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Direct Potable Reuse: The Singapore NEWater Project as a Role Model

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Abstract

In Singapore, indirect potable water reuse has been applied during the last two decades. Now, water reuse furnishes around 30% of the nation's water request and the well-known NEWater success story has greatly participated in transforming Singapore into a global hydro hub for pioneering novel water techniques. This work discusses the recent technological improvements and the outlooks for water reuse in Singapore as a model. Fields of attentions comprise membrane exploitation (involving forward, reverse and pressure retarded osmosis, as well as membrane bioreactors), advanced oxidation processes, electrochemical methods, and their combination as cost-effective tailored solutions to tackle novel dares as diverse as direct potable reuse. The challenge is to duplicate the Singapore NEWater success story throughout the world. Efforts should be accomplished to generalize such encouraging and rich experience especially in poor countries where humans are dying because of lack of water or due to diseases caused by contaminated water.

Subject Areas

Environmental Sciences, Hydrology

Keywords

Water Reuse, Direct Potable Reuse, Water Scarcity, Membrane Processes, Wastewater Treatment, Drinking Water

1. Introduction

Wastewater may be known as water whose quality has been damaged via agricultural, industrial or domestic use [1] [2]. Wastewater is considered as the novel oil, focusing attention on the indispensable significance of water as a natural resource, which in several regions is viewed as a gift [3] [4] [5]. In addition to climate modifications, especially global warming, anticipated transferring water accessibility across the Earth, affirming geographical disproportions and menacing to four billion people in areas that are mostly previously weak, measures are needed to reconsider water use models [6] [7] [8].

Singapore confronts several dares: shortage of ground and natural resources, civilian thickly inhabited nature, etc. With global renewable freshwater resources of 0.6 km^3 and a population of 5.6 million (*i.e.*, corresponding to less than 110 m^3 per capita), Singapore's water case is similar to that of Libya, Jordan or Sudan and causes it by far the most water-scarce state in South East Asia. With reference to past events, Singapore has counted on Malaysia for its freshwater supply but has commenced seeking water reuse as early as the 1970s [9]. Even though at that period, membrane technology [10] [11] [12] [13] was not considered feasible economically, the assiduous technology watch that resulted later conducted to a pilot demonstration in the 1990s pursued in the 2000s by the island-wide achievement of NEWater, the brand name attributed to reclaimed water by Singapore's Public Utilities Board (PUB). These days, four NEWater plants supply in average 30% of Singapore's water demand, a number that is expected to rise to 55% by 2060, at which point of time NEWater production could be as high as 2 million m^3 per day [3].

Having recourse to water reuse, which is more energy-efficient than desalination, releases area for more worthy land utilization [3]. Water reuse remains the judicious target to make the nation self-sufficient water-wise that has participated in wider public admission in Singapore than in proximate Australia for instance [14] [15].

Singapore has embraced a quite focused procedure to water reuse with a treatment train incorporating primary sedimentation/activated sludge/microfiltration (MF)/ultrafiltration (UF)/reverse osmosis (RO)/ultraviolet (UV) disinfection [16] [17] [18] [19] [20]. Consequently, the heart technology behind treating water in NEWater is pressure-driven RO, which lets particle removal firstly via size-exclusion by means of pores extending among 0.2 and 0.4 nm [21]. At this pore dimension, permeate is solid-free, comprising no rising pollutants, metals, salts, viruses or other microbes. However, the drawbacks of RO comprise elevated energy needs and membrane fouling, which are relieved via pre-treatment, containing consecutive steps of primary clarification, biological treatment, and low-pressure MF (0.1 - 0.2 mm)/UF (0.01 - 0.02 mm). In the improbable incident of RO solidity fracture, UV post-treatment guarantees that the permeate stays free of any microbiological content at all times [3]. With this multiple-barrier technique, NEWater exceeds the WHO drinking water quality guidelines [22] at a price under SGD 0.2/m^3 and a portion is directed towards industries needing ultrapure water (e.g., in the micro-electronics sector) while the remaining enters the reservoirs for remineralization and indirect potable reuse (IPR) [9].

This paper presents the recent technological improvements and the outlooks for water reuse in Singapore as a model. Fields of attentions comprise membrane exploitation (involving forward, reverse and pressure retarded osmosis, as well as membrane bioreactors), advanced oxidation processes (AOPs), electrochemical methods, and their combination as cost-effective tailored solutions to tackle novel dares as diverse as direct potable reuse.

2. Latest Advance in Water Reuse

2.1. Membrane Expansion

RO composes the central technology at the back of water reuse; however, elevated energy necessity and brine handling make severe hurdles [23]. The prime advantage of RO remains its potential to address salinity elimination. Concerning microorganisms and rising pollutants, it may well be replaced via a more cost-effective multi-barrier procedure involving the integration of biological, adsorption, MF/UF and AOPs [3] [24].

In the group of replacements of RO, the last decade has progressively intensified the potentials of the forward osmosis (FO) and pressure retarded osmosis (PRO) [25]. Throw taking advantage of a draw solution to naturally drive the osmotic process, FO advantages from fundamentally lower energy consumption and fouling propensity as contrasted to RO; nevertheless, the product of FO is not NEWater but a diluted draw solution that needs secondary treatment. This indicates that FO and RO may not automatically be reciprocally exclusive and actually, they may be integrated for energy optimization with RO concentrate being employed as the draw solution for FO (**Figure 1**) [3]. This method is essentially favorable for inland water reuse solutions where brine recycling is not a choice. In Singapore, the intrinsic restrictions of FO like the requirement for better membrane materials [26] up to this time shorten its utilizations in the next years. PRO, still, may form a coming approach to produce hydropower from RO brine as long as firm membranes are advanced that may resist the

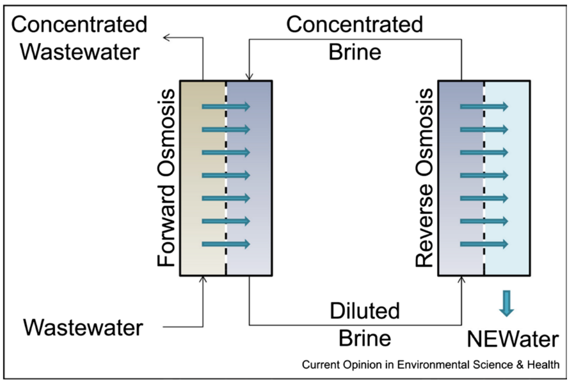

Figure 1. Integrating FO and RO methods for energy optimization. The RO brine would play the role of the draw solution in that NEWater production scheme [3].

elevated pressure of concentrated brine [25].

2.2. Advanced Oxidation Processes (AOPs)

Founded on the formation of hydroxyl radicals ($^{\bullet}$OH), AOPs have been efficiently applied for tertiary treatment of domestic wastewater, single or in integration with additional methods as a piece of a multiple-barrier technology in water reuse programs [3] [27]. In contrast to membranes, AOPs are devastating techniques that occasion the division of constitutional bonds and cause the transformation of the beginning contaminant into numerous intermediates at a percentage bigger than simple methods [28]. As a result, AOPs are usable before membranes methods to reduce fouling or later to eliminate micro-contaminants that may go through. Drawbacks of AOP methods comprise the generation of oxidation by-products [29] that, in defined situations, may gather in water and be more poisonous than the original compound. For instance, O_3/H_2O_2 and UV/H_2O_2 may conduct to either the generation or the decomposition of bromate [30], polyfluorinated chemicals [31] or halogenated disinfection by-products [32] [33] [34] [35] following the circumstances. N-Nitrosodimethylamine (NDMA) has been mostly well investigated and was detected to produce only when AOPs are implemented prior to RO [36] [37]. Nevertheless, AOPs can form more-reactive NDMA precursors staying in RO permeate and improving NDMA generation throughout final chloramination [32] [36] [37]. Due to both the AOP injection and the type of matrix play deciding roles, it is indispensable to accurately estimate such influences prior to applying for water reuse [38]. **Table 1** presents a list of different AOPs and their benefits and drawbacks [3].

Table 1. AOP juxtaposition [3].

Technique	Benefits	Drawbacks
Ozonation (O_3/H_2O_2, O_3/Fe^{2+}, $O_3/Fe^{2+}/UV$)	Field-proven	Production of oxidation by-products, air permit needed for ozone emissions, off-gas treatment system for ozone destruction. Elevated working prices because of low water solubility.
Photolysis (O_3/UV, H_2O_2/UV)	Field-proven, UV's disinfection impact	Interference from turbidity. UV's elevated price. UV's restricted domain.
Heterogeneous photocatalysis (TiO_2/UV)	Runs in a larger span of UV than photolysis like UVA (300 - 380 nm)	If TiO_2 is employed as a slurry, a separation stage is needed. Supported TiO_2 technique depicts promises in this direction; however, it has to be scaled-up.
Traditional Fenton reaction (H_2O_2/Fe^{2+})	Efficiency not touched via water quality. Greatly low-priced because of the H_2O_2 elevated solubility.	No full-scale usage. Optimal pH ~ 3.0*. Forms elevated quantities of Fe [39] sludge.
Electro-Fenton	The most effective of all AOPs. It may be automated. No chemical products but for the catalytic quantity of Fe (<0.1 mM), electrochemically produced at the cathode of the device. Little sludge generation.	No full-scale utilization. Needs acidic pH ~ 3.0. and persistent supply of O_2.

*(Solar) photo-Fenton has been largely tried during this decade as tertiary treatment technique for municipal wastewater reuse. Further, it may be used under more moderate circumstances (pH 5 - 6, lower concentrations of Fe and H_2O_2) [40]. This is due to the elimination of pollutants of emerging concern (frequently found in the order of ng/L) and microbial demobilization attributed to the smaller quantity of hydroxyl radicals formed contrasted to pH 3 method is enough. Further, employing complexing/chelating agents has been successfully studied too [41].

2.3. Electrochemical Technologies

Electrochemistry is more and more viewed as a central knowledge for expanding a possible society from fuel cells to waste electrochemical oxidation, desalination, and water reuse [42] [43] [44]. Electrochemical AOPs are magnetizing many of the awareness, thanks to their numerous benefits, comprising employing a more hygienic reagent (electricity), potential to attain outstanding levels of mineralization, versatility, elevated energy effectiveness [45], amenability of automation and safety [46] [47] [48] [49]. As shown in **Table 1**, electro-Fenton is fast rising as the most encouraging between electrochemical techniques [50] [51], particularly via the integration with nanomaterials like graphene [52] [53] or boron-doped diamond (BDD) to boost anodic oxidation as an extra source of $^{\bullet}$OH [3] [54].

In opposition to different membrane techniques, electrodialysis (ED) depends on charge exclusion and remains a strictly and economically feasible replacement to RO for brackish water desalination, particularly for small facilities [55] [56]. The less rigorous feed quality for ED as contrasted to RO participates in lower the pre-treatment costs [3]. On the other hand, capacitive deionization has proved the capacity to elevate water recovery from RO brine even with cleaning troubles [9] [57] [58].

3. Outlooks

3.1. Membrane Bioreactor

In Singapore, the following procedure for water reuse will be the expansion of the membrane bioreactor (MBR) [3]. This biological technique integrates the advantages of secondary treatment and MF/UF in one device, with the major merits being a compact structure and consistently good effluent quality. In Singapore, this MBR-RO technique has previously been investigated at the pilot stage [59]. A new expansion remains the FO-MBR accompanied by the benefit of energy efficiency [60]; however, the obstacle of low flux and augmented salinity over time inside the bioreactor, which may negatively touch sludge viability [61].

3.2. Direct Potable Reuse

Direct potable reuse (DPR) is considered as the novel limit of water reuse [3] [62] [63] [64]. The fundamental feature for such a strategy to triumph is treatment boost in a multiple-barrier path, which can conduct to the almost not available likelihood of insufficiency [65] [66]. Singapore possesses several benefits to put into action DPR. First, the PUB before now runs the full water cycle from potable water to wastewater treatment. Second, the administration of NEWater in Singapore has previously confirmed to be reliable over several years. For instance, over 300 persistent organic pollutants [67] [68] [69] [70] are previously routinely controlled [9]. At present, it is easy to control a large number of these chemicals at levels as low as parts per trillion [71].

4. Conclusions

The main points drawn from this work may be given as:

1) The success story of Singapore NEWater mirrors the total semi-permanent planning of the city-state in terms of sustainability. There is a necessity to persist in expanding water techniques and original reuse programs for Singapore. The secret is combining oriented merged solutions joining advanced degradation and separation techniques and their utilization at different levels to address diverse requests.

2) The challenge is to duplicate the Singapore NEWater success story throughout the world. Efforts should be accomplished to generalize such encouraging experience especially in poor countries where humans are dying because of lack of water.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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