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REVIEW PAPER

Parameters for Seawater Reverse Osmosis Product Water: A Review

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Abstract Today, seawater reverse osmosis (SWRO) desalination is one of the leading technologies for producing fresh water from the vast oceans which can augment water supply beyond what is available from the hydrological cycle. Quality of SWRO product water, whether used for drinking, domestic purposes, food production, or recreational purposes has an important impact on health. This review identifies 60 priority concerns for the benefit of drinking-water supply system under the framework of an integrated SWRO stages from source to tap, covering the development of up-to-date research trends and full-scale SWRO project experiences.

Keywords Product water · Seawater reverse osmosis desalination · Quality parameters

Abbreviations

DBPs	Disinfection by-products
EPA	Environmental Protection Agency
HAAs	Haloacetic acids
I-THMs	Iodinated THMs
I-HAAs	Iodinated HAAs
MF	Microfiltration
NF	Nanofiltration
RO	Reverse osmosis
SWRO	Seawater reverse osmosis
SDI	Silt density index
TDS	Total dissolved solids
THMs	Trihalomethanes
UF	Ultrafiltration
WHO	World Health Organization

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Introduction

Water is one of the necessities of life. More than one-third of the world's population already suffers from shortages of potable water—with a rise to 65 % expected by 2025 (Elimelech et al. 2011). Desalination is the only method to increase water supply beyond what is available from the hydrological cycle except for water reuse. Seawater desalination offers a seemingly unlimited, steady supply of high-quality water from the vast oceans, without impairing natural freshwater ecosystems (Peñate et al. 2012; Greenemeier, 2012). Seawater reverse osmosis (SWRO) desalination occupies an 80 % share in the total number of large-scale seawater desalination plants installed worldwide in modern times due to its low cost of the product water depending on the energy consumption, which can be around 0.50–0.70 US$/m^3 (Bruggen et al. 2002; Tularam et al. 2007). Currently, it is exploited all over the world, particularly in the eastern Mediterranean region, the United States, Australia, China, and Japan, with use rapidly increasing on all continents (Zheng et al. 2014).

Although SWRO is a well-established technology, no standardized universal strategies for SWRO product water analysis or results interpretation with reliable efficacy are in the control of this new source of man-made drinking water. A global emerging problem is up-to-date regulations and standards on the drinking-water quality have focused on desalinated seawater treatment system or reverse osmosis (RO) drinking-water treatment system intended for the treatment of household drinking water using surface water sources which is different from SWRO feed water. The available journals elaborating the operating experiences of SWRO process do not present sufficient data explaining the process parameters and the quality of the SWRO product water. Monitoring policies are developed by individual desalination plant laboratory analysis, but acceptable concerns are highly variable across and within the product water, projects, and countries. Since some of the product water hazards are similar to the challenges encountered in most piped water systems, others present differences, for example, those associated with pretreatment, post-treatment, and its interaction with the distribution system. Furthermore, non-regulated emerging hazards are present in the SWRO product water since disinfection by-products (DBPs) formation and speciation are different in seawater (Kundu et al. 2004; Roux et al. 2015; Simões et al. 2013). As for a number of potential contaminants reaching drinking-water supplies from upstream wastewater discharges, such as pharmaceuticals and hormones, however, have been largely shown not to be present in the SWRO product water (Escher et al. 2011; Radjenović et al. 2008). Hence, hazards and water ingredients to reach the consuming public in numbers or concentrations will have an impact on health or adversely affect the acceptability of the SWRO product water for human consumption (Payment et al. 1991). Explicit quality parameters for SWRO product water which center on primary prevention of waterborne and water-related diseases would not only protect human health but also promote socioeconomic development and well-being as well.

In this review, we highlight the framework of an integrated SWRO stages, including feed water, pretreatment, SWRO desalination process, post-treatment, and distribution of product water. Key results accumulated in the last few decades on SWRO product water are assessed to identify priority parameters for quality monitoring with special emphasis to their exploitation in sustainable freshwater supply, covering 78 literatures with the key words "drinking water quality parameters, desalinated water and seawater reverse osmosis desalination."

Effect of SWRO Product Water from Source to Tap

SWRO desalination is very efficient at rejecting inorganic chemicals and organics of molecular weight greater than about 50 daltons. Meanwhile, it usually provides a significant barrier to algal toxins, pathogens, and microorganisms. This includes monovalent ions, arsenic (V), nitrates, hardness, salinity, natural organic material (for example, humic, fulvic acids, by-products of algal and seaweed growth, geosmin from cyanobacteria), saxitoxin, domoic acid, cyanobacteria, dinoflagellates, and the cyanotoxin microcystin-LR. However, SWRO barrier is not necessarily absolute, and a number of contaminants migrate through the membrane, which reach consumers in numbers or concentrations and could potentially have an impact on public health. Thus, quality parameters for SWRO product water must not only evaluate contaminants that could have an impact on health in numbers or concentrations but also consider the acceptability of the water to consumer. Integrated SWRO desalination system affects the quality of desalinated seawater from source to tap, which contains feed water, pretreatment, SWRO desalination process, post-treatment, and distribution of product water (Fig. 1).

Feed Water

To produce a good quality SWRO drinking water, assessment of potential hazards in the product water requires an evaluation of the raw seawater and types of pollutant in the intake circumstances, including anthropogenic contamination, oil extraction activity, and industrial and shipping activities. Seawater intake is affected by geological situation of seawater siting, that is foulant, salinity, waste brine disposal options, and highly variable plant location (Fuentes-Bargues 2014). Feed water from coastal waters typically has poor quality, because of the proximity to terrestrial, fluvial, and continental shelf sources. In regions of oil production, potential hazards constituent of petroleum hydrocarbons related to volatile substances contamination, including benzene, toluene, ethylbenzene, xylenes, and solvents (for example, chloroform, carbon tetrachloride, trichloroethene, and tetrachloroethene), which cause unacceptable taste and odor in the product water at very low concentrations. Meanwhile, feed water is varied due to seasonal and climatic changes, which is characterized by temperature, pH, conductivity, turbidity, TDS, silt density index (SDI), suspended solids, and total organic carbon concentration (Yang et al. 2010). In addition, the pathway locations, flow path length, and hydraulic retention time from seawater intakes to the desalination plant play an

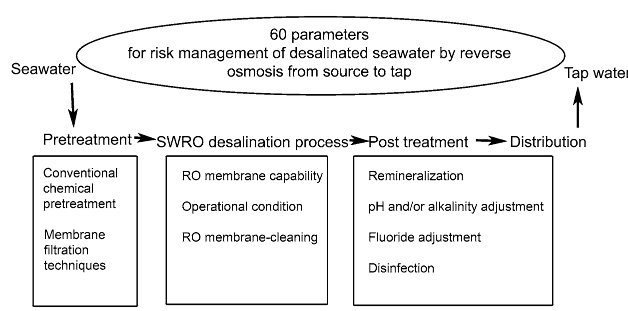

Fig. 1 Integrated seawater reverse osmosis desalination system affects the quality of product water from source to tap

important role in microbial community composition and removal of the organic matter (Levi et al. 2016; Manes et al. 2011). Furthermore, effects of organic matter developed during various temporal events (for example, algal blooms and oil spills) on DBPs formation and speciation should also be considered. Inorganic and organic compounds, particles, and microorganisms in intake seawater are mainly responsible for fouling of SWRO membranes, particularly with particulate matter greater than 1 µm. Based on the manufacturer's guarantee, the maximum allowable contaminants in the feed water are shown as follows: turbidity should be lower than 1.0 NTU; SDI $\leq$ 3.0 or 4.0; oil and grease $\leq$1.0 mg L^{-1}; and sparingly soluble concentration should lower the saturated concentration (Noka Prihasto 2009).

Pretreatment

Pretreatment of the feed water ahead of the SWRO process is normally designed to reduce or remove hazards to avoid scaling, fouling, or plugging, which is critical for successful long-term performance of SWRO plants. Residuals from the pretreatment process negatively affect SWRO membrane performance, thus can influence the permeate water quality indirectly. Pretreatment are commonly grouped into two categories, conventional chemical pretreatment and membrane filtration technique (Prihasto et al. 2009). Both of these treatments are currently applied in the SWRO plants in the world.

Conventional Chemical Pretreatment

Conventional chemical pretreatment needs consumption of chemicals, including antiscalant, corrosion-inhibiting chemical, antiseptic, coagulation, flocculation, membrane pretreatment chemical, and disinfectant (Edzwald et al. 2011). Acceptable quality for feeding SWRO desalination by this technique depends on various operating conditions, such as chemical type and dose, filtration rate, and temperature variations. Filtrate quality parameters routinely used in full-scale SWRO desalination plants consist of turbidity, SDI, and total organic carbon to meet the demand for intake water quality and filtration effectiveness of SWRO desalination (Mitrouli et al. 2008).

To prevent bacterial growth and control biofouling in the intake structures and to improve the performance of filters, disinfectants are used as a pretreatment before SWRO desalination plant. Chlorine is the most commonly used disinfectant, while alternative disinfectants include chloramines, chlorine dioxide, ozone, ultraviolet, and $KMnO_4$. These disinfectants result in increase in both water permeability and salt passage. Meanwhile, they can produce highly toxic DBPs during pretreatment (Valentino et al. 2015; Richardson 2011). Formation and speciation distribution significantly depend on the content of disinfectant dose, contact time, pH, temperature, and the characteristics of natural organic matter (Yu et al. 2015). The formation potential of DBPs includes *N*-nitrosamines, haloacetonitriles, halonitromethanes, bromophenols, as well as other unidentified compounds (Bougeard et al. 2010; Hong et al. 2015; Zeng et al. 2016). In addition, due to high levels of bromide and iodide concentrations in seawater, highly cytotoxic and genotoxic DBPs form. In both trihalomethanes (THMs) and haloacetic acids (HAAs), brominated species are predominant, especially tribromomethane, tribromoacetic acid, dibromoacetic acid, dibromochloroacetic acid, which are not detected in the piped water. Trichloromethane that is abundant in the piped water is barely observed in the SWRO pretreated water. As for monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, and monobromoacetic acid, all of them account for a smaller percent in the pretreated water as compared to the piped water. Iodinated DBPs are relatively low levels including iodinated THMs (I-THMs) and iodinated HAAs (I-HAAs) (Domínguez-Tello et al. 2015). Bromide is abundant in ozonated seawater (Ioannou et al. 2016). There is currently no available data in the peer-reviewed literature regarding DBPs formation in the feed water of desalination plants disinfected with ultraviolet or $KMnO_4$.

In terms of DBP rejection by SWRO, it is depended on compound-specific properties, membrane properties, and operation conditions (for example, transmembrane flux and temperature). Although SWRO membrane removal efficiencies of THMs and HAAs were >60 and >90 %, lower rejection rates were reported for haloacetonitriles (>50 %) and *N*-nitrosodimethylamine (10–50 %) (Kim et al. 2015), or other neutral low-molecular weight compounds which can potentially pass through SWRO membrane and may significantly affect the water quality of SWRO permeate and product water (Agus et al. 2009; Tu et al. 2013).

Membrane Filtration Techniques

Another method used recently for the pretreatment of feed water is membrane filtration, containing microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF) before directed to SWRO modules, which use fewer chemicals than conventional chemical pretreatment and have high removal efficiency of fouling matters, such as turbidity, iron, silica, algae, and microbial contamination (Oriol et al. 2013; Kumar et al. 2006). Removal rating depends on the molecular mass cut-off of the pretreatment membrane to clarify feed water under different operating conditions. MF typically operates at a particle size 0.1–0.2 micron prefiltration. UF generally represented by 0.01–0.02 micron pore size, some new materials even provide 0.005-micron filtration, which can exclude viruses. As for the UF performance in terms of the critical flux, rejection, and filtration resistance, it was influenced by various factors, such as seawater properties, membrane property, and hydrodynamic conditions (Xu et al. 2012). UF therefore provides the SWRO permeate water with high and constant quality than MF no matter regardless of feed water.

Membranes used for NF are cellulosic acetate and aromatic polyamide type, which have characteristics as salt rejections from 95 % for divalent salts to 40 % for monovalent salts and an approximate 300 molecular weight cut-off for organics. NF can remove turbidity, bacteria, hardness ions, and TDS (Zhou et al. 2015; Perez-Moreno et al. 2012). This kind of NF combinations has an effect on the desalination performance in terms of permeate recovery, salt rejection, and permeate flux values (Kaya et al. 2015).

In addition, membrane filtration combined with conventional chemical pretreatment is proven to be an effective desalination pretreatment than membrane filtration alone. MF was more effective than UF for the enhancement of filtration flux and turbidity removal by applying coagulation as pretreatment method. Submerged MF system coupled with in-line flocculation (for example, modified polyferric silicate and ferric chloride as pretreatment for SWRO) has the potential to remove organic compounds and mitigate fouling. MF followed by slow sand filtration is efficient in removing microorganisms. Furthermore, newly developed inorganic (ceramic) membranes offer unique advantages over the currently employed membranes. Zirconium dioxide UF membrane can offer consistent permeate quality and low fouling potential at high permeate fluxes (Gao et al. 2010). Direct filtration, containing single, dual, and mixed-media filtration, whose media are often small-grained silica sand or greensand, anthracite, and garnet, can remove color, iron, and manganese compounds, also achieve a very low SDI prior to the SWRO system (Headquarters 1986).

SWRO Desalination Process

Quality of product water depends on a combination of a series of controlling parameters in the SWRO desalination process, including RO membrane capability, operational condition, and RO membrane cleaning (Bellona et al. 2008; Greenlee et al. 2009).

Ro Membrane Capability

The membrane property greatly affects the water productivity and energy costs in the SWRO desalination process. At the core of the SWRO desalination process is a semipermeable membrane with pore size of 0.5–10 nm. Commercially viable membranes include an asymmetric cellulose acetate membrane before the 1980s, and robust thin-film composite membranes with polyamide-selective layers for nearly all SWRO desalination operations after the 1980s toward today. Due to a high chlorine tolerance, cellulose triacetate RO membranes are used in most of the SWRO plants located in the Middle East region (Khan et al. 2015). Thin-film composite membranes can reject 99.6–99.8 % of the salts dissolved in the seawater (Busch et al. 2004). However, polyamide semipermeable membranes typically used for SWRO desalination processes do not possess several of the key characteristics for fouling resistance, which are prone to fouling, reducing the amount, and quality of water produced. Meanwhile, the amide linkage in polyamide composite membranes is susceptible to attack by chlorine or other oxidants that are added to seawater to reduce or even prevent the growth of microbes on membrane surface, which can diminish SWRO performance (Do et al. 2012). Therefore, it is important to establish the RO membrane capability in reducing the amount of contaminants in the product water even when the RO barriers are working efficiently, because pathogens, boron, and some low-molecular weight neutral organics can pass through membranes to a significant degree. Breaches of integrity in the membranes or the O-rings could lead to the passage of pathogens into the process water. Furthermore, location of the membrane and gasket compromising influenced virus removal capability. If the RO membrane is in service for a long time (according to time units or quantity of water) recommended by the manufacture, RO efficiency starts to fall. At this time, all of the processes are key considerations for SWRO desalination and have the potential to introduce microbial and chemical contaminants into the desalinated water.

Current ongoing research aims at developing high-performance RO membranes, which have made it a feasible option for removing most contaminants of concern and attaining the highest possible reduction in waterborne and water-related diseases in SWRO product water. Next-generation RO membranes will improve flux and salt rejection, chlorine tolerance, fouling resistance, thermal stability (Ray et al. 2015). In addition, modification of current polymeric membrane materials minimizes interfacial interactions and enhances fouling resistance (Buonomenna, 2012; Li et al. 2010). Furthermore, molecular-level design approaches for fabrication of highly selective membranes, focusing on novel materials such as aquaporin, synthetic nanochannels, graphene and self-assembled block copolymers, and small molecules, are important (Werber et al. 2016a, b). Next-generation synthesis and separation performance of new polymer membranes, inorganic membranes, and mixed matrix membranes will represent an important advancement (Park et al. 2010; Pendergast et al. 2011; Xu et al. 2011; Liu and Chen 2013). These enhanced membrane performance will substantially reduce the potential hazards in SWRO plants and have an important role in improving SWRO product water quality.

Operational Condition

It was found that size exclusion and electrostatic interactions were the most significant parameters on the rejection efficiencies of RO membranes (Doederer et al. 2014). In addition, interactions between seawater composition and membrane properties impacted the rejection efficiency of membranes as significantly as seawater composition and membrane properties individually. Operational conditions such as temperature, pH, and ionic strength are determined by the membrane characteristics, flux, and operating pressure head. Under normal usage, there is a possibility for changes of the performance of the system according to the environmental conditions.

In the SWRO desalination process, boron, and some lower molecular weight organic substances (for example, low-molecular weight polar compounds, solvent-type low-molecular weight neutral organics) exclusion is not necessarily absolute. Rejection ratio of boron-containing anions (probably mostly as borate) which deteriorates the quality of the product water is less than that for most other inorganics. Rejection of boron depends mainly on the recovery and pH of the seawater. In addition, operating parameters such as feed solution temperature and ionic strength can directly influence the rejection of boron and at the same time alter the intrinsic dissociation constant of boric acid, hence, indirectly governing the rejection of boron by SWRO desalination (Tu et al. 2010). Rejection value of boron is between 40–60 % under normal conditions of operation (Prats et al. 2000), while the high rejection value of boron is above 96 % (Teychene et al. 2013).

Arsenic in the commonly high oxidation states of *V* is very effectively removed by RO (Ning 2002). Regarding arsenic (III) rejection, SWRO membranes exert higher removal, with a highest rejection value more than 99 %, even at low pH and low pressure (pH 7.6 and 24 bars). With further attention to the removal of the weakly acidic arsenic (III) species in waters by SWRO at sufficiently high pH makes possible by new antiscalant (Teychene et al. 2013). Practical processes can be developed with SWRO to remove all major species of arsenic from product water.

The presence of heavy metals such as mercury, lead, and cadmium released by SWRO desalination industries constitutes one of the currently recognized hazards affecting the organoleptic quality of the product water, which are responsible for several waterborne diseases (Bhutiani et al. 2016). The metalloid rejection depends on the membrane type, pH, and transmembrane pressure applied (Peng et al. 2003). Increasing pH above the dissociation constant (pKa) of each specie improves significantly the metalloid rejection by SWRO, whatever the membrane type.

Furthermore, permeation of DBPs through membranes is also governed by operational condition. Dibromoacetonitrile which is one of the haloacetonitrile species was detected in the SWRO permeate (Roux et al. 2015). Six commonly detected pharmaceutical and personal care products were rejected by three commercial thin-film composite polyamide RO membranes at pH values 3–10 (Lin et al. 2014).

RO Membrane Cleaning

SWRO membranes need to be cleaned with chemicals regularly because they are susceptible to fouling and scaling, which may be toxic to receiving waters (Tularam et al. 2007). Since the surface-active agent of the detergent may alter the surface potential of the membrane, the membrane selectivity in terms of salt rejection and the RO module performance in terms of product flux are influenced by the type of detergent (Flemming 1997; Sehn 2008). In addition, the product water contains traces of various chemicals used in RO membranes cleaning (for example anticorrosion products) has to be treated to acceptable levels. Although the longer term effects of such chemicals have not been documented, it is possible that small traces of toxic substances remained in the SWRO permeates may be harmful to human life.

Post-Treatment

Post-treatment of desalinated water requires stringent quality control to achieve a product water quality suitable for augmenting drinking-water supplies. Desalinated water is facing significant amount of practical issues that is low in minerals, poorly buffered, and slightly acidic, which is aggressive and corrosive toward materials used for distribution pipes, storage, and plumbing, making it unpalatable (Shemer et al. 2013; Birnhack et al. 2011, 2008; Lahav et al. 2007). If the SWRO-desalinated water is pumped directly into the distribution system without being post-treated, it tends to corrode iron pipes or water storage tanks, and dissolves protective layers containing metal ions (for example, calcium, cadmium, iron, zinc, copper, and lead) and other salts on the inner sides of the pipes (for example, asbestos, vinyl chloride, and benzo(α)pyrene) (Liu et al. 2013). One of the by-products of this chemical attack is ferric hydroxide, red-brown rust that results in what is known as “red water” on the distribution system and arrives at the consumer’s tap with a characteristic yellow–brown–red color. Current post-treatment research, that includes water palatability, chemical stability, biostability, and post-treatment engineering considerations, is attempting to circumvent and minimize these adverse effects by developing new methods for improving the quality of product water suitable for drinking before being transferred to the distribution system, which typically involves (1) remineralization, (2) fluoride adjustment, (3) disinfection, and (4) blending with surface or ground water (Tularam et al. 2007; Shih et al. 2014).

Remineralization

Desalinated water contains lower than usual concentrations of dissolved solids and essential elements which are commonly found in water. During post-treatment, the water must be stabilized or remineralized prior to distribution to reduce its corrosive nature. Additionally, residual concentration of the essential beneficial chemicals is normally present in relatively low concentrations in desalinated water, which is well below any significant contribution to recommended daily dietary intakes. For example, calcium and magnesium are the principal defining components of "hard water," which are very efficiently removed by SWRO desalination. The recommended daily dietary requirement of sodium is more than 1000 mg/day, potassium more than 3000 mg/day. Although drinking water typically contributes a small proportion to the recommended daily intake of essential elements, with most of the intake occurring through food, it needs to be added back to the product water by remineralization.

Remineralization is commonly achieved by use of lime or limestone (Azhar et al. 2012; Shemer et al. 2013). Other chemical constituents such as caustic soda, sodium bicarbonate, sodium carbonate, phosphates, and silicates, which are sometimes used alone or in combination (Marangou et al. 2001; Withers 2005). In general, it is accomplished by chemical addition, lime dissolution, and calcite bed filtration. Chemical addition is injecting chemicals directly into the desalinated water which is used normally for small SWRO-desalinated units. Lime dissolution is accomplished by lime slurry or powder, combined with carbon dioxide injection.

$$Ca(OH)_2 + 2CO_2 \rightarrow Ca(HCO_3)_2$$

Compared with the above two methods, an easier and safer remineralization is calcite bed filtration, which pass desalinated water dosed with CO_2 through a bed of limestone, reintroducing bicarbonate alkalinity and calcium hardness to the water. In the most cases, unreacted CO_2 must be removed by a degasifier to stabilize the SWRO product water.

$$CO_2 + H_2O \rightleftharpoons H_2CO_3$$

$$H_2CO_3 + CaCO_3 \rightleftharpoons Ca^{2+} + 2HCO_3^-$$

Occasionally, mineral acids such as sulfuric acid or hydrochloric acid are considered instead of CO_2.

$$2CaCO_3 + H_2SO_4 \rightarrow 2Ca^{2+} + SO_4^{2-} + 2HCO_3^-$$

The SWRO-desalinated water pH is often adjusted by alkaline chemicals, such as caustic soda, soda ash, or lime, in some cases, the desalinated water passes through an aeration column in which the pH is elevated from a value of approximately five to a value close to seven.

Key parameters for quality monitoring of the product water after remineralization is calcium, magnesium, alkalinity, hardness, bicarbonate ions, fluoride, sulfate, chloride, manganese, pH, and CO_2. It is also important to ensure that the minerals added are of an appropriate quality and do not introduce contaminants that adversely affect the product water quality.

Fluoride Adjustment

Fluoride would also be missing from desalinated water unless it is added during post-treatment, which may be considered by countries in which sugar consumption is high. The SWRO permeate water with a fluoride concentration of <0.03 mg L^{-1} is blended with the artificial ground water to ensure a low fluoride level in the drinking water. Daily water intake can vary significantly in different parts of the world, seasonally and particularly where consumers are involved in manual labor in hot climates. Local adjustments to the daily water consumption value may be needed in setting local standards, as in the case of fluoride.

Disinfection

Bacteria have been found in permeate samples of SWRO effluent, and they can proliferate in discharge lines. There are two reasons, one is that sterile conditions cannot be maintained, and the other is that bacteria can traverse through some RO membranes or membrane defects. Meanwhile, product water that comes out of the SWRO-desalinated plant has stagnated for long periods in household pipes and regrowth of bacterial contaminants can easily occur, such as total coliforms or fecal coliforms. Importantly, these pathogenic bacteria will remain present when the product water is delivered through a consumer's tap.

To inactivate pathogens, appropriate levels of residual disinfectants are maintained in the product water during distribution. In SWRO post-treatment, chlorine-based (for example, chlorine, chloramine, chlorine dioxide), ultraviolet light, ozone have been the main weapons used to reduce the possible bacteria risks. Although some DBPs could be removed by SWRO membrane, and the permeate water is expected to have low total organic carbon concentration which is another "precursor" for the formation of DBPs, DBPs should also be concerned in the post-treatment. Bromide is initially present in seawater in relatively large amounts ($\sim$80 mg L^{-1} in some regions), so even high (for example, >95 %) percentage removals will allow some bromide to be present in the post-treatment. When it comes into contact with chlorine, brominated organohalogen occurs to form non-regulated emerging DBPs. The bromide is oxidized to brominated THMs, bromate, particularly bromoform, and to a lesser extent, dibromochloromethane. Under artificial lab conditions, the chlorination (5 mg Cl L^{-1}) of the permeate water with bromide levels (0.3–0.8 mg L^{-1}) leads to the development of bromophenols (for example, 2-bromophenol, 2,4-and 2,6-dibromophenol), whose sensory threshold being in some cases lower than 10 ng L^{-1}, causing a variation of the organoleptic characteristics in the drinking-water supply which have led to odor (Albaladejo et al. 2012). When chloramine is used, nitrite formation by organisms in biofilms needs to be considered where chloramination is practiced and excess ammonia is present (Goslan et al. 2009; Kapoor et al. 1997). *N*-nitrosodimethylamine is known to be poorly removed by RO membranes because of its low molecular weight (Sakai et al. 2012). Thus, N-nitroso compounds may be carried over into the product water during drinking-water distribution.

Blending with Surface or Ground Water

Blending with surface or ground water during post-treatment processes is a preferred method for SWRO to enhance the product water quality. In many Middle East countries, desalinated product waters are often blended with brackish ground waters prior to distribution with inherently limited fresh water resources. In this way, it is a very effective technique practiced to provide alkalinity, buffering, and raise pH to an acceptable level, reducing the amount of post-treatment chemicals addition. The quality and the quantity of mixing with groundwater or surface water vary the product water quality, which is limited by the constituents in the desalinated water and the specific product water quality goals. Special care should be taken regarding the potential for changes in the taste and mineral characteristics of the water to prevent adverse impacts on consumer perception of quality, especially if blending is intermittent and the blending ratio is highly dynamic. Groundwater or surface water should be pretreated to ensure their microbial safety, because the post-desalination residual disinfectant level may be insufficient to control pathogens presented in the blending water. When subsurface intake rich in high levels of organic matter, residual disinfectants could react with organic matter to form various DBPs (for example, brominated and iodinated DBPs) at different mixing ratios, pH, and temperatures in the distribution system (Daekyun Kim, 2015). Dibromoiodomethane and bromodiiodomethane of I-THMs were detected in the product water with cellulose triacetate membranes (0.92 and 0.58 mg L^{-1}, respectively) (Richardson et al. 2008).

Distribution of Product Water

The distribution of product water is usually done by a long pipe from the SWRO desalination plant to the tap, which is often lengthy and underground. High temperatures of distributed water in warm climate areas and difficulty in maintaining disinfectant residuals during transport over long distances may lead to microbial growth, depending on nutrient availability. Although such growth is likely to be without health significance, it can contribute to problems of acceptability. Indicators including calcium carbonate precipitation potential and Langelier saturation index are used to evaluate the aggressiveness and corrosiveness of the SWRO product water when transport through cementitious or polymer-lined pipelines, steel components like pumps, valves, and pipes (Al-Rawajfeh et al. 2007; Gacem et al. 2012).

Key Monitoring Parameters of SWRO Product Water Quality for Drinking

The following set of quality parameters containing 60 species was proposed. Non-regulated emerging compounds listed in Table 1, even though their total mass concentration may be low, should be monitored and considered to assess the adverse impacts in the SWRO produce water.

Conclusions

In the coming decades, surging population growth, urban development, and industrialization will increase worldwide demand for fresh water. Providing evidence-based guidance and coordination, planning and monitoring stages, support for SWRO-desalinated water sanitation, and hygiene interventions are critical aspects of the SWRO-desalinated seawater quality parameters to obtain high-quality SWRO product water, although further studies are still needed in the establishment of what risks are posed to human health from long-term exposure to the water. With the 60 priority parameters, more countries, manufacturers

Table 1 Priorities quality parameters for risk management of SWRO product water

Contaminant	Sources of contaminant in SWRO product water	Potential health effects from long-term exposure
Microorganisms		
Aerobic microorganisms	Water quality indicator, identify contaminated SWRO product water	No health effects
Cyst	Water quality indicator	Cystic neoplasm
Heterotrophic plate count	Measure a range of bacteria that are naturally present in the SWRO product water	No health effects
Legionella	Found naturally in water; multiplies in heating systems	Legionnaire's disease, a type of pneumonia
Total coliforms (fecal coliform and *Escherichia Coli*)	Water quality indicator	Not a health threat in itself
Turbidity	Water quality indicator	Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites, and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches
Vibrio cholerae	Survive well in saline waters	Cause the disease cholera, cause diarrhea, and vomiting
Disinfectants		
Chloramines (as Cl_2)	Water additive used to control microbes	Eye/nose irritation; stomach discomfort; anemia
Chlorine dioxide (as ClO_2)	Water additive used to control microbes	Anemia; infants, young children, and fetuses of pregnant women: nervous system effects
Residual chlorine (as Cl_2)	Water additive used to control microbes	Eye/nose irritation; stomach discomfort
Disinfection by-products		
Bromate	Byproduct of SWRO permeate water disinfection, desalination processes ozonation or other similar oxidation processes of residual bromide	Increased risk of cancer
Bromide	Byproduct of ozonated disinfected seawater	Form brominated and mixed chloro-bromo by-products, such as trihalomethanes and halogenated acetic acids, or react with ozone to form bromate
Bromophenols (2-bromophenol, 2,4-and 2,6-dibromophenol)	Byproduct of SWRO water disinfection	Lead to the appearance of medicinal taste and odor
Dibromochloromethane	Byproduct of SWRO water disinfection	Male reproductive toxicity
Haloacetic acids (Tribromoacetic acid, Dibromoacetic acid, Dibromochloroacetic acid, Monochloroacetic acid, Dichloroacetic acid, Trichloroacetic acid, and Monobromoacetic acid)	Byproduct of SWRO water disinfection	Increased risk of cancer, neurotoxicity
Haloacetonitriles (Dibromoacetonitrile)	Byproduct of SWRO water disinfection	Induce oxidative stress in stomach
Halonitromethanes	Byproduct of SWRO water disinfection	Mutagenicity
Iodinated trihalomethanes (Dibromoiodomethane, bromodiiodomethane)	Byproduct of SWRO water disinfection	Cell toxicity
Iodoacetic acids	Byproduct of SWRO water disinfection	Genotoxic
Nitrite	Byproduct of chloramine disinfection	Infants below the age of 6 months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. symptoms include shortness of breath and blue-baby syndrome

Table 1 continued

Contaminant	Sources of contaminant in SWRO product water	Potential health effects from long-term exposure
N-nitrosodimethylamine	Byproduct of chloramine disinfection	A potent carcinogen
Total Trihalomethanes (Tribromomethane, Dibromochloromethane, and Trichloromethane)	Byproduct of SWRO water disinfection	Liver, kidney, or central nervous system problems; increased risk of cancer
Tribromomethane	Byproduct of SWRO water disinfection	Male reproductive toxicity
Inorganic chemicals		
Alkalinity	SWRO-desalinated water additive, prevent the release of metal ions from distribution system into the product water	No health effects
Asbestos (fiber >10 micrometers)	Decay of asbestos cement in water mains; erosion of natural deposits	Increased risk of developing benign intestinal polyps
Bicarbonate	SWRO-desalinated water additive	An essential beneficial chemicals
Boron (borate)	Abundant in the feed water, pass through SWRO membrane	A consistent target of toxicity
Cadmium	Corrosion of household galvanized pipes; erosion of natural deposits	Kidney damage
Calcium	SWRO-desalinated water additive	An essential nutrient
Chloride	Water quality indicator and filtration effectiveness	Cause aesthetic effects
Copper	Corrosion of household plumbing systems, fittings; erosion of natural deposits	Short-term exposure: gastrointestinal distress; long-term exposure: liver or kidney damage
Carbon dioxide	SWRO-desalinated water additive	No health effects
Fluoride	Fluoride adjustment which promotes strong teeth	Bone disease (pain and tenderness of the bones); children may get mottled teeth
Ferric hydroxide	Corrosion of metallic constituents	Cause aesthetic effects
Hardness	SWRO-desalinated water additive	Affect acceptability of SWRO product water
Iron	Corrosion of household plumbing systems	An essential nutrient
Iodide	Coming from source water	An essential nutrient
Lead	Corrosion of household plumbing systems, fittings; erosion of natural deposits	Infants and children: delays in physical or mental development; children could show slight deficits in attention span and learning abilities adults: kidney problems; high blood pressure
Magnesium	SWRO-desalinated water additive	An essential nutrient
Manganese	SWRO-desalinated water additive	An essential nutrient, adverse neurological effects following extended exposure to very high levels
Mercury (inorganic)	Coming from source water, particularly in regions of oil production	Kidney damage
Potassium	High concentration in the seawater	An essential nutrient
Sodium	High concentration in the seawater	An essential nutrient
Sulfate	SWRO-desalinated water additive	Cause noticeable taste
Zinc	Corrosion of household galvanized pipes plumbing systems	An essential nutrient
Organic chemicals		
Benzo(α)pyrene	Leaching from linings of water storage tanks and distribution lines	Reproductive difficulties; increased risk of cancer
Benzene, toluene, ethylbenzene, and xylenes	Coming from feed water	Cause unacceptable taste and odor
Marine algae toxins	Coming from feed water	Lead to neurological disorders symptoms
Trichloroethene	Coming from feed water	Cause unacceptable taste and odor
Tetrachloroethene	Coming from feed water	Cause unacceptable taste and odor

Table 1 continued

Contaminant	Sources of contaminant in SWRO product water	Potential health effects from long-term exposure
Vinyl chloride	Leaching from PVC pipes	Increased risk of cancer
Organoleptic indicators		
Conductivity	Water quality indicator	No health effects
Color	Water quality indicator	Cause aesthetic effects
Odor	Water quality indicator	Cause aesthetic effects
pH	Water quality indicator	Cause aesthetic effects
Silt density index	Water quality indicator	No health effects
Total dissolved solids	Water quality indicator	Low TDS values SWRO product water can be unpalatable and corrosive
Water temperature	Water quality indicator	No health effects
Stability indicators		
Calcium carbonate precipitation potential	Chemical stability of the SWRO product water	No health effects
Langelier saturation index	Water quality indicator	No health effects

of water treatment interventions, and academics can establish evidence-based water quality policies and coordination to respond to the specific desalinated water quality and health, so that SWRO desalination is sustainable and that global fresh water shortage is technologically solved.

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