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# Beyond NEWater: An insight into Singapore's water reuse prospects

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**Abstract**
Indirect potable water reuse has been implemented island-wide in Singapore over the last 15 years. Nowadays, water reuse provides in average 30% of the nation's water demand and the so-called NEWater success story has largely contributed to turning Singapore into a global hydrohub for pioneering new water technologies. In this context, this short review presents the latest technological advances and the perspectives for water reuse in Singapore. Areas of focus include membrane development (including forward, reverse and pressure retarded osmosis, as well as membrane bioreactors), advanced oxidation processes, electrochemical approaches, and their integration as cost-effective tailored solutions to tackle new challenges as diverse as direct potable reuse, industrial water reuse, decentralized water reuse and the circular economy.

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## Introduction

The 2017 theme for World Water Day was 'wastewater', which can defined as water whose quality has been deteriorated by agricultural, industrial or domestic use [1]. Concurrent to World Water Day was the launch of the World Water Development Report 2017 entitled 'Wastewater- The Untapped Resource' which refers to wastewater as the new oil, emphasizing the vital importance of water as a natural resource, which in many parts of the world is taken for granted [2]. With climate change expected to shift water availability over the world, emphasize geographical disparities and threaten up to four billion people in regions that are generally already vulnerable, action is required to rethink our water consumption paradigms [3].

As a tiny island-nation off the southern border of continental Malaysia, Singapore faces many challenges: lack of land and natural resources, highly urbanized densely-populated environment, etc. With total renewable freshwater resources of 0.6 $km^3$ and a population of 5.6 million, corresponding to less than 110 $m^3$ per capita, Singapore's water situation is comparable to that of Libya, Jordan or Sudan and makes it by far the most water scarce country in South East Asia. Historically, Singapore has relied on Malaysia for its freshwater supply but has started looking at water reuse as early as the 1970s [4]. Though at that time, membrane technology was deemed unviable economically, the assiduous technology watch that ensued later led to pilot demonstration in the 1990s followed in the 2000s by island-wide implementation of NEWater, the brand name given to reclaimed water by Singapore's Public Utilities Board (PUB). Nowadays, 4 NEWater plants supply in average 30% of Singapore's water demand, a number which is expected to rise to 55% by 2060, at which point of time NEWater production could be as high as 440 million imperial gallons per day (mgd).

Resorting to water reuse frees space for more valuable land usage in a megacity and is more energy efficient than desalination. Most importantly, it is the strategic goal to render the country self-sufficient water wise that has contributed to larger public acceptance in Singapore than in neighboring Australia for example [5]. Indeed, even though the NEWater success story is generally attributed to the seal of quality underlain under the branding of NEWater, which encompasses different layers of trust in technology, experts and government [4], research has demonstrated that the primary reason for acceptance was the positive discourse dominantly circulated by the media, which allowed the overcoming of visceral reactions, also known as the 'yuck' factor [5]. In particular, the development of a thick narrative, associating the issue of water reuse to water security and environmental constraints, making it imperative to recycle water, has contributed largely to the NEWater success story [6].

Singapore has adopted a highly centralized approach to water reuse with a treatment train consisting of primary sedimentation/activated sludge/microfiltration (MF)/ultrafiltration (UF)/reverse osmosis (RO)/ultraviolet

(UV) disinfection. Thus, the core technology behind the production of NEWater is pressure-driven RO, which allows particle separation primarily by size exclusion through pores ranging between 0.2 and 0.4 nm [7]. At this pore size, permeate is literally solid-free, including no emerging contaminants, metals, salts, viruses or other micro-organisms. The downsides of RO consist of high energy requirements and membrane fouling, which are mitigated through pre-treatment, consisting of successive stages of primary clarification, biological treatment, and low-pressure MF (0.1–0.2 μm)/UF (0.01–0.02 μm). In the unlikely event of RO integrity breach, UV post-treatment ensures that the permeate remains free of any microbiological content at all time. Following this multiple-barrier approach, NEWater surpasses the WHO drinking water quality guidelines [8] at a cost below SGD0.2/$m^3$ and a fraction is directed towards industries requiring ultrapure water (e.g., in the micro-electronics sector) while the remaining enters the reservoirs for remineralization and indirect potable reuse (IPR) [4].

## State of the art of water reuse research

### Membrane development

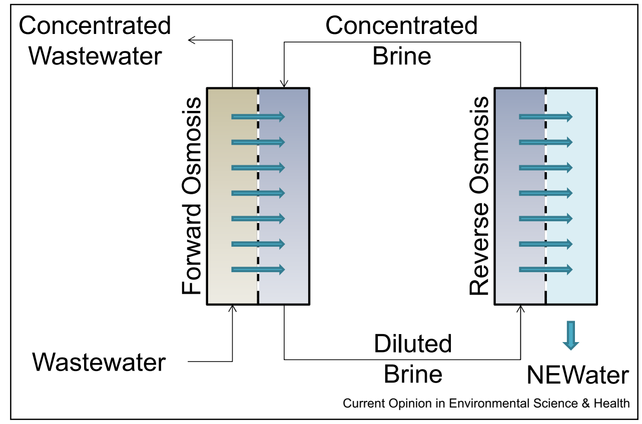
RO constitutes the core technology behind water reuse but high energy requirement and brine management constitute serious drawbacks. The main benefit of RO is its ability to deal with salinity removal. For pathogens and emerging contaminants, it could well be substituted by a more cost-effective multi-barrier approach implying a combination of biological, adsorption, MF/UF and advanced oxidation processes (AOPs) [9].

Among alternatives to RO, the recent years have increasingly emphasized the promises of forward osmosis (FO) and pressure retarded osmosis (PRO) [10]. By making use of a draw solution to naturally drive the osmotic process, FO benefits from drastically lower energy consumption and fouling propensity as compared to RO; however the product of FO is not NEWater but a diluted draw solution that requires secondary treatment. This implies that FO and RO may not necessarily be mutually exclusive and in fact they could be combined for energy optimization with RO concentrate being used as the draw solution for FO (Fig. 1). This approach is particularly promising for inland water reuse solutions where brine disposal is not an option. In Singapore, the inherent limitations of FO such as the need for better membrane materials [11] still limit its applications in the near future. PRO however could constitute a promising avenue to generate hydropower from RO brine provided sturdier membranes are developed that can withstand the high pressure of concentrated brine [10].

### Advanced oxidation processes

AOPs, based on the generation of hydroxyl radicals (·OH), have been successfully implemented for tertiary treatment of urban wastewater, alone or in combination with other technologies as an element of a multiple-barrier process in water reuse schemes. Unlike membranes, AOPs are destructive methods that cause the cleavage of structural bonds and induce the conversion of the initial pollutant into several intermediates at a rate higher than natural processes [12]. AOPs are thus applicable before membranes processes to decrease fouling or after in order to remove micro-pollutants that can pass through. Disadvantages of AOP technologies include the formation of oxidation by-products that, in certain circumstances, can accumulate in water and be more toxic than the parent compound. For example, $O_3$/$H_2O_2$ and UV/$H_2O_2$ can lead to either the formation or the degradation of bromate [13], polyfluorinated compounds [14] or halogenated disinfection byproducts [15] depending upon the conditions. N-Nitrosodimethylamine (NDMA) has been particularly well studied and was found to form only when AOPs are applied before RO [16,17]. However, AOPs can produce more-reactive NDMA precursors persisting in RO permeate and enhancing NDMA formation during final chloramination [15–17]. Because both the AOP dose and the nature of the matrix play determinant effects, it is necessary to carefully evaluate these effects before implementation for water reuse [18]. A summary of various AOPs and their advantages and disadvantages is compiled in Table 1.

**Fig. 1**




Combination of FO and RO processes for energy optimization. The RO brine would play the role of the draw solution in that NEWater production scheme.

### Electrochemical approaches

Electrochemistry is increasingly regarded as a core science for the development of a sustainable society from fuel cells to waste electrochemical oxidation, desalination and water reuse [21]. Electrochemical AOPs are attracting a lot of attention, owing to their many advantages, including use a cleaner reagent (electricity), possibility to reach superior degrees of mineralization,