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Algal blooms: an emerging threat to seawater reverse osmosis desalination

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ABSTRACT

Seawater reverse osmosis (SWRO) desalination technology has been rapidly growing in terms of installed capacity and global application over the last decade. An emerging threat to SWRO application is the seasonal proliferation of microscopic algae in seawater known as algal blooms. Such blooms have caused operational problems in SWRO plants due to clogging and poor effluent quality of the pre-treatment system which eventually forced the shutdown of various desalination plants to avoid irreversible fouling of downstream SWRO membranes. This article summarizes the current state of SWRO technology and the emerging threat of algal blooms to its application. It also highlights the importance of studying the algal bloom phenomena in the perspective of seawater desalination, so proper mitigation and preventive strategies can be developed in the near future.

Keywords: Seawater reverse osmosis; Algal blooms; Pre-treatment; Membrane fouling

1. Background

Economic and demographic growths have resulted in over-abstraction of conventional freshwater resources in various parts of the world. As of 2012, freshwater abstraction in the Arabian Peninsula, North Africa, and South Asia were about 500, 175, and 45% of their internal renewable water resources, respectively [1]. Many countries within these regions have been resorting to seawater desalination to ease the water supply shortage. Other measures have also been implemented such as utilizing water more efficiently, reducing leakages in public water supply networks, and wastewater reuse. These water saving measures are increasingly implemented, but their overall contribution to increasing the current water supply is still largely limited. Consequently, seawater desalination is often the preferred option to satisfy the demand.

As of 2010, about 44% of the global population and 8 of the 10 largest metropolitan areas in the world are located 150 km from the coastline [2]. Therefore, the prospect of widespread application of seawater desalination is very likely in near future. It is

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projected that a cost-effective application of desalination technologies will increase the global clean water supply by about 20% between 2020 and 2030 [3].

2. Seawater desalination

Seawater desalination is either thermal or membrane-based technology. Thermal desalination (i.e. MED, MSF, VC) are mainly applied in oil-rich countries of the Middle East, while reverse osmosis (RO) membrane desalination is almost exclusively used in the rest of the world. RO is currently the dominant seawater desalination technology (Fig. 1), and is widely applied for both drinking and industrial water production. The rapid growth of the application of RO desalination technology in recent years is not only driven by the steady increase in water demand, but also by the declining RO water production cost [4]. It is expected that by 2015, the average global production cost of RO desalinated water will be about 0.5 USD/m^3, which means that large scale application of Seawater reverse osmosis (SWRO) desalination will become more economically attractive and competitive with conventional water treatment processes [5].

The global desalination capacity is projected to reach 98 million m^3/d by 2015, a large majority of which will be based on RO desalination technology [4]. Currently, RO desalination plants have a global online capacity of 39.4 million m^3/d, which is about twice the current online capacity of thermal desalination (Fig. 2). Almost half (46%) of the RO desalinated water were from seawater and the rest were mainly from brackish, freshwater, and treated wastewater. This is a testament to the growing importance of RO

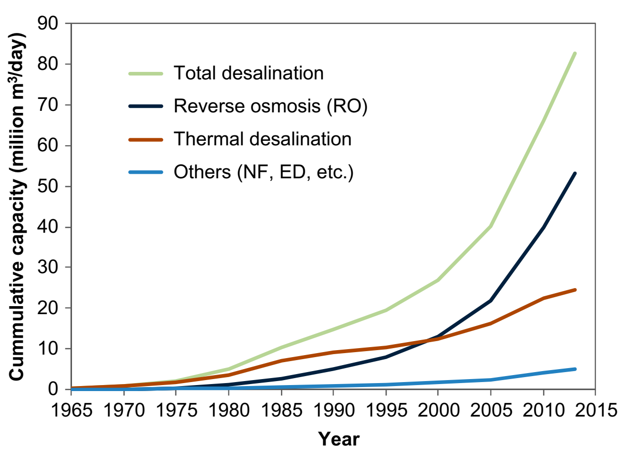

Fig. 1. Cumulative installed worldwide desalination capacity in terms of applied technology [6].

desalination in coastal areas in the world, where freshwater is a limited commodity or too polluted to be treated by just conventional water treatment processes.

Seawater desalination by RO is considered to be more energy efficient, more compact, and more flexible (modular) compared to other desalination processes. The current water production cost of RO desalination is generally cheaper than thermal desalination processes [5]. Such cost is expected to decrease further as more efficient and/or extra large RO systems will be installed in the near future [7]. Fig. 3 illustrates that high concentrations of operational seawater RO desalination plants are located in the Middle East region, the Mediterranean area (e.g. Spain, Algeria, Egypt, and Israel), the Caribbean, East Asia (e.g. China, Japan, and Korea), India, and the USA (e.g. Florida and California).

2.1. Membrane fouling and pre-treatment

Currently, the main "Achilles heel" for the cost-effective application of RO is membrane fouling [9]. The accumulation of particulate and organic materials from seawater and biological growth in membrane modules frequently cause operational problems in SWRO. These may result in one or a combination of the following:

(1) higher energy cost due to higher operating pressure;
(2) higher chemical consumption/cost due to additional chemical pre-treatment (e.g. coagulation) and frequent chemical cleaning of the membranes;
(3) higher material cost due to frequent replacement of damaged or irreversibly fouled membranes;
(4) lower rate of water production due to longer system downtime during chemical cleaning and membrane replacement; and
(5) declining product water quality due to increased salt passage through the membranes.

The above-mentioned problems have increased the necessity of pre-treating the RO feed water with conventional treatment processes, such as granular media filtration (GMF) or coagulation and sedimentation followed by media filtration, to maintain more stable and more reliable operation. This necessity also paved the way for the development of integrated membrane systems (IMS), in which RO systems are preceded

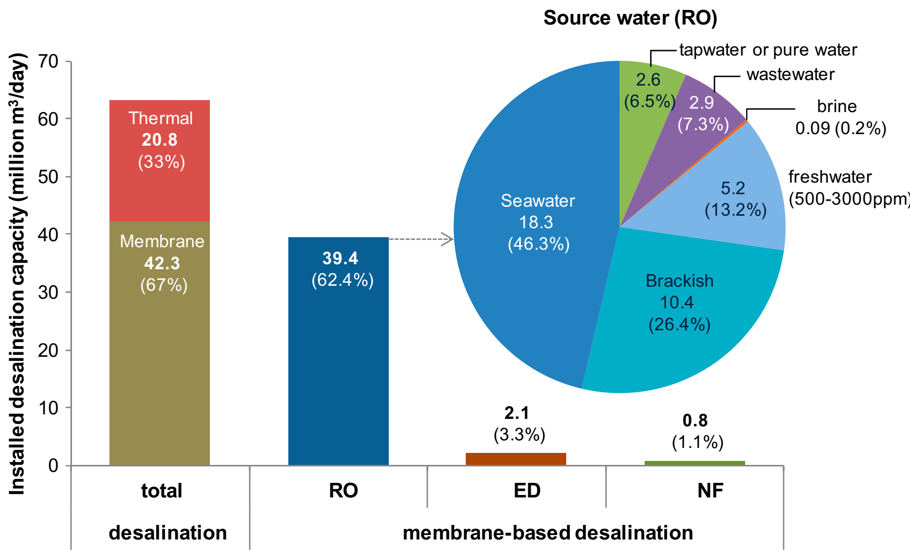

Fig. 2. The global online desalination capacity (in million m^3/d) as of June 2013 with regards to desalination technology and RO source water (inset chart). Primary data from Desaldata [6].

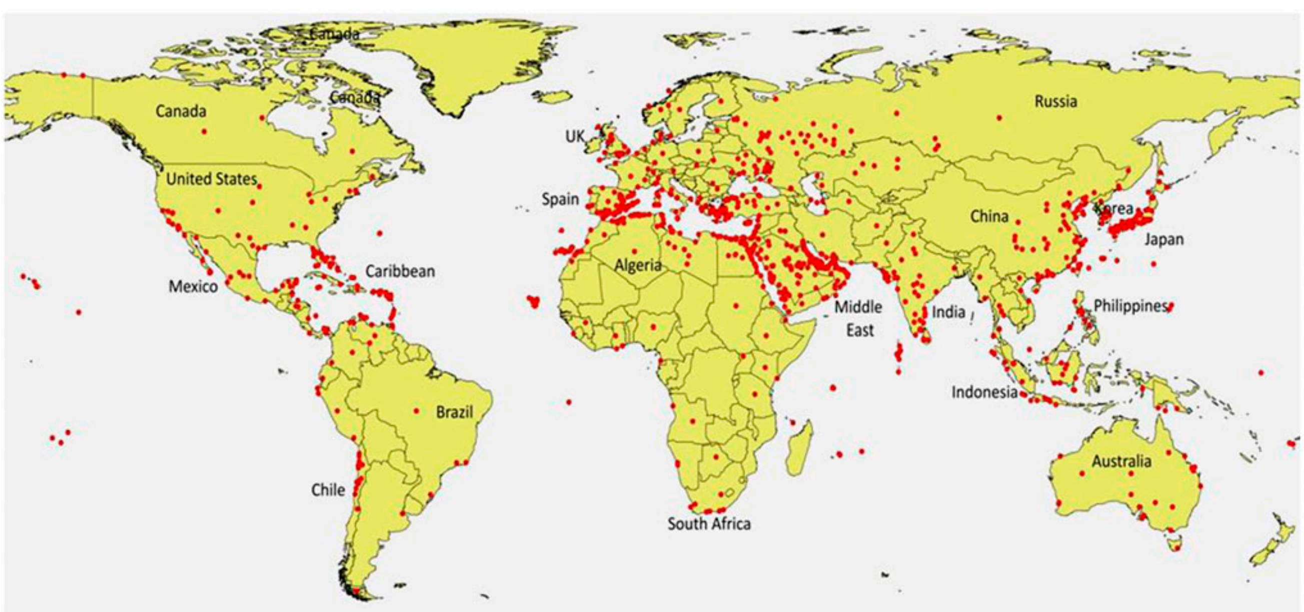

Fig. 3. Global distribution of major RO plants (circle dots) with installed capacity of > 30,000 as of January 2014. Map processed using ArcGIS 9 and plant coordinates from DesalData [8].

with different pre-treatment processes to remove potential foulants from the RO feedwater [10]. Among these pre-treatment processes, low pressure membranes (MF and UF) have been progressively applied in recent years to further reduce membrane fouling in RO/NF systems.

As shown in Fig. 4, the application of UF pre-treatment for SWRO has been rapidly increasing since 2006. As of 2013, SWRO plants with UF pre-treatment accounts for about 30% of total SWRO capacity. However, this percentage is expected to increase further in the future as UF is currently preferred for its better treatment reliability (in terms of maintaining low SDI or MFI in the RO feed water) and lower chemical consumption than conventional pre-treatment systems [11].

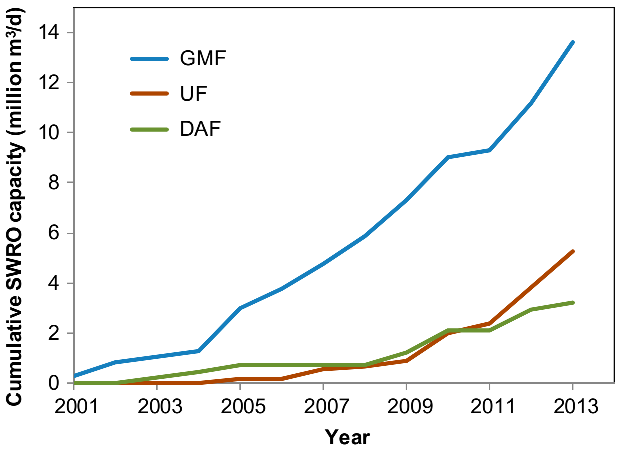

Fig. 4. Comparison of the application of pre-treatment technologies such as GMF, UF and DAF in 49 largest SWRO plants installed between 2001 and 2013 in terms of SWRO capacity. The DAF pre-treatment systems were installed in combination with GMF and/or UF. SWRO capacity based from DesalData [6].

3. Algal blooms

There is growing evidence that algae are a major cause of operational problems in SWRO plants. Many SWRO plants abstract raw water in coastal sources, where algal blooms frequently occur [12–14]. An algal bloom is a "population explosion" of naturally occurring microscopic algae, triggered mainly by seasonal changes in temperature, abundance of sunlight, and/or high nutrient concentration in the water. Some algal blooms are considered harmful because the causative algal species produce toxic organic compounds, which can cause illness/mortalities to humans and/or aquatic organisms. However, some harmful algal blooms (HABs) do not produce toxic compounds, but the algal biomass and algal organic matter (AOM) they produce can accumulate in dense concentrations near or below the water surface. Bacterial degradation of this organic material can lead to a sudden drop in dissolved oxygen concentration in the water, and eventually cause mortalities of aquatic flora and fauna. During the last decades, the number of HABs, the type of resources affected, and economic losses reported have all increased dramatically [15]. Economic losses mainly affect the fishing and aquaculture industry, but recently the desalination industry has been increasingly affected as well.

3.1. Bloom-forming algal species

The Intergovernmental Oceanographic Commission of UNESCO identified about 300 species of microalgae that were reported to cause blooms in aquatic environments [16]. An algal bloom is often dominated by a group or a species of algae. The duration of an algal bloom event can be for a period of few days to several months, depending on the life cycle of causative species, the environmental condition, and nutrient availability. The major groups of algae which are often reported to cause severe blooms in marine environment are diatoms and dinoflagellates, haptophytes, raphidophytes, chlorophytes, and cyanobacteria. Some examples of the common species of bloom-forming algae are illustrated in Fig. 5.

A wide variety of algae can form blooms in seawater ranging from 2 μm to 2 mm in cell size. Depending on the species, severe marine blooms can occur with cell concentrations as low as 1,000 cells/ml and as high as 600,000 cells/ml (Table 1). Severe blooms often bring adverse consequences to the marine environment and local economy (including the desalination industry) due to release of toxins and/or high organic/particulate load of the water.

3.2. Harmful algal blooms

Some species of algae can cause problems when they reach sufficient numbers, due to either their production of toxins or their high biomass concentration. Out of the 300 species of bloom-forming algae identified by IOC, about 60–80 species (75% of which are dinoflagellates) have been reported to cause harmful blooms [35]. High cell concentration is not necessarily an indication of HABs as it is rather dependent on the causative species. For example, in South Korea, a HAB alert is raised when *Cochlodinium polykrikoides* concentration exceeds 1,000 cells/mL, while during diatom blooms, an alert will only be issued when concentration exceeds 50,000 cells/ml [23,27].

"Red tides" are often perceived as synonymous to HABs. However, not all red tide blooms are harmful and not all HAB species cause red tides [36]. Red tides are increasingly associated with HABs because various red tide forming dinoflagellates and raphidophytes release toxic compounds, which can directly and/or indirectly affect other aquatic organisms and mammals, including humans and other land animals that live around or use the affected body of water as a food source. Other blooms, such as those caused by few species of cyanobacteria and diatoms (e.g. *Pseudo-nitzschia*), were also reported to produce toxic compounds. The common marine HAB species and the toxins they produce are presented in Table 2.

The severe consequences of toxic HABs include mortalities of fish, birds, and mammals (including human), respiratory or digestive tract problems, memory loss, seizures, lesions and skin irritation, and

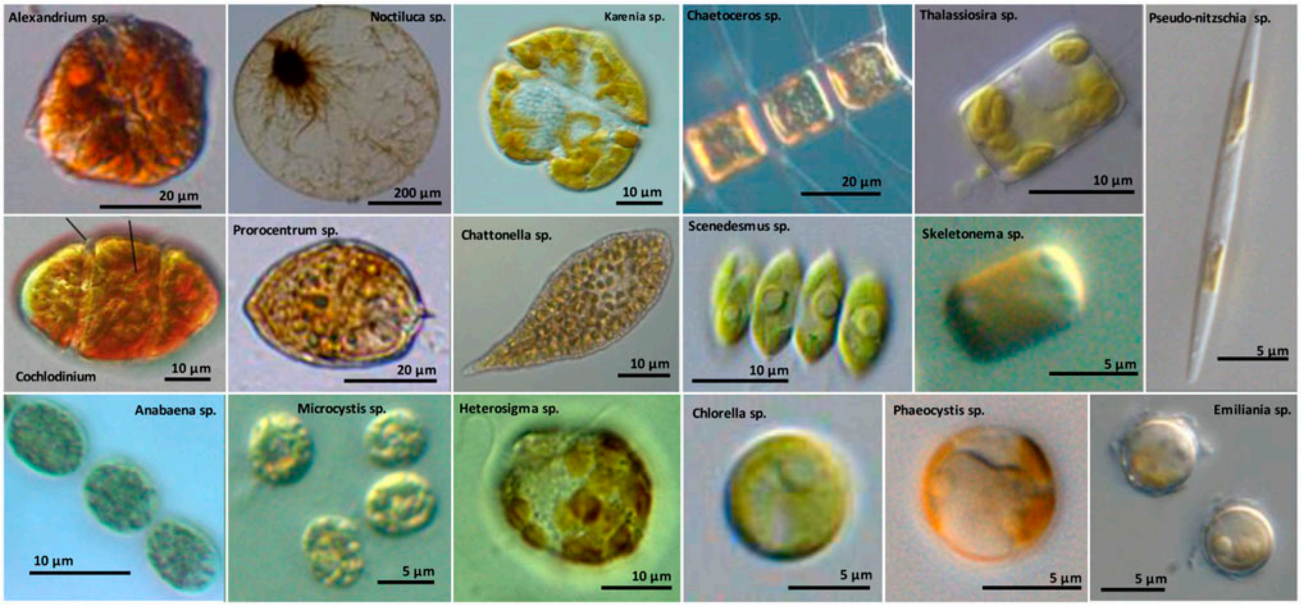

Fig. 5. Optical microscope images of common species of bloom forming algae in fresh and marine environments [13,17–21].

Table 1
Characteristics of common bloom-forming species of microscopic algae in marine systems

Bloom-forming algae	Cell size (μm)	Severe bloom (cells/ml)*	Potential adverse effect/consequences	Refs.
Dinoflagellates				
Alexandrium tamarense	25–32	10,000	Toxic bloom, red tide, O_2 depletion	[22]
Cochlodinium polykrikoides	20–40	48,000	Toxic bloom, red tide, O_2 depletion	[23]
Karenia brevis	20–40	37,000	Toxic bloom, red tide, O_2 depletion	[24]
Noctiluca scintillans	200–2000	1,900	Red/pink/green tide, O_2 depletion	[25,26]
Prorocentrum micans	30–60	50,000	Red/brown tide, O_2 depletion	[27]
Diatoms (golden brown)				
Chaetoceros affinis	8–25	900,000	O_2 depletion, fish gill irritation	[28]
Pseudo-nitzschia spp.	3–100	19,000	Toxic bloom, O_2 depletion	[29]
Skeletonema costatum	2–25	88,000	O_2 depletion	[30]
Thalassiosira spp.	10–50	100,000	O_2 depletion	[27]
Haptophytes				
Emiliania huxleyi	2–6	115,000	O_2 depletion	[31]
Phaeocystis spp.	4–9	52,000	Beach foam, O_2 depletion	[32]
Raphidophytes				
Chattonella spp.	10–40	10,000	Toxic bloom, red tide, O_2 depletion	[33]
Heterosigma akashiwo	15–25	32,000	Toxic bloom, red tide, O_2 depletion	[30]
Cyanobacteria (blue-green)				
Nodularia spp.	6–100	605,200	Toxic bloom, O_2 depletion	[34]

*Maximum recorded concentrations reported in literature.

damage of coastal resources, including submerged aquatic vegetation and benthic fauna [44]. Even when concentration of toxin-producing algae in the water is rather low, it may still cause health problems to humans who consumed bivalve mollusks (e.g. mussels, clams, oysters), which have accumulated

Table 2
Common types of human syndrome reported due to ingestion of or contact with toxins released by marine HAB species

Syndrome	Toxins	Causative algae	Commonly affected areas	Refs.
Paralytic shellfish poisoning (PSP)	Saxitoxins, Gonyautoxins	*Alexandrium spp.* *Gymnodinium spp.* *Pyrodinium spp.*	US west coast, Alaska, New England, Canada, Chile, Europe, South Africa, Asia, Australia, New Zealand	[37,38]
Neurotoxic shellfish poisoning (NSP)	Brevetoxins	*Kerenia brevis,* *Karenia brevisulcatum* *Chatonella spp.* *Fibrocapsa japonica* *Heterosigma akashiwo*	US Gulf coast, New Zealand, Japan, Australia	[37–39]
Diarrhetic shellfish poisoning (DSP)	Okadaic acid	*Dinophysis spp.* *Prorocentrum lima*	Europe, Japan, Canada (Atlantic coast), South Africa, Chile, Thailand, New Zealand, Australia	[37,40]
Amnesic shellfish poisoning (ASP)	Domoic acid	*Pseudo-nitzchia spp.*	US west coast, Alaska, Canada (Atlantic coast), Chile, Australia, New Zealand, United Kingdom	[37,38,41]
Azaspiracid shellfish poisoning (AZP)	Azaspiracid	*Protoperidinium crassipes*	England, Scotland, Ireland, France, Spain, Morocco, Norway	[37,38,42]
Ciguatera fish poisoning (CFP)	Ciguatoxins, Maitotoxins	*Gambierdiscus toxicus*	Hawaii, Gulf of Mexico, Puerto Rico, the Caribbean, Australia, many Pacific islands	[37,38,43]

toxins over time by ingestion of algal cells. Saxitoxins are one of the commonly occurring HAB toxins which can cause paralytic shellfish poisoning (PSP) to mollusc-feeding mammals. They are produced by various species of dinoflagellates under the genus *Alexandrium*, *Gymnodinium*, and *Pyrodinium*. The global distribution of HAB events involving these types of algae was documented in Anderson et al. [45]. Incidentally, HABs frequently occur in various areas where seawater desalination plants are installed (see Fig. 3).

Another commonly occurring HAB species not listed in Table 2 is *Cochlodinium polykrikoides*. So far, there is no clear consensus among marine scientists regarding the associated toxic mechanism or the chemical nature of toxins produced by this alga. Various studies categorized *Cochlodinium* species as a taxa with multiple toxins which may include neurotoxic, hemolytic, hemagglutinative, and zinc-bound PSP toxins [46]. Harmful blooms of *C. polykrikoides* have been recorded in various parts of the world including East and Southeast Asia, the Middle East, and the United States.

Some species of marine and brackish water cyanobacteria under the genus *Nodularia* also produce a toxin known as nodularin [47]. This toxin is a potent hepatotoxin and can cause damage to the liver of mammals who ingested it. Massive *Nodularia* blooms have occurred frequently in the Baltic Sea where it was reported to cover up to an area of more than 60,000 km^2 [48].

Some HABs are not caused by toxin producing species but species which tend to accumulate in dense concentrations on the surface of the water. This can be harmful to aquatic organisms because it can cause light deprivation as well as sudden drop of dissolved oxygen concentration (hypoxia) in the lower water column, resulting from excessive cellular respiration and bacterial degradation of dead algal material. Hypoxic conditions induced by cyanobacterial blooms (e.g. *Microcystis*) are often reported in large freshwater lakes (e.g. Lake Taihu, China [49]). In seawater, anoxic conditions, during the sedimentation phase of *Phaeocystis* blooms, were also reported to cause mortalities of wild and/or cultured marine fauna in Ireland [50], The Netherlands [51], China [52], and Vietnam [53].

4. Impact of algal blooms on SWRO operation

Caron et al. [12] pointed out two potential impacts of algal blooms in SWRO desalination facilities: (1) significant treatment challenge to ensure the desalination systems are effectively removing algal toxins from seawater and (2) operational difficulties due to increased total suspended solids and organic content resulting from algal biomass in the raw water. The latter is expected to be a major challenge in membrane-based desalination plants considering that majority of algal blooms does not produce toxic compounds. Furthermore, it has been shown that common HAB toxins can be effectively removed by NF (>90%) or RO (>99%) membranes [54,55].

The adverse effect of algal blooms on SWRO desalination systems started to gain more attention during

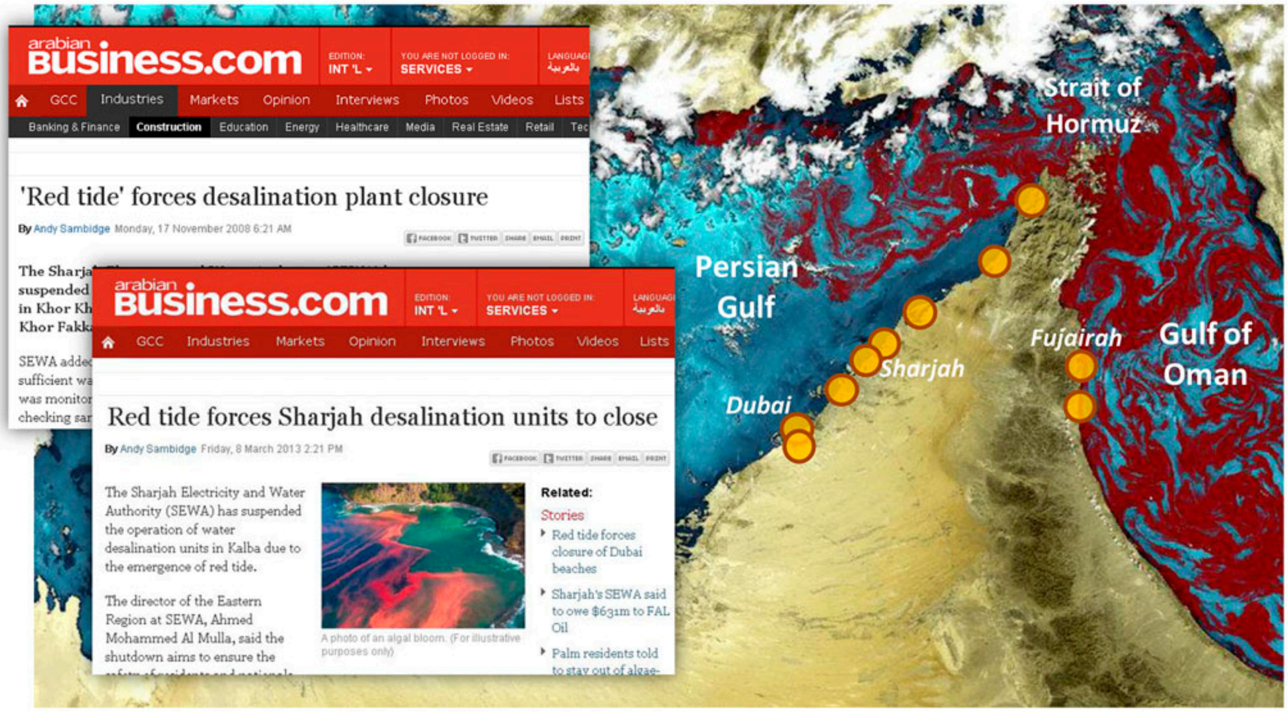

Fig. 6. The massive red tide bloom in the Gulf of Oman as shown in this satellite image generated by Envisat's MERIS instrument on November 22, 2008 (Credit: C-wams project, Planetek Hellas/ESA). Yellow points indicate location of large SWRO plants in the area. Inset screenshots of online news regarding SWRO plant shutdown due to red-tide in the gulf in 2008 and 2013 (www.arabianbusiness.com).

the severe "red tide" blooms in the Gulf of Oman between 2008 and 2009 (Fig. 6). The blooms forced several SWRO plants in the region to reduce or shutdown operations due to clogging of pre-treatment systems (i.e. GMF) and/or due to unacceptable RO feed water quality (i.e. silt density index, SDI > 5), which triggers concerns of irreversible fouling problems in RO membranes [13,56–58]. Generally, RO suppliers can only guarantee smooth operation with their RO membranes if the feed water has an SDI < 5. This incident highlighted a major problem that algal blooms may cause in countries relying largely on SWRO plants for their water supply. Several arid coastal regions in the world (e.g. Chile, California), which are increasingly using SWRO technology for water supply are also vulnerable to this problem [12,14].

In SWRO plants, GMF are usually installed to pretreat seawater before being fed to the RO system. During algal bloom, the GMF can remove most of the algal cells. However, a substantial fraction of AOM can still pass through the pre-treatment system, which can then potentially cause fouling in the downstream RO system. To solve the problem of poor quality of the pre-treated water (GMF effluent), a couple of options have been proposed such as incorporating and/or increasing the dose of coagulant in front of the GMF to improve the effluent water quality. However, an increase in coagulant dosage may further increase the rate of clogging in GMF. Installing a dissolved air flotation (DAF) system in front of the GMF will enable increase in coagulant dosage and improve the effluent quality, while reducing clogging problems in GMF. Another option is to install an ultrafiltration (UF) membrane system to replace GMF. UF pre-treatment can guarantee an RO feed water with low SDI even during severe algal bloom. However, some concerns have been expressed regarding the rate of fouling in UF membrane systems (e.g. backwashable and non-backwashable fouling) during algal bloom period [59–62]. To overcome this concern, incorporating in-line coagulation or a DAF system preceding a UF system has been recommended [63].

Algal blooms can cause fouling problems in both MF/UF and RO systems. During MF/UF treatment of algal bloom-impacted water, particulate, and organic materials comprising algae cells, and AOM can accumulate to form a cake layer on the surface of the membranes. This cake can cause a substantial increase in the required driving pressure to maintain the permeate flux in the system. RO systems are primarily designed to remove dissolved constituents in the water, but they are most vulnerable to spacer clogging problems by particulate material from the feedwater. For this reason, NF/RO systems are generally preceded by a pre-treatment process to minimize particulate and organic fouling potential of the feed water. When MF/UF is applied as pre-treatment for RO, particulate, and organic fouling problems during algal blooms is expected to mainly occur in the MF/UF pre-treatment system itself.

Ideally, the pre-treatment systems of an SWRO plant should effectively remove algal cells to prevent clogging in RO channels. Algae removal in GMF may vary from 45 to 90%, while MF/UF membranes are expected to have much higher removal efficiencies by (>99%). High algae removals (>75%) were also reported by sedimentation and DAF treatments. Cartridge filters, which are typically installed after the pre-treatment processes and before the SWRO system, have comparable removal with GMF [64].

So far, a limited number of studies have investigated the effect of algal blooms on the operational performance of MF/UF membrane systems (e.g. [27,59,65,66]). Most of these studies have suggested that the accumulation of AOM is the main cause of membrane fouling rather than the algae themselves. However, a synergistic effect between algal cells and AOM may intensify the rate of fouling in UF membranes, but more studies are needed to illustrate and to better explain such mechanisms. Under algal bloom conditions, operators often resorted to inline coagulation to stabilize operation of the MF/UF system. Schurer et al. [59] demonstrated in a pilot desalination plant that UF operation can be stabilized at relatively low doses of iron based coagulant (<1 mg Fe^{3+}/L) during the bloom period. Outside the bloom period, it was demonstrated that UF can operate effectively without the need of in-line coagulation.

In 2005, Berman and Holenberg reported for the first time that some types of AOM, particularly transparent exopolymer particles (TEPs), can potentially initiate and enhance biofouling in RO systems [67]. TEPs are a major component of AOM and are mainly compose of acidic polysaccharides and glycoproteins. They are characteristically sticky, so they can adhere and accumulate on the surface of the membranes and spacers. The accumulated TEPs may serve as a "conditioning layer"—a good platform for effective attachment and initial colonization by bacteria which may then accelerate biofilm formation in RO membranes [68–70]. Furthermore, TEPs might be partially degradable and may later serve as a substrate for bacteria [71,72].

The potential problems of TEP accumulation in RO can be more serious than in UF because RO systems are not backwashable and chemical cleaning might not be effective in removing these materials. Nevertheless, the current notion of the role of TEP on biofouling still needs to be verified and their effect on the operation of SWRO still needs to be demonstrated.

5. Conclusion and outlook

RO is currently the state-of-the-art seawater desalination technology, capable of providing safe and reliable water supply in freshwater scarce coastal areas of the world. A major obstacle for the successful application of this technology is (bio)fouling in the RO membrane itself and/or the pre-treatment system during algal blooms. The failure of GMFs to provide sufficient and acceptable feedwater quality for SWRO during the severe algal bloom outbreaks in the Middle East in 2008–2009 and 2013 has shifted the focus of the desalination industry to the application of UF as the main pre-treatment technology for SWRO. Thus, an extensive investigation on the impact of algal blooms on both UF and RO membranes is required.

A key to understanding why algal blooms affect the operation of membrane systems is to study their occurrence and growth dynamics of bloom-forming species as well as the chemical composition, size, and membrane fouling potential of AOM, including TEPs. During algal blooms, both particulate and organic fouling may occur in the pre-treatment system, while biofouling is more likely to occur in the RO system. To develop better strategies to control operational problems caused by these fouling phenomena, a better understanding of the processes involved is crucial. The use of optimized inline coagulation system to stabilize the operation of MF/UF pretreatment during algal blooms is promising but further investigation of its application for different types of severe blooms should be undertaken.

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