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MARINE HARMFUL ALGAL BLOOMS (HABs) IN WORLD'S TOURIST REGIONS

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Abstract

Harmful algal blooms (HABs) include toxic and non-toxic blooms of microalgae and macroalgae that are detrimental to aquatic ecosystems, have negative impacts on human health or socio-economic interests. All of these aspects are important for tourism and recreation related to marine areas, coastal waters, shorelines and coastal areas. They reduce the attractiveness of the regions in which they occur and can be a determinant of directional preferences for tourism activities. The aim of this study is to analyse the occurrence of typical HABs in tourist regions of the world, taking into account the taxa that cause them and the threats they pose. The analysis is based on a review of knowledge on the subject. It outlines the magnitude of the problems associated with the occurrence of HABs and demonstrates their relationship to the tourism sector. It also indicates the need for the tourism sector to obtain information on HABs in order to verify the availability of safe destinations for tourism.

Introduction

An algal bloom is a rapid mass growth of one or more species of organisms living in an aquatic environment, which can be generally referred to by the name algae (ASSMY and SMETACEK 2009, SMAYDA 1997). Algae are a morphological-ecological group that includes organisms that have similar environmental requirements but different origins and features of cell structure and form of morphological organization. They are photosynthesizing eukaryotic organisms from several unrelated evolutionary lineages, constituting a polyphyletic group that includes, both microscopic unicellular and multicellular organisms, and macroscopic organisms with a molluscan structure (BARSANTI and GUALTIERI 2014, CHAPMAN 2013). The microscopic algae that form blooms are mostly planktonic, less frequently

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benthic forms. The large macroscopic algae are the so-called seaweeds. The term algal bloom refers, most often, to the massive growth of microscopic phytoplankton algae rather than the rapid growth of macroscopic seaweeds. Photosynthesizing cyanobacteria as prokaryotes are not scientifically classified as algae, but the common name blue-green algae is still used synonymously with cyanobacteria (Barsanti and Gualtieri 2014, Castenholz 1992), and the term algal bloom often includes cyanobacterial blooms (Smayda 1997).

Algal blooms are not a new event. In the aquatic environment, the bloom effect is a natural phenomenon resulting from ecological succession, which is becoming increasingly common due to increasing anthropogenic eutrophication of waters and global climate warming. Blooms are becoming more frequent, more widespread and long-lasting, and their effects are increasingly affecting aquatic ecosystems directly, terrestrial ecosystems indirectly, as well as the economy, including tourism, and causing increasing losses (Kudela et al. 2017).

The global problem of blooms has led to the adoption of a separate definition of so-called harmful algal blooms. Harmful algal bloom (HAB) is a term that refers to toxic and non-toxic blooms of microalgae and macroalgae that are harmful to aquatic ecosystems, have negative impacts on human health or socio-economic interests (Kudela et al. 2017). The term harmful algal blooms (HABs) was introduced decades ago and is now preferred to the term 'red tide' because it covers all those varieties of algal blooms that are potentially harmful, including cyanobacterial blooms as CyanoHABs (Smayda 1997).

HABs can be harmful in two different ways. The first way in which HABs are harmful is through their high biomass accumulation, which can have a negative impact on the aquatic environment and consequently cause disturbance to aquatic ecosystems. Most often already in the bloom stage, massive algal growth can change the colour of the water, depending on the dominant species. The smell of the water also depends on the type of algal bloom. Already these visual and olfactory aspects are an adverse effect of the occurrence of a bloom and are indicative of a deterioration in water quality. During the duration of the bloom and during the decomposition phase, hypoxia of the water masses (anoxia) occurs, which can cause mortality of many marine animal species and consequently lead to the loss of natural marine resources. High mortality of marine animals also leads to negative changes in the coastal zone, where dead animal organisms discarded on the shore decompose, as does the mass of algae, emitting an unpleasant odour and sometimes also toxic gases (ammonia, hydrogen sulfide) (Sellner et al. 2003). A second way in which HABs are harmful is through the production and release of toxic compounds into the environment, which affect a variety of organisms, from plankton to humans (BIAŁCZYK et al. 2009). These compounds can be the direct cause of mass death in marine animals or can cause disease and death when the animals that have accumulated them are consumed by consumers in the food web. Accumulation of these compounds in organisms feeding on phytoplankton can cause numerous poisonings also in humans consuming so-called 'seafood'. Human poisoning induced by marine toxins has been divided into different types depending on the effects caused. These are: paralytic shellfish poisoning – PSP (the causative poison is saxitoxins), neurotoxic shellfish poisoning – NSP (the causative poison is brevetoxins and macrocyclic imines), amnesic shellfish poisoning – ASP (the causative poison is domoic acid), diarrheic shellfish poisoning – DSP (the causative poison is okadaic acid), ciguatera fish poisoning – CFP (the causative poisons are ciguatoxin and maitotoxin), azaspiracid shellfish poisoning (AZP) (the causative poison is azaspiracid) (VAN DOLAH 2000). In addition to toxins that accumulate in organisms at lower trophic levels and are passed up the food chain to higher trophic levels, there is a large group of toxins that have a direct lethal effect on marine organisms. These are mostly lipophilic and ichthyotoxin in nature, but the mechanism of action of many of them is not yet fully understood (MICHALSKI 2006, VAN DOLAH 2000).

The growing interest in HABs includes, concerns about public health safety and negative impacts on marine ecosystems Addresses the risks associated with the harvesting of fish and seafood and the potential to exploit the potential of natural marine natural resources and their attractiveness. All these aspects of HABs impacts are of interest to tourism and recreation related to marine areas, coastal waters, shorelines and coastal areas.

Materials and Methods

The paper is a review. Research articles on marine harmful algal blooms of the HABs type were used as the material for analysis. The search for articles required for the state of the art review was conducted using the ISI Web of Knowledge and Google Scholar databases of scientific publications. From the records obtained, a selection method was used to select all those articles that were thematically relevant and could be used to analyse general trends in the occurrence of HABs and the algal species that cause them. The species names used in the article follow the current taxonomic nomenclature adopted by AlgaeBase and refer to an entity that is currently taxonomically accepted. The division of the world into tourism regions used is consistent with UN Tourism (formerly UNWTO).

Results and Discussion

Harmful algal blooms cover various sea coasts in all tourist regions of the world. They occur on the Atlantic, Pacific and Indian Ocean coasts. Although all coastal regions experience the impact of harmful algal species, different HAB species live in different waters and cause different problems. Of the approximately 5,000 known species of marine algae, about 300 can occur in very high numbers, causing water blooms (ZOHDI and ABBASPOUR 2019). Each of these species needs a unique set of environmental conditions for dynamic mass growth forming HABs. Other factors that affect populations of bloom-forming algal species, such as coastal structure, hydrographic regimes, oceanography and other water-dwelling organisms, can alter the extent and severity of HAB impacts (SELLNER et al. 2021).

Americas region

The tourist region of the Americas includes both North America and South America, as well as Central America lying in between, which geographically belongs to North America. Harmful algal blooms pertaining to the Americas region occur in the western Adriatic and eastern Pacific waters (Table 1).

Table 1

Species forming HABs typical of the American tourist region, their taxonomic category and main toxins

Phylum	Class	Species	Toxins
1	2	3	4
Americas region: north-east coasts of North America			
Dinoflagellata	Dinophyceae	*Alexandrium catenella* (Whedon & Kofoid) Balech 1985	saxitoxins
Dinoflagellata	Dinophyceae	*Margalefidinium polykrikoides* (Margalef) F. Gómez, Richlen & D.M. Anderson 2017	TBD*
Dinoflagellata	Dinophyceae	*Karlodinium veneficum* (D. Ballantine) J. Larsen 2000	carlotoxins
Heterokontophyta	Pelagophyceae	*Aureococcus anophagefferens* Hargraves & Sieburth 1988	TBD*

cont. Table 1

1	2	3	4
Americas region: south-east coasts of North America			
Dinoflagellata	Dinophyceae	*Karenia brevis* (C.C. Davis) Gert Hansen & Moestrup 2000	brevetoxins
Dinoflagellata	Dinophyceae	*Pyrodinium bahamense* L. Płyta 1906	saxitoxins
Heterokontophyta	Bacillariophyceae	*Pseudo-nitzschia australis* Frenguelli 1939	domoic acids
Dinoflagellata	Dinophyceae	*Gambierdiscus toxicus* R. Adachi & Y. Fukuyo 1979	ciguatoxins
Dinoflagellata	Dinophyceae	*Dinophysis ovum* F. Schütt 1895	okadaic acids
Haptophyta	Coccolithophyceae	*Prymnesium parvum* N. Carter 1937	prymnesins
Americas region: Caribbean coasts and the east coast of Central America			
Dinoflagellata	Dinophyceae	*Gymnodinium catenatum* H.W. Graham 1943	saxitoxins
Dinoflagellata	Dinophyceae	*Pyrodinium bahamense* L. Płyta 1906	saxitoxins
Dinoflagellata	Dinophyceae	*Gambierdiscus toxicuss* R. Adachi & Y. Fukuyo 1979	ciguatoxins
Dinoflagellata	Dinophyceae	*Margalefidinium polykrikoides* (Margalef) F. Gómez, Richlen & D.M. Anderson 2017	TBD*
Heterokontophyta	Phaeophyceae	*Sargassum natans* (Linnaeus) Gaillon 1828	biomass
Heterokontophyta	Phaeophyceae	*Sargassum fluitans* (Børgesen) Børgesen 1914	biomass
Americas region: north-west coasts of North America			
Dinoflagellata	Dinophyceae	*Alexandrium catenella* (Whedon & Kofoid) Balech 1985	saxitoxins
Dinoflagellata	Dinophyceae	*Gymnodinium catenatum* H.W. Graham 1943	saxitoxins
Dinoflagellata	Dinophyceae	*Pyrodinium bahamanse* L. Płyta 1906	saxitoxins
Americas region: south-west coasts of North America			
Heterokontophyta	Bacillariophyceae	*Pseudo-nitzschia australis* Frenguelli 1939	domoic acids
Dinoflagellata	Dinophyceae	*Lingulaulax polyedra* (F. Stein) M.J. Head, K.N. Mertens & R.A. Fensome 2024	yessotoxins
Dinoflagellata	Dinophyceae	*Margalefidinium fulvescens* (M. Iwataki, H. Kawami & Matsuoka) F. Gómez, Richlen & D.M. Anderson 2017	TBD*

cont. Table 1

1	2	3	4
Dinoflagellata	Dinophyceae	*Akashiwo sanguinea* (K. Hirasaka) Gert Hansen i Moestrup 2000	TBD*
Heterokontophyta	Raphidophyceae	*Chattonella subsalsa* B. Biecheler 1936	TBD*
Americas region: west coasts of Central America			
Dinoflagellata	Dinophyceae	*Pyrodinium bahamanse* L. Płyta 1906	saxitoxins
Americas region: north-east coast of South America			
Dinoflagellata	Dinophyceae	*Dinophysis acuminata* Claparède & Lachmann 1859	okadaic acids
Dinoflagellata	Dinophyceae	*Gymnodinium catenatum* H.W. Graham 1943	saxitoxins
Americas region: south-east coasts of South America			
Dinoflagellata	Dinophyceae	*Dinophysis acuminata* Claparède & Lachmann 1859	okadaic acids
Dinoflagellata	Dinophyceae	*Dinophysis tripos* Gourret 1883	okadaic acids
Dinoflagellata	Dinophyceae	*Alexandrium tamarense* (Lebour) Balech 1995.	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium catenella* (Whedon & Kofoid) Balech 1985	saxitoxins
Dinoflagellata	Dinophyceae	*Prorocentrum lima* (Ehrenberg) F. Stein 1878	okadaic acids
Americas region: north-west coasts of South America			
Heterokontophyta	Raphidophyceae	*Heterosigma akashiwo* (Hada) Hada ex Y. Hara & Chihara 1987	TBD*
Dinoflagellata	Dinophyceae	*Dinophysis acuminata* Claparède & Lachmann 1859	okadaic acids
Americas region: south-west coasts of South America			
Dinoflagellata	Dinophyceae	*Alexandrium catenella* (Whedon & Kofoid) Balech 1985	saxitoxins
Heterokontophyta	Bacillariophyceae	*Pseudo-nitzschia australis* Frenguelli 1939	domoic acids
Heterokontophyta	Dictyochophyceae	*Pseudochattonella verruculosa* (Y. Hara & Chihara) S. Tanabe-Hosoi, D. Honda, S. Fukaya, Y. Inagaki & Y. Sako 2007	TBD*

* to be determined/decided/declared – toxins associated with the mechanism of lethal action on aquatic organisms are yet to be determined

In the western Atlantic, on the coasts of northeastern North America, harmful algal blooms (HABs) are most commonly caused (for 100 years) by *Alexandrium catenella*. This toxic thecate dinoflagellate produces saxitoxins that accumulate in shellfish and can cause paralytic shellfish poisoning in humans (PSP). It occurs along the east coast of Canada and the USA, from Maine to New Jersey (ANDERSON et al. 2021, MCKENZIE et al. 2021). Other HABs species causing problems in the region include *Margalefidinium polykrikoides*, *Karlodinium veneficum* and *Aureococcus anophagefferens*. The first two are athecate dinoflagellates and the third belongs to the heteroconta. They all generate toxins that affect marine organisms in different ways, in effect causing their death. This applies to both wildlife and aquaculture. These species also cause high biomass blooms that turn the water brown or red and reduce its visual and recreational value (ANDERSON et al. 2021). HABs occur on the south-eastern coasts of North America, which are most commonly formed by the dinoflagellates *Karenia brevis* and *Pyroidinium bahamense* and the diatom *Pseudo-nitzschia australis*. All three produce neurotoxins that accumulate in molluscs and crustaceans. Brevetoxins of *Karenia brevis* can cause neurotoxic shellfish poisoning in humans (NSP) Saxitoxins of *Pyroidinium bahamense* pose a risk of paralytic shellfish poisoning (PSP) in humans. Neurotoxins (domoic acid) produced, by *Pseudo-nitzschia australis*, can cause amnesic shellfish poisoning (ASP). For this reason, aquaculture areas affected by these algal blooms are being closely monitored and seafood harvesting from them may be halted to protect public health. Restrictions on shellfish farming due to these HABs are common in Florida coastal waters (ANDERSON et al. 2021). In addition, recreational harvesting of fish is prohibited in some Florida estuaries due to the potential for human ciguatera poisoning (CFP). Ciguatera fish poisoning (neurotoxins) is a concern in South Florida due to toxins produced by *Gambierdiscus toxicus*, a furry fish associated with macroalgae on coral reefs. Such blooms in July 2016 led to the destruction of many businesses and even the closure of some. Loss of revenue was reported by restaurants and hotels in South Florida (HEIL and MUNI-MORGAN 2021). Losses to tourism-related businesses due to *Karenia brevis* blooms in 2018 were estimated at $2.7 billion, meaning that HABs and their impact on tourism in the region could be considered a potential 'billion-dollar disaster' (ALVAREZ et al. 2024, BECHARD 2020). The Gulf of Mexico is experiencing blooms of *Karenia brevis*, as are the coasts of Florida, but also many other HABs. Shellfish farm closures have occurred in Texas due to *Dinophysis ovum* blooms, which can cause diarrhetic shellfish poisoning (DSP). The routes by which the toxins can enter the human body are mainly seafood. The overall economic impact of these HABs is difficult to determine, but in 2003 alone, more than US$ 6 million in profit from sport fishing and tourism was lost in Texas due to a bloom towards *Prymnesium parvum*, a haptophyte species that produces phycotoxins (prymnesins) that are lethal to fish (LUNDGREN et al. 2015).

HAB blooms also affect the waters of the Caribbean Sea and the coastal areas of the Caribbean islands, on the one hand, and the coasts of Central American countries, on the other. The most common HAB-forming species there are *Gymnodinium catenatum*, *Pyrodinium bahamense*, *Gambierdiscus toxicus* and, in recent years, *Margalefidinium polykrikoides*. Blooms of these and other algae are increasingly common there, causing mass mortality of fish and invertebrates and a major threat to food security in the region. Paralytic shellfish poisoning (PSP) caused by *Gymnodinium catenatum* and *Pyrodinium bahamense* blooms and ciguatera fish poisoning occurring as a result of *Gambierdiscus* blooms are also a problem (SUNESEN et al. 2021). However, the biggest problem for Caribbean coasts is macroalgal blooms. These are algae from the brown algae cluster mostly *Sargassum natans* and *Sargassum fluitans* species, reaching over a metre in length and highly branched. Representatives of *Sargassum* spp. occupy vast spaces in warm seas (SUMANDIARSA et al. 2021). Among others, they are found in the Sargasso Sea, where they provide food and breeding grounds for many species of fish, turtles and other juvenile marine life. Normally they occur in the open ocean, but for some time they have been accumulating in the coastal zone of Caribbean islands to form blooms. There, the huge concentrations of algae have a detrimental effect on the aquatic ecosystem, blocking light, depleting oxygen, altering habitats and causing the death of many species of aquatic organisms, stranded ashore they accumulate, up to 3 meters high. During the decomposition phase, they emit an unpleasant odour and toxic gases (hydrogen sulfide and ammonia). The gases emitted by *Sargassum* spp. can cause respiratory, skin and nervous system symptoms in both residents and tourists (ROBLEDO et al. 2021). Tourists are disillusioned with the aesthetics of Caribbean beaches and residents find it difficult to go to sea for work. *Sargassum* spp. blooms pose a serious threat to the local economies of HABs-affected countries, negatively impacting tourism, and approximately 70% of territories in the Caribbean region are financially dependent on tourism. Island societies are affected by HABs materially, financially and in terms of health (RESIERE et al. 2023).

In the eastern Pacific, along the northern part of the west coast of North America, from Alaska to California, blooms are usually formed by *Alexandrium catenella, Gymnodinium catenatum*, *Pyrodinium bahamanse* or other species of these genera. These are thecate dinoflagellates that produce neurotoxins (mainly saxitoxins) that accumulate in invertebrates and, over time, in fish and other vertebrates, leading to disease and death in a variety of marine organisms (McKenzie et al. 2021). They also cause economic losses. The coasts of Alaska and Georges Bank are ideal areas for crustaceans fishing, but they are often so contaminated by the presence of toxic algae that no fishing can take place there, due to the risk of paralytic shellfish poisoning (PSP) in humans. The largest shellfish shoal, George Bank, has been closed since 1989 due to the massive year-round presence of toxins in the water. Alaska's shellfish resources, estimated at $50 million per year, do not provide this economic benefit through HABs (Levitus et al. 2012). On the coasts of south-western North America (in southern California and Mexico), the cause of blooms is most often the massive growth of *Pseudo-nitzschia australis* (Ekstrom et al. 2020, Lewitus et al. 2012). The consequences of blooms can be disease and mortality of marine life and humans, as well as economically damaging fishery closures required to protect public health. These diatoms are toxic, produce, neurotoxins (domoic acid) and can cause amnesic shellfish poisoning (ASP) in humans. During this HAB in 2015, the detection of toxins in marine mammals – including whales, dolphins, porpoises, seals and sea lions – had the largest geographical coverage ever recorded. Accumulation of toxins in shellfish has resulted in fishery closures and failures in commercial crab farming, and recreational and local harvesting of shellfish has been banned. In coastal areas, blooms have prevented access to beaches for recreation and leisure, contributing to the loss of local tourism and recreation activities (Ekstrom et al. 2020). Along the coasts of south-western North America, *Lingulaulax polyedra* has also made massive appearances. A large bloom of this species occurred in the summer and autumn of 2005 and extended from San Diego to Ventura. *Lingulaulax polyedra* is a dinoflagellate that can produce a toxin called yessotoxin. Yessotoxins are a group of lipophilic toxins that are related to ciguatoxins, but their mode of action is different. These toxins bioaccumulate in the edible tissues of bivalves, thus allowing them to enter the food chain. In the region in question, HABs can also cause other dinoflagellates, most commonly and *Akashiwo sanguinea*, which in 2007 led to seabird deaths in Monterey Bay, California, caused by surfactant-like proteins produced by this alga (Levitus et al. 2012). However, on Mexico's Pacific coast in the Gulf of California, it was a bloom of *Chattonella subsalsa* belonging to the raphidophytes that caused the mass death of tuna in aquaculture. These harmful species produce toxins that interfere with oxygen transport, ultimately leading to suffocation. The effect of HABs has been linked to changes in oceanographic and atmospheric environmental conditions resulting from ENSO processes (García-Mendoza et al. 2018).

On the Pacific coasts of Central America, the most common HABs are formed by *Pyrodinium bahamense* (El Salvador, Costa Rica and Guatemala). In 2013, around 200 sea turtles died in El Salvador, poisoned by the saxitoxin produced by this dinoflagellate. The ecosystem losses were probably much greater. Paralytic poisoning (PSP) can also occur in humans after eating seafood or fish. In Nicaragua in 2005, a *Pyrodinium bahamense* bloom caused several dozen poisonings in humans (Cuellar-Martinez et al. 2018).

HABs blooms are also present on the coasts of South America, in both Atlantic and Pacific waters.

In the Atlantic Ocean, which borders the eastern part of the continent, the most common species of HABs are *Alexandrium catenella* and *Alexandrium tamarense*, *Gymnodinium catenatum* and the *Dinophysis acuminata* and *Dinophysis tripos* complex (Sunesen et al. 2021). Blooms of the harmful alga *Dinophysis acuminata*, are becoming recurrent on the northeast coast, where most marine shellfish farms are located. *Dinophysis acuminata* is causing major losses to shrimp and clam farms in Brazil there. It produces okadaic acid, which is accumulated by molluscs, especially bivalves (mussels, oysters, scallops, cockles). Toxic molluscs can cause diarrhetic poisoning in humans (DSP) (Simões et al. 2021). In the coastal waters of Brazil, there are also frequent blooms of *Gymnodinium catenatum*, which are responsible for paralytic shellfish poisoning (PSP) (Proença et al. 2001). The south-eastern coasts of South America also have blooms of *Dinophysis acuminata*, in addition, HABs are often caused by *Dinophystis tripos* and *Prorocentrum lima*, but their detrimental effects (DSP) are less severe in this part of the coast (Sastre et al. 2018). A much greater threat of HABs is caused by the mass occurrence of *Alexandrium tamarense* and *Alexandrium catenella.* In the Argentine Sea, blooms of this furball have led to fish and bird deaths, as well as human deaths from paralytic shellfish poisoning (PSP) (Fabro et al. 2017).

In the Pacific, on the northwestern coasts of South America, the most common HABs are caused by *Heterosigma akashiwo* and *Dinophysis acuminata* (Cuellar-Martinez et al. 2023). *Heterosigma akashiwo* is a raphidophyte that threatens marine organisms at all trophic levels, including fish. It causes high mortality in fish, whose cause of death is gill damage leading to hypoxia. However, the mechanism of action of *Heterosigma akashiwo* is not yet fully understood. Four different mechanisms of fish death are being investigated: mucus secretion, endogenous production of reactive oxygen species, toxin production and hemolytic activity (Allaf

2023). Threats from *Dinophysis acuminata* can include aquaculture losses as well as human diarrhetic poisoning (DSP). Other toxic types of microalgae found in the region include *Alexandrium*, *Pseudo-nitzschia*, and *Prorocentrum*. All pose a risk of human poisoning from ingestion of bivalves contaminated with phycotoxins causing PSP, ASP or DSP, respectively (Cuellar-Martinez et al. 2023). In south-western South America, on the Pacific coast, harmful blooms of toxin-producing microalgae are mainly *Alexandrium catenella*, *Pseudo-nitzschia australis* and *Dinophysis* spp. These species produce toxins that accumulate in molluscs or marine crustaceans and can cause serious human illnesses described as paralytic (PSP), amnesic (ASP) and diarrhetic (DSP) shellfish poisoning (Barría et al. 2022). They therefore threaten the sustainable exploitation of seafood in intensive aquaculture sites, which are abundant in the region. In 2016 in Chile, due to a severe HAB event caused by *Alexandrium catenella*, the loss of molluscs production was estimated at around US$ 30–40 million. But it was not the most common species that caused the greatest losses in Chilean aquaculture. In the same year, the HAB *Pseudochattonela verruculosa* caused an ichthyotoxic event causing massive mortality in salmon farming (more than 40 000 tones) and caused losses in excess of US$ 500 million (Díaz et al. 2019).

East Asia and Pacific region

The East Asia and Pacific tourist region comprises the Asian mainland countries on the west coast of the Pacific Ocean and the island countries in this part of the Pacific, including Australia. Harmful algal blooms pertaining to this region occur in the western Pacific (Table 2).

Table 2

Species forming HABs typical of the East Asia and Pacific tourism region, their taxonomic category and main toxins.

Phylum	Class	Species	Toxins
1	2	3	4
East Asia and Pacific region: north-east coasts of Asia			
Heterokontophyta	Raphidophyceae	*Heterosigma akashiwo* (Hada) Hada ex Y. Hara & Chihara 1987	TBD*
Heterokontophyta	Raphidophyceae	*Chattonella marina* (Subrahmanyan) Y. Hara i Chihara 1982	TBD*
Dinoflagellata	Dinophyceae	*Margalefidinium polykrikoides* (Margalef) F. Gómez, Richlen & D.M. Anderson 2017	TBD*

cont. Table 2

1	2	3	4
Dinoflagellata	Dinophyceae	*Karenia mikimotoi* (Miyake & Kominami ex Oda) Gert Hansen & Moestrup 2000	gymnocins
Dinoflagellata	Noctilucophyceae	*Noctiluca scintillans* (Macartney) Kofoid & Swezy 1921	TBD*
Haptophyta	Coccolithophyceae	*Phaeocystis globosa* Scherffel 1899	TBD*
Chlorophyta	Ulvophyceae	Ulva prolifera O.F. Müller 1778	biomass
East Asia and Pacific region: south-east coasts of Asia			
Dinoflagellata	Dinophyceae	*Pyrodinium bahamense* L. Płyta 1906	saxitoxins
Dinoflagellata	Dinophyceae	*Gymnodinium catenatum* H.W. Graham 1943	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium tamarense* (Lebour) Balech 1995.	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium catenella* (Whedon & Kofoid) Balech 1985	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium tamiyavanichii* Balech 1994	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium ostenfeldii* (Paulsen) Balech & Tangen 1985	saxitoxins
Dinoflagellata	Noctilucophyceae	*Noctiluca scintillans* (Macartney) Kofoid & Swezy 1921	TBD*
Dinoflagellata	Dinophyceae	*Gambierdiscus toxicus* R. Adachi & Y. Fukuyo 1979	ciguatoxins
East Asia and Pacific region: coasts of Australia			
Dinoflagellata	Dinophyceae	*Karlodinium veneficum* (D. Ballantine) J. Larsen 2000	carlotoxins
Dinoflagellata	Dinophyceae	*Karenia mikimotoi* (Miyake & Kominami ex Oda) Gert Hansen & Moestrup 2000	gymnocins
Haptophyta	Coccolithophyceae	*Prymnesium parvum* N. Carter 1937	prymnesins
Heterokontophyta	Coscinodiscophyceae	*Rhizosolenia chunii* Karsten 1905	TBD*
Dinoflagellata	Dinophyceae	*Alexandrium catenella* (Whedon & Kofoid) Balech 1985	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium minutum* Halim 1960	saxitoxins
Dinoflagellata	Dinophyceae	*Gymnodiniu catenatum* H.W. Graham 1943	saxitoxins
Dinoflagellata	Dinophyceae	*Dinophysis acuminata* Claparède & Lachmann 1859	okadaic acids

cont. Table 2

1	2	3	4
Dinoflagellata	Dinophyceae	*Dinophysis fortii* Pavillard 1924	okadaic acids
Cyanobacteria	Cyanophyceae	*Nodularia spumigena* Mertens ex Bornet & Flahault 1888	nodularins

* to be determined/decided/declared – toxins associated with the mechanism of lethal action on aquatic organisms are yet to be determined

The coasts of north-east Asia are an extensive zone of the north-west Pacific Ocean. In this region, raphidophyte blooms occur along Asian coasts, most commonly of the genera *Chattonella marina* and *Heterosigma akashiwo* as on the north-west coast of the Japanese islands. In the south-western coastal waters of Japan and off the coast of Korea, HABs cause *Margalefidinium polykrikoides* and *Karenia mikimotoi*. This is an athecate dinoflagellate that, unlike other species of the genus *Karenia*, does not produce brevetoxin, which is highly toxic to humans and marine fauna (Brand et al. 2012). However, blooms of this species cause massive mortality of marine fauna. This is due to haemolytic and cytotoxic effects, but the mechanism of toxicity to marine organisms is not fully understood. (Li et al. 2019). *Margalefidinium polykrikoides* has similar effects, producing reactive oxygen species that are lethal to pelagic fish as well as echinoderm and crustacean molluscs, even at low concentrations. In 1995, it formed a huge bloom along the southern coast of Korea, causing severe economic losses to aquaculture estimated at around US$70 million (Sakamoto et al. 2021). In the waters off the east coast of China, *Karenia mikimotoi* is also the main cause of massive fish mortality, in addition to *Heterosigma akashiwo* and *Chattonella* spp. In 2012, a massive bloom of *Karenia mikimotoi* along China's coast, caused massive mortality of farmed seafood, causing economic losses of approximately US$ 300 million (Sakamoto et al. 2021). Toxic phytoplankton, responsible for poisoning crustaceans, molluscs and fish in aquaculture and beyond, can cause poisoning in humans (Corrales and Maclean 1995). However, meticulous monitoring of farming means that fatal human poisoning cases from the consumption of commercially available seafood have become rare, although contamination of bivalves with paralytic toxins (PST) and diarrhetic toxins (DST) and the resulting trade restrictions are common (Sakamoto et al. 2021). In addition to the typically toxic HABs, algal blooms that are harmful due to the large biomass of the bloom are also common on the East Asian coast. These are the HABs *Noctiluca scintillans* and *Phaeocystis globosa*. Although *Noctiluca scintillans* is a species of dinoflagellate athecate that does not produce toxins that can kill marine organisms or threaten human health, massive blooms of this species have negative environmental impacts and can cause losses to aquaculture probably due to increased ammonia concentrations or low oxygen content during the degradation phase of the bloom (Xiaodong et al. 2023). *Phaeocystis globosa* belongs to the primnesiophytes and has the ability to form floating gelatinous colonies that can increase in size during blooms and, at the disappearance of the bloom, form bad-smelling clusters of algae and foam on beaches. This has a negative impact on coastal tourism. This effect can also have a negative impact on higher trophic levels in the marine ecosystem. *Phaeocystis globosa* blooms also cause massive mortality of aquacultured animals (Wang et al. 2021). Massive macroalgal blooms also occur in the same area (Yellow Sea). In the summer of 2008, the world's largest *Ulva prolifera* bloom took place here, and every year since then, this HAB covers an area of thousands of square kilometers and lasts for an average of 90 days, with significant inter-annual variability (Qi et al. 2016).

On the coasts of south-estern Asia (Philippines, Malaysia), common species forming HABs include *Pyrodinium bahamense*, *Gymnodinium catenatum* and *Alexandrium* spp. (*A. tamrense*, *A. catenella*, *A. tamiyavanichii*, *A. ostenfeldii*) (Azanza et al. 2024). The most common HABs are *Pyrodinium bahamense var. compressum* (*Pyrodinium bahamanse var. bahamense* occurs in the Central American and Caribbean region) (Usup et al. 2012). These are dinoflagellates that produce paralytic toxins (saxitoxins) that accumulate in marine crustaceans, as do *Gymnodinium* and *Alexandrium* species. By this, *Pyrodinium*, *Gymnodinium* and *Alexandrium* are the main cause of seafood toxicity and poisoning occurring in humans after consumption. Species causing paralytic shellfish poisoning (PSP) occur in the coastal waters of the Philippines and Malaysia annually at varying scales (Azanza et al. 2024). Bioaccumulation of toxins occurring at higher trophic levels, in marine mammals, birds and fish, can lead to massive mortality of these animals and contaminate beaches reducing the attractiveness of coastal areas for tourism. *Pyrodinium bahamense* is nevertheless seen as a tourist attraction, as it has the ability to bioluminesce and causes the water to glow spectacularly during a bloom (Usup et al. 2012). *Pyrodinium bahamense var. compressum* also forms blooms regularly in the Indonesian region, causing many negative impacts on fisheries, the aquatic environment and human health, including tourists. However, long-lasting HABs caused by *Chaetoceros* spp., *Noctiluca* spp. and *Skeletonema* spp. are most common in this region. Their harm lies primarily in the production of large biomass and the potential for hypoxia in coastal waters, resulting in the extinction of fish and marine invertebrates and damage to coral reefs (Sidabutar et al. 2024, Sidharta 2005). These blooms thus have a very negative impact on coastal tourism in the Indonesian region. Dangerous HABs in the region of both Indonesia and Malaysia and the Philippines are *Gambierdiscus toxicus* blooms, that have expanded their geographical range into the region. *Gambierdiscus* spp. produce ciguatoxins that accumulate in the muscles of some marine fish species. Ciguatoxins are a group of dangerous neurotoxins that cause ciguatera poisoning. The global spread of fish ciguatera poisoning (CFP) has meant that *Gambierdiscus* spp. and its toxins are considered a problem for the environment and human health worldwide. It is estimated that between 50,000 and 200,000 people worldwide contract CFP each year (Wang et al. 2022).

In Australia's coastal waters, HABs are formed by a variety of algal species whose mass growth varies in intensity, frequency and distribution. Their harmful effects also vary. High mortality of wild and farmed fish is associated with blooms of the dinoflagellates *Karlodinium veneficum* and *Karenia mikimotoi* and the haptophyte *Prymnesium parvum*. These species are capable of producing ichthyotoxic substances that have a pathological effect on the gills of fish, resulting in massive mortality (Hallegraeff 1992). Other HABs species found in the region are the diatom *Rhizosolenia chunii*, the dinoflagellates *Alexandrium catenella*, *Alexandrium minutum* and *Gymnodinium catenatum*. They all produce neurotoxins that accumulate in molluscs or crustaceans and can cause paralytic shellfish poisoning (PSP) (Parry et al. 1989). Less common are the HABs dinoflagellates *Dinophysis acuminata* and *Dinophysis fortii*, but their occurrence is associated with the risk of diarrhetic shellfish poisoning (DSP). On Australian coasts, blooms are also formed by *Gambierdiscus* spp. They are most abundant on the east coast, in the Great Barrier Reef region, and are the cause of frequent ciguatera fish poisoning (Kretzschmar et al. 2019). Poisoning of cattle and wildlife or contamination of drinking water supplies by blue-green toxins of the brackish water alga *Nodularia spumigena* is also a growing concern (Hallegraeff 1992). Australia's 2019 and 2020 wildfires also contributed to the magnification of blooms. Carried by wind over the Pacific, smoke and ash fertilized its waters, providing nutrients for algal blooms on a scale not seen in the region.

Middle East and South Asia region

The tourist region of the Middle East and South Asia comprises the western and southern parts of Asia located on the northern coast of the Indian Ocean. The blooms in the South Asian and Middle East coastal region are determined by the nature of the Indian Ocean waters (Table 3).

Table 3

Species forming HABs typical of the Middle East and South Asia tourism region, their taxonomic category and main toxins

Phylum	Class	Species	Toxins
Middle East and South Asia region: coasts of southern Asia			
Dinoflagellata	Noctilucophyceae	*Noctiluca scintillans* (Macartney) Kofoid & Swezy 1921	TBD*
Cyanobacteria	Cyanophyceae	*Trichodesmium erythraeum* Ehrenberg ex Gomont 1892	TBD*
Cyanobacteria	Cyanophyceae	*Trichodesmium thiebautii* Gomont 1890	TBD*
Dinoflagellata	Dinophyceae	*Margalefidinium polykrikoides* (Margalef) F. Gómez, Richlen & D.M. Anderson 2017	TBD*
Dinoflagellata	Dinophyceae	*Karenia brevis* (C.C. Davis) Gert Hansen & Moestrup 2000	brevetoxins
Dinoflagellata	Dinophyceae	*Karenia mikimotoi* (Miyake & Kominami ex Oda) Gert Hansen & Moestrup 2000	gymnocins
Heterokontophyta	Raphidophyceae	*Chattonella marina* (Subrahmanyan) Y. Hara i Chihara 1982	TBD*
Middle East and South Asia region: coasts of the Middle East			
Dinoflagellata	Dinophyceae	*Margalefidinium polykrikoides* (Margalef) F. Gómez, Richlen i D.M. Anderson 2017	TBD*
Dinoflagellata	Dinophyceae	*Gonyaulax polygramma* F. Stein 1883	TBD*
Dinoflagellata	Dinophyceae	*Prorocentrum lima* (Ehrenberg) F. Stein 1878	okadaic acids
Dinoflagellata	Noctilucophyceae	*Noctiluca scintillans* (Macartney) Kofoid & Swezy 1921	TBD*

* to be determined/decided/declared – toxins associated with the mechanism of lethal action on aquatic organisms are yet to be determined

In the South Asian region, along the west and east coasts of India and Pakistan, blooms are most commonly formed by the species *Noctiluca scintillans* and *Trichodesmium erythraeum* and *Trichodesmium thiebautii* (D'Silva et al. 2012). *Noctiluca scintillans* is a translucent athecate dinoflagellate and can occur in green or red form. The species has the capacity for bioluminescence occurring when the cell is irritated and its blooms cause a glowing effect in the water. It is one of the tourist attractions in the Maldives. *Noctiluca scintillans* do not produce toxins, but are considered harmful to the marine environment. They can cause high mortality of fish and invertebrates due to ammonia accumulation and depletion of the oxygen in the water (Gomes et al. 2014). *Trichodesmium erythraeum* and

Trichodesmium thiebautii are species of filamentous cyanobacteria found in colonies named 'sea sawdust'. *Trichodesmium* is the only known diazotroph capable of fixing nitrogen in daylight under aerobic conditions without the use of heterocysts and accounts for almost half of nitrogen fixation in marine systems worldwide (Bergman et al. 2012). *Trichodesmium* spp. blooms typically last for a very long time causing reduced oxygen availability during bloom die-off, which can lead to the death of marine organisms (Padmakumar et al. 2010). However, massive fish mortality in Indian coastal waters has been linked more to blooms of *Margalefidinium polykrikoides*, *Karenia brevis*, *Karenia mikimotoi*, *Chattonella marina*, although blooms of these algae occur less frequently (D'Silva et al. 2012).

In the Middle East region, green *Noctiluca scintillans* and other dinoflagellates such as *Margalefidinium polykrikoides*, *Gonyaulax polygramma* and *Prorocentrum lima* have become the dominant HABs, partly replacing the previously dominant diatoms and red *Noctiluca scintillans* (Harrison et al. 2017). *Margalefidinium polykrikoides* is a species that can produce allelopathic chemicals that inhibit the growth of other phytoplankton taxa in the water depths, and can also produce reactive oxygen species that are lethal to pelagic fish as well as molluscs and crustaceans, even at low concentrations. *Margalefidinium polykrikoides* blooms are responsible for the majority of fish deaths in the Arabian Sea, although it is *Noctiluca scintillans* that causes about 50% of HABs events in the region. In late 2008–2009 (November–February) in the Gulf of Oman in the Arabian Sea, a massive bloom of *Margalefidinium polykrikoides* occurred, causing massive fish die-offs, damage to coral reefs and disruption to seawater desalination plants (Harrison et al. 2017). In the Gulf, the long-term occurrence of HABs *Margalefidinium polykrikoides* has led to massive economic, environmental and social damage (Esmaeili et al. 2021). The toxic *Gonyaulax polygramma*, whose blooms are becoming more frequent, is also becoming dangerous to the marine environment in the region (Dias et al. 2023). A characteristic species forming blooms in the Red Sea is *Trichodesmium* spp. It causes the red colouration of the water during a bloom and is responsible for the name of this sea. *Trichodesmium* spp. blooms have also started to appear in the eastern Mediterranean, along the coasts of Middle Eastern countries (Spatharis et al. 2012).

Africa region

Africa's coasts are also visited by species that cause harmful algal blooms, both on the east and west coasts of the continent, in the waters of the eastern Atlantic and western Indian Ocean (Table 4).

Table 4

Species forming HABs typical of the Africa tourism region, their taxonomic category and main toxins

Phylum	Class	Species	Toxins
Africa region: north-east coasts of Africa			
Heterokontophyta	Bacillariophyceae	*Pseudo-nitzschia pungens* (Grunow ex Cleve) Hasle 1993	domoic acids
Dinoflagellata	Dinophyceae	*Blixaea quinquecornis* (T.H. Abé) Gottschling 2017	TBD*
Dinoflagellata	Dinophyceae	*Alexandrium affine* (H. Inoue & Y. Fukuyo) Balech 1995	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium leei* Balech 1985	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium tamarense* (Lebour) Balech 1995	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium tamiyavanichii* Balech 1994	saxitoxins
Dinoflagellata	Noctilucophyceae	*Noctiluca scintillans* (Macartney) Kofoid & Swezy 1921	TBD*
Cyanobacteria	Cyanophyceae	*Trichodesmium erythraeum* Ehrenberg ex Gomont 1892	TBD*
Africa region: south-east coasts of Africa			
Dinoflagellata	Dinophyceae	*Amphidinium carterae* Hulburt 1957	ciguatoxins
Dinoflagellata	Dinophyceae	*Gambierdiscus toxicus* R. Adachi & Y. Fukuyo 1979	ciguatoxins
Dinoflagellata	Dinophyceae	*Prorocentrum lima* (Ehrenberg) F. Stein 1878	okadaic acids
Dinoflagellata	Dinophyceae	*Ostreopsis ovata* Y. Fukuyo 1981	palytoxins
Africa region: south-west coasts of Africa			
Dinoflagellata	Dinophyceae	*Lingulaulax polyedra* (F. Stein) M.J. Head, K.N. Mertens & R.A. Fensome 2024	yessotoxins
Dinoflagellata	Dinophyceae	*Gonyaulax spinifera* (Claparède & Lachmann) Diesing 1866	yessotoxins
Dinoflagellata	Dinophyceae	*Prorocentrum lima* (Ehrenberg) F. Stein 1878	okadaic acids
Africa region: north-west coasts of Africa			
Dinoflagellata	Dinophyceae	*Dinophysis caudata* Kent 1881	okadaic acids
Dinoflagellata	Dinophyceae	*Dinophysis ovum* F. Schütt 1895	okadaic acids
Dinoflagellata	Dinophyceae	*Ostreopsis ovata* Y. Fukuyo 1981	palytoxins

* to be determined/decided/declared – toxins associated with the mechanism of lethal action on aquatic organisms are yet to be determined

On the eastern coasts of Africa (western Indian Ocean), HABs *Pseudo-nitzschia pungens*, *Blixaea quinquecornis* and *Alexandrium* spp. (*A. affine, A. leci, A. tamarense, A tamiyawanichii*) are found (HANSEN et al. 2001). They can cause toxin accumulation in shellfish or marine molluscs and transmission to humans in the form of ASP or PSP poisoning. Mass occurrences of the athecate dinoflagellate *Noctiluca scintillans* and the cyanobacteria *Trichodesmium erythraeum* also occur there, but do not have a major impact on the economy and tourism in the region (KITERESI et al. 2013). On the coasts of Madagascar and the Mascarene (Mauritus) archipelago, blooms of *Amphidinium carterae*, *Gambierdiscus toxicus*, *Prorocentrum lima* and *Ostreopsis ovata* occur and other species of these algal genera (HANSEN et al. 2001). In southern Africa, dinoflagellate blooms of the genera *Gonyaulax*, *Lingulaulax*, *Prorocentrum*, *Protoceratium* and *Tripos* cause massive anoxia-induced mortality of marine organisms during the disappearance of the bloom.

The HAB species most commonly found in the south-west coastal region of Africa (eastern Atlantic) are *Lingulaulax polyedra* and *Gonyaulax spinifera* (PITCHER and CALDER 2000). Both species belong to the dinoflagellates. *Lingulaulax polyedra* and *Gonyaulax spinifera* have heavily pigmented cells which, when present in mass numbers, gives the impression of staining the water various shades of red. Additionally, *Lingulaulax polyedra* has the ability to bioluminesce. Both species can also produce toxins from the yessotoxin group. These toxins bioaccumulate in the edible tissues of marine molluscs thus allowing the toxins to enter the food chain. These compounds become toxic to humans if concentrated in the food chain in large quantities. They also cause losses in aquaculture, such as on the south-west coast of Africa, where they caused the death of more than 250 tonnes of edible sea snails known as sea lugs, with an estimated value of US$ 33 million (STEPHEN and HOCKEY 2007). HABs caused by *Dinophysis caudata* and *Dinophysis ovum* and species of the genus *Alexandrium* also occur on the north-west coast of Africa (AKIN-ORIOLA et al. 2006). HABs of *Ostreopsis ovata* also occur in this region (Morocco). They can reduce the oxygen concentration in the water and clog the gills of filter-feeding organisms. Some of these dinoflagellates contain toxic chemicals stored by the animals that eat them, which can threaten public health and cause economic damage to fisheries (ALKHATIB et al. 2022). Coastal countries in the northern African region have blooms characteristic of the Mediterranean (TSIKOTI and GENITSARIS 2021).

Europe region

HABs events also occur in the oceanic and marine coastal area of the European region. These include the eastern Atlantic coasts and inland seas (Table 5).

Table 5

Species forming HABs typical of the European tourist region, their taxonomic category and main toxins

Phylum	Class	Species	Toxins
1	2	3	4
Europe region: southern coasts of Europe			
Dinoflagellata	Dinophyceae	*Alexandrium mediterraneum* U. John 2014	saxitoxins
Dinoflagellata	Dinophyceae	*Dinophysis acuminata* Claparède i Lachmann 1859	okadaic acids
Dinoflagellata	Dinophyceae	*Ostreopsis ovata* Y. Fukuyo 1981	palytoxins
Heterokontophyta	Bacillariophyceae	*Pseudo-nitzschia calliantha* Lundholm, Moestrup & Hasle 2003	domoic acids
Dinoflagellata	Dinophyceae	*Gambierdiscus australes* Chinain & M.A. Faust 1999	ciguatoxins
Dinoflagellata	Dinophyceae	*Fukuyoa paulensis* F. Gómez, D.J. Qiu, R.M. Lopes & Senjie Lin 2015	ciguatoxins
Dinoflagellata	Dinophyceae	*Vulcanodinium rugosum* Nézan i Chomérat 2011	pinnatoxins
Dinoflagellata	Dinophyceae	*Azadinium poporum* Tillmann & Elbrächter 2011	azaspiracids
Europe region: south-east coasts of Europe			
Dinoflagellata	Dinophyceae	*Dinophysis acuminata* Claparède & Lachmann 1859	okadaic acids
Dinoflagellata	Dinophyceae	*Dinophysis acuta* Ehrenberg 1839	okadaic acids
Dinoflagellata	Dinophyceae	*Ostreopsis ovata* Y. Fukuyo 1981	palytoxins
Dinoflagellata	Dinophyceae	*Lingulaulax polyedra* (F. Stein) M.J. Head, K.N. Mertens & R.A. Fensome 2024	yessotoxins
Dinoflagellata	Dinophyceae	*Alexandrium minutum* Halim 1960	saxitoxins
Dinoflagellata	Dinophyceae	*Gymnodinium catenatum* H.W. Graham 1943	saxitoxins
Dinoflagellata	Dinophyceae	*Pseudo-nitzschia australis* Frenguelli 1939	domoic acids

cont. Table 5

1	2	3	4
Dinoflagellata	Dinophyceae	*Azadinium spinosum* Elbrächter & Tillmann 2009	azaspiracids
Dinoflagellata	Dinophyceae	*Karenia mikimotoi* (Miyake & Kominami ex Oda) Gert Hansen & Moestrup 2000	gymnocins
Heterokontophyta	Raphidophyceae	*Heterosigma akashiwo* (Hada) Hada ex Y. Hara & Chihara 1987	TBD*
Cyanobacteria	Cyanophyceae	*Nodularia spumigena* Mertens ex Bornet & Flahault 1888	nodularins
Europe region: north-east coasts of Europe			
Haptophyta	Coccolithophyceae	*Prymnesium polylepis* (Manton & Parke) Edvardsen, Eikrem & Probert 2011	prymnesins
Haptophyta	Coccolithophyceae	*Chrysochromulina leadbeateri* Estep, Davis, Hargreaves & Sieburth 1984	TBD*
Dinoflagellata	Dinophyceae	*Dinophysis acuminata* Claparède & Lachmann 1859	okadaic acids
Dinoflagellata	Dinophyceae	*Prorocentrum lima* (Ehrenberg) F. Stein 1878	okadaic acids
Dinoflagellata	Dinophyceae	*Azadinium spinosum* Elbrächter & Tillmann 2009	azaspiracids
Dinoflagellata	Dinophyceae	*Alexandrium catenella* (Whedon & Kofoid) Balech 1985	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium ostenfeldii* (Paulsen) Balech & Tangen 1985	saxitoxins
Dinoflagellata	Dinophyceae	*Alexandrium minutum* Halim 1960	saxitoxins
Europe region: north-west coast of Europe (Russia)			
Dinoflagellata	Dinophyceae	*Alexandrium tamarense* (Lebour) Balech 1995	saxitoxins

* to be determined/decided/declared – toxins associated with the mechanism of lethal action on aquatic organisms are yet to be determined

The marine coast of southern Europe is the Mediterranean Sea, whose waters border the tourist region of Africa and the Middle East. The main algal taxa responsible for the algal blooms in the Mediterranean Sea are the dinoflagellates, *Alexandrium mediterraneum*, *Dinophysis acuminata*, *Ostreopsis ovata* and the diatoms *Pseudo-nitzschia* calliantha. HABs *Alexandrium* spp. and *Dinophysis* spp. are common, but their impact on aquaculture is well monitored and paralytic or diarrhetic shellfish poisoning in humans is rare. *Pseudo-nitzschia* spp. blooms are common, but domoic acid in crustaceans rarely exceeds regulatory levels (ZINGONE et al. 2021).

In contrast, regularly occurring HABs caused by *Ostreopsis ovata* may be associated with health problems in humans. This algae contains palytoxin, which is considered one of the most toxic non-protein substances known. Direct contact with the cells or mucus of *Ostreopsis ovata* results in skin irritation. Respiratory problems, dizziness and headaches in the presence of a bloom are caused by marine aerosols. Poisoning episodes associated with toxic *Ostreopsis ovata* blooms have occurred during the summer in the western Mediterranean, e.g. on the Mediterranean coast of Italy (in 2005 and 2006), Spain (in 2006), France (2006–2009) and Algeria (in 2009), causing a number of health problems for surfers, swimmers, sailors and beachgoers (FERRANTE et al. 2013). HAB species in the Mediterranean whose occurrence is not regular but is increasing are *Gambierdiscus australes* and *Fukuyoa paulensis* (TUDÓ et al. 2020, ZINGONE et al. 2021). This raises concerns about the risk of ciguatera, a disease previously known only for subtropical and tropical areas. Ciguatera is the most common form of seafood poisoning caused by harmful algal blooms worldwide, and its incidence and extent appear to be spreading with the spread of the algal species causing it (MARAMPOUTI et al. 2021). Also of concern are the appearances of the dinoflagellates *Vulcanodinium rugosum*, which produces pinnatoxins and *Azadinium poporum*, an azaspiracid producer. These toxins accumulate in crustaceans and could be a potential source of poisoning in humans (JAUFFRAIS et al. 2013).

On the eastern shores of the Atlantic Ocean, in the European part of the Atlantic Ocean, HABs events are also recorded annually over a large geographical area from southern Spain to northern Scotland and Iceland and further north. There are regional differences in the causal species associated with HABs events. Only *Dinophysis acuminata* and *Dinophysis acuta* are common in the waters of most Atlantic coasts of Europe. On the Atlantic coasts of southern Portugal, Spain and France, there are mass occurrences of *Ostreopsis ovata*, which in 2021 caused health problems in approximately 700 people resting on the coast (CHOMÉRAT et al. 2022). Along the French Atlantic coast, blooms of *Lingulaulax polyedra* also occur. This species produces yessotoxins accumulated in clams, oysters and cockles. Poisoning has not been transmitted to humans despite the touristic nature of the region. These blooms also often cause hypoxia due to the large biomass and long bloom duration (MERTENS et al. 2023). In addition, on the coasts of Spain and Portugal, blooms are often formed by the furuncles *Alexandrium minutum* and *Gymnodinium catenatum* and the diatom *Pseudo-nitzschia australis*, whose range also extends to the coasts of France, England and southern Ireland. Mass occurrences of these algae lead to the accumulation of paralytic (*Dinopystis* spp. and *Alexan-*

drium spp.) or amnesic (*Pseudo-nitzschia* spp.) toxins in aquatic organisms, which can be a threat to human health. However, in this region, there is only an economic loss to wild-caught seafood or aquaculture (BRESNAN et al.). In the coastal waters of Ireland, an additional threat is the presence of the toxic species the small dinoflagellate *Azadinium spinosum*, a producer of azaspiracids, which can accumulate in shellfish and cause disease in humans (McGIRR et al. 2021). In contrast, the majority of aquaculture events and wild fish mortalities have been associated with blooms of the brucellosis *Karenia mikimotoi* and the raphidophyte *Heterosigma akashiwo*. These fish kills are rare but can cause significant mortality. Shellfish mortality has also been linked to *Phaeocystis* spp. blooms, particularly in the southern North Sea (BRESNAN et al. 2021). In addition, the colonial stage of *Phaeocystis* spp. forms massive accumulations and can form periodically dense, very abundant, surface scum and cause threats to the safe use of seashores. In 2020, such scum was observed off the Dutch coast and resulted in drowning incidents (SMITH and TRIMBORN 2024). The Baltic Sea is not free of blooms either. Its narrow connection to the open ocean makes it a low-salinity reservoir. For this reason, blooms in the Baltic Sea are caused by cyanobacteria (PAERL 1996, PALINSKA and SUROSZ 2014). These include *Nodularia spumigena*, *Aphanizomenon* spp. and *Dolichospermum* spp. *Nodularia spumigena* is a toxic cyanobacterial species, producing the toxin nodularin (MAZUR-MARZEC et al. 2007). *Dolichospermum* spp. and *Aphanizomenon* spp. are potentially toxic taxa. They have the potential to produce toxins, but only some strains are toxic (OLOFSSON et al. 2020). This happens during certain periods, as in 2006, when toxic cyanobacteria were observed in different parts of the Baltic Sea. In Sweden, this situation has led to clear restrictions on the use of coastal zones. As a result of the changed leisure and recreation patterns, the island of Gotland and Öland have lost revenue in the order of SEK 150–200 million (approximately €15–20 million) (FOGHAGEN 2011, NILSSON and GOSSLING 2012). Harmful algal blooms (HABs) are also a recurrent phenomenon along the coast of the north-eastern Atlantic, in the waters of the North Sea, the Norwegian Sea and the Barents Sea. The main HAB taxa causing fish mortality in this region are the primnesiophytes of the genera *Prymnesium* (especially *P. polylepis*), *Chrysochromulina* (especially *Ch. leadbeateri*), the furuncles of the genera *Akashiwo*, *Karenia*, *Karlodinium* and the dictyochophytes of the genera *Dictyocha* and *Pseudochattonella*. Blooms of all of these algal genera cause huge economic losses to fish farmers in aquaculture. Shellfish farming and natural stocks are threatened by other HAB species. In northern Europe, diarrhetic shellfish poisoning (DSP) toxins are produced by several species of *Dinophysis* spp., dominated by *Dinophysis acuminata* and by the benthic *Prorocentrum lima*. Periodically, their concentrations in edible mussels, along the coasts of Norway, Denmark and the Swedish west coast, are above regulatory limits. *Azadinium spinosum* blooms have been unequivocally linked to the presence of azaspiracid toxins responsible for azaspiracid shellfish poisoning (AZP) in northern Europe. These toxins were detected in bivalves at concentrations above regulatory limits for the first time in Norway in mussels in 2005 and in Sweden in mussels and oysters in 2018 (KARLSON et al. 2021). However, among fur-browed mussels, *Alexandrium* species are the main source of toxins that often exceed regulatory limits. Several toxic *Alexandrium* species capable of producing toxins are common in northern European waters. Among these, *Alexandrium catenella*, *Alexandrium ostenfeldii* and *Alexandrium minutum* are the most significant producers of the neurotoxins responsible for paralytic shellfish poisoning (PSP) in this region. This is particularly important as the coastal and shelf regions of northern Europe provide a key supply of seafood (KARLSON et al. 2021).

The coasts of northern Russia, which belongs to the tourist region of Europe, are the Arctic belt and the north-western part of Pacific waters, including the Bering Sea and the Sea of Okhotsk In the Russian Far East seas, HABs are mostly formed by the diatom species *Pseudo-nitzchia spp.* or the *dinoflagellates Alexandrium* spp. and *Dinophystis* spp. The species present are toxic and can cause paralytic (PSP), amnesic (ASP) and diarrhetic (DSP) poisoning in humans. They are also detrimental to aquatic organisms causing high mortality, as occurred in the Bering Sea in Russia when a bloom of *Alexandrium tamarense* caused the death of cetaceans, fish and birds. Bloom species also pose a threat to aquaculture. Monitoring of ficotoxins in aquaculture was only introduced in Russia in 2007. Nevertheless, there is no effective government monitoring of HABs in Russia (VERSHININ and ORLOVA 2008).

Conclusions

Toxic algal blooms are an ever-growing problem in virtually every aquatic environment in the world. The number of HAB sites is still increasing. The reasons for this can be traced, on the one hand, to increasing eutrophication of waters related to anthropogenic activities and, on the other hand, to climate change also related to human activities (NWANKWEGU et al. 2019). Eutrophication of waters is caused by high nitrogen and phosphorus loads delivered by sewage discharges, industrial waste discharges, agricultural runoff and aquaculture activities and many other interrelated environmental factors (Davidson et al. 2014, Heisler et al. 2008). Climate change is proceeding in the direction of a warming climate and causing higher ocean water temperatures, which is a direct and indirect driver of the spread of algal blooms. Storms, winds, ocean currents, ocean circulations and other changing natural phenomena also enhance the formation of blooms (Gobler 2020).

All of these causes of HABs lead to negative effects through impacts on aquatic ecosystems and the human economy. The consequences of HABs for aquatic ecosystems include changes in their functioning, often combined with the death of marine organisms (Sellner et al. 2003). HABs also contribute to economic losses. The economic impacts of HABs arise from the costs of public health protection, commercial fishery closures and mass fish die-offs, decreased opportunities for coastal and marine recreation and tourism, and the costs of monitoring and managing HABs. The estimated economic impact of HABs in the United States is approximately US$ 100 million per year (Anderson et al. 2000). The comparable estimate for the European Union (EU) is an order of magnitude higher at US$ 1 billion per year (Hoagland and Scatasta 2006). Most other parts of the world report only ad hoc impact estimates resulting from extraordinary HABs events. An estimated rough breakdown of the costs associated with the impact of HABs on different economic sectors showed that 45% are costs incurred for public health protection, 37% of costs are due to closures and losses incurred by aquaculture and commercial fisheries, and 4% are the costs of monitoring and managing HABs. The economic loss incurred through lost recreation and tourism is 14% (Anderson et al. 2000).

The tourism and leisure industry loses directly through lower accommodation loads and fewer visitors to catering establishments and indirectly through a reduction in the staff needed to support tourism, which contributes to job losses. The reason for less tourism is the reduced attractiveness of the seashore under HABs conditions due to changes in water quality and coastal areas. The distinctive colour and unpleasant odour of the water, accompanying the blooms, significantly degrades water quality and its tourism and recreational value. In the case of toxic algal blooms, direct contact with the water is hazardous to health. The use of bathing and access to recreational water sports is restricted. Recreationally caught fish, crustaceans and molluscs are also a threat to human health. Recreational fishing grounds are closed, courses and cruises are cancelled. Commercial harvesting of fish and seafood is closely monitored to make sure it is safe, but the existing risk of poisoning causes fear of consumption. Coastal areas are also exposed to the negative effects of algal blooms. Decomposing micro or macro algae, dead aquatic organisms cast ashore, reduce the comfort of recreation in coastal areas. A threat to human health during coastal recreation (e.g. beach walks) are the compounds given off during algal decomposition (ammonia and hydrogen sulfide) or toxic algal compounds found in the air, in the form of aerosol. All of this has the effect of diminishing the attractiveness of coastal tourism under conditions where HABs are present and may be a determinant of preferences for the direction of tourism activities undertaken, which may influence the course of development of marine and coastal tourism in different tourist regions of the world.

In order to mitigate the detrimental effects of HAB events on human health, aquaculture, the tourism industry and coastal economies worldwide, it is essential to develop strategies to prevent, predict and control HABs. Several methods are available for monitoring and predicting HABs, including satellite surveys, laboratory studies, field observations and data sampling. A variety of techniques for monitoring, forecasting and early warning of HABs in coastal waters are being used, including space-based sensors, remote sensing, drones, biological identification, toxin analysis, molecular methods, modelling and citizen science programmes (Zahir et al. 2024). However, it is essential to develop an integrated effective monitoring and forecasting system for HABs that includes satellite observations, numerical modelling and machine learning algorithms with in-situ sensors and biosensors. Information extracted from such a system should be available to all economic sectors at risk of HABs, regardless of the region in the world (Alvarez et al. 2024). The tourism sector should be particularly interested in obtaining such information to be able to verify the availability of safe destinations for tourism.

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