Review

Harmful Algal Blooms (HABS) along Mexican coasts

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Abstract: Harmful algal blooms (HABs) are natural events produced by massive concentration of toxic phytoplankton that can color red, ocher, brown or yellow large extensions of water, its intensity depends on the different species of phytoplankton involved in the proliferation. The spreading of these formations involves an interaction of biological, chemical, meteorological and anthropogenic factors. Several species with potential toxicity have been reported along Mexican coasts, such as *Gymnodinium catenatum*, *Karenia brevis*, *Pyrodinium bahamense* var. *compressum*. The toxic bloom not only causes an impact during the event, it produces negative effects afterward, such as accumulating deposits of organic matter, alterations of benthic community structure and composition, species presence/absence, and bioaccumulation of toxins in organisms such as bivalve molluscs mainly. Poisoning may occur by consuming contaminated seafood or by direct exposure to aerosols of the toxins, which can provoke diarrhea or even death. Due to the impact of this type of event on the economy, environment and public health, strategies for monitoring, prevention, and systematic mitigation have been implemented for the evaluation of HAB effects. The aim of this review was to determine the state-of-the art of HAB, their reports and effects on the environment and public health in Mexico.

Keywords: marine biotoxins; contaminated seafood; public health

Key Contribution: The Mexican coast has been the scene of HAB, possibly as a result of the effects of climate change over the years. It is important to identify vulnerable areas, classify and distribute risks, to facilitate decision-making in safeguarding public health.

1. Introduction

Harmful algal blooms (HABs) are natural phenomena that have manifested throughout history. Currently, its impact on aquaculture, fisheries and public health has increased worldwide. Climate change is a phenomenon that affects ecological, cultural and economic relations; as a result, diverse communities around the world will be potentially exposed to damaging environmental changes. In a particular way, the areas or regions (marginalized) with anthropogenic activities that are precursors of this phenomenon will have greater affectations [1]. An example of this is the increase in the frequency of the HABs, as a consequence of some factors associated with climate change [2]. Blooms formation involves the interaction of biological, chemical, meteorological and anthropogenic elements. Where a symbiosis between microalgae and bacteria, known as "Microbial ring" [3] takes place, plus other antagonistic microorganisms that can even decline HABs. Bacteria play an important role in algal blooms control by regulating the impact of its toxicity [4]. Toxic HABs not only cause an impact during the event, they also produce negative effects after this, such as: accumulation and deposit of organic matter, alteration of the benthic communities and

bioaccumulation of biotoxins in filtering organisms such as bivalve molluscs, mainly [5]. In addition to causing large economic losses due to mortality of tons of fish, shellfish, birds and marine mammals [6]. Intoxication caused by microalgae, producers of marine toxins, is associated with the consumption of marine organisms or exposure to their aerosols [7,8]; these are classified according to the signs and symptoms presented. The death of mammals, birds and other marine animals through the food chain are also attributed to them [7,9,10]. Due to the impact of HABs in economy and environmental and public health, some strategies for monitoring, prevention and systematic mitigation have been implemented to evaluate their effects, besides the implementation of a HAB alert network and a surveillance system in establishments with purification systems. The aim of this bibliographic review was to know the state-of-the art of HABs in Mexico, reports on them and their effect on the environment and public health. The Mexican coast has been the scenario of HAB, possibly as a result of the effects of climate change. The use of coastal beaches as recreational areas and the consumption of contaminated aquatic organisms has created the need for constant monitoring of lagoon systems and coastal beaches, carried out by governmental and private institutions. Even when predictions of the potential effects of climate change have been questioned, the possible consequences can be used as a basis in the decision-making and implementation of mitigation actions; besides helping in the design of ecological and political strategies to try to reduce their impact [11].

2. Harmful Algal Blooms (HABs)

HABs are phenomena, which are characterized by population increase of species of phytoplanktonic, toxic or noxious microorganisms of different nature, especially dinoflagellates, diatoms and cyanobacteria. Its presence causes negative effects in the natural populations of marine organisms, in public health and in the development of aquaculture, of tourist and recreational activities in coastal areas [12]. HABs produce a change in color hue of the seawater surface, in the form of "patches or spots", in areas delimited both in extension and in depth. They have different pigments that color the area when the abundance of phytoplankton microorganisms increases. These blooms of microorganisms, in addition to decreasing the dissolved oxygen in the water, have a great ecological impact in many regions of the world and cause mortality of aquatic organisms such as bivalve molluscs, crustaceans [13-15] fish, corals, seabirds [16] and marine mammals [17].

Algal blooms have been described as ecosystems because they have their own structure and an important variability in space and time. Conditions of the physical environment determine the presence of different phytoplankton communities; these being related to the rhythms of intensification and relaxation of the blooms, circulation and contribution of the different water masses [18]. According to Reguera [19], the appropriate term to name this phenomenon is "Phytoplankton Proliferation".

2.1. Elements that trigger HABs

In some regions, HABs are presented as annual phenomena. Its appearance increases the population of microalgae, which favors its concentration [20]. Meteorological changes such as: the decrease of the ozone layer, the greenhouse effect, the phenomenon of the Niño, and the upwellings produced by periods of turbulence or agitation [21,22] are some of the factors that trigger HABs. In addition, the contribution of inland waters used as ballast in ships, and the dumping of industrial, domestic and agricultural waste in coastal areas [23]. In general, for Glibert et al. [24], the factors that determine HABs and its effects are the physical stress, the supply of nutrients, the type and behavior of the organisms.

2.2. Factors that influence the increment of microalgae

The eutrophication of aquatic systems is the cause of the increase of nutrient levels, especially nitrogen and phosphorus (N and P), from: a) Specific contributions, without treatment, of domestic, urban or industrial wastewater; with high content of N and P due to the fluvial drainage of the

lands. b) Contributions of water from the washing of soils from cultivated areas and fertilized with N and P, or pastures with livestock.

The permanence of the contributions in the aquatic system favors the dominance of dinoflagellates in the phytoplankton community. Likewise, the descent and rise in water temperature influence the encystment and excystation of dinoflagellates, respectively. These cysts play an important role in the dispersal dynamics of the species, and may even be an important source of toxins for other aquatic organisms [25].

Light intensity is an essential factor for the processes of photosynthesis in the vegetative form. Changes in salinity produced by a contribution of fresh water or by a high rainfall, favor the appearance of HABs. Turbulence in the water produced by marine currents (upwelling) favors the concentration and dispersion or transport of microalgae. And the presence of organic matter from the drainage of lands, decomposition of marine plants, dead fish or other organisms, triggers their appearance and permanence. Physiological, behavioral and trophodynamic interactions of HABs depend on, interactions with other members of the microbial community, swimming capacity, aggregation, allelopathy, and the use of specific nutrients [24]. Even some producing species have developed various allelochemical strategies to compensate ecological disadvantages [25].

Climate change is a phenomenon that affects ecological, cultural and economic relationships around the world [1]. An example of this is the increase in the frequency of HAB, as a consequence of the interaction of biological, chemical, meteorological and anthropogenic elements in coastal areas [2,20,24].

2.3. Association Bacteria-Phytoplankton

The association between heterotrophic bacteria from coastal waters and toxic phytoplankton is known as the "microbial ring". The resulting bacterio-phytoplankton interaction forms a fundamental part of the ecosystem due to its direct interaction with the environment [3]. The bacteria play the role of recyclers of organic matter due to the release of inorganic nitrogen during its decomposition. They also absorb nutrients and produce proteins that promote microalgal growth [3,26,27].

There are other bacterial components capable of lysing microalgal cells [28]. These specific interactions between bacteria and phytoplankton produce a positive (symbiosis) or negative (antagonistic) effect [3]. Currently, techniques are used that allow the visualization of intracellular bacteria within the dinoflagellates that multiply independently, this phenomenon is called: "bloom inside the bloom". This phenomenon has been observed in the dinoflagellates *A. catenella*, *Protoceratium reticulatum* and *P. micans* [29]. The number of bacteria observed is a result of its intracellular bacteria multiplication or re-infection from broken cells with high heavy bacterial infection. Additionally, the bacteria isolates from each dinoflagellate are capable to re-infect both dinoflagellates regardless of their origin. Furthermore, the interaction between intracellular bacteria and the dinoflagellate is bimodal, that is to say; during the logarithmic phase of cultivation it is mutualistic, while in the stationary phase bacteria become parasitic, thus killing the host cell. This is probably the cause of the rapid decline of blooms in nature [30,31]. The antagonistic effect of phytoplankton on bacteria can also occur between pathogenic bacteria and diatoms such as *Skeletonema costatum*, which has a pharmaceutical application [32]. The use of the symbiosis between microalgae and bacteriophages, as agents of biological control in the elimination of *Vibrio harveyi*, has been reported in the Mexican Pacific Ocean. Likewise, in aquaculture, microalgae have been used for their effectiveness and selectivity on *V. furnissi*, due to the inhibitory effect of secondary metabolites [33,34]. Orozco et al. [35] reported the predominance and association of *V. alginolyticus* and *V. parahaemolyticus*; with HAB producing species such as *Akashiwo sanguinea*, *Messodinium rubrum* and *Prorocentrum minimum*, and the dinoflagellate *Cochlodinium polikrykoides*.

3. Environmental effects

The algal blooms are not necessarily toxic, but they can be harmful. The term blooming can imply a risk or danger to the environment and public health problems when it occurs in a range of several billions of cells per liter. When fish or shellfish consume these microalgae or come into contact with aquatic biota, they die due to the destruction of the tissue structure of the gills, digestive system and circulatory system [36]. Moreover, the effect or negative impacts on the populations of vulnerable species such as migratory birds, which feed on toxic marine organisms [37]. Toxic HABs not only cause impacts during the event, they also have subsequent negative effects, such as, alteration of the ecosystem, accumulation and deposit of organic matter, modification in benthic communities, and also accumulation of biotoxins in organisms that feed by filtration, mainly [5]. The accumulation of biotoxins goes through a biological amplification, this causes that people who have consumed fish or shellfish with phycotoxins in their tissues, become intoxicated [38].

4. Toxins

The toxins produced by HAB-forming microorganisms are responsible for a series of syndromes or poisonings associated with the consumption of marine organisms, or to the exposure to these in the form of aerosols [8]. These toxins are odorless, colorless, thermostable and stable under acidic conditions. Generally, they accumulate in viscera and other tissues of fish and molluscs [39], which are consumed by man and tend to be manifested by a symptomatology that will depend on the type and concentration of the toxin [40]. Mutations have been identified in bivalve molluscs that confer the ability to accumulate paralytic toxins; this phenomenon can act as a natural selection agent in clam populations. However, for humans, this increases the risk of intoxication [41]. Neurotoxins damage the nervous system of vertebrates and invertebrates differently. For example, some dinoflagellate toxins cause mortality in the stages of larvae, juveniles and adults of different species, due to the direct exposure of the dissolved toxin or by the intake of harmful dinoflagellates. On the other hand, vertical poisoning may occur when the toxin is transferred to the fish through herbivore zooplankton [42]. Experimentally, it has been observed that intoxicated fish swim erratically, fall to the bottom of ponds and remain paralyzed until their death [43,44].

Groups of toxins have been classified according to the signs and symptoms of the syndrome or poisoning they cause. Also, depending on the type of organism that contains it [14,40] (Table 1):

- 1) Paralytic Shellfish Poisoning (PSP), produced by saxitoxin.
- 2) Amnesic Shellfish Poisoning (ASP), produced by the domoic acid toxin.
- 3) Neurotoxic Shellfish Poisoning (NSP), produced by brevetoxin.
- 4) Diarrhetic Shellfish Poisoning (DSP), produced by the Okadaic acid toxin.
- 5) Ciguatera Fish Poisoning (CFP), produced by the ciguatera toxin.
- 6) Intoxication by cyanotoxins, produced by Cyanobacteria.

All poisonings, except ASP, Ciguatera and those caused by cyanobacteria, are caused by toxins or biotoxins synthesized by phytoplankton, or dinoflagellates. Diatoms produce the domoic acid toxin, and toxins from reef fish cause CFP. Ciguatera toxins are transferred through the food chain of reef fish, to larger carnivorous fish of commercial value [40].

Table 1. Types of marine biotoxins and human diseases associated with Harmful Algal Blooms (HABs), along the Mexican coast.

Biotoxin/ Route of Acquisition	Poisoning/ Intoxication	Microalgae	General Symptoms	Mechanism of Action
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Saxitoxin/ Consumption of cultivated or wild molluscs from affected areas.	Paralytic Shellfish Poisoning (PSP), from consumption of molluscs.	Dinoflagellates: Previous Name: <i>Alexandrium catenella</i> , <i>Acatenella tamarensis</i> . Current Name: <i>Gymnodinium catenatum</i> (*), <i>G. mikimotoi</i> A. <i>minutum</i> (*), A. <i>tamiyavanichi</i> (*), A. <i>andersoni</i> , A. <i>cohorticula</i> , A. <i>minutum</i> , A. <i>tamarensis</i> , A. <i>monilatum</i> (*), <i>Pyrodinium bahamense</i> <i>var. compressum</i> (*) Cyanobacteria. <i>Cochlodinium</i> , <i>Polykrikoides</i> (*).	After 30 minutes: tingling; numbness in the face, neck and hands; headache; nausea; vomiting; diarrhea; difficulty breathing; muscle paralysis and death from respiratory failure within 2- 24 hours after consumption.	Binds to the sodium channel and inhibits electrical signals that maintain nervous system activity, vegetative and synaptic.
Brevetoxin/ Consumption of cultivated or wild molluscs from affected areas; aerosols of the toxins produced by wave action.	Neurotoxic Shellfish Poisoning from the consumption of molluscs (NSP).	Dinoflagellates: Previous Name: <i>Ptychodiscus brevis</i> , <i>Gymnodinium breve</i> Current Name: <i>Karenia</i> <i>brevis</i> (*, **), <i>K. brevisulcatum</i> , <i>K. selliformis</i> , <i>K. bidigitata</i> , <i>Karenia</i> spp. <i>Pfiesteria piscida</i> (neurotoxic), <i>P.</i> <i>Shumwayae</i> .	Neurological symptoms after 3-6 hours: chills; headache; muscle weakness; nausea; vomiting; diarrhea; feelings of hot and cold; irritated eyes; double vision; difficulty speaking and swallowing; death from respiratory arrest.	Depolarizing acts on active sodium channels, altering the properties of the membrane of excitable cells to favor the inward flow of sodium ions.
Domoic Acid/ Consumption of molluscs from affected areas	Amnesic Shellfish Poisoning from the consumption of contaminated molluscs (ASP).	Diatoms: <i>Nitzschia</i> <i>pungens</i> var, <i>Multiseria</i> <i>Pseudonitzschia</i> <i>delicatissima</i> , <i>Pseudonitzschia</i> <i>multiseria</i> , <i>P.</i> <i>Pseudodelicatissima</i> (*). Previous Name: <i>N. pseudoseriata</i> Hasle Current Name: <i>Pseudonitzschia australis</i> (*), <i>P. seriata</i> (*, **), <i>P.</i> <i>Fraudulenta</i> (*), <i>P.</i> <i>multistriata</i> , <i>P. Pungens</i> (*), <i>P. Calliantha</i> (*), <i>P.</i> <i>Cuspidata</i> (*), <i>Amphora</i> <i>coffaeiformi</i> , <i>Nitzschia</i> <i>navis-varingica</i> , <i>Thalassiosira</i> .	After 3-5 hours, gastrointestinal symptoms such as vomiting, diarrhea and abdominal cramps occur, with mild to severe pain, and dyspnea. Neurological symptoms such as disorientation, nausea, dizziness, low temperature, confusion and temporary memory loss.	Domoic acid binds with glutamate receptors located in the central nervous system. Domoic acid activates these receptors opening ion channels that allow passage into neurons of high concentrations of calcium ions, causing destruction of these cells and the loss of short- term memory in affected individuals.

Okadaic Acid/ Consumption of molluscs from affected areas.	Diarrheic Shellfish Poisoning from the consumption of molluscs (DSP).	Dinoflagellates: <i>Dinophysis acuminata</i> (), <i>Dinophysis caudata</i> (*,**), <i>D. norvegica</i> (*), <i>D. fortii</i> (*,**), <i>D. sacculus</i> (*,**), <i>D.</i> <i>miles</i> (), <i>D. acuta</i> , <i>D.</i> <i>mitra</i> , <i>D. rotundata</i> , <i>D.</i> <i>rapa</i> , <i>D. tripos</i> , <i>Dinophysis</i> <i>spp.</i> , <i>Prorocentrum lima</i> (*,**), <i>P. arenarium</i> , <i>P. belizeanum</i> , <i>P.</i> <i>cassubicum</i> , <i>P. concavum</i> , <i>P. emarginatum</i> , <i>P. hoffmannianum</i> , <i>P. maculosum</i> , <i>P. dentatum</i> (*), <i>P. minimum</i> (*), <i>P. gracile</i> , <i>Procentrum spp.</i> , <i>Phalacroma rotundatum</i> .	After 30 minutes, gastrointestinal symptoms such as diarrhea, nausea, vomiting, abdominal pain and chronic exposure promotes the formation of tumors in the digestive system.	Phosphorylase and phosphatase inhibitor with the latter regulating cellular functions such as mutagenesis.
Ciguatera Scaritoxin Maitotoxin Ciguatoxin/ Transfer through the trophic chain; consumption of tropical and subtropical fishes.	Ciguatera	Dinoflagellates: <i>Gambierdiscus toxicus</i> (Maitotoxin) (*,**), <i>G. australes</i> , <i>G. pacificus</i> , <i>G. polynesiensis</i> , <i>G. yasumotoi</i> , <i>Ostreopsis</i> <i>heptagona</i> , <i>Ostreopsis spp.</i> (*,**), <i>Coolia spp.</i> (,), <i>Prorocentrum lima</i> (*,**).	Development of symptoms after 12 to 24 hours: gastroenteric symptoms such as acute gastroenteritis, metallic taste, nausea, diarrhea, stomach pains; neurological symptoms such as numbness and tingling of hands and feet, muscle pain, paresthesia in extremities, tachycardia, bradycardia, hallucinations, and death from respiratory failure.	Depolarizing activates sodium channels, altering membrane properties of excitable cells to favor the inward flow of sodium ions.
Neosaxitoxin Saxitoxin/ Direct contact or water consumption.	Cyanobacteria	<i>Cyanophyta</i> , <i>Aphanazomenon flosaquae</i> , <i>Anabaena circinalis</i> . <i>Ocillatoria</i> . <i>Microcystis sp.</i> <i>M. aeruginosa</i> . <i>Trichodesmium</i> <i>erythraeum</i> (*,**) and <i>T.</i> <i>Thiebautii</i> .	Acute toxicity: skin irritation, atypical pneumonia, vomiting abdominal pain and acute gastroenteritis, liver diseases, tumors by chronic exposure.	Binds to the sodium channel and inhibits electrical signals that maintain higher nervous system, vegetative and synaptic activity.

*Records in the Mexican Pacific, **Records in the Mexican coast of the Gulf of México. Modified of: Suarez & Guzmán [45]; Ricourt-Regús [46]; Vergara [47]; Hernández-Orozco & Gárate-Lizárraga [48]; Masó & Garcés [49]; Erdner et al. [9]; Herrera et al. [8]; Pérez et al. [10]; COFEPRIS [50].

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5. Incidence of HABs in the Mexican coast

Mexico has 11,000 km and 1,567,300 ha of coastal areas and bays, including 58 ports and stations in the Pacific Ocean and 59 in the Gulf of Mexico and the Caribbean Sea [51]. Because of its geographical location and terrestrial ranges, the following ports serve as economic corridors and are classified as ports of national scope: Cayo de Arcas, Veracruz, Coatzacoalcas, Tuxpan, Altamira in the Gulf of Mexico; Punta Venado in the Caribbean Sea; and Ensenada, Isla Cedros, Lázaro Cárdenas, Manzanillo in the Pacific Ocean. And thus receive more than 89% of the 288 million tons of total cargo [52]. This has caused coastal shipping, yachts and fisheries to be the most important commercial activities in Mexican ports since 1998. This has also resulted in around 50 million cubic meters of ballast water to be discharged into waters off the Mexican coast [53].

Mexico lacks regulations for ballast water of ships, and the flora and fauna that can be transported in it; scarce regulation for the management of aquaculture species, trade in of marine resources with economic potential, and other transport routes for non-native aquatic species [54]. This may be the main cause of the incidence of HAB and the presence of non-endemic phytoplankton species in the coasts of the Mexican littoral.

In studies conducted on the coasts of the Mexican Pacific Ocean, the Gulf of Mexico and the Caribbean Sea, from 1980 to 1992, HABs were reported and thirteen species of toxic microalgae were identified. Among those that stand out: *Pyrodinium bahamense*, *Gymnodinium catenatum*, *Alexandrium* sp, *Karenia brevis* and *Prorocentrum minimum* [55]. In these different littorals there are reports of HAB produced by the dinoflagellate *Karenia brevis* [56,57], as well as in the Gulf of Tehuantepec [58].

In Mexico, intoxications such as PSP and NSP have been reported as a consequence of the presence of these microalgae. There are also reports of ASP, DSP and Ciguatera for consumption of bivalve molluscs, mainly clams, but less frequently [48,59,63].

Poisonings caused by dinoflagellates have been recorded in the coasts of the Gulf of California, Baja California Sur, Sonora, Sinaloa, Colima, Michoacán, Jalisco, Guerrero, Oaxaca, Chiapas in the Pacific littoral, and Quintana Roo in the Caribbean Sea [59,60].

Tropical fish are another type of vector causing the poisoning called ciguatera, caused by the ciguatera toxin produced by the dinoflagellate *Gambierdiscus* spp.

5.1. Gulf of California and Mexican Pacific Ocean

Poisonings caused by dinoflagellates have been recorded in the coasts of the Gulf of California, Baja California Sur, Sonora, Sinaloa, Colima, Michoacán, Jalisco, Guerrero, Oaxaca, and Chiapas in the Pacific littoral [59,60]. In addition to the presence of diatoms that produce the domoic acid toxin in the Gulf of California, Baja California Sur, Sinaloa, Nayarit and Chiapas [50,60]. Plus, species of *Alexandrium* spp, *Alexandrium minutum*, *Pyrodinium bahamense* var. *compressum*, *Pseudo-nitzschia* sp., *Porocentrum dentatum*, *P. minimum*, *Gymnodinium catenatum*, *Cochlodinium polykrikoides* in the Mexican Pacific Ocean [12,61-63].

HABs have generated a public and environmental health problem, causing effects on natural resources, tourism and ecosystems of almost the entire world [63]. In Mexico, cases of intoxication have been reported in humans and marine species [12,55,56,59].

An example of this is the event that affected the coastal fauna of La Paz Bay caused by *Pseudo-nitzschia fraudulenta*, *P. pseudodelicatissima*, *P. pungens* and other diatoms. The authorities of Baja California Sur government estimated that 650 fishing families in this bay were affected. As a result, the government distributed economic support and food pantries for a total of \$ 70,000. The region was declared in a state of emergency and federal agencies such as SEDESOL, SAGARPA, among others, provided additional resources to the affected fishermen through programs such as "temporary employment" [64]. In the state of Oaxaca, during the period 1989 to 2014, 14 HABs originated by paralytic toxin-producing species have been identified; 139 intoxications and 9 deaths were reported due to the consumption of molluscs contaminated with saxitoxins. These events represented more than half a million dollars in losses and 708 days of sanitary closure to avoid the risk to public health [65].

Mass mortalities of approximately 64,172 marine animals occurred in Bahía Magdalena, BCS in 1992; including 37 species of wild animals, 24 species of fish, 10 species of birds, 2 species of marine mammals and one species of marine turtle [66].

In 2007, the proliferation of the dinoflagellate *Ceratium divaricatum* on the northeast coast of Ensenada, Baja California, caused anoxic conditions that produced an ecological catastrophe in benthic organisms such as lobsters, starfish and crabs. The lobster population was the most affected, with a dead biomass of more than 5 tons. This caused a considerable economic loss for the fishing sector [67]. In that same year, in the region of Punta Abreojos to La Bocana, BCS, HABs caused by the dinoflagellate *Akashiwo sanguinea* were reported, causing the death of approximately 100,000 locusts (*Panulirus interruptus*), the equivalent of 45 tons; most of them were ovigerous females. In addition, there was a mortality of 2.5 tons of abalone (*Haliotis* spp.), cultivated oysters (*Crassostrea* spp.), and various species of snails and fish [68,69]. This event resulted in an estimated loss of \$1,784,616.

HABs and its marine toxins are causing an important impact on the health of wild and cultivated organisms in the Gulf of California, as well as on the economy of the fishing communities [6]. In this sense, for more than three decades, information on species that cause HAB in the Gulf of California has been generated, determining its temporality, geographic distribution and harmful potential. There have been found 94 species of algae-forming microalgae. The blooming of dinoflagellates is of greater attention, due to the duration and toxicity of species such as *G. catenatum*, *P. bahamense* and *C. polykrikoides*. The latter was registered for the first time since 2000 [70]. In the Pacific Ocean, in the state of Oaxaca, in the last 25 years, mortalities of up to 20 tons of fish have been reported, with their consequent economic loss [65].

The main marine toxins that have caused an impact on the ecosystem and public health in the Gulf of California are: Domoic acid (DA); Okadaic acid (OA) and analogues; P-Ciguatoxins (P-CTX); Lyngbyatoxins (LbTx); Saxitoxin (STX) and analogues; Tetrodotoxin (TTX) and analogues.

It is important to implement monitoring programs in areas where the incidence of these events has been recurrent, for example; Mazatlan Bay, Sin., Concepción Bay, BCS., La Paz, BCS., El Pardito Island and Punta San Evaristo, Cerralvo Island, Ensenada de Muertos and El Sargento, Bay of Guaymas, Son.; Balandra Beach, BCS., Guerrero Negro, La Paz, Vizcaino, San Juan de la Costa, BCS; Teacapán, Sin., Mazatlán, Sin., and Upper Gulf of California [71]. Including the areas where these events are beginning to be detected as: Matanchén, Bahía de Banderas, Nayarit, and Kun Kaak Bay, Son. Other impacts that are difficult to notice and that may affect other populations of marine organisms with lethal and sublethal effects on fish, larval and juvenile embryos have been identified [6]. Therefore, the economic risks and losses for fishing, aquaculture and tourism development zones generated by these events must be considered.

The predominance of the genus *Gymnodinium* sp. HAB trainer in the Mexican Pacific Ocean is due to its distribution and that tolerates a wide range of temperature, salinity and proportions of N: P [72]. *Pyrodinium bahamense* is another dinoflagellate producing paralyzing toxins; it has been reported in the Gulf of Tehuantepec [73], in the Coast of Guerrero [74], and Michoacán [75].

5.1. Gulf of Mexico and Caribbean Sea

According to Núñez-Vázquez *et al.* [71], as a result of the HABs, there have been human intoxications and 20 deaths, in the last 35 years in the Gulf of Mexico, in addition to massive mortality of wild animals (fish, birds and marine mammals) and culture (shrimp and fish). The main species that gave rise to these impacts were the dinoflagellates *Akashiwo sanguinea*, *Cochlodinium polykrikoides*, *Dinophysis* spp., *Gymnodinium catenatum*, *Noctiluca scintillans*, *Prorocentrum minimum*; the diatoms *Chaetoceros* spp., *Pseudo-nitzschia australis*, *P. fraudulenta*, *Pseudo-nitzschia* sp., *Thalassiosira* sp.; the raphydiaceae *Chattonella subsalsa*, *Chattonella marina*, *Chattonella* sp., *Fibrocapsa japonica*, *Heterosigma akashiwo*, and cyanobacteria *Lyngbya majuscula* and *Schizotrix calcicola*.

HABs have increased since 1994 in the Gulf of Mexico; these events have been recorded in the states of Tamaulipas, Veracruz, Tabasco and Yucatan being caused by different dinoflagellates [50, 56,59,60.] (Figure 1).

Figure 1. Phytoplankton, which produces toxins in HABs, is reported in the Mexican littoral. Modified by Ochoa [60]; COFEPRIS [50]; García-Mendoza et al. [76]; Bustillos-Guzmán et al. [77]; Gárate-Lizárraga et al. [78]; Núñez-Vázquez et al. [79]; Pérez-Morales et al. [80]; Quijano-Scheggia et al. [81]; Sánchez-Bravo et al. [82].

One of the main problems of the Yucatan Peninsula is the contamination of groundwater by organic matter and nutrients, which are discharged into the coastal zone. This condition favors the frequency, intensity and magnitude of the algal blooms in the Yucatán coast [83]. In the state of Veracruz, poor wastewater management is the main cause of nutrient inputs to coastal waters. The increase of orthophosphates and nitrates correspond mainly to the rain regime. In the coastal area of the port of Veracruz, Boca del Río and Anton Lizardo, there are records of microalgae reported as potentially toxic species with high abundances such as *Trichodesmium erythraeum*, *Pseudo-nitzschia delicatissima*, *Pseudo-nitzschia pseudodelicatissima*, *Pseudo-nitzschia pungens*, *Amphidinium carterae*, *Coolia monotis* and *Prorocentrum lima* [84]. According to Poot-Delgado [85], in Campeche the presence of potential harmful species such as *Karenia brevis*, *Pyrodinium bahamense* var. *bahamense*, *Prorocentrum mexicanum*, *P. minimum* and the cyanobacterium *Cylindrospermopsis cuspis*; with maximum abundances during the rainy season (June-September).

In the Laguna de Términos, Campeche in 2011, 32 HAB forming species were identified, 10 of which produce toxins by the dinoflagellates *Gonyaulax spinifera*, *Prorocentrum cordatum* and *P. rhathymum* and the cyanobacteria *Anabaenopsis circularis*, *A. elenkinii*, *Aphanizomenon ovalisporum*, *Cylindrospermopsis cuspis*, *C. philippinensis*, *Dolichospermum circinalis* and *Pseudanabaena catenata* [86].

In the port of Veracruz, in 2001 and 2002, responsible personnel reported the death of six sharks recorded on the Isla de Sacrificios, and manifestations of stinging in throat and eyes at the time of handling the dead specimens. This event was associated with a blooming of the dinoflagellate *K. brevis* [84].

In the Gulf of Mexico, ciguatera is a recurrent event due to the presence of three toxic species: *G. toxicus*, *G. yasumotoi* [87], and *Prorocentrum lima*. The latter is responsible for DSP poisoning [54]. Particularly, in the Yucatan Peninsula, ciguatera is caused by potentially harmful species such as *Gambierdiscus* spp., *Prorocentrum* spp., *Ostreopsis* spp., *Dinophysis* spp., *Pseudo-nitzschia* spp., *Pyrodinium bahamense* var. *bahamense*, *Trichodesmium erythraeum* and *Dolichospermum flosaquae*. In addition, the presence of ciguatoxins, tetrodotoxin and analogues, and paralyzing toxins (saxitoxin and analogues) has been confirmed [79].

Other species, such as *Dinophysis caudata*, has been reported in the Gulf of Mexico [88]. In addition to this, the presence of the species *K. Brevis*, producer of brevetoxins, has been detected, this species is responsible for neurotoxic shellfish poisoning (NSP) especially in the Gulf of Mexico, where it has caused impacts on public health and wildlife. During the period 1996-2015, at least 244.5 tons of dead fish from different wild species were counted, as well as some crustaceans. Tamaulipas and Veracruz are the main states affected by the number and duration of closures for the extraction and commercialization of bivalve molluscs [79]. The proliferations of toxic species such as *Pseudonitzschia pseudodelicatissima*, *P. fraudulenta* and *P. australis*, are producers of domoic acid causing ASP poisoning, which causes havoc in public health and causes the death of large quantities of aquatic species [89,90].

6. Climate change and HABs in coastal zones

The impact caused mainly by anthropogenic activities on coastal ecosystems and oceans worldwide is increasing due to the growth of human settlements, change of land use in hydrological basins, deforestation, use of agrochemicals in agriculture and industrial waste, among others. This has caused an increase in the load of rivers and streams that flow into coastal ecosystems, worsening water quality, raising the level of turbidity and eutrophication, plus generating zones of hypoxia and anoxia [91]. The deterioration of coastal ecosystems, especially those with longer residence times and low dispersion rates, is produced by the accumulation of nutrients and organic matter from surface runoff and groundwater, atmospheric depositions of greenhouse gases, meteorological phenomena and effects produced by climate change. Such as, increase in temperature, viscosity and stratification of the water column, increase in salinity, floods and droughts. Therefore, all of these elements accelerate the process of eutrophication in coastal ecosystems, produce changes in current patterns and geography, increase hypoxia zones, and cause phenomena such as harmful algal blooms [2]. It has been projected that increases in the concentration of greenhouse gases will have a negative impact on the climate. The risk for marine and freshwater systems is the increase in surface temperature, to the extent of causing physicochemical changes in the water column [92].

According to Hallegraeff [93], predictions of the impact of climate change on HABs present a series of difficulties. Ecophysiological experiments show the following scenarios: 1) the expansion of hot water species at the expense of the cold water species, 2) specific changes in the abundance and seasonal window of growth of the taxa of the species, 3) the precocity of the maximum production of some algal organisms and 4) secondary effects for marine trophic networks. Anderson et al. [25] indicate that the detection of these events requires records of algal blooms from a single location, of at least 30 consecutive years. However, the set of available data and short-term studies related to El Niño episodes are very useful.

Mexico has more than 100 coastal ecosystems in its territory, mostly shallow and of organic origin, with muddy bottoms and an important content of organic matter. The coastal systems are of great importance for their productivity; they offer a shelter to juvenile species for their reproduction, habitat, and breeding; besides offering food to a biodiversity of species. These ecosystems are of ecological and economic interest, both for the environmental services they provide, and because they harbor various aquatic resources of high commercial value [94].

The effects of climate change are observed in different sectors of production, one of which is the aquaculture-fishing sector. The environmental impacts have undoubtedly affected the life cycle of aquatic species, and hence, its capture, handling, benefit and transport. According to Soto and Quiñones [95], climate change will have a direct and indirect impact on marine capture fisheries and inland waters affecting economies dependent on fishing. The use of fossil fuels in fishing and aquaculture activities have contributed, albeit moderately but significantly, to greenhouse gas emissions. The consequences of this can be diverse, that is; the acidification of the oceans, the damages produced by the change of land use in coastal areas, the changes in oceanographic circulation patterns, the effect of rainfall and the decrease in the availability of fresh water; they can

produce biophysical changes in the distribution and production of marine and inland water resources [11].

According to Bintz et al. [96], the increase of the temperature in the summer and the enrichment of the coastal lagoons favor the presence of HABs. Its effect has been observed during the last decade, for example; the decrease in the abundance of seagrass contributes to the low availability of the substrate for the fixation of various organisms. In addition, the damping of currents, the increase of hypoxic areas, as well as the impact on other services of reproduction, breeding, shelter and feeding. The intensity of these effects is related to the availability and enrichment of nutrients in the water. The decline of seagrass beds in the coastal areas of the country has been caused, mainly, by anthropogenic activities [97].

7. Impact on Public Health

According to Perpezak [98], the effects of climate change include the 4°C increase in water temperature and its stratification. Undoubtedly, this brings about an increase of algal blooms of harmful species and an increase in the number of poisonings caused by the ingestion of contaminated marine foods [5]. Currently, interest in these events or phenomena has increased worldwide, as a result of the high mortalities of marine organisms caused by the degradation of ecosystems.

In addition to the economic losses that affect, mainly, regions where aquaculture activities are important [6], the presence of blooms by cyanobacteria has become a serious problem. Not only because of the effects it causes on the water resource and the ecosystem, but also because of the damage it causes to public health.

Since these cyanotoxins are considered the most important source of risk because poisoning by cyanobacteria is associated with drinking and recreational water from lakes, rivers, seas, beaches and [99,10]. Currently, in Mexico, there are few studies on algal blooms by cyanobacteria and their effects on fresh or artificial bodies of water. There is little attention to the assessment of risks to human health and the associated biota [80].

There are also blooms due to oscillatory cyanobacteria, such as those reported in Bahía de la Paz in the Gulf of California. In this place, between 2005 and 2007, there were seven blooms produced by *Trichodesmium erythraeum* and *T. Thiebautii*, without negative effects on the marine biota of the area [100]. In Mexico, the main species of cyanobacteria reported as forming blooming belong to the genera, *Anabaena*, *Anabaenopsis*, *Cylindrospermopsis*, *Microcystis*, *Nodularia*, *Phormidium*, *Planktothrix* and *Pseudanabaena*. Reports of the presence of cyanotoxins in the central zone of the country have been made (2000- 2015), such as *microcystins*, *cylindrospermopsins*, *saxitoxins*, *nodularins* and *lipopolysaccharides* [80].

Due to the potential impact of the HABs in the different sectors, monitoring strategies have been implemented for the prevention and systematic mitigation for the evaluation of their effects [101,102]. For the specific case of HAB by cyanobacteria, timely attention is recommended through continuous monitoring and training of personnel specialized in the identification of species and analysis of cyanotoxins [80]. In Mexico, federal and local government institutions are collaborating and conducting monthly monitoring for the early detection of HAB by quantifying phytoplankton. The maximum permissible limits of the different phytoplankton species, in seawater, are: *Alexandrium* spp. (PSP) 1000 cel/l, *Pyrodinium bahamenses* var *compresum* (PSP) 5000 cel/l, *Gymnodinium catenatum* (PSP) 5000 cel/l, *Dinophysis* spp. (DSP) 200 cel/l, *Prorocentrum lima* and *P. concavum* (DSP) 200 cel/l, *Pseudonitzschia* spp. (ASP) 50,000 and *Karenia brevis* (NSP) 5000 cel/l [50]; in the case of cyanobacteria 100,000 cel/l [99].

Public education institutions and research centers have carried out systematic monitoring on the coasts of Baja California. The Ministry of the Navy maintains a permanent program of HAB monitoring in coastal areas of the middle part of the Mexican Tropical Pacific. On the other hand, in the Gulf of Mexico, buoys have been installed for HAB monitoring, mainly of *Karenia brevis* [63,103]. In Veracruz, the "Red Tide" program has monitoring stations for blooming detection of microalgae that produce brevetoxins in order to send timely warnings on the coasts of the Gulf of Mexico [104].

8. Final Comments

Even when predictions of the potential effects of climate change have been questioned, the possible consequences can be used as a basis in the decision-making and implementation of mitigation actions; besides helping in the design of ecological and political strategies to try to reduce their impact [11].

It is important to emphasize the identification of vulnerable zones for the classification and distribution of risks. Also, promote resilience as part of a maintenance system [1]. In consideration of the extensive environmental and economic services provided by the coastal and oceanic systems, it is important to prevent the imminent collapse of these ecosystems through management for restoration, care of the water bodies and ecological biodiversity [105].

The Mexican coast has been the scenario of HAB, possibly as a result of the effects of climate change. The use of coastal beaches as recreational areas and the consumption of contaminated aquatic organisms has created the need for constant monitoring of lagoon systems and coastal beaches, carried out by governmental and private institutions. These institutions play an important role in the creation of networks and in the integrated system of HAB observations. This allows the planning and implementation of new management strategies for the sustainability of the environment and rivers, for the reduction and treatment of nutrients and other pollutants discharged in the riparian zones and damp wetlands; as well as the management of governmental regulatory measures.

It is important to address issues such as the standardization of sample monitoring and analysis methods, the use of real-time satellite information systems, and research on the isolation of innocuous marine bacterial strains with antagonistic activity on phytoplankton-producing HAB species. This allows us to generate and expand research lines in our country on the adequate management of water resources, introduction of exotic and harmful species, molecular tools, socioeconomic analysis and impact on aquaculture, wildlife and fisheries. And also, there are strategies to contribute to the knowledge of this phenomenon and its causes, such as mitigation, genotoxicity, chronic exposure and biotechnology of HAB species.

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