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Harmful Algal Blooms and Shellfish Poisoning in Chinese Seas: Current Knowledge and Future Perspectives

Ziyue Liu

University of Southern California, 3551, Trousdale Pkwy, Los Angeles, CA, United States
ziyueliu33@gmail.com

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Abstract: Harmful algal blooms (HABs) have increased in frequency, diversity, and toxicity across the China Seas, including the Bohai Sea, Yellow Sea, East China Sea, and South China Sea, driven by nutrient pollution, climate change, and coastal development. These blooms pose significant threats to marine ecosystems, aquaculture, and human health through the accumulation of diverse biotoxins in shellfish, such as paralytic, diarrhetic, amnesic, and neurotoxic shellfish poisoning toxins. Despite advances in traditional and remote sensing monitoring techniques, current efforts remain regionally fragmented and lack integration across biological, chemical, and environmental data. Drawing on successful interdisciplinary frameworks from the US and Europe, this review highlights the need for a comprehensive, integrated ocean observing system in the China Seas that combines molecular detection, toxin quantification, real-time monitoring, and predictive modeling. Such an approach, supported by standardized data protocols and multi-stakeholder collaboration, will enhance early warning capabilities, risk assessment, and sustainable management of HABs and shellfish toxins, safeguarding marine resources and public health. Harmful algal blooms (HABs) have increased in frequency, diversity, and toxicity across the China Seas (Bohai Sea, Yellow Sea, East China Sea, and South China Sea), driven by eutrophication, climate change, and coastal development. These events threaten marine ecosystems, aquaculture, and human health through the accumulation of biotoxins (e.g., paralytic, diarrhetic, amnesic, and neurotoxic shellfish toxins) in shellfish. Despite advances in monitoring (e.g., remote sensing, *in-situ* measurements), current efforts remain regionally fragmented and lack integration of biological, chemical, and environmental data. This review highlights the need for a comprehensive, integrated ocean observing system incorporating molecular detection, toxin quantification, real-time monitoring, and predictive modeling. Supported by standardized protocols and multi-stakeholder collaboration, such a system would enhance early warning capabilities, risk assessment, and sustainable management of HABs and shellfish toxins, safeguarding marine resources and public health.

1. Introduction

Harmful Algal Blooms (HABs) refer to algal blooms, or the proliferation of phytoplankton in the water column, that cause negative impacts on the environment, economy, or human health[1]. The occurrence and severity of HABs have increased significantly across global coastal waters since early documentation, which is attributed to the degradation of water quality resulting from increased nutrient pollution, altered nutrient composition, and climate change[1-3]. HABs can be categorized into several broad functional types based on their nature and consequences, including hypoxia created by over-proliferation of harmless species, damage to marine life from non-toxic species through clogging or damaging gills, and production of toxins that accumulate in seafood or are transferred through the food web, causing shellfish poisoning or other health effects on humans[1]. These consequences lead to wide-reaching and growing economic impacts from public health costs and commercial fishery losses to tourism declines and monitoring expenses.

Shellfish poisoning occurs when shellfish are contaminated by toxins released by toxin-producing algae, which leads to direct health damage and potentially lethal consequences[1]. Filter-feeding shellfish, such as bivalves, are more susceptible to toxin accumulation and become vectors of toxins when humans consume them[4]. Toxins that accumulate in shellfish originate from specific algal taxa and are linked to distinct poisoning syndromes (Table 1). Saxitoxins, produced by dinoflagellates such as *Alexandrium*, *Gymnodinium*, and *Pyrodinium*, are responsible for Paralytic Shellfish Poisoning (PSP). Domoic acid, the agent of Amnesic Shellfish Poisoning (ASP), is synthesized by diatoms of the genus *Pseudo-nitzschia*. Diarrhetic Shellfish Poisoning (DSP) arises from okadaic acid and its derivatives, produced by *Dinophysis* and *Prorocentrum*, while Azaspiracid Poisoning (AZP) is linked to toxins from *Azadinium spinosum* and *Amphidoma languida*. Neurotoxic Shellfish Poisoning (NSP), caused by brevetoxins, is associated with *Karenia brevis*. These species-toxin associations underpin the monitoring and regulation of harmful algal blooms worldwide, which differ in geographical distribution and causative species, and can cause a range of symptoms from gastrointestinal distress to respiratory paralysis and long-term neurological damage[4-7].

As can be seen in Table 1, a summary of marine biotoxins relevant to shellfish and seafood poisoning including the syndrome, toxin class, group, key analogs, and notes on sources, producers, and remarks, according to the reviewed studies[8-14]. It covers well-known toxins (e.g., saxitoxins causing PST, okadaic acid causing DSP, domoic acid causing ASP), emerging toxins (e.g., cyclic imines, palytoxins, tetrodotoxins), and their primary producers such as Alexandrium, Pseudo-nitzschia, Karenia brevis, and Ostreopsis. Key information includes analog variants, metabolic transformations (e.g., decarbamoyl or sulfocarbamoyl forms), and human health implications.

Table 1. Summary of marine biotoxins relevant to shellfish and seafood poisoning.

Syndrome	Toxin class	Group	Key analogs	Notes (sources/producers, remarks)
PST	Guanidinium neurotoxins	Saxitoxin (STX) family	STX, NEO	Produced mainly by *Alexandrium*, *Gymnodinium catenatum*, *Pyrodinium bahamense*; voltage-gated Na^+ channel blockers.
PST	Guanidinium neurotoxins	Gonyautoxins (GTX)	GTX1/4, GTX2/3, GTX5 (B1), GTX6 (B2)	Carbamate (GTX1–6) and N-sulfocarbamoyl (B1/B2) analogs; potency varies by analog.
PST	Guanidinium neurotoxins	N-sulfocarbamoyl toxins (C toxins)	C1/C2, C3/C4	Generally lower toxicity; can convert to more toxic forms during processing or digestion.
PST	Guanidinium neurotoxins	Decarbamoyl analogs	dcSTX, dcNEO, dcGTX2/3	Often formed by shellfish metabolism or bacterial action; intermediate toxicity.
PST	Guanidinium neurotoxins	Other/rare PST analogs	M-toxins (M1–M12), GC-toxins	Less commonly monitored; reported in some regions and species.
DSP	Polyether fatty	Okadaates	Okadaic acid	*Dinophysis, Prorocentrum*; protein

	acids		(OA)	phosphatase inhibitors; cause GI symptoms.
DSP	Polyether fatty acids	Dinophysistoxins (DTX)	DTX1, DTX2, DTX3 (acyl esters of OA/DTX)	DTX3 = shellfish fatty-acid esters; hydrolyzed during analysis to quantify total OA-group toxins.
DSP	Macrocyclic polyethers	Pectenotoxins (PTX)	PTX1, PTX2, PTX2-sa, PTX11	Now toxicologically separated from OA-group in some regulations; produced by *Dinophysis*.
ASP	Kainoid amino acids	Domoic acid family	Domoic acid (DA), epi-DA, iso-DA	Produced by *Pseudo-nitzschia spp.*; causes memory loss and neurological effects.
AZP	Azaspiracids	Azaspiracid family	AZA1, AZA2, AZA3 (others exist)	Produced by *Azadinium*/*Amphidoma*; EU-regulated mainly AZA1–3.
NSP	Brevetoxins	Brevetoxin family (PbTx)	PbTx-1, PbTx-2, PbTx-3 (others)	*Karenia brevis* and related species; voltage-gated Na^+ channel activators.
—	Yessotoxins	YTX family	YTX, 45-OH-YTX, homoYTX, 45-OH-homoYTX, carboxyYTX	Produced by *Protoceratium reticulatum*, *Gonyaulax*; cardiotoxic in animals; separate regulatory class.
—	Cyclic imines	Spirolides (SPX)	SPX-1, SPX-A–G (various)	Produced by *Alexandrium*/*Ostreopsis*; fast-acting nicotinic/muscarinic antagonists; emerging monitoring targets.
—	Cyclic imines	Gymnodimines (GYM)	GYM-A, GYM-B, GYM-C	Fast-acting cyclic imines; sporadic occurrences.
—	Cyclic imines	Pinnatoxins (PnTX)	PnTX-A–H	Produced by *Vulcanodinium rugosum*; detections in several regions; toxicologically potent.
—	Cyclic imines	Other cyclic imines	Prorocentrolide, Pteriatoxins	Less common; structurally related fast-acting toxins.
—	Palytoxin-like	Palytoxins / Ovatoxins	PLTX, ovatoxin-a–g	Produced by *Ostreopsis*; human health impacts mainly via aerosols/skin, but shellfish contamination has been reported in some events.
—	Guanidinium neurotoxins	Tetrodotoxin (TTX) family	TTX, 4-epiTTX, anhydroTTX	Traditionally, pufferfish; increasing reports in bivalves (e.g., oysters, mussels) in temperate waters.

HABs have been observed with significant changes since the 1970s among Chinese coastal waters, including the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea, with the general trend of shifting to smaller, more harmful, and diversified algae species[15-16]. The coastal regions of China have undergone extensive population and economic growth, construction, and aquaculture expansion during the past decades[17-18], where HABs have resulted in significant damage to the economy, marine environment, and human health[16]. Traditional *in-situ* monitoring and sampling methods, including ship navigation, *in-situ* observation, sample collection, microscopic or molecular counting methods, and analysis of water chemistry factors, have witnessed significant progress over the past 40 years. Additionally, remote sensing techniques and marine ecological models have gained increasing significance since the 1990s. The development of new disciplines and technologies is also pushing the understanding and monitoring of HABs in Chinese coastal waters[16],[19]. Despite increasing HABs and shellfish toxin reports along China's coast, significant research gaps remain globally between human health and HAB exposure[20], which is a trend also evident in Chinese literature.

This review aims to synthesize current knowledge on HAB species and their toxins, and evaluate the state of monitoring and reporting practices in the China Seas. We will discuss the recent occurrence and spatial extent of HABs, together with the occurrence of shellfish poisoning based on previous literature, data, and bulletins. We will further provide interpretations and suggestions for future interdisciplinary research and monitoring of HABs and shellfish poisoning.

2. Shellfish Toxins and HABs-forming Algae in the China Seas

2.1 Bohai Sea

The earliest record of HABs in the Bohai Sea dates to 1952, with only 3 events recorded from 1952–1989, 21 in the 1990s, and 148 from 2000–2014[21]. Hotspots were mainly along the coastline, particularly Bohai Bay near Tianjin, Qinhuangdao, and Liaodong Bay near Yingkou[21-22]. Li et al. reported 64 causative taxa (51 species), mainly dinoflagellates and diatoms[22], while Chen et al.expanded this to 70 taxa, including 33 toxic species[23]. Many HAB species have rarely or never caused blooms, with certain species dominating events[24]. Based on historical trends, the HAB record can be divided into three periods: Before 2000, blooms were dominated by large-celled dinoflagellates (e.g., *Noctiluca scintillans*, *Tripos furca*, *Dinophysis fortii*), diatoms, and *Trichodesmium*. From 2000 to 2008, the phytoplankton community diversified to include haptophytes (*Phaeocystis globosa*), ciliates, raphidophytes, and more toxic dinoflagellate species such as *Karenia mikimotoi* and *Alexandrium tamarense*. After 2009, small-celled taxa (e.g., pelagophytes, cryptophytes, prasinophytes, and eustigmatophytes) became more prominent, with recurrent brown tides caused by *Aureococcus anophagefferens*[22]. Overall, there is increasing species diversity, a greater dominance of noxious taxa, and a trend toward smaller cell sizes.

Importantly, the diversification of HAB taxa over the past two decades has coincided with the detection of multiple toxin groups in seawater and shellfish, particularly those produced by *Alexandrium*, *Dinophysis*, and *Pseudo-nitzschia*. PSTs present in the Bohai Sea mainly include N-sulfocarbamoyl toxins (C1/C2), carbamate toxins (GTX1/4 and GTX2/3), decarbamoyl toxins (dcGTX2/3 and dcSTX), and saxitoxin (STX). Shellfish with higher toxicity levels had a greater proportion of high-potency PSPs like STX, NEO, and GTX1–4, whereas phytoplankton typically contain lower-potency C1/C2 unless toxicity is unusually high[25]. PSTs in the Bohai Sea were dominated by GTX2, GTX3, and dcGTX2. In spring, GTX2, GTX3, dcGTX2, and GTX4 appeared, and C1/2 were also detected; in summer, GTX1/4, GTX2/3, and dcGTX2/3, but not C1/2, were detected in the surface waters at lower rates than those in the spring, which is especially apparent for GTX4, whose detection rate was about 11 times higher in the spring than that in the summer[26].

AST and DST are also evident; however, such studies are limited in both number and scope[27]. Domoic acid is detected at low concentrations, but in the southern Bohai Sea, especially in Laizhou Bay, the concentration can reach as high as 38.20 ng/L[27]. DSTs, primarily okadaic acid (OA), dinophysistoxin-1 (DTX-1), and pectenotoxin-2 (PTX-2), are present in shellfish mariculture areas in Laizhou Bay, particularly in the Dongying and Laizhou coastal waters, and OA was the dominant component; toxin levels peaked between May and July 2020, correlating with higher seawater temperatures (20–30 ℃) and eutrophication, which promoted the growth of toxin-producing algae (e.g., *Dinophysis* and *Prorocentrum* spp.)[28]. Toxins are higher in Dongying coastal waters than in Laizhou coastal waters, likely due to greater land-based pollution and weaker water exchange; in contrast, shellfish ponds in Shouguang and Changyi coastal waters show lower toxin levels and lack DTX-1, possibly due to lower algal densities and shallow water[28]. These seasonal and spatial patterns mirror the shifts in bloom composition described above, suggesting that toxin surveillance remains closely tied to the dynamics of specific HAB taxa but is still limited in scope, leaving significant gaps in understanding long-term risk.

2.2 Yellow Sea

Li et al.[29] summarized 165 HAB events that occurred in the Yellow Sea from 1972 to 2017, mainly caused by dinoflagellates, diatoms, and raphidophytes. After 2000, bloom frequency and size increased, particularly in Dalian Bay, Jiaozhou Bay, and Haizhou Bay, with a growing dominance of toxic dinoflagellates like *Alexandrium tamarense* and *Karenia mikimotoi*. The composition of HAB species is different between the northern and southern Yellow Sea. While *Noctiluca scintillans* has been abundant in both areas, *Skeletonema* spp., *Heterosigma akashiwo*, and *Chattonella marina* are more evident in the north. Seasonal peaks shift earlier, and bloom duration changes differently between the northern and southern Yellow Sea. Notably, the Yellow Sea experiences frequent green tides from the blooms of macroalgae *Enteromorpha prolifera*[30], which isn't toxic by itself but creates other negative consequences, including hypoxia and regional acidification[31].

The composition of PSTs in the Yellow Sea is similar to that of the Bohai Sea. In spring, C1/2, GTX1/4, GTX2/3, and dcGTX2/3 are detected, and C1/2 is dominant in the surface waters; detection rates for GTX2/3 are high, while GTX1, GTX4, and dcGTX3 are low and account for a negligible portion of the total toxin molar concentration; the same set of toxins is found in summer, but C1/2 has much lower detection rates and concentrations compared to spring, and dcGTX2 became the dominant component, especially in the southern Yellow Sea[26]. DSTs, including OA, DTX1, PTX2, and YTX, were detected in seawater and scallops in Lingshan Bay in samples collected in 2012 at low levels[32]. More recent studies have found the dominance of OA, DTX1, and PTX2, while most other toxins are absent, in both seawater and sediments of the Yellow Sea[33]. Toxins concentrate in the North Yellow Sea and nearshore regions; OA and DTX1 decline in summer while PTX2 rise, and sediments act as a sink and potential source of lipophilic shellfish toxins for benthic organisms and food webs, with evidence of historical toxin deposition over the past century (Li et al.[33]).

2.3 East China Sea

The East China Sea (ECS) has experienced the highest frequency of HABs among the China seas, with 813 of 1393 events since 1998[34]. Records date back to 1933, when *Skeletonema costatum* and *N. scintillans* dominated; since 2000, *P. donghaiense* has prevailed[35]. In the Yangtze River Estuary, Liu et al.[36] identified *Alexandrium pacificum* as the primary toxic species, especially from February to June. High-throughput metabarcoding of 96 water samples from Zhejiang ECS in May 2019 revealed dinoflagellates as the dominant protists (3,173 ASVs, >79% of reads), with Syndiniales and Dinophyceae most speciose and abundant, respectively. Fifty-eight HAB species were detected, 25 of which were dinoflagellates, including *P. donghaiense*, *Lebouridinium glaucum*, and *N. scintillans* that contributed to a multispecies bloom with elevated chlorophyll *a* (>6.4 μg/L) and surface discoloration; diatom HAB taxa (*Pseudo-nitzschia pungens*, *Chaetoceros lorenzianus*, *Thalassiosira diporocyclus*), as well as species from Haptophyta and Chlorophyta, were also identified. Multiple ASVs for species like *Heterocapsa rotundata* and *Karenia papilionacea* suggest cryptic diversity within HAB lineages; nitrate, temperature, and salinity significantly correlated with the abundance of dominant taxa, particularly *P. donghaiense* and *L. glaucum*[37].

In the southern ECS, 77 HAB species were identified, including toxin producers (*Pseudo-nitzschia* spp., *Alexandrium* spp., *Dinophysis* spp., *Karlodinium veneficum*), with *N. scintillans*, *K. veneficum*, and *H. rotundata* highly abundant; localized blooms of *Chaetoceros*, *Skeletonema*, and *Pseudo-nitzschia* were linked to salinity, pH, and nutrient variation[38-39]. *Gymnodinium catenatum* was also identified as a major toxin producer[40].

Phytoplankton sampling efforts in the Yangtze River Estuary and adjacent regions from 33 °to 25 ° N, 120 °to 125 °E detected four major toxins, including OA, DTX1, PTX2, and Gymnodimine, and PTX2 was the dominant toxin by mass and proportion[41]. Liu et al.[36] further found multiple PST components in phytoplankton samples, including C1/2, GTX1/4, GTX2/3, GTX5, dcGTX2/3, dcSTX, and NEO, where the dominant toxin composition shifted from C1/2 (February to June) to GTX4 (from July onwards). The research revealed a seasonal pattern of PST content, peaking in May and June before declining sharply in July. High levels of PST were concentrated in three offshore regions:

north, east, and near Zhoushan Island south of the CRE, with a notable northward migration of toxins observed throughout the sampling period. Environmental factors, including nutrient availability and temperature, significantly influence the growth of harmful algal blooms and PST production[36].

Shellfish sampling in Zhejiang also found the widespread occurrence of lipophilic shellfish toxins, including OA, DTX-1, PTX2, homoYTX, and YTX. Paralytic shellfish toxins, including STX, neoSTX, dcGTX3, dcGTX2, GTX3, dcSTX, GTX2, and GTX5, are also evident, particularly concerning *Alexandrium* species[42-43]. A DST incident, which was also the first official report of DSP illness in China, was reported in May 2011 in Ningbo City (Zhejiang) and Ningde City (Fujian), caused by contaminated mussels. OA and DTX1 were found at extremely high levels - over 25 × EU regulatory limit for OA-group toxins, and >40 × after the base hydrolysis due to toxin esters (mainly palmitic acid esters)-pectenotoxins (PTX) present: PTX2 is below EU limit, but very high PTX2sa and 7-epi-PTX2sa were detected[44]. Isolated strain MEL11 of *Gymnodinium catenatum* exhibited 11 PSTs, dominated by N-sulfocarbamoyl toxins (C1-4, GTX5-6) and GC toxins, including GC2, GC3, GC5, and GC6[40].

2.4 South China Sea

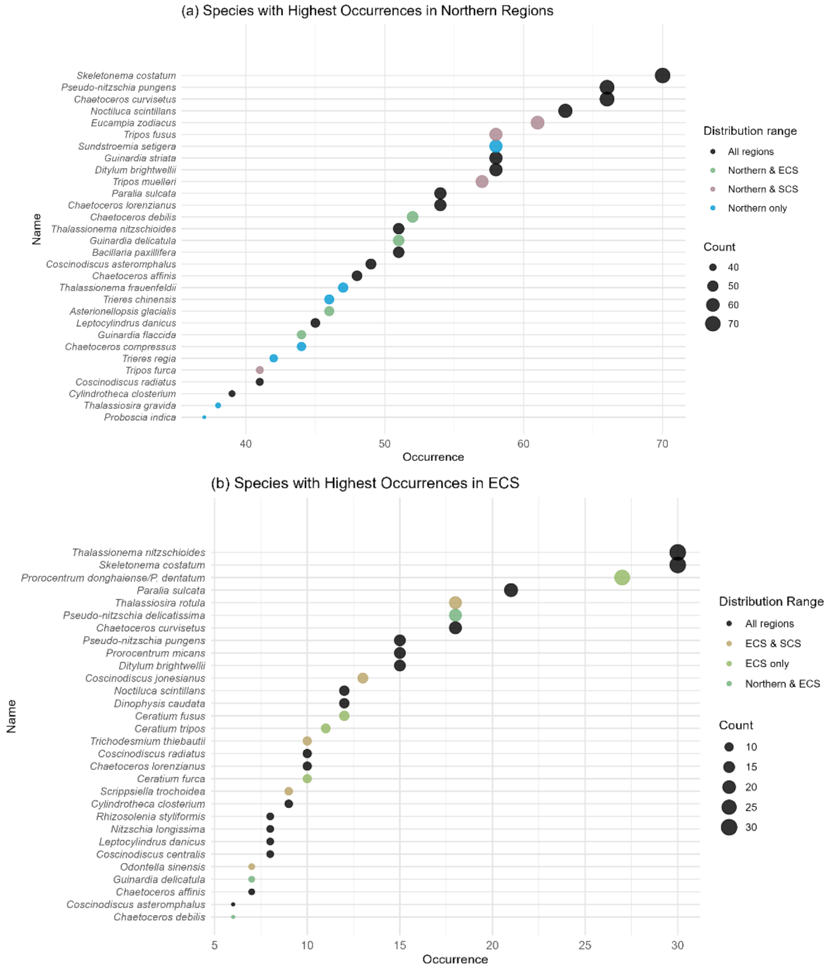
Huang et al.[45] identified 19 HAB species along the Guangdong coast (8 Dinoflagellata, 5 Bacillariophyta, 3 Haptophyta, and 1 each of Ochrophyta, Chlorophyta, and Cyanobacteria). Between 1980–2016, 337 HAB events were recorded, mainly caused by *Noctiluca scintillans*, *Phaeocystis globosa*, *Skeletonema costatum*, and *Scrippsiella trochoidea*. Toxic blooms with negative impacts involved *Heterosigma akashiwo*, *Chattonella marina*, *Karenia mikimotoi*, and *P. globosa*; as in other seas, HAB frequency increased during the 1990s and has remained high, with more events in spring compared to other Chinese seas[46]. In the Beibu Gulf (Guangxi), 39 HABs occurred from 1985–2017: *Trichodesmium erythraeum* and *Microcystis* spp. dominated before 2000; co-occurrence of cyanobacteria (*T. hildebrandtii*, *T. erythraeum*, *M. flos-aquae*), dinoflagellates (*N. scintillans*), and diatoms (*S. costatum*, *Guinardia flaccida*) was common in 2001–2010; and *P. globosa* dominated afterwards[47]. Hainan is less studied, but potentially harmful dinoflagellates were recorded, including CFP species (*Prorocentrum hoffmannianum*, *P. lima*, *P. rhathymum*), DSP species (*P. hoffmannianum*, *P. lima*, *Dinophysis acuminata*, *D. caudata*, *Protoperidium oceanicum*, *Pro. pellucidum*), and YTX species (*Lingulodinium polyedrum*)[48].

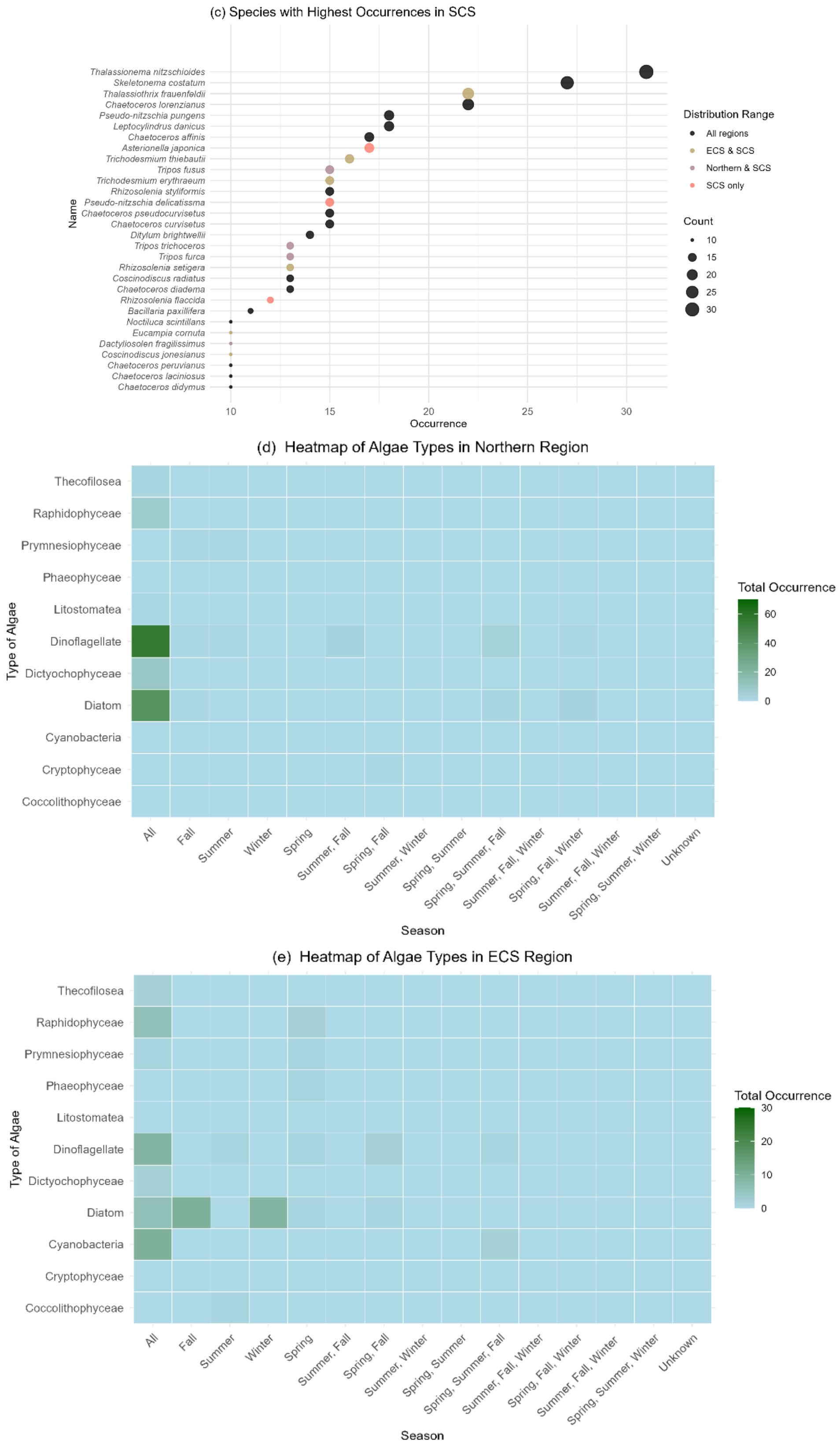
Analysis of the PSTs in coastal SCS hot spots in 2006-2008 and 2015 included GTX 1/ 4, GTX2/3, GTX5, NEO, STX, dcSTX, dcGTX2/3, and C1/2, which exhibit distinct seasonal, geographical, and temporal differences: between 2006 and 2008, PST peaks occurred in late autumn and late spring, primarily affecting mollusks in hotspots with high-potency NEO and widespread low-potency C2 as the dominant toxins; by 2015, PSTs appeared in more sites across mollusks, crustaceans, and fish, peaking in early spring and early summer, with low-potency C1 often at high concentrations and a broader toxin spectrum[49]. Detection rates, high-content samples (> 2 nmol g^{-1}), and high-toxicity cases (> 800 μg STXeq/kg) all rose slightly, with maximum toxicity values exceeding safety limits in both periods[49]. A more recent effort focused on STX-group toxins, DA, and LSTs. STX-group toxins, dominated by GTX4 and GTX3, were mainly detected in the Pearl River Estuary (PRE) during summer, with *Alexandrium* complex species identified as the likely producers in offshore SCS waters. Despite low intracellular concentrations in microalgae, high trophic magnification factors suggest potential seafood safety risks[50]. DA was detected in over one-third of phytoplankton samples, concentrated east of the PRE and along the Guangdong coast, with *Pseudo-nitzschia spp.* identified as the primary source; LSTs, dominated by PTX2, homo-YTX (hYTX), GYM, and DTX1, were relatively widely detected, with PTX2 likely produced by *Dinophysis acuminata* complex and *D. caudata*, and hYTX linked to *Gonyaulax spinifera*[50].

2.5 HABs Species Occurrence and Taxonomy Among Regional Seas

The distribution of harmful algal bloom (HAB) species in China's coastal waters exhibits marked regional heterogeneity. According to Chen et al.[51], among the 215 HAB species detected in Chinese seas, 76 are present in all four regional seas, 53 only in the Bohai Sea and the Yellow Sea, and 8 only in the East China Sea and the South China Sea. The northern seas, including the Bohai Sea and Yellow Sea, harbor species such as *Tripos furca*, *Tripos fusus*, *Alexandrium catenella*, *Chaetoceros curvisetus*, *Heterosigma akashiwo*, and *Aureococcus anophagefferens*, which tend to thrive in temperate to cold shallow waters and frequently form blooms in these regions.

The East China Sea serves as a biodiversity hotspot, supporting a wide array of HAB species, including *Karenia mikimotoi*, *Prorocentrum donghaiense*, *Skeletonema costatum*, *Chaetoceros curvisetus*, and *Alexandrium pacificum*, with many blooms occurring during warmer months; in contrast, the South China Sea and other subtropical waters predominantly host species such as *Dinophysis caudata*, *Akashiwo sanguinea*, *Gymnodinium catenatum*, *Margalefidinium polykrikoides*, and *Phaeocystis globosa*, which favor warmer temperatures and often cause extensive blooms with significant ecological and economic impacts; important estuarine and bay areas, including Jiaozhou Bay, Pearl River Estuary, and Yangtze River Estuary, provide critical habitats for species like *Gymnodinium catenatum*, *Scrippsiella acuminata*, and *Eucampia zodiacus*, where frequent monitoring has revealed high species richness despite their relatively small spatial extent[52]. These spatial differences (Figure 1) highlight the impact of regional environmental factors, including temperature, salinity, nutrient availability, and hydrodynamics, on the composition of HAB species and bloom dynamics across China's coastal seas.




(c) Species with Highest Occurrences in SCS
Thalassionema nitzschioides
Skeletonema costatum
Thalassiothrix frauenfeldii
Chaetoceros lorenzianus
Pseudo-nitzschia pungens
Leptocylindrus danicus
Chaetoceros affinis
Asterionella japonica
Trichodesmium thiebautii
Tripos fusus
Trichodesmium erythraeum
Rhizosolenia styliformis
Pseudo-nitzschia delicatissma
Chaetoceros pseudocurvisetus
Chaetoceros curvisetus
Ditylum brightwellii
Tripos trichoceros
Tripos furca
Rhizosolenia setigera
Coscinodiscus radiatus
Chaetoceros diadema
Rhizosolenia flaccida
Bacillaria paxillifera
Noctiluca scintillans
Eucampia cornuta
Dactyliosolen fragilissimus
Coscinodiscus jonesianus
Chaetoceros peruvianus
Chaetoceros laciniosus
Chaetoceros didymus
Name
10
15
20
25
30
Occurrence
Distribution Range
All regions
ECS & SCS
Northern & SCS
SCS only
Count
10
15
20
25
30
(d) Heatmap of Algae Types in Northern Region
Thecofilosea
Raphidophyceae
Prymnesiophyceae
Phaeophyceae
Litostomatea
Dinoflagellate
Dictyochophyceae
Diatom
Cyanobacteria
Cryptophyceae
Coccolithophyceae
Type of Algae
All
Fall
Summer
Winter
Spring
Summer, Fall
Spring, Fall
Summer, Winter
Spring, Summer
Spring, Summer, Fall
Summer, Fall, Winter
Spring, Fall, Winter
Summer, Fall, Winter
Spring, Summer, Winter
Unknown
Season
Total Occurrence
60
40
20
0
(e) Heatmap of Algae Types in ECS Region
Thecofilosea
Raphidophyceae
Prymnesiophyceae
Phaeophyceae
Litostomatea
Dinoflagellate
Dictyochophyceae
Diatom
Cyanobacteria
Cryptophyceae
Coccolithophyceae
Type of Algae
All
Fall
Summer
Winter
Spring
Summer, Fall
Spring, Fall
Summer, Winter
Spring, Summer
Spring, Summer, Fall
Summer, Fall, Winter
Spring, Fall, Winter
Summer, Fall, Winter
Spring, Summer, Winter
Unknown
Season
Total Occurrence
30
20
10
0

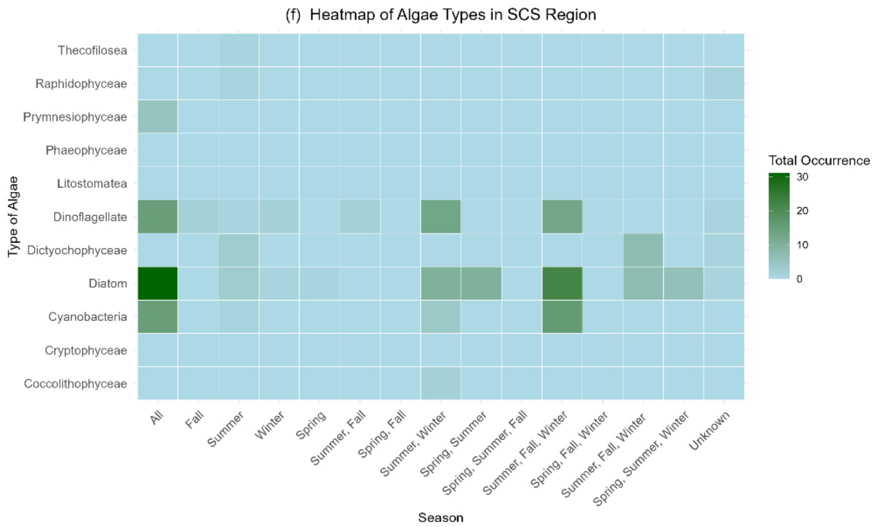


Figure 1. A summary of HAB species detected throughout the sampling efforts in the Chinese seas.

As can be seen in Figure 1, A summary of HAB species detected throughout the sampling efforts in the Chinese seas[52-54]. (a-c) Bubble sheets of harmful algal bloom (HAB) species detected across the Chinese coastal seas according to available sampling efforts. Bubble size is proportional to total Occurrence (number of presence records across all samplings); color indicates geographical extent of detection: Northern (adjacent waters of Shandong including Bohai Sea and Yellow Sea), ECS (East China Sea), SCS (South China Sea), or All (species present in all regions). Larger bubbles represent taxa that were recorded most frequently, while the color shows whether those taxa were regionally restricted or broadly distributed. (d-f) Heatmaps of algae types detected by season (x-axis) and region (d: Northern; e: ECS; f: SCS); colors indicate algal type (legend). The counts and the time ranges of voyage samplings are 119 efforts, 1936~2020 for Northern; 67 efforts, 1958~2019 for ECS, and 44 efforts, 1987~2018 for SCS. Species presented did not necessarily form blooms.

3. Discussion

3.1 Monitoring and Reporting Efforts

An integrated ocean observing system is beneficial for studying HABs as it provides reliable, real-time data and services tailored to the needs of various user groups, including government agencies, the seafood industry, researchers, and the public, enabling informed decision-making regarding public health and ecosystem management by offering critical information on the location, extent, and intensity of HABs, along with forecasts of their trajectories. By integrating sustained observations and advanced modeling, the system enhances HAB detection and forecasting capabilities, ultimately supporting effective management and response strategies[55]. Similarly, linking HAB research with broader environmental and health frameworks will provide better understanding and support more effective and sustainable management[16].

A variety of methods in HABs monitoring have been carried out and are constantly being renewed in China since the 1980s, including satellite remote sensing, aerial remote sensing, field tracking, survey ships, online monitoring of water quality, remote warning systems of shore-based stations, and volunteer monitoring[19]. The development and identification of HABs involves multiple environmental aspects, and a web-based, integrated system involving different methods, including *in-situ* and remote sensing of hydrological and biological features, numerical modeling, and GIS technologies, will allow for easier and more comprehensive analysis and forecast of HABs and shellfish toxins[56]. China's Marine Environment Bulletin and China's Marine Disaster Bulletin, as products of the HAB monitoring network, provide general overviews of HAB occurrences in the four regional seas[57]. Integrated approaches are also performed at the local levels. For example, the Shenzhen Planning and Natural Resources Bureau (SPNRB) has constructed a monitoring system including thirteen surface buoys and four tidal stations that provide real-time water quality and tidal data, and the Hong Kong Environmental Protection Department has a more extensive system, with 94 stations for marine waters and 60 for bottom sediments[56]. Monitoring of biotoxins is also routinely implemented around aquaculture zones, and some studies have performed analysis on water column samples (Yu et al.[16]), shellfish samples[58], and laboratory simulations of bivalve toxin intakes from toxic algae species [59].

These existing frameworks for monitoring HABs in the Chinese seas align with the principles of an integrated observing system, which integrates multiple monitoring techniques ranging from satellite remote sensing to *in-situ* observations and automatic buoy monitoring, and environmental parameters including hydrological factors like temperature and salinity, biological indicators such as chlorophyll concentration, and meteorological conditions, creating a holistic view of the marine ecosystem[19].

3.2 Research and Knowledge Gaps

Despite the intense efforts taken in the field of HABs and shellfish toxins, the scope of studies on either HABs or shellfish toxins is usually limited due to several gaps.

Firstly, the studies are confined to specific areas and cases, which undermine the importance of broad-scale, interdisciplinary studies and may fail to capture important events in HAB development, as well as overlook special and temporal dynamics[25],[36],[50],[60]). Shellfish toxin samplings are usually performed locally, which are scattered and cannot be applied in multidisciplinary studies. While new research initiatives, such as the Harmful Algae and Algal Toxins in Coastal Waters of China: Investigation and Database Project (HAATC), adopt interdisciplinary efforts to synthesize the knowledge of HABs, algal toxins, and environmental factors[61], outcomes remain scarce, and efforts are still largely under-focused.

Secondly, although research on toxin detection and risk of exposure is abundant and wide-scale assessments have been made across coastal regions for contamination risks[62], the impacts of shellfish toxins in greater contexts, such as ecotoxicology, socioeconomics, and epidemiology, are not well-focused, and the properties of toxins, including aspects like biokinetics and transformation, are also under-evaluated, with only a few studies explicitly mentioned[63]. For example, as climate change progresses, suitable habitats and species richness of harmful dinoflagellates are expected to decline at lower latitudes while stabilizing or increasing at higher latitudes. This shift may lead to a decrease in harmful dinoflagellates in the South and East China Seas, while increases are projected for the Yellow and Bohai Seas. And different species exhibit varying responses to climate change: species like *P. lima* and *K. mikimotoi* are expected to increase in risk, while *G. catenatum* may decline in the South China Sea due to its preference for cooler waters[64].

Meanwhile, very few studies shed light on the impacts of shellfish toxins in ecotoxicology (such as how environmental factors like climate change may lead to dynamics in toxins) and socioeconomics (such as how coastal populations and fisheries may be affected by the shift), and case studies on epidemiology are similarly rare [65].

3.3 Future Directions of Studying HABs and Shellfish Toxins in the China Seas

Several practices could be taken to address the current gaps in HABs and shellfish toxin studies in the Chinese seas. Adopting a multi-faceted monitoring strategy that integrates cell identification, toxin quantification, and treatment evaluation will improve early warning capabilities and support sustainable shellfish aquaculture under varying bloom conditions.

To further enhance this framework, future efforts can focus on advancing *in-situ* monitoring technologies, integrating AI and big data for improved HAB forecasting, developing holistic prevention and control strategies (such as standardized modified clay applications and ecological methods like macroalgae cultivation), and expanding studies on HAB biodiversity, molecular ecology, and the impacts of climate change[16]. The importance of integrated monitoring of HABs and their associated toxins should be emphasized, as the detection of multiple toxins in the water column will occur alongside low concentrations of HAB cells, meaning that monitoring programs should combine sensitive molecular methods for early and accurate detection of HAB species with comprehensive toxin analyses; such an approach captures both intracellular and extracellular toxins, including those released from lysed cells, providing a more complete assessment of potential risks.

Additionally, understanding the efficacy of water treatment steps in removing both cells and toxins is critical for managing hatchery water quality[66]. Adopting a multi-faceted monitoring strategy that integrates cell identification, toxin quantification, and treatment evaluation will improve early warning capabilities and support sustainable shellfish aquaculture under varying bloom conditions[66], as well as provide a clearer view of scientific research. Furthermore, understanding the mechanisms of toxins and their potential effects on the environment, relevant species, and human beings will provide insights into ecosystem and human health and resilience. Laboratory studies resembling Liu et al.[63], aimed at understanding the mechanisms of toxicity and transformation, needs to be applied to a wider scope of algal toxins and marine organisms.

Moreover, integrating socioeconomics into these studies will help assess the economic implications of HABs on local fisheries and aquaculture, enabling stakeholders to make informed decisions that balance environmental sustainability with economic viability. The report of Suddleson and Hoagland[67] suggested the application of qualitative methods that utilize local ecological knowledge (LEK) through interviews and rapid ethnographic assessments to capture community effects and resilience, economic methods that apply quantitative techniques to estimate changes in consumer and producer surpluses in established markets, such as seafood and tourism, as well as regional economic impacts using input-output models, and public health analyses that focus on cost-of-illness estimates, accounting for lost income and healthcare expenses, while often neglecting the intangible costs associated with pain and suffering. Through an agenda that recommends community-level surveys to assess economic changes, transferable research methods, and benefit transfers to understudied areas, emphasizes rapid ethnographic assessments, social impact research, socio-economic thresholds, and effective policy responses, and integrates diverse methodologies and fosters cross-disciplinary collaboration, our understanding of HAB impacts and our ability to perform effective interventions could be enhanced [67].

Similarly, the principles of community-level partnerships between public health and environmental agencies can be applied to enhance epidemiological practices to effectively address public health issues related to HABs, and implementing standardized case definitions and protocols for reporting suspected illnesses can help mitigate under-reporting. A collaborative, data-driven approach contributes to clinical research that investigates the health effects of HABs, enhances response to HAB-related health risks and better protects communities at risk[68].

To summarize, addressing the challenges posed by harmful algal blooms (HABs) and shellfish toxins in Chinese seas requires a comprehensive and integrated approach that combines advanced monitoring strategies, socio-economic assessments, and collaborative partnerships. By adopting a multi-faceted monitoring framework that includes cell identification, toxin quantification, and treatment evaluation, we can enhance early warning systems and support sustainable aquaculture practices. Furthermore, incorporating socio-economic research will provide valuable insights into the economic impacts of HABs on local fisheries and communities, enabling informed decision-making that balances ecological health with economic viability. Emphasizing community-level partnerships between public health and environmental agencies, along with standardized reporting protocols, will improve epidemiological practices and reduce under-reporting of HAB-related illnesses. Ultimately, fostering cross-disciplinary collaboration and leveraging innovative technologies will enhance our understanding of HAB impacts, promote effective interventions, and safeguard both ecosystem and human health in the face of these environmental challenges.

4. Conclusion

This review synthesizes current knowledge on the occurrence, species composition, and toxin profiles of HABs in the China Seas, emphasizing the Bohai Sea, Yellow Sea, East China Sea, and South China Sea. HAB events have increased markedly since the 1970s, with a shift toward smaller, more toxic, and diverse algal species. Key shellfish toxins detected include PSTs, DSTs, domoic acid, and emerging toxins such as cyclic imines and palytoxins. Monitoring efforts have evolved from traditional *in-situ* sampling to incorporate remote sensing and ecological modeling, yet remain limited by regional fragmentation and inconsistent data integration. Ultimately, an interdisciplinary research framework that bridges marine biology, chemistry, ecology, hydrology, remote sensing, data science, and social sciences will be essential to address the complex drivers and impacts of HABs in the China Seas. Such collaboration will support sustainable aquaculture, protect marine ecosystems, and reduce human health risks associated with shellfish toxins.

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