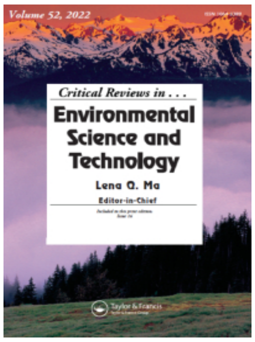

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Aquaculture in coastal urbanized areas: A comparative review of the challenges posed by Harmful Algal Blooms

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ABSTRACT

Increasing global population has resulted in increased urbanization of coastal areas across the globe. Such an increase generates many challenges for sustainable food production and food security. The development of aquaculture has proven to be an extremely good option to ensure food security (uninterrupted supply and good quality of food) by many countries, especially those with urban areas affected by space limitations such as Singapore. However, the implementation of aquaculture is not without its challenges and impacts to the environment, with Harmful Algal Blooms (HABs) being one of the major concerns in coastal waters. In this review we analyze the development of the aquaculture industry with respect to HABs in Singapore and compare it to similar urban areas such as Hong Kong (SAR China), Salalah (Oman), Cape Town (South Africa), Valencia (Spain), Rotterdam (The Netherlands), Tampa bay (USA), Vancouver (Canada), and Sydney (Australia). Along with HABs, the abovementioned urban areas face different challenges in sustainably increasing their aquaculture production with respect to the economy and geography. This review further assesses the different production and monitoring strategies that have been implemented to counter these challenges while sustainably increasing production. The ongoing COVID-19 pandemic has affected the world with lockdowns and border closures resulting in logistical difficulties in seafood trade which has further accentuated the dependencies on food import. We conclude that the challenges faced by urban areas for sustainable achievement of food security through development of the aquaculture industry can be effectively managed through proper planning, management and collaboration of knowledge/skills on an international level.

KEYWORDS HABs; urbanization; aquaculture; food security; mitigation; Singapore

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Introduction

The United Nations (UN) has projected that the world population would increase from 7.7 billion in 2019 to 9.7 billion by 2050 (UN, 2019). To date, it is estimated that 55% of the world's current population lives in urban areas (UN, 2018). Despite low levels of urbanization, Asia is home to 54% of the world's urban population, followed by Europe and Africa with 13% each (UN, 2018). The projected increase in the world's total population combined with that of urbanization could add another 2.5 billion people to urban areas by 2050, with close to 90% of this increase taking place in Asia and Africa (UN, 2020).

This increase in population will require a concurrent increase in food production. The global aquaculture sector expects productions to increase by over 50% to meet global food demands in the next two decades and this needs to be done in an economically, socially and environmentally sustainable manner. In all respects, an aquaculture dominant food production ecosystem to meet future demand is desirable because of its limited impacts on deforestation and land use in general (Froehlich et al., 2018). Yet, the expansion of aquaculture in both northern and southern hemispheres has been associated with environmental issues of harmful algal blooms (HABs) leading to indiscriminate killings of aquatic organisms, closure of beaches and restriction of recreational activities (Anderson et al., 2012). The definition of HABs in the context of this review is adopted from Hallegraeff et al. (2004) and includes i) the proliferation of microalgae to high biomass causing harmless water discolorations but indiscriminate killings of marine organisms through oxygen depletion; ii) the proliferation of microalgae to high biomass, nontoxic to humans but killing fish and invertebrates through mechanical damage or clogging of their gills and iii) the production of toxins by microalgae harmful for marine organisms and for humans by transfer through the food chain and physical contact.

HABs in the past forty years have increased in frequency, intensity and geographical distribution (Dale & Yentsch, 1978; Heisler et al., 2008, Hallegraeff, 2010; Anderson et al., 2012; Lin et al., 2020). The increase of such events is not always well understood and has been attributed to different factors that can increase the amount of nutrients into the water such as discharge from waste-water treatment plants, shipping, oil-refinaries, tourism, port- activities, housing, deslination plants, coastal farms and aquaculture (Figure 1; Trottet et al., 2018). Figure 1 shows two-way interactions in the case of desalination plants, coastal farms and aquaculture farms which can stimulate HAB events, but can also be affected by HABs resulting in clogging of the filters in desalination plants and killing of fish stocks. In addition to human activities that can stimulate HABs, natural climatological factors such as seasonal changes can stimulate HABs too in some

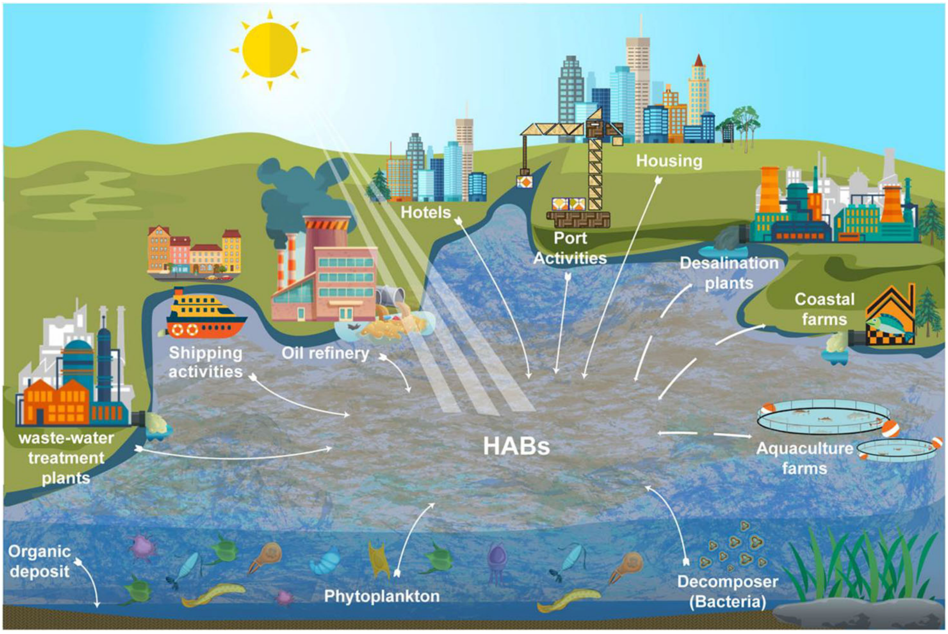

Figure 1. A conceptual diagram showing the various coastal urban developments in the discussed urban areas, contribution of these processes to eutrophication and the occurrences of HABs. Urban infrastructure such as desalination plants and aquaculture farms are represented by a two-way arrow showing both their contribution to the development of HABs and also how they can be impacted by HABs.

areas (Al-Azri et al., 2013). Many of these HAB species are cosmopolitan with serious negative impacts on the ecosystem, economies of the affected areas and on public health as documented in the past HAB events across the globe (Anderson et al., 2012).

HABs tremendously impact aquaculture resulting in devastating economic losses locally or regionally and may even lead to a shortage of food supply or retail of fish with compromised quality (FAO, 2020a). Food supply and quality are crucial aspects of food security which has become an increasing global concern especially for developed countries which are heavily dependent on food imports. These food imports can further be affected by political unrest, conflict and wars between nations, diseases and epidemics such as the ongoing COVID-19 and other factors which have led many nations to adopt strategies to improve their food security measures. Such measures should be centered on the development of technological advancements to improve self-sufficiency and shorten supply chains, thereby enabling sustainable aquaculture practices (Nat.Plants, 2020; Teng, 2020). The concept of sustainable aquaculture adopted in this review follows the FAO definition - "An ecosystem approach to aquaculture (EAA) is a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems" (FAO, 2010).

As majority of the urban infrastructure is expected to develop in Asia in the next few years (Teng, 2020), many nations in this region could accommodate to this growth by protecting food security with sustainable development of their aquaculture industry. This may become challenging for knowledge-based economies in Asia such as Singapore. Located in Southeast Asia, the city-state of Singapore is an island of 718.3 km2 bounded by the Straits of Johor in the north and the Straits of Singapore in the South and characterized by a very dense population of 5,791,901 inhabitants and intense port activities (Table 1, Figures 2 and 3) (Gin et al., 2006). With such dense population and limited space achieving self-production becomes a challenge (Teng, 2020). However, the advantage that Singapore has is the coastline which is being exploited to maximize the urban infrastructure and aquaculture production potential. With such rigorous coastal developments, increased nutrient discharges would inevitably increase the risks of HAB occurrences and therefore their associated negative impacts on the economy and food security objectives.

We review the situation in urban areas with similarities to Singapore within countries located in every continent except Antarctica (i.e. urban areas experiencing rapid coastal developments, having an emerging aquaculture industry in a limited space). These urban areas along with Singapore were reviewed on all key aspects of their water bodies, population, port activities, and aquaculture production (Table 1). The chosen urban areas include Hong Kong (SAR China), Salalah/Oman, Cape Town area (South Africa), Valencia (Spain), Rotterdam (The Netherlands), Tampa bay (USA), Vancouver area (Canada), and Sydney (Australia) (Figures 2 and 3). We recognize that the significance of the key aspects chosen for comparison differs for the different urban areas. A record of HAB events for each urban area with year, location, organisms involved, cause and characteristics with economic and/or environmental losses are presented in Table 2 based on the availability of these records. Therefore, we recognize that the information in Table 2 may not be an exhaustive list as there may have been HAB events which may not have been recorded. Mitigation and management measures were also included when available (Table 2).

Singapore: a reference for sustainable 'self-sufficiency' through aquaculture

Due to lack of natural resources such as land and water Singapore has transitioned from a fishing village in the 1950s to an urbanized, high-income economy based on knowledge and technology (Chou, 2006; Ludher & Paramasilvam, 2018). Therefore, Singapore has become heavily reliant on

Table 1. Description of cities being investigated with respect to their demographics, surrounding water bodies, port activity (in twenty-foot equivalent units, TEUs) and ranking as well as aquaculture and fisheries production. Description of aquaculture activities is also included.

City (Country)	Region (Water body)	Population (hab.)[1]	Port (10^3 TEUs) / Rank[2]	Aquaculture production (tonnes) [7]	Fisheries production (tonnes) [7]	Developing Aquaculture activities	Reference
Singapore (Singapore)	Asia (South China Sea / Pacific Ocean)	5,791,901	36,599 / 2	5,335*	1,418*	There are approximately 127[#] fish farms including several land-based hatchery/culture farms. The fish species produced are mostly groupers, seabass, snappers and milkfish. Most coastal-based aquaculture farms are in the Straits of Johor and use open net cage systems to grow their fish. In the Straits of Singapore, there is one open sea farm producing Asian seabass. Local fish production in 2019 was estimated to 4,707 tonnes. RAS systems are being operated on land and tested on pilot-scale on floating structures in the Straits of Johor	SFA, 2020
Hong Kong SRA (China)	Asia (South China Sea)	7,428,887	19,596 / 7	4,133	124,299	Aquaculture includes marine fish culture, pond fish culture and oyster culture. In 2019 production from the aquaculture sector was 3,284 tonnes valued at HKD 138 million. Currently, there are 26 marine fish culture zones occupying a total sea area of 209 ha with some 923 licensed operators. Majority of the licensed farms are small, family-based and consisting of one to two rafts. The estimated production in 2019 was about 889 tonnes valued at HKD 72 million which catered about 5% of local demand for live marine fish. Other aquaculture production includes pond fish culture in brackish and freshwater and oyster culture, with 2,278 tonnes (HKD 52 million) and 117 tonnes (HKD 14 million) respectively in 2019	AFCD, 2020
Salalah /Oman	Middle East (Arabian Sea)	374,582	3,385 / 51	451	553,445	Aquaculture in Oman began in 2003 with the production of gilthead seabream representing 89 percent of the total. In 2004, aquaculture production was valued at USD 2.5 million. Production of shrimp started from 2007 with total production of 85 tonnes and dominates the aquaculture production. There are currently 21 integrated tilapia farms, one shrimp	Lund, 2019; The Fish Site, 2020

						farm one marine cage farm in Oman. Oman's Ministry of Agriculture and Fisheries reported total aquaculture production in 2019 at 1,054 tonnes valuing OMR 2 million from sea bream and tilapia.	
Cape Town area (South Africa)	Africa (South Atlantic Ocean)	3,740,026[3]	882[5]/ -	7,868	570,545	Diverse marine species produced in South Africa with mollusks (abalone, oyster and mussels) and trout as dominant species produced. Region of Western Cape has most farms accounting for 67% of South Africa marine farms	DAFF, 2012; Britz & Venter, 2016
Valencia (Spain)	Europe (Mediterranean Sea)	789,004	5,129 / 29	347,825	928,791	Valencia is a national hotbed of aquaculture production, with output up to 9,278 metric tonnes of seafood valued at EUR 38 million (USD 53 million) in 2011. In its Fisheries Master Plan 2008-2013, the regional Department of Agriculture, Fisheries, Food and Water aimed to create new economic opportunities along Valencia's coast, providing employment, capitalizing on local resources and encouraging investment. Spanish aquaculture production reached a total volume of 226,222 tonnes in 2013 for a total value of EUR 429 million, mussel production representing 76.1% of total volume and 98 operational farms as of 2014.	Towers, 2015; European-Commision, 2014b; Dove, 2011
Rotterdam (The Netherlands)	Europe (North Sea)	623,652	14,513 / 11	52,285	411,714	Three main production categories exist in the Netherlands namely, the largest being that of blue mussels as bottom cultures followed by oyster production and then the land-based production of fish, mostly eel and catfish. The Dutch aquaculture sector is dominated by small companies with fewer than 5 employees. As of 2011, there were 115 aquaculture farms (58 mussel production companies, 19 oyster production companies and 38 fish production companies). The Dutch aquaculture sector produced a total of 43,500 tonnes in 2011 amounting to EUR 64.4 million.	European-Comission, 2014a
Tampa Bay (United States of America)	North America (Gulf of Mexico)	3,091,399[4]	57[6] / -	468,185	4,756,997	Multiples aquaculture species including molluskan and clams with a value of USD 71.6 million for 325 farms in Florida in 2018.	FDACS, 2020
Vancouver area (Canada)	North America (Pacific Ocean)	675,218	3,397 / 50	191,323	839,224	Aquaculture in Canada is dominating by finfish production with 149,418 tonnes produced in 2018	

(*continued*)

Table 1. Continued.

City (Country)	Region (Water body)	Population (hab.)[1]	Port (10^3 TEUs) / Rank[2]	Aquaculture production (tonnes)[7]	Fisheries production (tonnes)[7]	Developing Aquaculture activities	Reference
						(equivalent of CAD 1.325 billion in 2018). Marine salmon farming, which started in the early 1970s is leading the market and most of the salmon are produced in British Columbia with more than 87,000 tonnes for market value of CAD 772 million. Canada is the 4th largest producer of salmon in the world. Shellfish aquaculture is dominated by mussel and oyster production, Prince Edwards Island as main producer, with total production of 41,841 tonnes (= CAD 106 million) in 2018	Fisheries and Oceans Canada, 2020
Sydney (Australia)	Oceania (South Pacific)	4,321,535	2,648 / 72	96,799	186,576	Aquaculture in Australia represent AUD 1.42 billion gross production value for 97.7 thousand tonnes production in 2017-2018. Main species produced are Salmonids (62% of Australia production,) followed by Tunas (9%) and Oysters (7%). Barramundi and Abalone are increasing in production representing 7% of production together. New South Wales hosts shellfish production, which has increased from AUD 38 million in 2010-2011 to AUD 70.8 million in 2017-2018. Production is dominated by one oyster, *Saccostrea glomerate* (Sydney rock oyster) which represent 51% of NSW production.	Farrell et al., 2013; NSW EPA, 2020

1 http://m.statisticstimes.com/demographics/countries-by-population-density.php.
2 https://lloydslist.maritimeintelligence.informa.com/one-hundred-container-ports-2019.
3 http://www.statssa.gov.za/?page_id=993&id=city-of-cape-town-municipality(2011).
4 http://www.tampabay.com/blogs/baybuzz/2018/03/23/census-tampa-bay-saw-10th-biggest-metro-population-gain-in-2017.
5 https://frontrunner-bucket.s3.amazonaws.com/2FC9C5A5-5056-907D-8DE3-152D117B6920.pdf.
6 https://www.transnetnationalportsauthority.net/Commercial%20and%20Marketing/Pages/Port-Statistics.aspx.
7 http://www.fao.org/fishery/statistics/global-production/query/en.
*https://www.sfa.gov.sg/docs/default-source/tools-and-resources/yearly-statistics/local-production.pdf.
#https://www.sfa.gov.sg/docs/default-source/food-farming/licensed-fishing-vessel.pdf.

Figure 2. The urban areas described in this review are represented on a color-coded scheme for the ratio of aquaculture to fisheries production in 2018 (except for production in Singapore 2019) and the recorded number of HAB occurrences represented by color coded dots till date.

international food and water imports to meet over 90% of its daily requirements (Teng & Escaler, 2010). This dependence on imports and its sustainability was challenged during the food crisis of 2008, when a stunted global food supply chain and price fluctuations uncovered Singapore's vulnerability in maintaining food security (Teng & Escaler, 2010).

With a population projected to reach 6.9 million by 2030 and an average of 10 million tourists per year, placing increasing pressure on the current food sources, the government aims to increase food self-sufficiency, secure good quality food at source at sustainable cost and regular supply (Sin, 2018; Teng & Escaler, 2010). Diversification of food imports from multiple sources, contract farming with China and Malaysia for products consumed in Singapore and increasing local productivity through innovative urban farming were some of the approaches adopted to reduce dependency on a single or few exporting countries (Teng & Escaler, 2010).

Seafood, especially fish, is a crucial component of the Singaporean diet and many efforts have been directed toward achieving fish production to supply 15% of local fish consumption (vs 5% in 2010), further limiting reliance on international imports (Teng & Escaler, 2010). The Marine Aquaculture Center (MAC) established in 2003 by Singapore Food Agency (SFA) on St. John's Island aims to increase Singapore's annual fresh fish production by developing large scale hatcheries and open cages to rear fishes (Ludher & Paramasilvam, 2018; AVA, 2019).

Since the formation of the Singapore Food Agency (SFA) in 2019, there was a greater focus on increasing local food production to meet 30% of the nutritional needs by 2030, also known as "30 by 30" (SFA, 2020). Given Singapore's limited geographical spread and constant coastal developments, achieving an increase in fish production requires better incentives for farmers, higher public and private sector investments (local and international) into research and development to adopt new technologies and maintenance of optimal water quality (FAO, 2009, Teng & Escaler, 2010; Gin et al.,

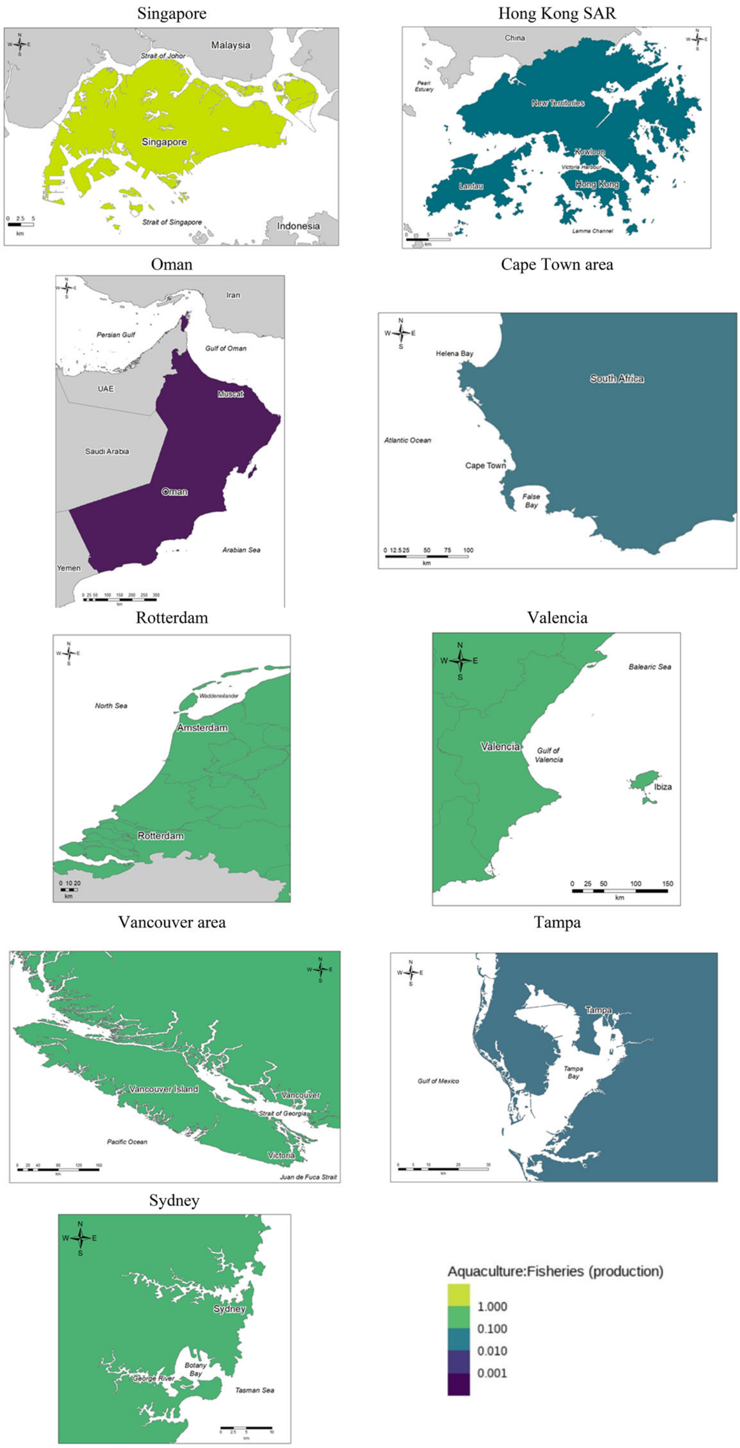

Figure 3. Maps of each of the urban areas representing their aquaculture to fisheries production ratio.

Table 2. Information on HABs events for each urban area with year, location, organisms involved, cause and characteristics with economic and/or environmental losses. Mitigation and management measures are also included when available.

Year	Location	Organisms	Causes and characteristics	Economic / environmental loss	Mitigation and management	Reference
SINGAPORE						
1987	Johor Straits	*Cochlodinium* sp.	Anthropogenic inputs, warm weather	fish kills		Gin et al., 2000
Unspecified	Johor Straits	Diatoms, *Trichodesmium* sp., *Gymnodimnium*-like species				Gin et al., 2000
1989	East Johor Straits	*Gymnodinium catenatum* and *Chattonella* sp.		caged fish kills		Gin et al., 2006
Dec. 2009	East Johor Straits	*Karenia* cf. *australe*	3.50 × 10 4 cells.L^{-1}	200,000 farmed fish mortalities		Leong et al., 2015; Trottet et al., 2018
March 2010	East Johor Straits	*Chattonella subsalsa*	> 500 cells.L^{-1}			Leong et al., 2015
Jan. 2011	Johor Straits	*Karenia mikimotoi*	> 200 cells.L^{-1}			Leong et al., 2015
Dec. 2011	East Johor Straits	*Prorocentrum* sp.; *Chattonella subsalsa*; *Heterosigma akashiwo*	dominant species *Prorocentrum* sp. > 2,500 cells.L^{-1}			Leong et al., 2015
2012	Lim Chu Kang (West Johor Straits)	*Chattonella subsalsa*	> 5,000 cells.L^{-1}	no associated fish kills		Leong et al., 2015
June 2013	Lim Chu Kang fish farm - North west of Singapore	Unidentified		90,000 kg farmed fish mortalities		Leong et al., 2015; Trottet et al., 2018
Feb. 2014	East (Punggol Marina) and West Johor Straits	*Gymnodinium* sp., *Karlodinium* cf. *veneficum*, *Takayama xiamenensis*	1.23 × 10 5 cells.L^{-1} at Raffles Marina (Tuas).	150,000 kg of farmed fish mortalities from 53 fish farms along the West Johor Straits		Leong et al., 2015
April 2014	East Johor Straits	*Karenia mikimotoi*	Patches of *Karenia mikimotoi*. > 5,000 cells.L^{-1}. First time such high cell densities were recorded for this species			Trottet et al., 2018
Feb - March 2015	West Johor Straits			700,000 kg of farmed fish mortalities = loss of SGD 1.3 million/farmer	Deployment of canvas bags to create a closed containment unit and emergency harvests saving market-sized fish stocks	AVA., 2016; Trottet et al., 2018
Dec 2016	East Johor Straits (shoreward of Lower Seletar Reservoir barrage)	Diatoms	1.52 × 10^{4} ± 652 cells.mL^{-1}			Kok & Leong, 2019
Dec 2016	East Johor Straits (seaward of Lower Seletar Reservoir barrage)	Diatoms	3.18 × 10^{4} ±3.37 × 10^{3} cells.mL^{-1}			Kok & Leong, 2019
Jan 2016	East Johor Straits (shoreward of Lower Seletar Reservoir barrage)	*Chattonella subsalsa* (86.2%), *Heterosigma akashiwo* (13.8%)	1.47 × 10^{4} ± 400 cells.mL^{-1}			Kok & Leong, 2019
Jan 2016	East Johor Straits (seaward of Lower Seletar Reservoir barrage)	*Chattonella subsalsa* *Karenia mikimotoi, Ansanella* sp.	142 ± 12 cells.mL^{-1} 1.25 × 10^{3} ± 25 cells.mL^{-1}			Kok & Leong, 2019
Feb 2016	East Johor Straits (shoreward of Lower Seletar Reservoir barrage)	*Karenia mikimotoi* (77.1%), *Ansanella* sp. (22.7%) , *Karlodinium* sp.	3.94 × 10^{3} ± 153 cells.mL^{-1} Patches of *Karenia mikimotoi.* > 8000 cells.L^{-1}. Highest cell			Kok & Leong, 2019

(*continued*)

Table 2. Continued.

Year	Location	Organisms	Causes and characteristics	Economic / environmental loss	Mitigation and management	Reference
			densities recorded for this species in Singapore			
Feb 2016	East Johor Straits (seaward of Lower Seletar Reservoir barrage)	*Lauderia* sp. , *Skeletonema* sp.	1.65×10^4 $\pm 1.71 \times 10^3$ cells.mL^{-1}			Kok & Leong, 2019
Oct 2017	East Johor Straits (at jetty near the causeway linking Singapore and Malaysia)	• *Heterosigma akashiwo* • *Skeletonema* sp., *Chaetoceros* sp • Major dinoflagellate species :*Gyrodinium* spp, *Protoperidinium* spp. Minor dinoflagellate species - *Scrippsiella* sp. , *Karlodinium* sp	• 110 ± 4 cells.mL^{-1} • $2.58 \times 104 \pm 824$ cells.mL^{-1} • 113 ± 14 cells.mL^{-1}			Kok & Leong, 2019
Oct 2017	East Johor Straits (at mouth opening into the Singapore Straits)	• *Heterosigma akashiwo* • *Skeletonema* sp., *Chaetoceros* sp • Major dinoflagellate species : *Gyrodinium* spp, *Protoperidinium* spp. Minor dinoflagellate species - *Scrippsiella* sp. , *Karlodinium* sp	• 442 ± 21 cells.mL^{-1} • $4.39 \times 103 \pm 371$ cells.mL^{-1} • 110 ± 8 cells.mL^{-1}			Kok & Leong, 2019
Nov 2017	East Johor Straits (at jetty near the causeway linking Singapore and Malaysia)	• Diatoms • Major dinoflagellate species : *Gyrodinium* spp, *Protoperidinium* spp. Minor dinoflagellate species - *Scrippsiella* sp. , *Karlodinium* sp	• 2.99×10^3 ± 304 cells.mL^{-1} • 124 ± 1 cells.mL^{-1}			Kok & Leong, 2019
Nov 2017	East Johor Straits (at mouth opening into the Singapore Straits	• Diatoms • Dinoflagellate	• $2.80 \times 103 \pm 28$ cells.mL^{-1} • 55 ± 5 cells.mL^{-1}			Kok & Leong, 2019
HONG KONG						
1976 – 2001	Tolo Harbor	Unidentified	semi enclosed and poorly flushed water body		Agriculture Fisheries and Conservation Department (AFCD) acts as a coordinator of Red Tide Reporting Network, to investigate and warn marine fish farmers of associated risks and employs appropriate measures to reduce loss. Since 1999, the government has established the Red Tide/HAB management framework and various action plans such as: i) Mariculture Action Plan by AFCD, ii) Algal Biotoxin Action Plan by Food and Environmental Hygiene Department (FEHD) and Department of Health (DH) and iii) Beach Action Plan by Leisure and Cultural Services Department (LCSD)	Lee et al., 2006; AFCD, 2020
1988	Kat O, Long Harbor, Tolo Harbor, Port Shelter and southern waters	Unidentified		major fish kills, fish culture zones in Tolo harbor affected with huge loss		Lee et al., 2006; AFCD, 2020
late 1997 - early 1999		*Phaeocystis globosa*		1,500 tonnes of farmed fish killed (50% of HK production in 1998)		Tang et al., 2003; AFCD, 2020
March 1998 - April 1998		Unidentified				Tang et al., 2003; AFCD, 2020
Nov. 1998		*Gymnodenium* cf *catenatum*				Tang et al., 2003; AFCD, 2020
Unspecified		*Karenia digitata*		3,400 tonnes of cultured fish stock (80%) - more than HKD 312 million		Wong et al., 2007; AFCD, 2020
Unspecified	Deep Bay in the west	Unidentified	nutrient inputs from heavily contaminated Shenzen river and Hong Kong			Lee et al., 2006; AFCD, 2020
Unspecified	Pearl river estuary	*Noctiluca scintillans, Skeletonema costatum, Chattonella marina, Rhizosolenia alata f. gracillima, Gonyaulax polygramma, Pseudonitzschia pungens, Thalassiosira subtilis, Scrippsiella trochoidea, Prorocentrum sigmoides, and Gymnodinium mikimotoi*	high concentrations of inorganic nitrogen, phosphate and turbidity. river discharge during dry season(summer) as the river plume is pushed seaward			Lee et al., 2006; AFCD, 2020

2015	Hong Kong waters	*Karenia mikimotoi*		Fish kill at Yim Tin Sai fish culture zone		EPD, 2016
Jan-Feb 2016	Tolo and Long Harbors	*Karenia mikimotoi, K. papilionacea*		Estimated loss of about 220 tonnes of cultured fish (mainly Sabah Grouper) at nine fish culture zones		EPD, 2017
SALALAH / OMAN						
Aug. 1976	Salalah (along the Salalagh coast between Taqah and Raysut)	Unidentified	first red tide in Oman	mass mortality of fish - estimated 7,000 to 10,000 tons		Thangaraja et al., 2007; Al-Azri et al., 2015; Burt et al., 2016
Oct. 1976	Muscat	*Gonyaulax* sp. and *Noctiluca* sp				Thangaraja et al., 2007; Al-Azri et al., 2015; Burt et al., 2016
Feb. – April 1988 (2 times)	Muscat,Sidab, Al-Bustan, Qantab	*Noctiluca scintillans*		Fish mortality (thousands of pelagic fish)		Al-Azri et al., 2015
Sept. 1988	From Seeb to Qurm along 30 km coastal stretch, Al-Ghubrah	*Ceratium fusus, C. macroceros* and many species of diatoms	Large blooms of diatoms caused first discoloration of the water. Low oxygen level was recorded (2.64 mg.L^{-1} and 1.87 mg.L^{-1}) at water depths of 2-3 meters and 8-10 meters respectively.	First major fish kill in the Gulf of Oman. 3 to 5 tons of dead fish were strewn all along the Al-Ghubra beach.	The regular monitoring of phytoplankton blooms and red tide phenomena in Omani waters were initiated after this fish kill	Al-Azri et al., 2015
Feb. – Apr. 1989 (3 times)	Qurum to Qantab	*Noctiluca scintillans*		Fish mortality		Thangaraja et al., 2007
April 1989	Al-Ghubrah	*Rhizosolenia* sp.				
September 1989	Al-Ghubrah	*Pleurosigma* sp., *Ceratium* spp.		Mortality of marine organisms		
March and May 1990	Al- Bustan, Mattrah (March) Sidab-Al, Bustan (May)	*Noctiluca scintillans, Ceratium furca, C. macroceros*, *Prorocentrum micans*, *Pyrophacus horologicum*, *Peridinium* sp.				
January 1990	Musandam	*Noctiluca scintillans*				
September 1990	Al-Ghubrah	*Rhizosolenia* sp., *Pleurosigma* sp., *Nitzchia* sp., *Coscinodiscus* sp., *Fragilaria* sp., *Triceratium* sp., *Chaetoceros* sp., *Ceratium* spp.				
Aug. – Sept. 1991	Muscat	*Coscinodiscus marginatus*, *Asteromptelus* sp., *Chaetoceros* sp., *Rhizosolenia* sp., *Ceratium* spp.				
March - April 1992	Al-Ghubrah and Al-Bustan	*Noctiluca scintillans*				
April 1992	Musandam (Dibba)	*Noctiluca scintillans*				
June 1992	Musandam (Khasab)	*Trichodesmium* sp.				
April 1993	Muscat, Sidab, Al-Bustan & Qantab	*Noctiluca scintillans*		Fish		
September 1993	Mina Sultan Qaboos port	*Gonyaulax* sp.		Fish mortality (2-3 tonnes)		
September 1993	Al-Bustan, Sidab	*Trichodesmium* sp.				
October 1993	Barka (Gulf of Oman)	*Dinophysis* spp., *Ceratium* spp.		Fish mortality		
Aug. and Nov. 1993	Raysut	Diatoms and Dinoflagellates		Fish mortality		
March, April and July 1994	Muscat, Qantab, Al-Bustan	*Noctiluca scintillans*				
March 1994	Bimmah	*Noctiluca scintillans*				Thangaraja et al., 2007
September 1994	Bandar Khairan	*Noctiluca scintillans*				
August 1994	Mina Sultan Qaboos port/ Muttrah, Muscat	*Gonyaulax* sp.		Fish mortality (50 kg)		

(*continued*)

Table 2. Continued.

Year	Location	Organisms	Causes and characteristics	Economic / environmental loss	Mitigation and management	Reference
January 1995	Kalbu	*Trichodesmium* sp.				
April 1995	Muscat, Sidab, Al-Bustan	*Noctiluca scintillans*				
Feb. – April 1996						
Jan. and Feb. 1997						
February 1997	Muscat – Sur (about 300.km.)	*Noctiluca scintillans*				
April 1997	Al-Bustan, Sidab	*Noctiluca scintillans*				
Aug. and Sept. 1999	Al-Bustan, Muscat, Al-Ghubrah	*Noctiluca scintillans* (Green tide)				
September 2000	Barka	*Coscinodiscus apiculatus*, *C. perforatus*, *C. janischii*, *C. gigas* and *C. jonesianus*	Depletion of dissolved oxygen.	Second major fish kills recorded in the Gulf of Oman		
Aug. and Sept. 2000	Sidab and Bustan coast	*Gonyalaux* sp./red tide				
August 2001		*Gonayalaux diegensis*/ red tide bloom				
November -December 2001	Arabian Sea	*Karenia selliformis, Prorocentrum micans, P. minimum*		Fish, turtles, dolphins and bird mortalities. 27 tons of fish were found floating near the coast of Batinah, Sur and South Oman		
April 2004	Coast of Duqm			100 tonnes of sardines		Piontkovski et al., 2012
October 2005	East of Masirah Island	*Noctiluca scintillans, Prorocentrum micans, Trichodesmium erythraeum*	Mortalities coincided with warmer surface temperatures, upwelling	Dead and weakened fish and invertebrates observed on or near the surface of the water and along the tide line on the shore. Large numbers of swimming crabs (Portunidae) observed on surface.		Busaidi et al., 2008
September 2006	Bay of Bandar Khayran	*Leptocylindrus minimus, Pseudo-nitzschia delicatissima* and *pungens*	abundances of 64 × 10 3 cells.L^{-1}, 51 × 10 3 cells.L^{-1} and 47 × 10 3 cells.L^{-1} respectively			Al-Azri et al., 2015
2006 and 2007	Bay of Bandar Khayran	*Dinophysis caudata* and *Gonyaulax spinifera*	higher abundances at 10 m			Al-Azri et al., 2015
late SWM and early NEM of 2008	Bay of Bandar Khayran	*Ceratium fusus*	more abundant at the surface			Al-Azri et al., 2015
Oct. - Dec. 2008	from the North West of the Gulf of Oman reaching the Bay of Bandar Khayran and extended to the south past Muscat and several hundred km into the Persian Gulf past the Musandam peninsula	*Cochlodinium polykrikoides*	Large fluctuations observed in dinoflagellate abundances ranging from 214 cells.L^{-1} to 16 × 10^3 cells.L^{-1} and up to 200 × 10^3 cells.L^{-1}. Chlorophyll levels were at a high of 78.0 μg/L. Bloom influenced by an elevated nutrient load, warmer than normal temperatures and provoked hypoxia. The bloom lasted for 10 months covering about 86,462 Km^2 across the Arabian region.	200 tons of fish, including 70 tons of caged fish, 70 tons of shellfish, and 60 tons of wild fish. Closure of desalination plants due to clogging at the intake resulting in serious disruption of the potable water supply, closure of refineries, electric power stations and tourist sites. Schools closed in the Muscat region due to intense odors (methyl sulfide compounds) and cancelation of beach hotel bookings.		Richlen et al., 2010; Berktay, 2011; Al-Azri et al., 2012; Al Shehhi et al., 2014; Al-Azri et al., 2015; Burt et al., 2016

2006 – 2010	Bay of Bandar Khayran	*Prorocentrum minimum* and *Scrippsiella trochoidea*	abundances of these species were significantly higher during SWM (August–September). *Prorocentrum minimum* reached 14×10^3 cells.L^{-1} . *Scrippsiella trochoidea* reached 13×10^3 cells.L^{-1}.			Al-Azri et al., 2015
Fall and early winters 2006-2011 (except 2008 and 2009 during *C. polykrikoides* bloom)	Sea of Oman and Arabian Sea	*Noctiluca scintillans*	cell concentrations are higher during NE and SW monsoons. Moderate rain fall, wind velocity and direction, advection of water masses or even the allelopathic properties of *C. polykrikoides* enhance *N. scintillans* blooms			Al-Azri et al., 2015
CAPE TOWN AREA						
1994	Saint Helena Bay	*Alexandrium catenella* and other toxic species		Death of estimated 60 tonnes of the West Coast rock lobster *Jasus lalandii* (Milne Edwards), and 1,500 tonnes of fish, mainly the southern mullet, *Liza richardsonii* (Smith)		Branch et al., 2013
January and May every year	Along the west coast	Commonly dominated by Dinophyceae, but also Bacillariophyceae, Raphidophyceae, Pelagophyceae, Haptophyceae, Euglenophyceae		Vary yearly		Branch et al., 2013
VALENCIA						
1983	Balearic-Catalan Sea	*Alexandrium catenella*				Penna et al., 2005
1990	Mediterranean coast(Valencia)	*Gymnodinium catenatum*	1.6×10 6 cells.L^{-1}			Vila et al., 2001
1994	Valencia harbor	*Alexandrium catenella*	abundance of 1.0×10 4 cells.L^{-1}			Penna et al., 2005
1998 and 1999	100 km of the Catalan coastline of Spain	*Alexandrium catenella*				Penna et al., 2005
end of March-beginning of April 2014		*Prorocentrum cordata*	10 3 cells.L^{-1}			ICES, 2017
2014 – 2016	harbor of Valencia	*Karlodinium* sp	10 3 cells.L^{-1}			ICES, 2017
April and May 2016 2015 and 2016	harbor of Valencia	*Ostreopsis* sp	3.9×10 3 cells.L^{-1}and 2.9×10 3 cells.L^{-1}			ICES, 2017
June 2015 and May 2016	Valencia	*Pseudo-nitzschia* sp.	3×10 5 cells.L^{-1}			ICES, 2017
May 2016		*Dinophysis sacculus*	1.4×10 3 cells.L^{-1}			ICES, 2017
Jan. and June 2016	Alicante	*Pseudo-nitzschia* sp.				ICES, 2017
Annual/Seasonal	North Balearic front	Unidentified	late-winter/early-spring bloom lasting for more than three months			Garcés & Camp, 2012
ROTTERDAM						
2001	Originated in the Voordelta offshore (between South	*Phaeocystis globusa*	millions of cells.L^{-1}and high amounts of chlorophyll-*a* provoke hypoxia	Economic damage to commercial shellfish industry in the south eastern part of the North Sea	Enumeration of phytoplankton cells from samples collected from	Van der Woerd et al., 2006

(*continued*)

Table 2. Continued.

Year	Location	Organisms	Causes and characteristics	Economic / environmental loss	Mitigation and management	Reference
	Holland and Zeeland) then transported to shore				monitoring, remote sensing suggested as a monitoring measure.	
2003	Voordelta, originated in the Oosterschelde estuary which is an area of intense mussel cultivation	*Phaeocystis globusa*	> 10 million cells.L^{-1}, chlorophyll-*a* exceeding 40 $\mu g.L^{-1}$.	No mussel mortality. Unclear why the bloom in 2001 caused mass mussel mortality whereas the bloom in 2003 did not, although observed *Phaeocystis* sp. concentrations did not differ much.	The Dutch Ministry of Transport and Public Works has maintained a continuous monitoring in both fresh and marine waters for suspended matter, chlorophyll-*a* and phytoplankton species composition. Combination of remote sensing and computer models to produce timely and accurate information of HABs in the coastal areas of the southern North Sea.	Van der Woerd et al., 2006
Annual basis	South Bight of the North Sea	*Phaeocystis globosa*	summer and winter blooms			Peperzak, 2003
Annual basis	Dutch coastal zone	*Dinophysis acuminata, Prorocentrum minimum, Pseudonitzschia multiseries, Fibrocapsa japonica, Chattonella marina, C. antiqua* and *Phaeocyctis globosa*	high temperatures, salinity stratification and irradiance in late spring or summer			Peperzak, 2003
TAMPA BAY						
2005-2006	South West of Florida	The bloom persisted for 17 months			Florida Fish and Wildlife (FWC) Conservation Commission has implemented HAB monitoring and fish kills report accessible online	Maze et al., 2015; fwc.com
2012-2013	South West of Florida		Brevetoxin detected	Death of hundreds of manatees and other marine life		Maze et al., 2015; fwc.com
Nov. 2015 - April 2016	Charlotte Harbor and Tampa Bay region	*Karenia brevis*		Charlotte Harbor region being closed almost 40% of that time period, while harvest in Tampa Bay region was closed almost 80% of the time. Loss of USD 3.25 million dollars		Adams, 2017; fwc.com
Nov. 2017 - Jan. 2019	Tampa Bay region	*Karenia brevis*	The bloom happened two months after Hurricane Irma: could be related to release of water from Florida's Lake Okeechobee to prevent flooding, fertilizer-rich waters flowed to the ocean and helped fuel the current bloom	USD 90 million dollars in tourism losses		Resnick, 2018; fwc.com
VANCOUVER AREA						
late 1980s and 1990s	Vancouver region	*Heterosigma akashiwo* and *Chaetoceros* spp.	physical damage or irritation of gill tissues, reaction to ichthyotoxic agents or hypoxia from oxygen depletion	Salmon farms in BC and Washington State lost in excess of USD 35 million	Harmful Algae Monitoring Program (HAMP) began in 1999, sampling around Vancouver Island and in the BC Central Coast. Weekly analysis for harmful species identification and count, consultation with salmon aquaculture industry when HAB or fish kills occur, training farm staff in phytoplankton identification	Haigh and Ensenkulova, 2014
1999	Vancouver region	*Cochlodinium* sp.		approximately CAD 2 million losses		
2009 – 2012	British Columbia (BC)	*Heterosigma akashiwo, Chattonella* cf. *marina, C. convolutus*, and *Chaetoceros concavicornis*		direct losses to BC salmon aquaculture from HABs exceeded CAD 16 million.		

July-Aug 2011	Strait of Georgia (BC)	Dinoflagellates (i.e. *Dinophysis* spp., *Prorocentrum* spp.)	Diarrhetic Shellfish Poisoning (DSP) due to consumption of cooked mussels	62 clinical cases, closure of harvest-zones	Canadian Shellfish Sanitation Program (CSSP) leaded by Canadian Food Inspection Agency	Taylor et al., 2013
2014	Marsh, Port Hardy	*Heterosigma akashiwo* bloom		280,000 dead salmons		Towers, 2015
2018	Vancouver region	*Heterosigma akashiwo* bloom	gills irritation	250,000 dead fish (1,000 tonnes) in two salmon fish farms estimated to CAD 4 million loss		Robinson, 2018
SYDNEY						
Unspecified	South Eastern Region	*Alexandrium* spp.			Monitoring programs are implemented by each state (NSW Shellfish Program includes Sydney)	Farrell et al., 2013; Ajani et al.,2013
2010	South Eastern Region	*Alexandrium* sp.				Farrell et al., 2013; Ajani et al.,2013
Unspecified	coasts and estuaries in South eastern Australia	Unidentified		Mortalities of large numbers of finfish, mollusks and crustaceans	The Marine Biotoxin Management Plan outlines "Phytoplankton Action Limits" (PALs) whereby additional shellfish flesh testing and/or harvest zone closures are initiated based on cell concentrations of potentially harmful algae. The minimum PAL for *Alexandrium* spp. is 200 cells.L^{-1}	Murray et al., 2015
2011	Jervis Bay, South eastern Australia	*Karlodinium veneficum*		fish kills		Murray et al., 2015
2012	Coastal lagoon, Sydney	*Amphidinium cartarae*				Murray et al., 2015

2006; Schmoker et al., 2014). For example, the Aquaculture Innovation Center (AIC) was established in June 2019 in collaboration with eight partners including tertiary institutes (Temasek Polytechnic and other polytechnics, the National University of Singapore (NUS)), governmental agencies (SFA), Agency for Science Technology and Research (A*STAR) and fish farms to work together aiming to increase the local seafood production through high tech urban marine farming focusing on nutrition, disease management and breeding of super fish (Begum, 2019). Other methods that Singapore has adopted are to increase contract farming agreements for seafood as well as increase the number of open water and land-based aquaculture farms (Teng & Escaler, 2010).

One of the most important factors that determines successful and large-scale aquaculture practices rely on good water quality with minimal pollution and a good balance in nutrient levels. The rapid coastal developments over the past 50 years such as port activities, land reclamation, oil refineries, desalination and waste treatment plants, aquaculture and other industries have affected the water quality causing it to be eutrophic in the Straits of Johor and oligo-to-mesotrophic in the Straits of Singapore (Chénard et al., 2019; Gin et al., 2000, 2006; Kok & Leong, 2019). Such anthropogenic activities have triggered HABs in Singapore causing massive fish kills and tremendous economic losses as described in Table 2.

Singapore's dependency is in not limited to food solely but also on water supply. To date 60% of Singapore's daily water requirements is met with the water import contract with Malaysia, which expires in 2061 (Leidinger & Hustiak, 2019). To increase water self-sufficiency, on-going developments of desalination plants is estimated to provide 30% of the drinking water by 2060 (Leidinger & Hustiak, 2019). The treated effluents from these plants are discharged into Singapore waters following regulations where it is diluted and dispersed (Gin et al., 2006). These additional nutrient loading can potentially exacerbate the issue of eutrophication and of HABs.

The occurrences of HABs may also be caused by the introduction of invasive species from ballast tank discharges from ships called to Singapore ports. Ballast water may include dinoflagellate species such as *Gymnodinium catenatum* and *Karlodinium* sp. in the form of resting stages that had never been previously described to be native to the region (Chan et al., 2006; Gin et al., 2006; Trottet et al., 2018). Furthermore, there is evidence of the presence of the resting stages/cysts in the sediments of the Johor Straits which can occasionally be resuspended resulting in HABs (Trottet et al., 2018). The frequency and extent of sediment re-suspension has increased due to the intense ship traffic and associated propeller wash in the region (Liao et al., 2015).

Most of the HABs occurring along the Johor Straits have caused hypoxia and massive kills of marine organisms during bloom decay as described in Table 2 (Gin et al., 2006). Apart from the issues caused by HABs, a study commissioned by SFA had shown that the farms in Johor Straits have almost reached their carrying capacity (Tan, 2020). Therefore, SFA is considering the development of more aquaculture zones in the Singapore Straits to ramp up and meet Singapore's food production target by 2030 (Tan, 2020).

Despite the maritime activity, Singapore Straits has the potential to support further aquaculture developments (Chou, 2006). Unlike the Johor Straits, only one fish farm is operating at present in the Singapore Straits (Tan, 2020). These waters are teeming with high biodiversity in marine life, good hydrodynamic factors enabling good water exchange and flushing (Chou, 2006). Although HAB species can be found in the Singapore Straits, the strong mixing of these waters seems to inhibit the establishment of HAB blooms (Chan et al., 2006; Gin et al., 2006; Tan, 2020). However, the planned expansion of farming in the area requires additional understanding of the ecosystem including the fluctuation in algal cell densities, the flushing and/or potential presence of resting stages all of which are crucial for proper site selection for aquaculture (Trottet et al., 2018).

Water quality parameters of Singapore waters are routinely monitored by the National Environment Agency (NEA) using real time systems and field monitoring to collect key physical, chemical and microbiological parameters (NEA, 2020). Specific water quality monitoring of coastal fish farms is conducted by SFA. This data can be accessed online by farmers and a 'color-coded SMS' alert system provides timely warning to farmers on plankton levels which can help them to activate timely mitigation strategies (AVA, 2016). An Inter-Agency Bloom Working Group and Inter-Agency Management Framework was established by AVA for monitoring, provision of timely updates and management of HABs (AVA, 2016). However, limited time series records contributing to baseline plankton data are available (Schmoker et al., 2014; Trottet et al., 2018). The lack of information on phytoplankton species identity, many of which are yet to be properly identified and characterized, is particularly worrying in view of the upcoming aquaculture developments planned by Singapore (Trottet et al., 2018).

To circumvent risks associated with fluctuating water quality affecting the open-net cage farms, SFA encourages farms to adopt the use of technology such as closed containment systems/recirculating aquaculture systems (RAS). Such technologies have been proposed as sustainable technologies by SFA which provide a controlled environment for growth, enable automation of processes enabling better deployment of manpower and mitigate the impacts of farming on the environment (SFA, 2020).

Currently, RAS is being operated by Apollo Aquaculture on floating structures in the Straits of Johor by Aquaculture Center of Excellence (ACE) and Singapore Aquaculture Technologies (SAT) (Ludher & Paramasilvam, 2018; AVA, 2019). Farmers can apply for the Agriculture Productivity Fund (APF) administered by SFA to improve or adopt new technologies which contribute to sustainable aquaculture (SFA, 2020).

Comparative case studies in aquaculture practices and associated issues of HABs from around the world

Hong Kong - SAR China

The Hong Kong Special Administrative Region (HKSAR) has a sea area of 1,648 km for a coastline which is 1,197 km long. Excluding Hong Kong Island and Lantau Island, there are 261 islands in the territory (EPD, 2019). Hong Kong is a highly developed territory and has become one of the most significant commercial ports of the world (Table 1, Figures 2 and 3). Hong Kong is located at the south east corners of the Pearl River Estuary (PRE), which for the last 30 years has received a very high load of anthropogenic nutrients due to rapid industrial developments, agricultural activities and urbanization (Lu & Gan, 2015).

In Hong Kong, seafood consumption has reached approximately 70 kg per capita in 2017 which is four times the global average of 18.9 kg (FAO, 2020a). Even if local seafood production from aquaculture does not meet the local demand, and therefore most products must be directly imported from China, aquaculture does still exist in Hong Kong and is characterized by a diverse production of fish in marine water (high value), ponds (main contributor by volume), but also oyster production (Table 1). The marine fish farming is mostly comprised of small size farms (294 m^2) and is located from Tolo Harbor on eastern side, to Lamma Island in the south to Lantau Island in the west (AFCD, 2020).

Due to the high nutrient loads and organic wastewater discharges from the PRE and local sewage discharges, the coastal waters in Hong Kong experience frequent HAB events (Wong et al., 2009; Yin et al., 2000). The most common species encountered during phytoplankton blooms in Hong Kong waters is *Noctiluca scintillans* which accounts for 31% of reported events between 1980 and 2015 (EPD, 2016). Algae bloom events have been associated with seasonal variations and physical processes, with HABs being observed more often during the winter- spring period when downwelling allows phytoplankton biomass to increase (Xu et al., 2010). In summer, rainfalls generate runoff events which reduce water residence times and thus decrease phytoplankton concentration in more enclosed areas (i.e. bays, harbors) (EPD, 2019; Xu et al., 2010). Geographically, data analyses have shown that events occurred more frequently in the eastern and southern waters of Hong Kong and these events reached peaks in 1988 with 88 incidents reported to reduce to 8-45 events per year (EPD, 2016). The Environmental Protection Department (EPD) has implemented a marine water quality monitoring program since 1986 to i) evaluate the state of marine waters, ii) monitor long term change of water quality, iii) provide proper scientific data for planning water pollution strategies (EPD, 2019). This monthly monitoring includes traditional physico-chemical water quality analyses, sediment quality and phytoplankton sampling. In the late 1990s, sewage management strategies were implemented for sewage reduction by the government, which was successful in the case of Tolo Harbor where a reduction of 90% in sewage loading has resulted in significant decrease of inorganic nutrient loads directly reducing eutrophication (Xu et al., 2010).

The EPD monitoring is associated with additional monitoring by Agriculture Fisheries and Conservation Department (AFCD) which leads HAB management framework and action plans (Table 1). Additional to regular water quality monitoring, AFCD has put into place a specific real time online water quality monitoring at 13 fish culture zones for early detection of changes and issuance of alerts to mariculturists which is accessible online[1]. Regular phytoplankton monitoring is also put into place in all fish culture zones with increased monitoring frequency when harmful species or high density of phytoplankton is observed to inform and alert farmers if needed and weekly updates on algae bloom events made accessible online on AFCD website[2].

Salalah (Oman)

Situated in the Middle East, the coast of Oman is a shallow continental shelf, surrounded by the Straits of Hormuz in the North, Gulf of Oman in the North-East and the western Arabian Sea in the South (Al Shehhi et al., 2014) (Table 1, Figures 2 and 3). The western Arabian Sea connects to the Gulf of Oman at the frontal zone of Ras Al Hadd and the Gulf borders the coast of Iran and Pakistan in the north, (Al Shehhi et al., 2014; Harrison et al., 2017). The water basins along the coastline of Oman are crucial shipping and trade routes for exports of crude oil and others with high oil tanker traffic (Al Shehhi et al., 2014). Oman experiences two monsoon cycles namely the South-West (SW) summer monsoon from June to September, contributing 70-90% of annual rainfall, and the North-East (NE) winter monsoon from November to March (Al Shehhi et al., 2014).

[1]http://202.74.40.143/~afcdxyle/main_en.php

[2]https://www.afcd.gov.hk/english/fisheries/hkredtide/update/redtide_cur_week.html

Moreover, frequent sandstorms during the intermonsoon period from May to July bring in dust deposition of iron (Al Shehhi et al., 2014).

The distribution of nutrients in the coastal waters of Oman are governed mainly by seasonal monsoon dynamics especially the SW monsoon, when dust deposition of iron from the sandstorms and upwelling, increase the input of limiting nutrients and thereby favoring biological productivity (Al Shehhi et al., 2014; Harrison et al., 2017; Piontkovski et al., 2012; Zhao et al., 2015). This characteristic along with the shallow continental shelf enabling cold water access for land-based aquaculture and its proximity to bigger seafood markets (United Arab Emirates, India and South Africa) make Oman an ideal place for aquaculture development (Lund, 2019).

Oman intends to develop its fisheries and aquaculture industry to be one of the five main economic pillars through the Fisheries and Aquaculture Vision 2040 (Vision 2040) targeting to produce 220,000 tons of fish per year (USD 500-900 million) and creating 11,000 jobs (Lund, 2019). Currently products from the 23 aquaculture farms in Oman as detailed in Table 1 sustain the local seafood markets (Lund, 2019). According to Vision 2040, The Oman Aquaculture Development Company (ODAC) channels resources for foreign investments and expertise to secure growth (Lund, 2019). Thus, the Ministry of Agriculture and Fisheries (MAF) have streamlined seven zones spanning the entire coastline of Oman as potential aquaculture sites for various species such as abalone, shellfish and seaweed (Lund, 2019). The development of the aquaculture sector in Oman has spurred international collaborations bringing together local and international expertise in various fields. For example, the MAF and the UK Center for Environment Fisheries & Aquaculture Science (CEFAS) have been working on guidelines for aquaculture health and disease management (Lund, 2019).

Seasonal changes and increased anthropogenic inputs due to ongoing coastal developments has led to increased nutrient loadings causing higher frequency, intensity and expansion of HABs caused by diatoms and dinoflagellates in the Gulf of Oman and the Arabian Sea in the last few decades as described in Table 2 (Al Shehhi et al., 2014; Al-Azri et al., 2015).

Seasons play an important role in the distribution of nutrients, the NE monsoon is known to cause more HABs than the SW monsoon due to its strong winter convective mixing (i.e. *Notiluca scintillans* as in Table 2) (Al Shehhi et al., 2014). The SW monsoons are known to cause dinoflagellate and cyanobacteria specific HABs in the Arabian Sea due to strong winds which cause the water to mix leading to high nutrient enrichments, strong upwelling along the coastal margins in the south of Oman, higher sea temperatures and river discharges (i.e. October 2005 in Table 2) (Al Shehhi et al., 2014; Al-Azri et al., 2012; Burt et al., 2016; Busaidi et al., 2008).

Apart from transporting nutrients, currents in the Straits of Hormuz, Gulf of Oman and Arabian Sea also cause the natural dispersion of HAB species making the entire basin highly susceptible to blooms (Al Shehhi et al., 2014). A good example of this dispersion was observed in 2008 when the *Cochlodinium polykrikoides* bloom, firstly observed in the NW Gulf of Oman in late October, extended its geographical impacts throughout the entire Gulf of Oman and Arabian sea by early December aided by eddies (Al Shehhi et al., 2014; Al-Azri et al., 2014; Zhao et al., 2015).

Huge amounts of fish-kills and closures of desalination plants were the notable economic impacts reported in Oman due to HABs as detailed in Table 2 (Al Shehhi et al., 2014). Desalination plants are extremely crucial in the arid Arabian region as it is an important source of drinking water accounting for 90% of potable water (Zhao et al., 2015). The presence of HABs clogs the intake filters, cause bio-fouling of the sensitive reverse osmosis membranes compromising the quality of desalinated water due to its inability to remove toxins, eventually causing them to shut down for expensive repairs resulting in a shortage of drinking water and electricity shutdowns as seen during the *Cochlodinium* sp. bloom in March 2009 (Al Shehhi et al., 2014; Al-Azri et al., 2014, 2015; Richlen et al., 2010; Zhao et al., 2015).

The Arabian Seas with high shipping traffic are also affected by oil spills, bio-invasion through ballast water, ship hulks and other forms of pollution (Al Shehhi et al., 2014; Al-Azri et al., 2015). Thus, some HAB species detected in the Gulf of Oman and Arabian Sea manifest a shift in their regular geographic distribution suggesting their global expansion such as the *Cochlodinium polykrikoides* bloom occurring for the very first time in Oman in 2008 (Al-Azri et al., 2015; Zhao et al., 2015).

There is a lack of baseline plankton composition and abundance data in the coastal waters of Oman (Al-Azri et al., 2015; Thangaraja et al., 2007). Satellite image monitoring such as MERIS fluorescence data accurately detected the *Cochlodinium polykirkoides* bloom in 2008, providing species-specific signatures and enabling it to be distinguished from other species in the region despite environmental disturbances (Zhao et al., 2015).

Cape Town – South Africa

Located on the southwestern side of South Africa, Cape Town is the second most populated city in South Africa after Johannesburg, having more than 60% of the population of the Western Cape province (Table 1, Figures 2 and 3). Cape Town shore which is part of Table Bay is one of the richest fisheries zone in the world as it is influenced by the Benguela current, a cold body of water moving up the western coastline of southern Africa bringing accumulated nutrients from the sea floor, which when coupled with sunlight provides massive phytoplankton blooms sustaining fisheries (Branch et al., 2013; Pitcher et al., 1998; Pitcher & Greville, 2006).

The aquaculture sector in South Africa is largely dominated by mariculture and is expected to increase continuously within the next 10 years (Britz & Venter, 2016). This is part of South Africa's National Development Plan and Vision 2030, as a sector with high growth potential to alleviating poverty, unemployment and inequality through enhanced food security (Hayes, 2013). For aquaculture, the governmental actions included both regulations and financial support since 2013. The Government has adopted a unified National Aquaculture Policy Framework and launched an Aquaculture Development Enhancement Programme providing 45 million USD to support farmers to buy equipment and increase job creation (Hayes, 2013, GCIS, 2013). A first edition of the legal guide for the aquaculture sector in South Africa was instituted by the Department of Agriculture, Forestry and Fisheries (DAFF). Although the marine sub-sector operates less than 50 farms, compared to almost 200 freshwater operations, it accounts for approximately two-thirds of production volume and more than 80% of value, mainly due to the contribution of the well-established, high-value abalone sub-sector (Britz & Venter, 2016) with productions expected to further increase by 61.8% from 2018 to 2030 (FAO, 2020a).

Algal blooms commonly occur along the South African west coast and have been recorded since March 1994, when a dense bloom developed due to upwelling and causing fish kills at times (Branch et al., 2013, Table 2). Although no proper HAB monitoring strategies have been implemented in the country, the use of satellite imagery has enabled the detection of HAB events which persisted from March to June 2017 off the western South African' coast in the southern Benguela current (Ever-King et al., 2020). Additionally, the South National Biodiversity Institute (SANBI) has established the first comprehensive National Biosystematics Research Strategy that deliberately emphasizes the research component of taxonomy for multiple organisms including algae and archaea between 2013 and 2018, promoting taxonomic research throughout South Africa (Victor et al., 2013).

Valencia -Spain

Valencia, the third largest city in Spain, borders the North Western (NW) Mediterranean Sea which is a semi-enclosed body of water connecting to the Atlantic Ocean through the Gibraltar Straits (Table 1, Figures 2 and 3) (Dove, 2011; Penna et al., 2005). The increasing number of ports, harbors, housing, paved roads, tourism and recreational activities along the coast of Valencia have led to eutrophication in the western Mediterranean basin and specifically in the Gulf of Valencia, transforming it from one of the most oligotrophic basins' in the world to one becoming increasingly eutrophic (Gadea et al., 2013; Garcés & Camp, 2012).

This region has recently secured significant growth in the aquaculture sector, farming a variety of seafood species, enabling more investments and providing opportunities for employment (Table 1) (Dove, 2011). The quality of Valencia's waters allows for cultivation of diverse species (Dove, 2011; Ministry of Environmental Rural and Marine Affairs, 2011). The quality of the production and the growth of the sector is considered exceptional compared to other Spanish cities and is expected to supply the local and international markets by reducing dependency on imported seafood from France (Dove, 2011; Ministry of Environmental Rural and Marine Affairs, 2011; Towers, 2015). This growth has been supported by a large range of public and private institutions. The Funds for the Regulation and Market Organization of Fishery and Aquaculture Products (FROM), the National Food and Agriculture Research and technology Institute (INIA) and the Spanish Aquaculture Observatory (OESA) works directly with the Ministry of Agriculture, Fisheries and Food for the promotion of aquaculture products within local markets and conducts research related to pathology and the development of the aquaculture sector in Spain (FAO, 2017a). Such impressive growth in the aquaculture industry in Valencia and other Spanish cities has made Spain one of the top Member State of the European Union in terms of aquaculture production (Towers, 2015).

However, increasing frequency and intensity of HABs in the past 50 years have been recorded in the North Western (NW) Mediterranean basin, including the Gulf of Valencia (Table 2; Penna et al., 2005; Gadea et al., 2013). Records of HAB events have since expanded along the Spanish coastlines and include paralytic shellfish poisoning (PSP) dinoflagellate *Alexandrium catenella* (Garcés & Camp, 2012; Penna et al., 2005). Ballast water exchange without use of ballast water treatment systems has been considered the vector of *A. catenella* spread in the Mediterranean Basin from its natural habitat in the Western Pacific Ocean (Penna et al., 2005). Although the shipping industry is crucial for trade including that of aquaculture products, it "poses biosecurity risks for the aquaculture" industry through the introduction of invasive species which could cause potential HAB outbreaks, impairing food security measures and human health (Drillet et al., 2018).

In addition to anthropogenic influences, seasonal dinoflagellate spring blooms in the neighboring waters challenge the operations of many aquaculture farms warranting stricter monitoring (Gadea et al., 2013; Garcés & Camp, 2012; ICES, 2017). The National Advisory Board for Marine Aquaculture (JACUMAR), the official institute involved in the mitigation of HABs, has ordered a number of farm closures during HAB outbreaks causing massive economic losses (FAO, 2017a; ICES, 2017).

Rotterdam – The Netherlands

The Netherlands is a densely populated country in western Europe and despite its lack of natural resources, it is one of the largest exporters of agricultural products in the world (Viviano, 2017). As a result, the port of Rotterdam has grown to become the largest port in Western Europe (Table 1, Figures 2 and 3) (Port of Rotterdam, 2019). Rotterdam is in proximity to the Province of Zeeland located in the southern Dutch coastal zone which is bordered by the southern North Sea (Van der Woerd et al., 2006). The southern North Sea is maintained in a eutrophic state by river discharges from the Nieuwe Waterweg of Rotterdam harbor, the Rhine, Meuse, other small rivers and fish farms (Van der Woerd et al., 2006).

Although the aquaculture industry does not contribute significantly to the Dutch economy, the shellfish industry is economically more significant than finfish, with almost 60-70% of production being exported (FAO, 2017b). The aquaculture industry is expected to grow given the increasing demand for fish products and increasing awareness on the benefits of fish consumption both locally and internationally as well as generating more employment and income (FAO, 2017b).

Shellfish cultivation is mainly practiced as bottom cultures in the estuaries in the Southwest Province of Zeeland and in the shallow Wadden Sea bordering the northern part of The Netherlands, representing an intense loading of nutrients into the southern North Sea and impacting water quality (FAO, 2017b). In the past century, intense anthropogenic activities in the region have created eutrophication issues in turn increasing the frequency and intensity of high biomass phytoplankton blooms as well as toxin producing HABs in spring and in summer as detailed in Table 2 (Peperzak, 2003; Van der Woerd et al., 2006). Annual spring blooms, that develop offshore and move near shore to sites of shellfish cultivation, are known to cause massive economic loss to the shellfish industry (Van der Woerd et al., 2006).

Monitoring systems have been implemented by the Dutch Ministry of Transport and Public Works and includes measurements of chemical and biological parameters in marine and freshwater systems since 1970 (Van der Woerd et al., 2006). The Netherlands have also implemented an early warning system that uses remote-sensing satellite imagery (MERIS - MEdium Resolution Imaging Spectrometer) to detect elevated chlorophyll-a levels as a proxy for high biomass HABs. This early implementation was proven to be successful in detecting offshore high biomass blooms (FAO, 2017b; Van der Woerd et al., 2006).

The Dutch aquaculture industry has evaluated the applicability of heated RAS and vertical farming to produce more tropical species but this was seen as an economical challenge due to its increased investment and operating costs; therefore funds were allocated to support alternative production strategies (FAO, 2017b). A national and provincial government funded initiative to test out alternative breeding grounds such as outdoor basins and ponds to the costly RAS commenced in 2007 to support farmers (FAO, 2009).

Tampa - USA

Tampa Bay, which consists of seven major water bodies, is Florida's largest open water estuary on the Gulf of Mexico coast extending over 1,000 km^2 characterized by subtropical climate providing heavy rainfall between June and September (Table 1, Figures 2 and 3) (Sherwood et al., 2016; Wang et al., 1999). For the past century the coast of Tampa Bay has undergone drastic modifications associated with urbanization and, to a lower extent, agriculture and phosphate mining that have affected its hydrology and water quality (Sherwood et al., 2016). Port development and shipping activities have also been established since the 1880s and today Tampa Bay ranks among the U.S.'s most productive ports (Sherwood et al., 2016; Table 1).

Although aquaculture is a relatively modest sector in the USA in terms of production, the nation supplies a variety of advanced technologies, feed, equipment and investment capital to other producers around the world (NOAA Fisheries, 2020). Aquaculture production in Tampa Bay is dominated economically by both oysters and clams, representing 80% of the production values in 2017, followed by salmon, mussels and shrimps (National Marine Fisheries Service, 2020). Florida, by its subtropical climate, extensive marine and freshwater resources, cargo shipping and extensive coastline, has also developed a uniquely diverse aquaculture sector (alligators, aquatic plants, fish, bivalves) and was ranked 9th for total overall aquaculture values in the USA in 2018 with USD 71.6 million (FDACS., 2020).

HABs have been occurring for decades and have caused considerable damage to the environment and local economies. This poses a threat to public health in Tampa Bay, with the last recorded event lasting more than a year during a bloom of *Karenia brevis*. HAB events have been associated with increased eutrophication due to the increasing population in Tampa Bay from approximately 125,000 people in the 1950s to almost 4 million in the late 2010s within the metropolitan community (Walsh et al., 2011). An increase of chlorophyll-*a* from 7 $\mu g.L^{-1}$ in 1953 to 45 $\mu g.L^{-1}$ in 1969 due to releases of untreated sewage waters, rich in nitrogen and phosphorus which enhanced biological productivity to such an extent that large blooms of cyanobacteria *Schizothrix calcicola* were observed (Walsh et al., 2011). With the implementation of wastewater treatment systems in 1979 to control severe eutrophication problems, inputs of nitrogen and phosphorus decreased significantly, but blooms of dinoflagellates persisted presumably due to accumulation of nutrients in sediments and presence of benthic cysts of *Alexandrium monilatum* (Chen et al., 2010; Walsh et al., 2011). Additional species of dinoflagellates were observed during such events, such as *Alexandrium* spp, *Pyrodinium bahamense* or *Karenia brevis*, causing multiple fish kills during the last decade. (ICES, 2017; Table 2, Maze et al., 2015). To monitor such events, the Florida Fish and Wildlife Conservation Commission (FWC) has implemented a monthly HAB monitoring and fish kills report which are accessible online (Chen et al., 2010). Recently, a proposition to create Centers of Excellence on HABs have been introduced by members of the US House to bolster the existing work on HABs, formalizing partnership between local, state and federal stakeholders to develop ways to prevent, respond to and mitigate HABs (Derby, 2020).

An executive order was taken on May 7th, 2020 in the USA to promote seafood competitiveness and economic growth by promoting Aquaculture Opportunity Zones in federal waters to increase local aquaculture production as 85% for fish and seafood are imported (NOAA Fisheries, 2020; Smith, 2020).

Vancouver - Canada

Located on the west coast of Canada, Vancouver lies along the Strait of Georgia which is the most densely populated region of British Columbia (BC) with 75% of the total population of the region (Krepakevich & Pospelova, 2010) (Table 1, Figures 2 and 3). The principal link between the Pacific Ocean and inner Strait of Georgia is the Juan de Fuca Strait, which is fed by deep, nutrient-rich flow enhanced by offshore upwelling and river runoffs from the mainland (Krepakevich & Pospelova, 2010). The Strait of Georgia experiences intense shipping traffic because it is the most used marine channel in BC. Additionally urban developments with industrial and commercial activities has contributed significantly to marine environmental degradation (Radi et al., 2007). Inputs from rivers, sewage, groundwater discharges are high and are associated with high nutrient concentrations enhancing chlorophyll levels to as high as $20\,\mu g.L^{-1}$ in some areas (Radi et al., 2007).

As observed in other countries, seafood demands have increased in Canada and seafood farming occurs in all provinces and territories with about 56 species of organisms and plants commercially cultivated in marine, freshwater ecosystems, land-based ponds and tanks facilities. Farming, fish processing activities represent significant economic benefits by generating CAD 2.2 billion in GDP and more than 26,000 jobs in 2017 (Canadian Aquaculture Industry Alliance, 2018). As presented in Table 1, BC leads the market by being the major producer in salmon through open cage farming around Vancouver Island in the Pacific Ocean and the Strait of Georgia (Haigh & Ensenkulova, 2014).

Since salmon farming industry began, HABs issues appeared and have been identified as the largest cause of mortality of farmed salmon in BC in early 2010s, costing millions of dollars (Table 2; Haigh & Ensenkulova, 2014). These events have been associated with diverse phytoplankton species, such as the raphidophyte *Heterosigma akashiwo*, which was regularly observed in salmon fish kills for the past 25 years (Table 2). Other species observed belongs to diatoms and dinoflagellates (Table 2), the latter being associated with a Diarrhetic Shellfish Poisoning (DSP) event due to consumption of mussels in 2011 (Taylor et al., 2013). Associated with these different events of fish kills and DSP, two specific monitoring regimes have been implemented in BC. Following the different fish kill events from the 1990s, the monitoring program (HAMP) was implemented in collaboration with fish farmers in BC (Table 2; Haigh & Ensenkulova, 2014). This program was initiated under the egis of Fisheries and Oceans Canada (DFO) in 1999 and run independently since 2004. HAMP has three mandates: i) regular monitoring of selected sites near or at salmon farms with collection of phytoplankton and environmental data; ii) real-time monitoring of fish-killing blooms, and identification of causative species in support of salmon aquaculture companies; and iii) education of farm personnel on sampling and identification of marine phytoplankton, especially those species that have been harmful to local fish (Environment and Climate Change Canada, 2019). Regarding shellfish poisoning, the Canadian Shellfish Sanitation Program (CSSP) was established to ensure that shellfish harvested in Canada are safe for consumption and is a key component of the Government's commitment to protecting the health and safety of Canadians. Three federal government agencies work together to deliver this program: i) the Environment and Climate Change Canada analyzes water quality in shellfish harvesting areas and identifies waters that do not meet sanitary standards, ii) the Canadian Food Inspection Agency monitors for biotoxins in shellfish in harvesting areas and is responsible for issuing licenses and inspecting shellfish that is processed for interprovincial trade or export, and iii) the Fisheries and Oceans Canada patrols and closes harvest areas, and bans the harvesting of shellfish whenever bacteria or toxin levels exceed safety standards. Stringent food safety guidelines for bacteria, biotoxins and other contaminants are set by Health Canada (Environment and Climate Change Canada, 2019). Since 2015, a Citizen Science Oceanography Program funded by the Pacific Salmon Foundation supported the Ocean and Networks Canada and DFO has been implemented to monitor 80 defined locations simultaneously allowing full coverage of the Strait of Georgia every year (Esenkulova & Pearsall, 2019). The monitoring includes phytoplankton analyses, enabling a better understanding of the seasonal and spatial variations along the Strait of Georgia (Esenkulova & Pearsall, 2019)

Sydney - Australia

Located on the east coast of Australia, Sydney is the New South Wales (NSW) capital and with its surroundings regroup 65% of the population of NSW (SMCMA, 2011). Botany Bay (to the south of Sydney) is influenced by intense anthropic inputs from its catchment area draining through Georges and Cook Rivers (SMCMA, 2011) (Table 1, Figures and 3). The main pollutions are related to industrial and urban development, characterized by chemical pollutions (metals) and storm waters (nutrients) (Spooner et al., 2003; SMCMA, 2011). The Bay is also influenced from its contact to the Pacific Ocean. Botany Bay hosts the busiest airport of Australia on its northwestern side and a large container terminal on the east. The southern shore of the bay, despite its relative isolation, is dominated by an unusual mixture of pristine national parks and heavy industrial activities including a desalination plant, a fuel terminal, a sewage treatment plant and historical sand mining facilities (SMCMA, 2011). By its proximity to Sydney, Botany Bay has been a logical site for industrial development for decades, associated with residential development in the neighborhood. Port Botany, the second busiest port in Australia has recently undergone a major expansion of its shipping container operations and some major industries (NSW EPA, 2020).

Seafood demand in Australia has increased considerably over the last three decades and current consumer demand for seafood exceeds the supply from domestic production and is predicted to continue to grow (ABARES, 2020). Aquaculture production occurs from the tropical north to the temperate south which allows the production of multiple species. In NSW, Sydney rock oysters represent the main production (Table 1), grown with other species along the 2,000 km of coastline and estuaries such as Botany Bay/Georges River area (Farrell et al., 2018).

HABs have been encountered for decades in Australia and have been associated with some fish kills in the area of Botany Bay/Georges River HABs (Table 2; Farrell et al., 2013; Murray et al., 2015). NSW agencies reported approximately 20 events of fish kills annually over the past 40 years, affecting shellfish, finfish and crustaceans (Murray et al., 2015). Out of the 20 HAB species identified in Botany Bay/Georges River near oyster growing areas, most of them are dinoflagellates (Ajani et al., 2013) such as *Amphidinium caterae, Dinophysis caudata,* or *Karlodinium veneficum* and *Alexandrium* spp. (Murray et al., 2015, Farrell et al., 2018). *Alexandrium* sp. resting stages have been identified in Georges River (Tian et al., 2018). Monitoring programs have been implemented by each of the Australian states and in NSW, the Shellfish Program and the Marine Biotoxin Management Plan have been implemented to provide "phytoplankton action limits" (PAL) to determine potential harvest zone closures depending on cell concentrations levels of harmful species (e.g. PAL of *Alexandrium* spp. is 200 cells.L^{-1} and 500 cells.L-1 for *Dinophysis* spp.) (Ajani et al., 2013; Farrell et al., 2013; NSW FA, 2017). A Water Quality Improvement Plan has been developed for Botany Bay and its catchment to reduce pollution loads by 2030 for total nitrogen, total phosphorus and total suspended solids (SMCMA, 2011) as nutrient loads have a direct impact on chlorophyll-*a* concentrations by encouraging productivity.

Comparing and contrasting the strategies adopted by different countries to develop the aquaculture sector and mitigate the impacts of HABs

With increasing population, the development of aquaculture has proven to be an extremely good option to ensure food security (uninterrupted supply and good quality of food).

Different urban areas face different challenges in sustainably increasing their aquaculture production with respect to the following:

- Geography – space allocation
- Economy – resources for training, collaborations and building infrastructure
- Ecology – HAB occurrences and mitigation

We recognize that the criteria mentioned above are limited to the data available summarized in the previous sections.

This section evaluates the various methods adopted by the urban areas of the aforementioned countries to develop their respective aquaculture sector, extrapolate the applicability of some of these strategies to other countries, their associated constraints and the potential solutions that can circumvent these production issues.

Section 1: Improving aquaculture production with modern farming and education

Rapid extension of aquaculture in different cities/countries undergoing increased urbanization, brings about space constraints and increased public concerns on risks to the degradation of aquatic ecosystem (Galland & McDaniels, 2008; Hamouda et al., 2005). New ways for sustainable aquaculture such as RAS, allows control of key parameters such as water quality, effluent and solid waste release, protection against predators and harmful events such as HABs (Losordo et al., 2009). Therefore, urban areas with space constraints and intense nutrient loadings such as Singapore, have encouraged some farms to adopt technologies such as the RAS. In combination with other coastal farms, Singapore's local production levels for fish has reached almost 10% of the annual total consumption of food fish in

2019 (Moore & Guerrero, 2020). Such methods could be potentially applied in other countries facing similar space constraint issues such as Hong Kong.

In comparison, aquaculture farms in countries like Oman, are not constrained by space but constantly challenged by seasonal blooms, that could be mitigated by the introduction of RAS, using cold waters from their shallow continental shelves (Lund, 2019). Similarly, Valencia does not face spatial constraints, but the waters of the Gulf of Valencia are constantly plagued by seasonal blooms forcing farm shutdowns. Here too, RAS systems could serve as a great alternative to supplement production. However, such farming infrastructure is expensive to build, requires trained farmers and might not be economically viable depending on the market price of the type of organisms produced (Losordo et al., 2009). For example, in the Netherlands, the high operating cost has been identified as a limitation of RAS due to the cold waters of the south North Sea (FAO, 2017b).

Other recent technological developments have enabled offshore aquaculture practices further away from the coastlines, where space is not an issue. Following Drumm's definition (2010), "offshore aquaculture may be defined as taking place in the open sea with significant exposure to wind and wave action, and where there is a requirement for equipment and servicing vessels to survive and operate in severe sea conditions from time to time. The issue of distance from the coast or from a safe harbor or shore base is often but not always a factor". Such production reduces potential environmental impacts by allowing farm discharges to be diluted in larger open areas, creating a natural "dilution" of aquaculture effluents, thus limiting the environmental impact of the discharge as mentioned by Welch et al. (2019). This development is not universally approved and concerns have been pronounced regarding proper environmental data assessment for this new farming technique to ensure proper implementation (Simke, 2020). Some long-term data on offshore aquaculture have been published and the results suggest little or no impact on water quality and sediment enrichment (Welch et al., 2019). Oman, while moving toward its 2040 plan, is currently building offshore farms as an effective strategy to minimize nutrient loading from aquaculture activities (Lund, 2019).

Modernization of aquaculture needs skilled workers, highlighting the need for proper training such as the official inclusion of aquaculture courses into academic programs which would help to nurture a workforce dedicated toward the sustainable and profitable expansion of the sector (FAO, 2017a). Moreover, Southeast Asian Fisheries Development Center/ Aquaculture Department (SEAFDEC/AQD) encourages the sustainable development and the responsible stewardship of aquaculture by promoting science-based aquaculture technologies, developing and strengthening capacities through training in the Southeast Asian region. Thus, providing both knowledge-based and technical skills to farmers setting up new aquaculture businesses (FAO, 2017a). In addition, public awareness on the interdependency of HABs and aquaculture through regular campaigns and public involvement in visual HAB detection is on the rise as witnessed in Canada, US and Europe (Lauro et al., 2014, Esenkulova & Pearsall, 2019).

Section 2: Monitoring and mitigation strategies

Wherever open cage fish farms are implemented, proper governmental regulations need to be enforced for site selection and environmental impact assessment (EIA) to determine the optimal carrying capacity of the farms and the associated risks. The administration of EIA has been implemented in different countries such as Singapore, United States, or Europe, with criteria for risk evaluation varying from one country to another. Transition from familial businesses to global companies through investments and acquisitions to adopt high tech farming strategies can improve and increase productions (Basu, 2019).

As observed in other intensive large-scale production systems, diseases by pathogens (recurring or new) (e.g. shrimp 'glass postlarvae' in China) and effective control of infectious diseases are also a very important concern in aquaculture (Harkel, 2020). The nature of the sector's production systems, ongoing intensification, reliance on international trade, importance for livelihoods and food security in resource-limited countries, make it prone and extremely sensitive to the impact and spread of diseases. As per traditional water quality monitoring, understanding the life cycle of pathogens, genetic screening coupled to modeling could be key in effective management of the sector.

As observed in Oman, Hong Kong, Cape Town, Rotterdam and Valencia, HAB events can display seasonal patterns requiring altered course of farm operations. Such outbreaks further aggravate the economic concerns as they can cause shutdowns of desalination plants as seen in Oman and further brings about water shortages in the region.

Farming practices are also under increasing pressure by emerging threats such as the input of plastics in the marine environment. In particular, microplastic particles can be ingested by marine organisms, resulting in the bioaccumulation of toxic substances in the food chain and ultimately affecting human health (Lusher et al., 2017). This will impact some aquaculture sectors more than others since the likelihood of humans ingesting microplastic particles while consuming seafood is small for many of the larger fish species (where the gastrointestinal tract of the fish is removed), but higher for bivalves and several species of small fishes which are consumed whole. Furthermore, microplastic particles have been shown to act as a hotspot for the dispersal of HABs (Masó et al., 2003) and the accumulation of human pathogens (Bowley et al., 2021), which could directly affect both aquaculture and human health.

Therefore, as urbanization processes continues and aquaculture operations need to be expanded to ensure adequate food for the growing population, proper regular monitoring of water quality regime should be enforced including physical, chemical and biological parameters as detailed in the examples of this review. When possible the use of satellite imagery coupled with monitoring, can become an efficient warning system for high biomass HABs especially those occurring offshore as seen in Rotterdam during the 2001 bloom (Van der Woerd et al., 2006). This information when incorporated into hydrodynamic and ecological models could be pivotal in the forecasting of water quality and HABs. Additionally, the use of inexpensive, rapid and portable third generation sequencing devices (e.g. Oxford Nanopore MinION), incorporated into regular monitoring can enable the precise characterization of microalgal species (George et al., in-press). Such monitoring and predictive modeling results should be made accessible to professionals, decision makers, potentially to the public and when coupled with proper mitigation measures, developed according to Governmental policies, ensure the sustainability of aquaculture operations and other industrial activities. A good example where information of this nature is made publicly available online since early 2000 is in Hong Kong based on their regular and long-term monitoring procedures.

Furthermore, engaging citizen scientists and other partners to monitor the onset of harmful algal blooms and help to rapidly characterize their identity may also become an economical way to address HABs holistically (Lauro et al., 2014, Esenkulova & Pearsall, 2019, Murray Darling Citizen Scientists[3]).

Conclusion

As of today, the ongoing COVID-19 pandemic has affected the world globally and to reduce the spreading of the virus many countries have instituted stricter regulations and border closures. The implemented lockdowns have resulted in logistical difficulties in seafood trade, particularly in relation to transportation and border restrictions (FAO, 2020b). The shrimp and salmon industries, in particular, have suffered from increased air freight costs and cancelation of flights (FAO, 2020b). Some shortages of seeds, feeds and related aquaculture items (e.g. vaccines) have also been reported due to restrictions on transportation and travel of personnel, impacting the aquaculture industry (FAO, 2020b). Drop in Chinese market due to lockdown has resulted in decrease of fish and seafood consumption

[3]https://uonblogs.newcastle.edu.au/bluegreen/murray-darling-citizen-scientists/

affecting international trade (FAO, 2020b). Growing evidence of unsold produce has resulted in an increase of live fish stocks resulting in higher feeding costs and greater risk of fish mortalities (e.g. seabass production in Australia[4]). This pandemic has encouraged the stakeholders of the aquaculture sector (e.g. farmers, feed providers, traders, international agencies, NGOs, governments) to share information about their situations locally and internationally. This will enable identification of short-term and long-term impacts of catastrophic events such as this, as well as the technological evolution of aquaculture.

Nonetheless, proper planning, management and collaboration of knowledge and skills on both local and international levels could ensure sustainable development of the aquaculture industry and food security in urban areas.

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[4]https://www.abc.net.au/landline/barra-blues:-calls-to-eat-more-home-grown-barra/12352900?nw=0

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