# Harmful Algal and Cyanobacterial Harmful Algal Blooms in the Arabian Seas: Current Status, Implications, and Future Directions

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**Abstract** Harmful Algal Bloom (HAB) and Cyanobacterial Algal Bloom (CyanoHAB) events, pose a threat to ecosystem and human health, and their environmental management requires the formulation of shared specific action plans. In this chapter, we compile historical and current knowledge on the causes and consequences of bloom events and report instituted policies and regulations, with a focus on the geographic area of the Arabian Seas. We outline the organismal diversity involved in such blooms as well as the diverse toxins that they can produce with associated syndromes and diseases. The causes of HABs and CyanoHABs can be broadly divided into those that are climatically driven versus those that are driven by anthropogenic activities that over exploit and mismanage natural resources to meet the demands of a growing global population. We consider climatic conditions that affect blooms such as dust and wind storms, seawater salinity and temperature, as well as the effect of anthropogenic activities including industrial development, the transportation of goods, production of aquatic food, and the preparation of drinking water supplies. The major negative health, ecological, and financial impacts of blooms are also presented here. We conclude the chapter pinpointing gaps in current knowledge, policy, and management of HABs and CyanoHABs, and offer specific recommendations on how to improve monitoring, use research-based solutions, and make cooperation across boundaries more effective.

**Keywords** HABs · CyanoHABs · Toxins · Arabian seas · Globalization · Sustainable development · Earth systems · Management · Marine food webs

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# 1 Background and Current Understanding

## 1.1 HABs and CyanoHABs: Organismal and Toxin Diversity

Within marine environments, microalgae, comprising prokaryotes and eukaryotes, are important primary producers (Duarte and Cebrián 1996). Although they are essential at the base of food webs, their presence in large numbers has the potential to adversely affect the environment and ultimately human health. The introduction of large amounts of nutrients, such as nitrogen and phosphorous into aquatic habitats, in conjunction with sunlight and calm weather conditions, can result in the formation of blooms comprised of mass accumulations of microalgal cells (Ryther and Dunstan 1971). The microalgal cells are generally diatoms and/or dinoflagellates in the case of Harmful Algal Blooms (HABs) or cyanobacteria in the case of Cyanobacterial Harmful Algal Blooms (CyanoHABs). Even though these large blooms are aesthetically unpleasant and can have associated odors, the greatest concern comes from their ability to produce small molecular weight highly potent toxins (Metcalf and Codd 2012). Often, toxins are isolated and identified as a result of their association with the consumption of contaminated shellfish, which has been responsible for human and animal sickness and death (Anderson et al. 2012; Metcalf and Codd 2012). These illnesses occur on a regular basis and have resulted in the need to monitor waters and shellfish to protect human health. In the marine environment, a range of organisms are capable of forming HABs with a variety of toxins potentially being produced or present (Table 1).

Although many of the HAB toxin structures are complex, they are largely either polyether or alkaloid compounds. They have a variety of molecular modes of action and are capable of causing a number of poisoning syndromes with severe acute and long-term effects. Domoic acid is a potent neurotoxin, originally isolated after a

**Table 1** Examples of HAB forming organisms and their toxins

| Poisoning/syndrome | Toxins | Organisms |
|---|---|---|
| Amnesic Shellfish Poisoning (ASP) | Domoic acid | *Pseudo-nitzschia* spp. |
| Azaspiracid poisoning (AZP) | Azaspiracids | *Protoperidinium* spp. |
| Diarrhetic Shellfish Poisoning (DSP) | Okadaic acid, dinophysistoxins | *Dinophysis* spp., *Prorocentrum* spp. |
| Paralytic Shellfish Poisoning (PSP) | Saxitoxins | *Alexandrium* spp., *Pyrodinium* spp. |
| Palytoxin poisoning (PTX) | Palytoxins | *Ostreopsis* spp., *Palythoa* spp. |
| Yessotoxin poisoning (YTX) | Yessotoxins | *Protoceratium* spp., *Gonyaulax* spp., *Lingulodinium* spp. |
| Neurotoxic Shellfish Poisoning (NSP) | Brevetoxins | Karenia brevis (Florida Red Tide) |
| N/A[a] | Spirolides | *Alexandrium* spp. |

[a] Not applicable

**Table 2** Examples CyanoHAB toxin-producing organisms and toxins

| Toxin type | Toxins | Genus |
|---|---|---|
| Hepatotoxins | Microcystins, nodularins | *Microcystis*, *Dolichospermum*, *Planktothrix*, *Nodularia*, *Hapalosiphon* |
| Neurotoxins | Anatoxin-a, anatoxin-a(*S*), saxitoxins | *Phormidium*, *Aphanizomenon*, *Dolichospermum*, *Cylindrospermopsis* |
| Genotoxic alkaloids | Cylindrospermopsins | *Cylindrospermopsis*, *Aphanizomenon*, *Oscillatoria*, *Raphidiopsis*, *Dolichospermum* |
| Endotoxins | Lipopolysaccharide (LPS) | All |
| Non-canonical neuro-toxic amino acids | ß-*N*-Methylamino-L-alanine (BMAA) | All |

poisoning event in Canada in 1987, with many symptoms including those of gastrointestinal and cardiovascular disease (Table 1; Pulido 2008). Of particular interest were neurological symptoms, specifically permanent loss of short-term memory, which ultimately gave the poisoning syndrome associated with this biotoxin its name: Amnesic Shellfish Poisoning (ASP). Similar in structure to kainate, domoic acid affects glutamate receptors resulting in neurotoxic effects.

The azaspiracids are considered to be causative agents of gastrointestinal upsets, largely through damage to intestinal villi (Table 1; Twiner et al. 2008). Okadaic acid and dinophysistoxins, the causative agents of Diarrhetic Shellfish Poisoning (DSP), also cause gastrointestinal upset (An et al. 2010). Within the mammalian cell, these toxic compounds are able to inhibit protein phosphatases. The saxitoxins are a group of alkaloids that are capable of inhibiting mammalian sodium channels, leading to muscle paralysis (Metcalf and Codd 2012). The palytoxins are vasoconstrictors and the yessotoxins are related to the marine ciguatoxins. Consequently, marine HAB species have the capacity to produce a wide range of highly potent, small molecular weight molecules which, in addition to the contamination of shellfish, can potentially cause human suffering, illness, and death (Anderson et al. 2012).

In addition to the HAB species, which are largely diatom or dinoflagellate-based, cyanobacteria are also capable of blooming in marine and freshwaters, again with the potential to produce a range of potent toxins that incur both acute and chronic toxicity (Table 2).

As with marine HABs, the cyanobacterial toxins have been isolated, determined, and identified through poisoning incidents and testing of bloom material and isolated cyanobacterial strains. Perhaps, the most common and high profile are the microcystins, protein phosphatase inhibitors, and potentially, through low-dose chronic exposure, tumor promotors (Table 2; Ueno et al. 1996). The neurotoxins make up a group of alkaloids comprising anatoxin-a, an acetylcholine mimic; anatoxin-a(*S*), a naturally occurring organophosphate; and the saxitoxins, sodium channel-blocking alkaloids, which are also produced by marine dinoflagellates (Metcalf and Codd 2012). The cylindrospermopsins were identified after an outbreak of hepatic enteritis linked to a drinking water reservoir (Hawkins et al. 1985) and the non-canonical amino acid BMAA has been linked to human neurodegenerative diseases including Amyotrophic Lateral Sclerosis (ALS) or motor neuron disease, Parkinson's, Alzheimer's, and dementia (Cox et al. 2016; Davis et al. 2020). Unlike the diatoms and dinoflagellates, which are eukaryotes, the prokaryotic cyanobacteria are Gram-negative bacteria and consequently also contain Lipopolysaccharide (LPS) endotoxins in their outer membrane with the potential to cause gastroenteritis (Lindsay et al. 2009).

## *1.2 Historical Occurrence*

Although much of the isolation and elucidation of the structures of HAB and CyanoHAB toxins was carried out in the latter part of the twentieth century, microalgal and cyanobacterial mass populations and their toxicity were already known based on reports from the twelfth century concerning unpleasant odors originating from lakes and nineteenth-century reports on cases of animal deaths associated with scums of cyanobacteria recorded in Europe and Australia (Hald 1833; Francis 1878; Benecke 1884; Codd 1996). Toxicity was confirmed in Australia when the dosing of sheep with scums of the cyanobacterium *Nodularia spumigena* resulted in illness and death (Francis 1878). In the Arabian Seas, the first recorded occurrence of the CyanoHAB species *Trichodesmium erythraeum* and the HAB dinoflagellate *Noctiluca scintillans* along the Indian coastline was in 1908 (Hornell 1908), followed by reports in 1976 of a HAB outbreak of *Gonyaulax* and *Noctiluca* species transported from the Indian coastline to the Gulf of Oman, both HAB events leading to massive fish kills (Thangaraja et al. 2007 and references therein). Approximately 33 HAB events have been recorded in the Arabian Seas between the years 1908 and 2009 (D'Silva et al. 2012; Al Shehhi et al. 2014).

In the marine environment, toxicity associated with shellfish has been known for many decades and common lore has for years dictated that shellfish should not be consumed during months that do not contain the letter "r", roughly corresponding to summer months when algal blooms could contaminate the shellfish. Through many decades of research, new types of poisonings have manifested after consumption of shellfish, often presenting with different symptoms and associated with new algal and cyanobacterial species or genera. Through rigorous study of these events, the active compounds have been identified, and techniques have been developed for their precise analytical detection, along with toxicology and risk assessment. Certainly, geographical differences can arise in terms of the organisms producing the toxicological agents, although ultimately most of the algal toxins have the potential to be found in aquatic habitats worldwide.

HABs and associated intoxications have been observed in and around the Arabian Gulf and surrounding seas (Al Shehhi et al. 2014). Their presence is largely inferred from associated fish kills and reports of adverse health effects. HAB-forming dinoflagellates and cyanobacteria, such as *Trichodesmium*, have been observed in the Arabian Gulf (Al Muftah et al. 2016), in North Africa (Ramos et al. 2005), and off the west coast of India (Krishnan et al. 2007). These blooms, as elsewhere in the world, have resulted in associated fish kills (Thangaraja et al. 2007; Richlen et al. 2010; Al Gheilani et al. 2011) and the deaths of cetaceans (Collins et al. 2002), in addition to the contamination of shellfish (Glibert et al. 2002). Furthermore, due to the reliance on fish as a major protein source in this geographical area surrounded by the Arabian Seas, and the fact that cyanobacterial toxins have been found in different species of this marine food web, monitoring and testing of fish destined for human consumption is important (Chatziefthimiou et al. 2018).

Similar to many marine environments, the Arabian Gulf suffers from HAB and CyanoHAB species, bloom events, and associated poisonings. However, the Red Sea and the Arabian Gulf and surrounding waters are unique environments when compared with other marine counterparts. First, due in part to the extreme climatological conditions, habitats have been formed that host unique animals including birds, cetaceans, and corals, while the ability of microorganisms to produce and exist as macrostructures has been demonstrated by the large cyanobacterial marine mats and crustose cyanobacterial structures that comprise the coastline (Johns et al. 1999; Naser 2011). Secondly, the Red Sea and the Arabian Gulf are effectively enclosed seas, with water entering through rivers in the north, mixing with marine water originating from the Arabian Sea, and exiting to the south, through the Gulf of Aden and the Strait of Hormuz/Gulf of Oman, respectively. Coupled with this is the fact that there are many countries surrounding these waters, resulting in a complex geopolitical landscape (Sheppard et al. 2010 and references therein). Consequently, any large-scale alterations and modifications in one country can have trickle down negative and transboundary effects on many countries. Finally, although small seas by global standards, significant engineering of the coastlines, in addition to the negative effects of war and pollution on the marine environment and wildlife, have been noted (Crowe et al. 2000).

## *1.3 Salinity*

Due to the arid climate's inherent scarcity of freshwater and the excessive abstraction of groundwater for irrigation in the Middle East-North Africa (MENA) region, the marine water of the Arabian Seas is the only major waterbody present within the region. Therefore, it is the source of water used for desalination to meet population and industry water needs. Except for Yemen, relying strictly on groundwater to meet its needs, Arab countries abstract marine waters from the Mediterranean Sea, Red Sea, Arabian Gulf, and Arabian Sea at an estimated rate of 24 million $m^3$ per day equivalent to about 40% of world output, which is projected to reach 50% by 2025 (UNDP 2013; Odhiambo 2017). The abstraction of marine water for the preparation of drinking water, in addition to the high evaporation rates characteristic of these seas, and construction of artificial islands and modification of coastlines, can have significant impacts on salinity and its heterogeneity. This is largely due to changes in water flow that result in areas of high versus low salinity (Heileman et al. 2008).

Certainly, within the northern reaches where freshwater inflows occur, salinities can be of a range conducive to the growth of algae, including microalgae and cyanobacteria. However, due to hydrographical issues, salinities >39 psu occur in most waters, with highs of up to 70 psu (Heileman et al. 2008). The ability of salinity to change within these seas may affect the production of toxins by microorganisms and with this heterogeneity of salinity, up-shocks and down-shocks of salinity may occur to phytoplankton, which in the case of *Microcystis* has been shown to affect the cell size and the production of microcystins by these cyanobacterial cells (Matthiensen et al. 2001; Tonk et al. 2007).

## *1.4 Seasonality*

Although the environment around the Arabian Peninsula is considered to be a hot desert, some seasonality exists within the Gulf region. In terms of air temperatures, high temperatures can be achieved in summer, with cooler and drier weather in winter. Water temperatures echo this trend with sea surface temperatures greater than >30 °C in summer and around 20 °C in winter in the open waters (Heileman et al. 2008). However, as many coastal, inter-tidal and sub-tidal areas in the Gulf are shallow, with insufficient mixing, very large temperatures, in some cases up to 45–50 °C, can be achieved. These temperatures are sufficient to support phytoplankton growth and potentially allow the proliferation of toxic species.

Stratification is more pronounced in the Gulf during the summer months, when the North Westerly Al Shamal winds, prevailing in the area, are weaker. On the other hand, the stronger wintertime shamal forcing, may create convective vertical mixing in the Gulf, disrupting stratification and sometimes deepening the mixed layer by as much as 30 m (Johns et al. 1999; Thoppil and Hogan 2010).. In this sense, the seasonality of the Red Sea is starker, being more pronounced in the winter months, characterized by a classic 2-layer exchange flow, while the summer Al Shamal winds cause a 3-layer flow with a thin surface outflow from the Red Sea, an inflow of Gulf of Aden thermocline water and a weak deeper layer that outflows (Johns et al. 1999). This mixing of cold, nutrient-rich waters into warmer, nutrient poor waters leads to the release or resuspension of nutrients back into the water column which may promote HAB and CyanoHAB formations.

Due to the geographical location of the Gulf, the light quality is generally good with intense bright sunlight. Although the Gulf is relatively shallow, the photic zone is only approximately 10 m (Naser 2011), while that of the Red Sea is about 120 m (Johns et al. 1999). Certainly, in the case where light and nutrients are sufficient to allow phytoplankton growth, then bloom formation have been shown to occur.

The Arabian Gulf and surrounding waters are important areas for researching and understanding the impacts of climate change, urban and coastal engineering, shipping and oil spills, on the marine environment and patterns of Harmful Algal and Cyanobacterial Harmful Algal Blooms.

## 2 Factors that Exacerbate the Incidence and Proliferation of HABs and CyanoHABs

Most factors that affect and lead to the increase of HAB and CyanoHAB magnitude and frequency of occurrence stem from the pressures incurred by human actions and activities in the Anthropocene era (Paerl and Huisman 2009; Kudela et al. 2015; EPA 2016; Johnson et al. 2017). Globalization, the increase in international trade, has played a predominantly catalytic role in the growth of the global human population and has catered to its demands for development, industry, transportation of goods, and production of aquatic food and drinking water supplies (Fig. 1; La Croix et al. 2003). These activities put pressure on thresholds and equilibria of Earth systems, decoupling environmental processes and disrupting ecological interactions, central to HAB and CyanoHAB initiation, that would otherwise keep them in check (GEOHAB 2001; Rockström et al. 2009).

In this section, we explore the three common causes of HAB and CyanoHAB formations, namely, eutrophication, global warming, and imbalance of ecological species interactions (competitions and predator/prey). We also discuss the ways that individual or aggregated globalization-driven activities disturb the planetary

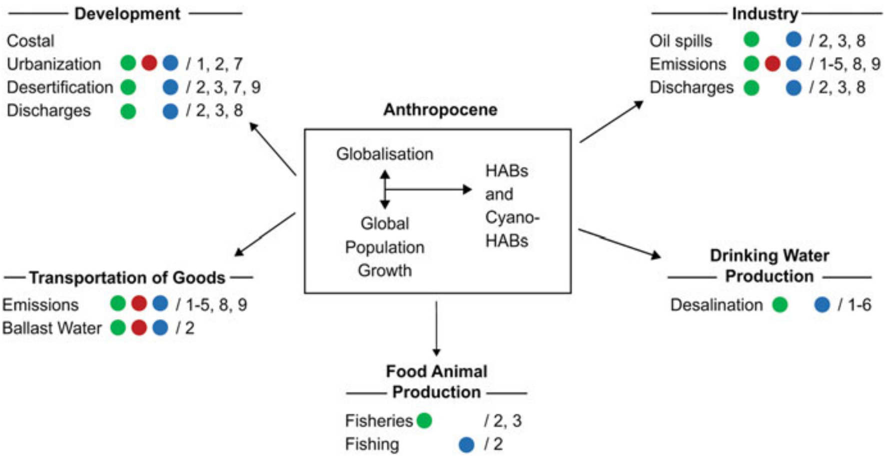

**Fig. 1** Figure depicting the interconnection between globalization-driven development, industry, transportation of goods, and production of aquatic food and drinking water supplies and the exacerbation of Harmful Algal and Cyanobacterial Harmful Algal Blooms in the Anthropocene era. Colored circles signify the three common themes of HAB and CyanoHAB formations and numbers correspond to the planetary boundaries, whose threshold is under pressure due to each of these grouped activities. Green circle, eutrophication; red circle, global warming; blue circle, competition and predator/prey imbalance. Key to planetary boundaries: (1) climate change; (2) rate of biodiversity loss; (3) interference with the N and P cycles; (4) stratospheric ozone depletion; (5) ocean acidification; (6) global freshwater use; (7) change in land use; (8) chemical pollution; (9) atmospheric aerosol loading

boundaries as described in Rockström et al. (2009), while exacerbating HABs and CyanoHABs (Fig. 1).

## 2.1 Development

Whether it is due to access to centralized government services, employment opportunities, or recreation, the last century has seen an unprecedented rate of urbanization with 54% of the global population currently inhabiting urban cities (UN-HABITAT 2016). Coastal areas are especially attractive real-estate locations experiencing rampant development. Globally, the population inhabiting areas within 100 km from the coast reaches 40% (Burke et al. 2011; Kummu et al. 2016), while specifically in the countries with coastlines bordering the Arabian Seas, 61% of the population inhabit coastal areas (El-Raey 2009). Physical alteration of the coasts leads to habitat loss, fragmentation, and biodiversity loss (Fig. 1). Often, through the process of development, enclosed shallow waterbodies are created where temperature is maintained at high levels from a lack of mixing and high evaporation rates (i.e., Palm developments in the UAE, the Pearl development in Qatar; Sale et al. 2010). These conditions are conducive to the formation of HABs and CyanoHABs and further accelerate it when combined with eutrophication hot spots near point sources of wastewater discharges into coastal areas, as in the case of the 2001 HAB event in Kuwait Bay that resulted in massive fish kills (Sheppard et al. 2010).

Coastal development can also be a driver to desertification. Although it is usually conceptualized in a terrestrial setting, physically altered coasts can be susceptible to desertification through soil/sediment erosion and rises in the salinity of marine waters (MEA 2005). Additionally, climate change-induced droughts and intensification of natural dust storm events further compound the negative effects of desertification (IPCC 2013; MEA 2005). The input of dust/sediment originating from the Northern Arabian and the Sudan-Ethiopia and Southern Arabian dust storm trajectories, which falls out in the counties bordering the Arabian Seas, is 61–392 tonnes/km$^2$/year (Al-Dousari et al. 2013 and references therein). These events not only increase the atmospheric aerosol loading, but due to the binding of minerals and nutrients like iron on the airborne particles, when they fall out, they may lead to eutrophication and prime HAB species such in the case of the toxic dinoflagellate *Gymnodinium breve* in coastal areas of Oman and Kuwait (Subba Rao and Al-Yamani 1999; Walsh and Steidingler 2001; Rockström et al. 2009; Manivasagan and Kim 2015). Microbes attached to airborne particles are also of concern. The atmosphere is one of the most harsh and extreme of environments, and the microbes that survive on airborne particles are exceptionally stress-tolerant (Weil et al. 2017). Thus, they may become invasive in the introduced environment, outcompeting the natural resident communities, potentially amplifying the formation of HABs and CyanoHABs (Walsh and Steidingler 2001; Weil et al. 2017).

## 2.2 Industry

Collectively, the Gulf Cooperation Countries (GCC) hold 25.4% of global total reserves of gas and 42.6% of global total oil reserves, while 60% of the oil and gas transported annually by ships around the world traverse the Strait of Hormuz (Haapkylai et al. 2007; Luomi 2016). Carbon dioxide ($CO_2$) emissions related to the extraction and production of these natural resources and the associated generation of energy reach 698.7 million tonnes/year, (Luomi 2016). Additional to the consequence of $CO_2$ emissions on ocean acidification and HAB formation discussed in the section on transportation of goods below, the oil/gas industry aggravates HAB formations through oil pollution from routine-operation oil spills, discharges in marine and ballast waters, as well as other effluents (Fig. 1; Al Shehhi et al. 2014). Although these point sources of oil pollution impact ecosystem health, they may not compare in magnitude to the impact caused by the intentional release of a maximum of 820,000 tonnes of oil released during the Gulf War of 1991 from tankers and coastal terminals (Khordagui and Al-Ajmi 1993). For comparison, during the catastrophic Deepwater Horizon oil spill in the Gulf of Mexico, USA, 627,000 tonnes of oil were spilt (USGS 2010). Oil spills result in an increase of bioavailable Total Organic Carbon (TOC) and the detergents/dispersants that are employed to remediate, contain, and release sulfur compounds into the marine environment in addition to the sulfur released by the oil itself (Khordagui and Al-Ajmi 1993; Bælum et al. 2012). Combined, these nutrient sources lead to eutrophication and the dismantling of the local food web, potentially resulting in HAB and CyanoHAB formations (GEOHAB 2001; Kudela et al. 2015).

## 2.3 Transportation of Goods

About 90% of world trade is carried by the international shipping industry (UNCTAD 2016). The reliance on shipping for the transportation of goods around the globe incurs a double negative effect on ecosystem health through emissions and ballast waters that may benefit HAB and CyanoHAB formations (Anil et al. 2002). First, international shipping fuel consumption between 2007 and 2012 reached 201–272 million tonnes/year, with emissions of 596–921 million tonnes/year of $CO_2$ and 10.6 million tonnes/year, of Sulfur Oxides ($SO_X$), accounting for about 15% of global emissions from anthropogenic sources (IPCC 2013; IMO 2015). $SO_X$ deposition may increase nutrient levels locally, while elevated $CO_2$ levels are responsible for global warming and acidification of marine waters (Fig. 1; IPCC 2013). It has been shown in situ and in pure cultures that acidification enhances photosynthetic activity of bloom-forming rhodophyte and chlorophyte macroalgae of the genera *Gracilaria* and *Ulva*, respectively (Young and Gobler 2016). Enhancement of nitrogen-fixing activity has been shown as well, as in the case of the cyanobacterium *Trichodesmium*, which benefits from the inhibition of nitrification and reduction of nitrate availability caused by acidification (Hallegraeff 2010).

Secondly, ballast waters used to maintain stability and operational efficiency in ships may inadvertently facilitate the transport, dispersal, and global expansion of HAB-forming species. At any given port, ballast marine waters are drawn into the ship at the time of cargo unloading and released, while cargo is loaded to maintain stability. Approximately, 3–5 billion tonnes/year of ballast water are transferred this way globally (UNCTAD 2016). The fish-killing dinoflagellate *Cochlodinium polykrikoides* implicated in the 2008–2009 Arabian Gulf red tide bloom that persisted for 8 months and led to the killing of thousands of tonnes of fish was closely related to the "American/Malaysian" ribotype and was suspected to have been transported in ballast waters (Richlen et al. 2010). The success of this bio-invasion may be likely due to the ability of this dinoflagellate to survive under the new environmental conditions and its capacity to outcompete natural and resident microbial assemblages for available nutrients/resources (Sale et al. 2010).

## *2.4 Production of Aquatic Food*

Throughout the world, the supply of fish as a source of protein in the human diet is becoming increasingly important, including countries of the MENA region bordering the Arabian Seas (FAO 2016; Chatziefthimiou et al. 2018). Globally, capture fisheries have increased landings from 69 million tonnes to 93 million tonnes, while aquaculture production has seen an increase from five million tonnes to 63 million tonnes from 1998 to 2008 (World Bank 2013). The Gulf regional share of the global total fish production is 2.5% with projections to increase to 22% by 2030. It is estimated that 80% of global marine fish stocks are overexploited or exploited, further intensifying a need to rely on aquaculture production, which, in 2014, for the first time overtook fish supply from capture fisheries destined for human consumption (FAO 2009, 2016; Burke et al. 2011). Exploitation of marine resources is a cause for imbalance of equilibria of ecological interactions. Removal of top predators from the marine food web through over-fishing allows for an unchecked population growth of smaller fish in the lower food web tiers that excessively prey on zooplankton. This in turn leads to a decrease of grazing pressure on phytoplankton, including HAB and CyanoHAB-associated microbes, and an increase in their growth (Hallegraeff 2010).

Aquaculture on the other hand contributes to HAB initiation and exponential growth, in cases where nutrient runoff occurs. This type of pollution is suspected to be the cause of two major HAB outbreaks and massive wild-fish-kills in Kuwait Bay, by the dinoflagellate *Karenia selliformis* and the diatoms *Prorocentrum rathymum* in 1999 and *Ceratium furca* in 2001 (Glibert et al. 2002; Al-Yamani et al. 2000). Finally, aquaculture runoff can create circular problems, since the same HAB and CyanoHAB species that cause wild-fish-kills also cause aquacultured fish killings. The captive fish, may suffer even greater mortality as they have no way of escaping their fishponds to evade the toxicity of blooms like wild fish do (Hallegraeff 2010; Drobac et al. 2016)..

### 2.5 Production of Drinking Water Supplies

Dependency on water desalination, especially in Gulf countries which accounts for 40% of the global production and 81% of the desalination capacity among MENA countries, can exacerbate HABs and CyanoHABs in additional ways related to the brine discharge (UNDP 2013). Eutrophication occurs when high molecular weight organic compounds used in thermal desalination systems are not volatilized before being discharged and remain in the discharged brine (Dixon et al. 2017). This also occurs in reverse osmosis desalination systems, when antiscalants added to minimize negative impacts of brine discharges don't fully biodegrade and instead cause an increase in organic matter when released into the environment (Weinrich et al. 2015). Finally, in situations of active HAB and CyanoHAB formations near desalination plants, toxins that have entered through the water intake may remain unaffected by most of the pretreatment processes, including chlorination, which has been shown to not be effective in removing brevetoxins that cause Neurotoxic Shellfish Poisoning (NSP; Table 1; Laycock et al. 2012; Dixon et al. 2017).

## 3 Harmful Consequences of Blooms

Cyanobacteria have the potential to have a positive effect on environmental $O_2$ production, desert soil stabilization, trophic level dynamics, and atmospheric nitrogen fixation (Powell et al. 2015). Likewise, dinoflagellates and diatoms are primary producers which form the basis of many aquatic food chains. Despite these benefits, harmful algal blooms have been linked to a variety of problems with regard to health, biodiversity, and ecosystem level impacts. In some instances, HABs and CyanoHABs are directly responsible for damage, and in others they represent a contributing factor. These problems are well documented globally and also specifically in the waters of the Arabian Gulf and surrounding seas.

One of the most prevalent concerns is that of oxygen depletion, where HABs and CyanoHABs represent a contributing factor. Rapid expansion of photosynthetic biomass in response to nutrient influx eventually results in the accumulation of a large amount of organic material. Once environmental conditions change and the bloom(s) begins to senesce, this increased amount of decaying organic matter within the water column is microbially degraded (Diaz and Rosenberg 2008). The subsequent increase in microbial respiration can rapidly deplete dissolved oxygen (DO) concentrations to hypoxic (DO $\leq$ 2 ml of $O_2$ /liter) or anoxic conditions which can lead to invertebrate and fish kills, animal behavioral shifts, a loss of biodiversity, and, when recurrent, ecosystem level shifts (Diaz and Rosenberg

2008). Fish die-offs can adversely affect fishery industries (capture fisheries and aquaculture), and since they are particularly noticeable to lay people, they can negatively impact tourism and recreation.

Within the Middle East, hypoxic conditions have been documented for many years (Kamykowski and Zentara 1990; Thangaraja et al. 2007). *Noctiluca* blooms have also been responsible for fish mortalities in Oman, at least some of which are related to oxygen deprivation in correlation with HABs (Al Gheilani et al. 2011). In the Arabian Gulf, low dissolved oxygen concentrations, in addition to other environmental stresses, contributed to the large 2001 fish kill (Glibert et al. 2002). In the Sea of Oman, dissolved oxygen concentrations have been noted to contribute to changes in species composition (Al-Hashmi et al. 2012). As a result of eutrophication, *Noctiluca scintillans* blooms caused a small decrease in dissolved oxygen in the Red Sea with the noted potential for induced ecosystem level changes (Mohamed and Mesaad 2007). In Oman, oxygen depletion was directly attributed to a *N. scintillans* bloom in 1988 which resulted in fish kills (Al-Azri et al. 2007).

A decrease in dissolved oxygen concentration is one reason for fish kills, but direct toxicity from HABs is another. Numerous species of toxin producing dinoflagellates have been reported from waters in the Middle East with numerous related toxins (Subba Rao and Al-Yamani 1998; Subba Rao et al. 1999; Morton et al. 2002; Thangaraja et al. 2007; Mohamed and Mesaad 2007; Moradi and Kabiri 2012; Alkawri 2016). Specific incidents of deaths associated with HABs have been recorded. In 2008–2009 a *Cochlodinium* species bloom in the Gulf of Oman and the Arabian Gulf had a major negative ecological and financial impact. This bloom lasted in excess of 8 months and resulted in thousands of tonnes of fish being killed, decimating local fisheries and ultimately damaging the coral reefs (Richlen et al. 2010). The bloom also affected the local desalination plant resulting in modified operations (Richlen et al. 2010). Coastal tourism was also negatively affected by this bloom (Richlen et al. 2010).

Additional concerns of microscopic algal blooms include their detrimental effects on water desalination equipment through water fouling. Excessive biological material from HABs clog intake filters and water purification membranes of desalination plants. This is a problem of crucial significance since human habitation in the region is intrinsically dependent on the supply of drinking water from desalination. Thus, closure of plants due to HABs and CyanoHABs may have immediate repercussions on the quality of life and the ability to inhabit this region (Richlen et al. 2010; Berktay 2011; Villacorte et al. 2015).

Within desert ecosystems, biological soil crusts (biocrusts) stabilize the ground surface, where CyanoHAB toxins can accumulate and become persistent in the soil (Metcalf et al. 2015; Richer et al. 2015; Chatziefthimiou et al. 2020). Of concern for human health is the potential for toxins to become airborne following heavy winds and anthropogenic disturbance (Chatziefthimiou et al. 2015). Besides being directly inhaled by humans, these airborne toxins can also be introduced into drinking water supplies adding a further compounding exposure risk in arid environments (Chatziefthimiou et al. 2016).

## 4 Current Policy in HAB and CyanoHAB Management and Recommendations for Future Directions

There are two organizations, among the countries of this region, that are part of the United Nations Environment Programme/Regional Seas Programme (UNEP/RSP), which has a mandate for the sustainable protection, management, and use of the marine and coastal environment (UNEP/RSP 1982). Countries with coastlines along the Arabian/Persian Gulf, Bahrain, I.R. Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, form the Regional Organization for the Protection of the Marine Environment (ROPME 2017a), while Djibouti, Egypt, Jordan, Somalia, Saudi Arabia, Sudan, and Yemen form the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA 2017). Although HAB and CyanoHAB management is not named explicitly as 1 of the 4 themes of the vision of the UNEP/RSP: pollution, climate change and ocean acidification, extraction, and governance, it is intrinsically connected to and affected by all of them, and regional organizations are encouraged to follow guidelines, protocols, and policies produced by the Intergovernmental Oceanographic Commission's (IOC) Harmful Algal Bloom Programme (Kudela et al. 2015; UNEP/RSP 2016).

PERSGA and ROPME have created and administered many programs and actions that Member States can implement and carry out to protect marine natural resources, adapt to climate change and build human capacity through educational programs that raise environmental awareness (PERSGA 2017; ROPME 2017a). PERSGA has also published Environmental Impact Assessment guidelines for aquaculture projects, whereby the assessment of risk of diseases, HABs, and bio-invasions resulting from operation is a basic requirement (PERSGA 2004). Furthermore, ROPME provides its Member States with warning alerts on the probability of HAB events based on satellite imagery depicting parameters of algal patches, chlorophyll, and sea surface temperature (ROPME 2013, 2017b).

Although this collective of actions and policies are in place, there are some impediments to their implementation. First, funding that would enable the ratification and adoption of conventions, maintenance of monitoring systems, and enactment of regional indicator systems is often scarce (UNEP/RSP 2014). Second, as these regions encompass many diverse geo-ecological features and because systematic surveys and baseline studies of the ecosystem and biodiversity are lagging, it is difficult to assess the actual state of the marine environment and to determine and pinpoint the exact effects that globalization-driven activities may have on HAB and CyanoHAB initiation and proliferation. Finally, due to the unrest and conflict among Member States in both PERSGA and ROPME, international communications may be severed and access to data and data-sharing may be limited. Since all the Arabian Seas are trans-boundary bodies of water, and thus management of resources and pollution inherently requires inter-nation actions and resolutions, this lack of knowledge transference and absence of concerted efforts in management may well be the greatest impediment to proper protection and sustainable development of the Arabian Seas (Uitto and Duda 2002).

As we move forward, it would be prudent to designate a Member States or a single international team as the primary coordinator of efforts pertaining to HABs and CyanoHABs and thus centralize management, and enforcement of the regional action plans, as well as to coordinate data-sharing efforts. Having a united single group with the support and power to execute those action plans would increase the probability of success. Investments of local funds to support HAB and CyanoHAB monitoring, as well as research-based methods for their control and mitigation, should become a priority for Member States. Finally, a concerted effort toward the development of educational and informative campaigns to engage professionals and the general populations of these countries is essential in raising awareness, which could encourage and promote sustainable development and lifestyles.

Furthermore, the presence of CyanoHAB toxins in the organs of a number of marine species in the Arabian Gulf points to a need to mandate routine toxin monitoring and testing of these organisms intended for consumption by the human population (Chatziefthimiou et al. 2018). Routine monitoring and testing should also be instated for water produced through the desalination process. Although there are many managerial options for the removal of a variety of toxins from water-sources, it is still unclear whether current technologies can efficiently remove the low molecular weight neurotoxins that have been found in desalinated water supplies (Chatziefthimiou et al. 2016). Thus, it is of essence that funds be allocated to Research and Development to shed light on this issue and to develop new technologies in the case that the current ones are not sufficient in removing these toxins. Finally, research efforts to elucidate bioaccumulation potentials in food chains and studies to assess toxicity thresholds in animal models can serve as the basis for the development of guideline values and science-based policy to protect human health from toxin exposure.

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