and industrial areas.

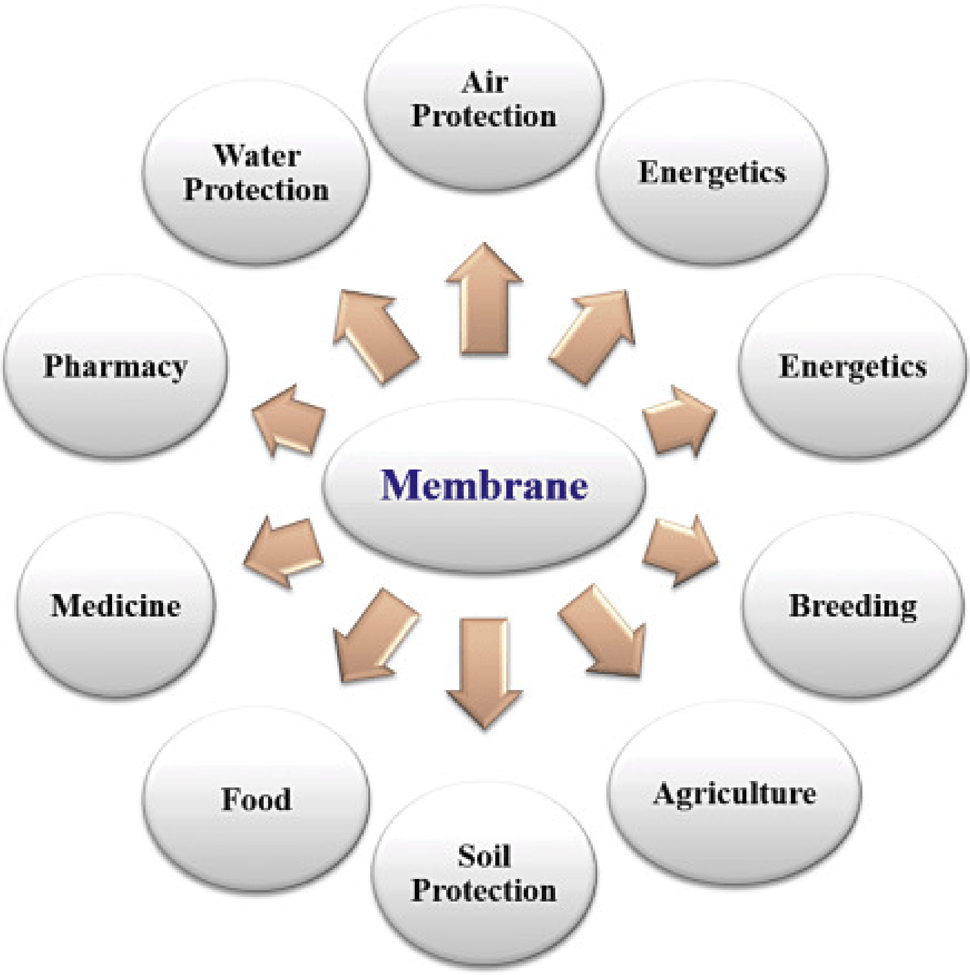
Type of Wastewater	Main Contaminants	Treatment Objectives	Membrane Technologies	Limitations
Produced water	• Drilling fluid additives • Oil and grease • Divalent cations	• Reduce salinity • Oily compounds elimination	• MD • FO • NF • RO	• Large water consumption • High total dissolved solids • Disposal regulations • High membrane fouling
Municipal wastewater	• Microbial pathogens • Micropollutants • Phosphates • Ammonia	• Degradable organic materials • Microbial removal • Eliminates nutrients	• MF • UF • NF • RO	• Need for potable reuse • Large footprint • Treatment plant odor • High membrane fouling

MD: membrane distillation, FO: forward osmosis, NF: nanofiltration, RO: reverse osmosis.

Contaminants in wastewater and their corresponding membrane technologies. Source: MDPI

Applications for Membrane Technologies

Undoubtedly, there are different applications of various types of membranes in various industries. One such application is the separation process for cleaning and regenerating water for human consumption and agricultural purposes (Azile et al., 2018). Applications like these make it possible to use membrane technology for water treatment, in line with the circular economy strategy. Conversely, the utilisation of membrane technologies has become useful to treat industrial wastewater (Al-Asheh et al., 2021), municipal wastewater from vegetable oil mills (Stoller et al., 2016), and saltwater desalination (Crutchik et al., 2022).



Basic membrane science and technology.
Source: Nanomaterial and Polymer Membranes

According to Rodriguez-Garcia et al. (2013) and Zorpas (2013), the water industry utilises membrane technology to improve water quality for use, reuse, and discharge into the environment, and wastewater. Furthermore, protozoa, bacteria, and even ions are removed using membrane processes with porous or nonporous structures (Fane et al., 2011).

challenges and future projections for membrane technologies

Interestingly, the worldwide expansion of the membrane market observes the quick development of membrane technology applications. According to the Compound Annual Growth Rate (CAGR) of nearly 9%, the size of the global membrane filtration market is anticipated to rise from USD 5.4 billion in 2019 to USD 8.3 billion by 2024.

According to the Global Membranes Market Report 2020, the market for membranes in Asia-Pacific nations (including China, Indonesia, India, Vietnam, Thailand, and Malaysia) has enormous growth potential. For this period, the ultrafiltration (Hussain & Nuzhat, 2022) market will significantly increase. This includes an average CAGR of 5.7% from $4.2 billion to $5.5 billion (Global Market BCC Research report, 2020).

Additionally, its important to consider The Millennium Project's "State of the Future" report. It provides an assessment of the world's current position, including future challenges and prospects. Moreover, TMP's system includes a framework of 15 Global Challenges identified as the most pressing current issues facing humanity during the past 17 years. Concurrently, it is possible to track the progress of each challenge. In 2001, The Millennium Project identified five of the 15 global challenges facing humanity as grouped together. Interestingly, this was due to membrane technology.

Main challenges and important research/issues needs for future membrane technology.

Challenge	Related issues/research questions
Sustainable development and climate change	New membranes (polymeric membranes, composite membranes, enzyme-based contained liquid membrane, nanocomposite membranes, hyperbranched polyimides, amorphous glassy polymers and perfluorinated copolymers polymeric magnetic membranes) for water and gas separation New processes (such as membrane/solvent hybrid technology), and high temperature membrane reactors for CO_2 capture from pre- or post-combustion flue gas Green buildings/infrastructures, remediation (such as ion-exchange membranes used in electrodialytic soil remediation) and environmental monitoring (passive samplers, sensors) Decentralized water/wastewater treatment, food/beverage processing processes, power generation systems, and other industries (reducing water consumption in power plants)
Water scarcity and water quality	New RO membranes New FO membranes and draw solutes Extension to large-scale wastewater/greywater/stormwater reclamation/reuse
Balance Population and resources	Water distribution systems/wastewater treatment systems/solid and hazardous management systems Transportation systems (such as membrane-based separators in automotive batteries)/energy supply systems (like gas separation, fuel cells) Incorporate membrane technology with food production and agricultural engineering
Health issues and reduction of diseases and immune microbes	Development of membrane technology for extra-corporal systems (such as liver support, hemodialysis, hemapheresis and lung etc.) and for industrial white and red biotechnology (like manufacturing with disposability, membrane adsorbers, tissue engineering and bioelectrochemical applications) Drug delivery and controlled release New sensors (such as membrane sensors for detecting emerging contaminants, pathogens, etc.), rapid analytical/sampling methods (such as membrane chromatography for trace element speciation), and process control strategies
Renewable energy and energy conversion	Fossil-fuel-based power plants (such as use inorganic membranes for CO_2 capture, dense ceramic membranes for hydrogen separation) New proton exchange membranes for fuel cells, besides the more conventional Nafion-type materials New semipermeable membranes for efficient generation of blue power with PRO New membrane separators (like the Separation) in automotive batteries

The main challenges and important research/issues for a bright future.
Source: Sustainable Chemistry and Pharmacy

In fact, according to MDPI Applied Sciences, membrane technology can make a significant contribution to achieving sustainable industrial development. Additionally, membrane technology is used in the separation of gases for carbon capture (Sanni et al., 2021; Song et al., 2016). Without a doubt, we can address the recycling of water from various sources using membrane technology (Teow et al., 2017

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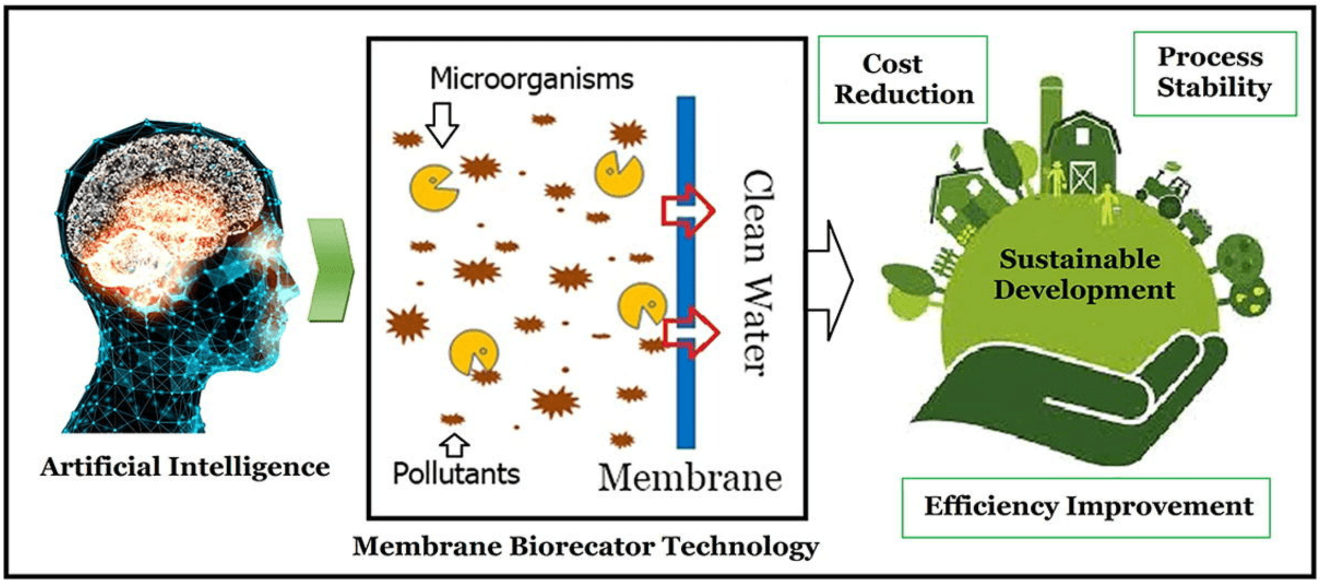
). There are many sustainable approaches, including discussions of health and energy (Sridhar, 2019).

Future Focus: Artificial Intelligence (AI) based Membrane Bioreactor

Membrane Bioreactors (MBRs) require high efficiency, sustainability, dependability, and cost-effectiveness. Research suggests that the adoption of Artificial Intelligence (AI) will have a favourable effect on the existing criteria. The performance of MBR systems to recover clean water from polluted sources can be predicted using AI models. To cope with high strength and highly polluted effluents, additional work is still required to achieve an outstanding match. Nonetheless, we must create a match between predictions generated by the AI-based algorithms and the experimental outcomes.

Interestingly, modifying and/or incorporating the currently used AI-based techniques is useful. One of the top priorities for promoting the use of MBR technology in large-scale applications is the creation of suitable factors to improve the performance of MBRs. The aim is to boost their effectiveness to cope with resistant pollutants such as contaminants of emerging concern (CECs) (Mohammadreza Kamali, et al., 2021).



Artificial Intelligence as a sustainable tool in wastewater treatment.
Source: Chemical Engineering Journal

Evidently, we choose the most appropriate membrane-based separation technologies (MBSPs) based on their wastewater pollutant load. The accessible, economically viable, environmentally friendly and sustainable technologies are also taken into account (M. von Ahnen et al., 2019). Additionally, when implementing any of the MBSPs for Water & Wastewater treatment, it is especially important to adhere to sustainable development goals in order to achieve the technical, environmental, economic, and social requirements for their performance outputs. Future research in this area needs to address the significance of the circular economy and sustainability concepts, in addition to developing novel membrane materials and technologies.

strategies for sustainable water management

Sustainable Water Strategies (SWS) secure a region's long-term water supply, used to identify threats to water availability and water quality. Interestingly, these strategies include policies and actions to help water users.

1. **Conservation:** Conserving a resource entails utilising less of it. The amount of water extracted from surface water or groundwater sources decreases by reducing the amount of water consumed. Essentially, this does not guarantee that more water will flow back into the sources than is withdrawn. Conservation is an essential step in managing a restricted water supply.
2. **Redirecting Excess Water:** United, we must take steps to replenish the water from surrounding environments to its eventual buried location. Currently, we pipe surface water into a section of the aquifer and keep it isolated from the rest of the subterranean.
3. **Desalination:** The removal of minerals, such as salt, from the water, is another effective approach that has been proven useful in places near salt water (desalination). Desalination can create water with a quality similar to that of drinking water from sewage water. Although this water is not suitable for drinking, it is suitable for use in crops, saving water from the surface and subsurface freshwater supplies.
4. **Employing New Methods in Agriculture:** Burying the water pipe at the roots of plants can create a decrease in freshwater waste in irrigation. Water can be absorbed by the roots as it pours out of the pipe.

5. **Encouraging Humans to Save Water:** Some public water suppliers charge extra fees for increased water use, which helps pay to keep surface and groundwater sources clean and sufficient. This encourages businesses and individuals to conserve water in their homes.

Why Should We Focus on Membrane Technologies for Sustainable Water Management?

Without a doubt, many fields widely use membrane technologies. As one of the most cost-effective water treatments available, membrane technologies save water resources (Shi et al., 2021). Most commonly, membrane filtration is applied to wastewater treatment. It's a good scientific treatment, and when recycled, can be used to produce considerable economic, social and environmental benefits. The widespread use of membrane technology is beneficial to the wastewater treatment field. Its reuse in a circular economy with sustainable water resources management still faces several obstacles. In fact, the expenses associated with the accompanying investments, operations, and maintenance remain considerable (Sagar et al., 2018).

Unfortunately, nearly 2.6 billion people lack basic sanitation, and without membrane technologies, millions would perish from diseases brought on by contaminated water. In addition to managing clean water resources, wastewater treatment is crucial for water safety. Membrane technologies are a more sustainable approach to dealing with problems related to water stress. (Shannon et al., 2008; Yalcinkaya et al., 2020).

Over 2 billion people experience water scarcity, according to the United Nations (UN 2019). The population will rise from 7.7 billion in 2019, to 8.5 billion in 2030, and 9.7 billion in 2050. Only 2.5% of the world's water is fresh, while the majority (97.5%) is salty. That salty water covers nearly 70% of the planet. Sadly, human activities contaminate industrial facilities. Wastewater treatment facilities, uncontrolled sewage sludge disposal, oil exploration, mining, and pesticide and fertiliser residues from agricultural practices all contribute (Zorpas et al., 2011a; Ngoc et al., 2016; Jellali et al., 2021).

achieving the United Nations Sustainable Development Goals (SDGs)

The development of Sustainable Development Goals can assist in balancing competing water needs globally. Undeniably, everyone deserves access to clean water and sanitation. Membrane technologies interweave with SDG targets and include safe and affordable drinking water, access to sanitation and hygiene, improved water quality, wastewater treatment and safe reuse, increased water-use efficiency and freshwater supplies, implementation of integrated water resources management, and protection and restoration of ecosystems that are related to water (UN 2018).

Sustainable Development Goal 6 (SDG6) aspires to confirm access to safe drinking water and sanitary facilities on a worldwide scale. The 2030 Agenda emphasises the value of water resources for sustainable development. As well as the significant contributions that improve drinking water, sanitation, and hygiene, we need to turn our focus to other areas of development, such as education, health, and poverty reduction. In order to meet the rising demand for clean water and to ensure environmental sustainability for future generations, seawater desalination appears to be one of the options for living in dryer climates (Elimelech et al., 2011).

A Thrivable Framework

Sustainable water management is necessary if we want to thrive. We must meet the present global water needs without compromising the ability of future generations to do the same.

Despite advancements in water membrane technologies, 1 in 3 people globally do not have access to clean drinking water. Unfortunately, poor reachability and difficulty in instilling appropriate technologies remain a constant. Housing schemes are at risk as they lack connection to adequate water supply networks, increasing public demand. Population growth remains one of the many challenges faced by developing countries. In conclusion, THRIVE encourages innovation and technological advancements, focusing more attention on these challenges in meeting adequate, clean water demand with more accessible water purification technologies.

To learn more about water management and the development of sustainable resources visit the THRIVE blog. THRIVE is a research, education and advocacy organisation dedicated to a ‘thrivable’ future. Join the THRIVE community and become a part of the solution.