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Membrane desalination as one of the sustainable option for water needs of coastal India

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ABSTRACT

India would move to water-starved country by 2030 (per capita availability ~ 1,000 m^3/year) from water surplus (~6000 m^3/year) in 1947. To make potable water available, desalination by membrane processes will play a major role. The desalination membrane research has been carried out since 1969 at CSIR-Central Salt and Marine Chemicals Research Institute, Bhavnagar (Gujarat) with an aim to develop technology to meet the demand for clean water. The institute has given research priority on this membrane-based water desalination over the years, and now it has the capability on providing solutions as per the locational requirements. However, worldwide, a core environmental concern of desalination plants is the reject stream discharge from the plant. Zero-liquid-discharge process by rightful management of reject stream, is key towards achieving sustainable desalination.

Keywords: Membrane process, Desalination, Reject stream discharge, Environment, Sea water, Potable water

INTRODUCTION

India would move to water-starved country by 2030 as average annual per capita water availability in India is predicted to be at around 1000 m^3 only. Desalination can increase availability of potable water by converting seawater/ brackish water into potable water. Desalination by membrane processes can play a major role for providing potable water, as the process is more viable than the other processes. Besides, the membrane processes can reduce the pollution by removing undesired dissolved salts, a wide range of components ranging from suspended solids to pathogens, toxic metals, small organic compounds and other harmful ions. At CSIR-Central Salt and Marine Chemicals Research Institute (CSMCRI), (Bhavnagar, Gujarat), membrane research program was initiated in the year 1969 with an aim to develop technology to meet the demand for clean water through desalination. In the initial period during 1970-1985, RO membranes for brackish water desalination were developed. Cellulose Acetate (CA) membranes are the first generation commercial RO desalination membranes. CA membrane type is a semi-permeable membrane that allows the water containing low amount of dissolved salt to permeate through, but it retains water containing high amount of dissolved salt when operated under external pressure in excess of the osmotic pressure of the saline feed water. In this way, it is the ‘reverse osmosis’ process of forcing potable water from brackish or seawater through the membrane by applying a pressure in excess of the osmotic pressure. This is reverse to the natural process of osmosis in which solvent from dilute solution moves towards the concentrated solution across the membrane. A better membrane separation technology that allows the usage of less material, low energy consumption and permit recovery and reuse of process streams, is certainly desirable. It can be low-pressure desalination of seawater at high recovery using combinatorial approaches of advanced material preparation and integrated systems.

POTABLE WATER AVAILABILITY IN INDIA

There is acute water shortage in various regions of the world and one major aspect that a number of towns and/or cities located in such regions have in common is the lack of adequate treatment processes for producing sufficient quantities of portable drinking water. Hence, there is a significant requirement for the development of efficient and economical water treatment technologies for production of safe and portable drinking water, water for re-use for industrial, agricultural or domestic purposes or for treatment of industrial effluents to ensure safe disposal. Most water sources in India are contaminated by mixing with various industrial and sewage effluents. Although, access to drinking water has improved, significant amount of communicable diseases in India are from contaminated water. Providing safe drinking water at affordable cost is the top priority for the country as every year, millions of people suffer from water-borne disease (disease caused by microbes and pathogens). Safe water for drinking and cooking uses is an essential component of effective policy for health protection. To counter the water problems, various water treatment technologies have emerged which include physical, chemical and biological processes.

The water problem in India has been serious and it is towards water-starved country by 2030 as mentioned above as average annual per capita water availability in India is predicted as 1000 m^3 only (Figure 1). According to press release by Ministry of Jal Shakti, Government of India dated 25 MAR 2021 PIB Delhi, the average per capita per annual water availability in India is 1486 cu m which is in decrement by more than four folds from 6000 cu m of the average per capita per annual water availability in 1947 (https://pib.gov.in/PressReleaseIframe Page.aspx?PRID=1707522). The Department of Drinking Water and Sanitation, Government of India, has already taken significant steps to meet this challenge. It has made some progress in the supply of safe water to its people, but gross disparity in coverage exists across the country. The widespread occurrence of water-borne diseases resulted from poor hygiene, causing public health challenges, indicating that significant portion of the country have still inadequate sanitation and limited access of safe drinking water sources.

The National Water Policy in 1987, 2002 and 2012 by Government of India laid down principles for drinking water, irrigation, industrial and ecological environmental aspects, sanitation and treatment methods for water to make potable. The general perception on the quality of drinking water by the masses whether the water is good or bad, is on physical tests of taste, smell and looks. Bureau of Indian Standards IS 10500: 2012, has now drinking water specifications, that the drinking water should be considered safe after the acceptable specification set by BIS being the water tested by standard laboratory for all the organic and inorganic contaminants. Overall, it requires delivering potable water for the masses in aligned with Swastha Bharat and Swaccha Bharat. The Make-In-India delivering the indigenous water technologies would be better, which can link to the entrepreneurs in this sector that will save foreign exchange and can generate employments in the sector.

One of the most important water technology is desalination that can increase availability of potable water by converting seawater/ brackish water into potable water. Conventionally, it is done by thermal method, where the saline water is heated by heating system converting liquid water into water vapor, which on further condensation through a separately arranged condenser including circulation pumps, lead to separated potable water from the saline water. However, since the process involves phase change along with the multiple stages/effects and pumping systems, the overall process of thermal desalination is bulky and expensive. On the other hand, in the membrane reverse osmosis (RO) process, the saline water (seawater or brackish water) is pumped through a clarifier system operated under a lower pressure where the suspended particles, microbes and other small colloids are removed. The clarified saline water is then pumped through RO membrane system operated at a higher pressure, where excess minerals of dissolved salts are removed, giving rise to mineral balanced healthy and pathogen-free safe water. In this membrane system, there is no phase change; it only requires electrical energy to pump water through the clarifier and membrane systems. As a result, the membrane process is the most cost-effective desalination technology.

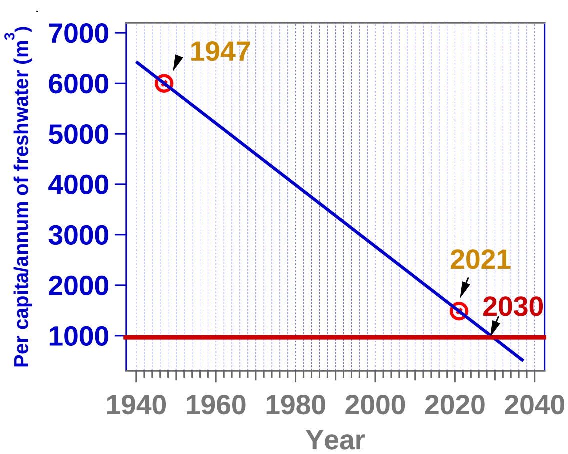

Figure 1. Declining availability of water in India with time

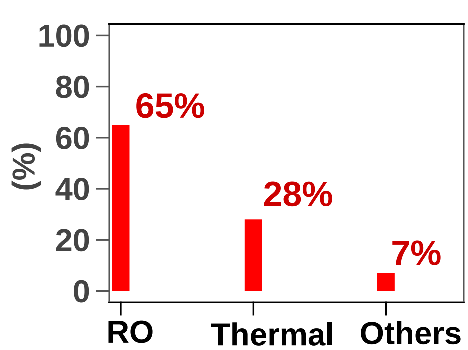

Figure 2. Total worldwide installed desalination capacity in percentage by technology (RO membrane, thermal and others)

MEMBRANE DESALINATION TECHNOLOGY

The membrane desalination process was first initiated by Sidney Loeb and Srinivasan Sourirajan (Loeb and Sourirajan, 1963) through cellulose acetate membrane. The preparation of the cellulose acetate (CA) membrane was achieved by first dissolving a desired amount of the CA in a suitable solvent to form a casting dope, followed by casting of the CA solution into the formation of the CA membrane. The CA membrane exhibits asymmetric pore structure comprising of dense skin and gradient pores underneath that acts as semi-permeable membrane allowing the water containing low amount of dissolved salt by the reversal of flow of osmosis process through the membrane.

The membrane desalination technology has been playing a major role for providing potable water, as the membrane process is more viable than the other processes (Imbrogno and Belfort, 2016; Wenten and Khoiruddin, 2016). As shown in Figure 2, the installed membrane desalination worldwide is more than twice of the installed thermal desalination (Fane, 2018). Besides, the membrane processes can reduce the pollution by removing undesired dissolved salts, a wide range of components, ranging from suspended solids to pathogens, toxic metals, small organic compounds and other harmful ions (Quist-Jensen et al., 2015; Fane et al., 2015).

MEMBRANE RESEARCH AT CSIR-CSMCRI, INDIA

At CSIR-Central Salt and Marine Chemicals Research Institute (CSMCRI), membrane research program was initiated in the year 1969. In the initial period during 1970-1985, the CA membranes for brackish water desalination were developed. The following steps were used for manufacturing of the CA membranes.

(i) Preparation of CA solution

(ii) Casting of the CA solution on a suitable support

(iii) Formation of CA membrane by immersion in a coagulating water bath.

This process results in the conversion of polymer solution on the support to a solid film with porous structure. The porous film was then separated out from the support and subjected for annealing at different temperatures for different time in hot water. This results in the creation of a membrane with an appropriate pore size for desalination. By using the CSIR-CSMCRI CA membranes, several plants (400-2000 Liters/h capacity) were set up for brackish water desalination in various part of the country during 1980-1990. The technology was highly beneficial for supplying good quality to people of coastal area of India and regions with high salinity groundwater such as Rajasthan. The desalination of seawater and high saline groundwater to the drinking quality was a noble approach for providing potable water to the common masses, provided proper maintenance was regulated and village folks was trained for the decentralized plant operation. The most satisfying moment in the CA membrane technology came in when Govt. of India gifted two CA based RO (1250 Liter/h capacity) plants to Govt. of Thailand in 1989 (Figure 3). Subsequently, Govt of Thailand had placed an order for 4000 sq. m of RO membrane. The technology for manufacturing cellulose acetate asymmetric RO membranes was licensed to BHEL, Hyderabad and Arrow Technology Pvt Ltd, Ahmedabad.

Figure 3. RO desalination installed plants based on CSIR-CSMCRI CA membranes

However, the CA membrane type has certain disadvantages because of various factors. Firstly, it is made from a single material in a single step by phase inversion process that resulted an integral membrane structure, which is asymmetrically porous comprising of top skin layer and porous sub-layer. The top skin layer is responsible for selective passing of salt and the porous sub-layer for providing mechanical support with practically negligible barrier resistance to the transport of the permeating molecule. Thinning of the top skin layer for higher water permeability was hardly possible as the structure is an integral one. Secondly, since it is natural polymer, the biological fouling is severe and tolerance in harsh environment is limited.

Both the high water permeability and salt rejection efficiency are desirable characteristics of the RO membrane as well as endurance for long life that can tolerate harsh environments and high resistant to fouling. In the pursuit, another RO membrane known as thin-film-composite (TFC) membrane was prepared in which the top selective layer is polyamide formed by interfacial polymerization by reaction between meta-phenylene diamine (MPD) and trimesoyl chloride (TMC) in the early 1980s (Cadotte, 1977, 1981; Cadotte et al., 1980, 1981).

The TFC membrane sheet is comprised of three layers such as, top selective layer of dense polyamide, middle sub-layer support of porous polymer and bottom non-woven fabric as depicted in Figure 4. It has several advantages in views of longer membrane life, mechanically high strength, high salt rejection efficiency and high water permeability and wide tolerance in pH range of 3 - 11. The TFC membrane is prepared in 2 steps. In the first step, Polymer support membrane (PSM) is prepared by a phase inversion process from polymer casting solution, prepared by dissolving a desired amount of polymer such as polysulfone in a suitable solvent. The process itself is controlled by both the thermodynamic and the kinetic factors that greatly influence on membrane morphology, surface pore size and porosity that is crucial on development of improved membranes (Singh et al., 2006; Veerababu et al, 2014).

Figure 4. TFC membrane, module and recently installed few RO desalination plants as per CSIR-CSMCRI membrane design (2020-2021).

In the second step, deposition of a dense polyamide layer over the PSM is achieved using a coating process known as interfacial polymerization (IP). The PSM is first contacted with an aqueous solution of m-phenylenediamine (MPD) to allow absorption of the MPD monomers in the PSM. The MPD absorbed support is then contacted with an organic solution of trimesoyl chloride (TMC) to allow IP process over the support. Various factors affect the properties of TFC membrane. They are the nature of the PSM, reaction condition of the IP, curing of the nascent polyamide formed after the IP, washing protocol to remove residual monomers and protective layer coating of the final TFC (Rao et al., 2003; Singh and Aswal, 2007; Jadav and Singh, 2009; Singh et al., 2011, 2012; Rangarajan et al., 2011; Agrawal and Singh, 2012). The RO desalination technology based on the TFC membrane is presently the most energy efficient of all the seawater desalination technologies (Greenlee et al., 2009; Misdan et al., 2012).

CSIR-CSMCRI developed a large-scale facility (200 m^2 per batch) for the production of such membranes and licenced the technology for commercial production of TFC membranes and modules to M/s Uniqflux Membranes LLP, Pune, Rinzai Hydratech, Ahmedabad, and OM Tech, Rajkot (Joshi et al., 2004; Shah et al., 2004, 2005; Singh et al., 2013). The institute continues to improve its RO membrane technology (Sharma et al., 2009; Bera et al., 2015; Rana et al., 2015; Gohil and Ray, 2017; Singh et al., 2020; Thummar et al., 2023), while making the plants ever more simple and robust including the use of alternative energy source such as solar or animal-powered plant. It has capability to develop water desalination tailor made RO units as per the locational requirements starting from the development of appropriate membrane to the module making by integrating customized pretreatment system and desired automation for hassle free operation. It has installed several water desalination plants across the country and abroad (Kenya, Afghanistan). The installation of RO desalination plants of various capacities in the last 25 years are shown in Figure 5. The institute also had designed and developed a mobile desalination for water desalination and purification with the key feature that the required power to operate the plant is obtained from the bus engine itself. The mobile desalination provides the potable water on spot during draught, cyclone, earth quake, or any type of national calamities. It was deployed for providing drinking water in West Bengal (North 24 Parganas) after Aila cyclone 2009, North India flood in Uttarakhand 2013, Drought in Latur in Maharashtra 2016, Cyclone Phailin in Odisha 2013, Kerala floods in 2018, Cyclone Fani in Odisha 2019, Cyclone Tauktae in Gujarat 2021, and the Konkan Floods in Maharashtra 2021.

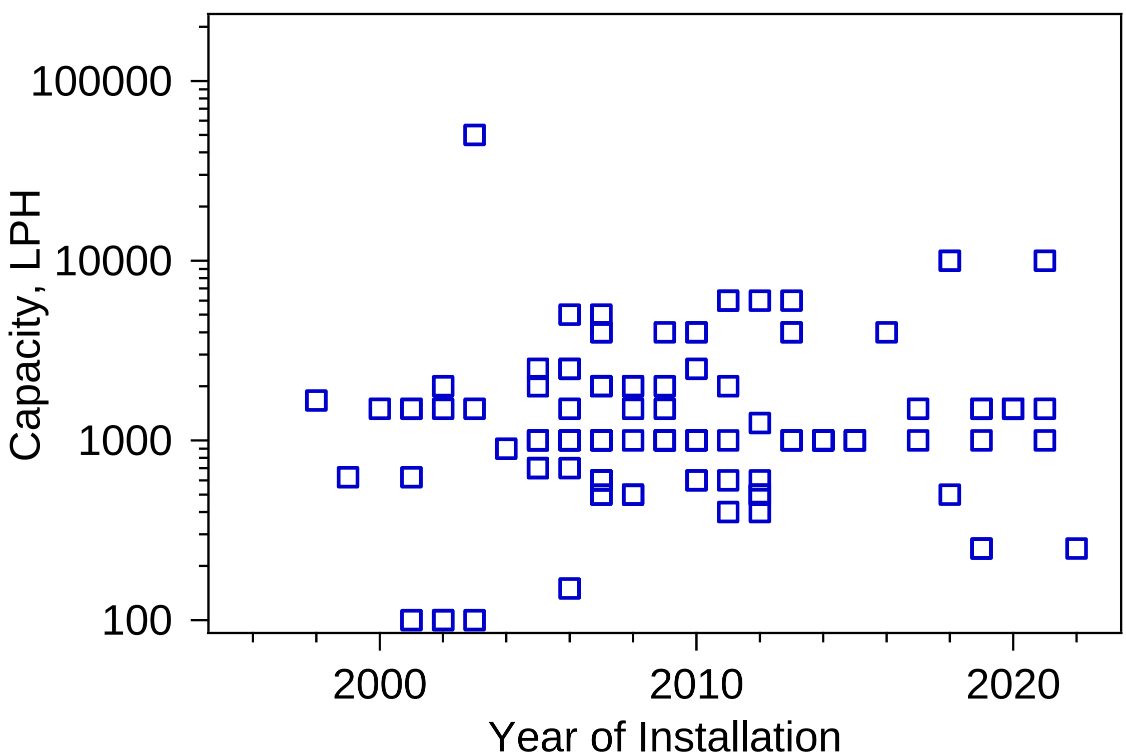

Figure 5. Installation of CSIR-CSMCRI designed RO desalination plants of various capacities in various parts of India during the last 25 years

CONCLUSIONS

CSIR-CSMCRI has given impetus on membrane-based water desalination as a research priority over the years and has capability on providing solutions as per the locational requirements by the integration of appropriate membrane modules with customized pre-treatment system for hassle free process. For India, decentralized RO plants using indigenously manufactured membrane, other consumables and capital items would reduce the overall cost. Besides, it will be of easy operation and maintenance as the service and miscellaneous items outsourced locally. Furthermore, for a medium sized seawater desalination, diffusion of about 80 m^3/h reject stream in open sea would not create any significant change in local salinity thereby no adversity in sea environment.

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Author Credit Statement

Writing original draft, review and editing, methodology and conceptualization.

Data Availability

Data will be made available on request.

Compliance with Ethical Standards

The author declares that the work reported here is in compliance with ethical standards and adhere to copyright norms

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