Review

Algal Toxins, Food Safety, and Bioterrorism: A Food-and-Water Defense Perspective

Antonello Novelli , M.T. Fernández-Sánchez , Ann M. Marini , Peter Pressman , A. Wallace Hayes *

Posted Date: 26 June 2026

doi: 10.20944/preprints202606.1989.v1

Keywords: algal toxins; harmful algal blooms; food defense; water security; cyanotoxins; seafood safety; drinking water; emergency preparedness

 doi:10.20944/preprints202606.1989.v1

Review

Algal Toxins, Food Safety, and Bioterrorism: A Food-and-Water Defense Perspective

Antonello Novelli [1,2,3], M.T. Fernández-Sánchez [4], Ann M. Marini [5], Peter Pressman [6] and A. Wallace Hayes [7,*]

[1] University Institute of Biotechnology of Asturias (IUBA), University of Oviedo, 33006 Oviedo, Spain
[2] Department of Psychology, University of Oviedo, 33003 Oviedo, Spain
[3] Institute for Health Research of the Principality of Asturias (ISPA), 33011 Oviedo, Spain
[4] Department of Biochemistry and Molecular Biology, University of Oviedo, 33006 Oviedo, Spain
[5] Department of Neurology, Programs in Neuroscience, Molecular and Cellular Biology, Graduate School of Nursing, Uniformed Services University of the Health Sciences, Bethesda, Maryland, USA
[6] University of Maine, Orono, Maine, USA
[7] University of South Florida, Tampa, Florida, USA
* Correspondence: awallacehayes@comcast.net

Abstract

Food defense encompasses both the prevention of accidental contamination and the protection of food and water systems against deliberate adulteration. Within this framework, algal toxins deserve greater attention because they occupy a critical intersection of water security, seafood and drinking-water safety, environmental change, supply-chain continuity, and public health preparedness. The novelty of this review lies in reframing algal toxins from a primarily environmental, seafood-safety, or clinical-toxicology topic into an integrated food-and-water defense problem. This perspective brings together harmful algal bloom ecology, toxin toxicology, seafood safety, drinking-water protection, preparedness for intentional adulteration, climate-change risk, surveillance, and emergency response. Algal toxins can enter the human supply chain through multiple marine and freshwater pathways, are often undetectable by taste, odor, or appearance, may resist routine preparation measures, and can generate high-consequence disruptions even when contamination begins locally. The analysis further shows that prevention depends largely on upstream measures--including environmental surveillance, harvest-area restrictions, source-water protection, testing, supply-chain controls, and rapid public communication--rather than on consumer behavior. Framed in the context of the U.S. Food and Drug Administration's Intentional Adulteration Rule under the Food Safety Modernization Act, this paper situates algal toxins within a preventive defense model that integrates monitoring, vulnerability reduction, and emergency preparedness. Although most harmful algal bloom events are naturally occurring, algal toxins warrant attention in food-defense planning because they can contaminate seafood and drinking-water systems, complicate detection and attribution, and expose vulnerabilities across interconnected food and water infrastructures.

Keywords: algal toxins; harmful algal blooms; food defense; water security; cyanotoxins; seafood safety; drinking water; emergency preparedness

Introduction

The case for treating algal toxins as a food-and-water defense issue begins with their diverse routes of entry into the human food and water supply. In marine systems, filter-feeding shellfish—including oysters, clams, and mussels—bioaccumulate toxins produced by toxic phytoplankton, while certain finfish acquire these compounds through trophic transfer. These exposures are associated with recognized seafood poisoning syndromes, including paralytic shellfish poisoning caused by saxitoxins, amnesic shellfish poisoning caused by domoic acid, diarrhetic shellfish

 doi:10.20944/preprints202606.1989.v1

poisoning caused by okadaic acid and dinophysistoxins, neurotoxic shellfish poisoning caused by brevetoxins, azaspiracid shellfish poisoning, and ciguatera fish poisoning caused by ciguatoxins [1,2]. In freshwater systems, cyanotoxins such as microcystins, cylindrospermopsin, anatoxin-a, and saxitoxins may contaminate drinking-water sources, recreational waters, fish, irrigated crops, and blue-green algae dietary supplements [2,3]. Together, these pathways show that algal toxins are not confined to isolated ecological niches; they move through interconnected food, water, and consumer-product systems in ways that complicate prevention and response.

Their defense relevance is heightened by the fact that many algal toxins cannot be detected by consumers through taste, odor, or appearance. The Centers for Disease Control and Prevention notes that algal toxins in fish and shellfish may be organoleptically undetectable and that neither cooking nor food preservation reliably eliminates them [4]. Similarly, boiling water contaminated with cyanotoxins does not render it safe and may instead concentrate the toxin [5]. This combination of concealment and resistance shifts risk management away from end-user behavior and toward upstream controls such as environmental monitoring, harvest-area closures, product testing, source-water management, and rapid public notification. The central problem is therefore not simply exposure, but the failure of routine consumer safeguards to interrupt exposure once contamination has occurred.

This logic also explains why algal toxins remain relevant to bioterrorism and intentional-contamination planning, even though most harmful algal bloom events are naturally occurring rather than deliberate. Their importance lies not in evidence of common use in attacks, but in the convergence of features central to defense analysis: they are biologically derived toxins, can affect widely consumed foods and water supplies, may cause illness without obvious sensory warning, and can initially be difficult to distinguish from naturally occurring contamination events. Saxitoxin is particularly notable because it is both a naturally occurring algal toxin associated with paralytic shellfish poisoning and an HHS select toxin identified by the Federal Select Agent Program as capable of posing a severe threat to public health and safety [6,7]. This designation underscores a broader point: food-defense systems must be designed to detect and manage high-consequence toxin hazards regardless of whether an incident is ultimately judged accidental, environmental, or intentional (7a).

The contribution of this review is therefore not to suggest that algal toxins are commonly used as deliberate agents, but to show why they should be incorporated into the same preparedness architecture used for other high-consequence food-and-water hazards. Existing harmful algal bloom literature often treats bloom ecology, seafood poisoning, drinking-water management, and clinical toxicology as separate domains. A food-and-water defense perspective integrates these domains around the operational questions that matter during a serious incident: where contamination can enter or concentrate, how quickly it can be detected, which products or water systems may be affected, how exposure can be stopped, and how public health authorities can communicate credible risk information before preventable illness occurs.

Table 1 summarizes the principal algal toxin classes discussed above, highlighting their source organisms and dominant molecular targets (6b).

Table 1. Major Algal Toxin Classes, Representative Toxins, Source Organisms, and Primary Molecular Targets.

Toxin class	Representative toxins	Main source organisms	Primary molecular target/action
Paralytic shellfish poisoning (PSP)	Saxitoxin, neosaxitoxin, gonyautoxins	Alexandrium, Gymnodinium, Pyrodinium, some cyanobacteria	Blockade of voltage-gated sodium channels (7r-7u)
Amnesic shellfish poisoning (ASP)	Domoic acid	Pseudo-nitzschia	Agonist at ionotropic glutamate receptors; excitotoxicity (7v,7w)
Diarrhetic shellfish poisoning (DSP)	Okadaic acid, dinophysistoxins	Dinophysis, Prorocentrum	Inhibition of protein phosphatases 1 and 2A (16g,7x,7y)

 doi:10.20944/preprints202606.1989.v1

Ciguatera fish poisoning (CFP)	Ciguatoxins, maitotoxin, palytoxin-like compounds	Gambierdiscus and related dinoflagellates	Persistent activation of voltage-gated sodium channels; related membrane disruption (7g)
Neurotoxic shellfish poisoning (NSP)	Brevetoxins	Karenia brevis	Persistent activation of voltage-gated sodium channels (7g)
Azaspiracid poisoning (AZP)	Azaspiracids	Azadinium and related dinoflagellates	Multitarget cytotoxic effects; mechanism of action remains incompletely defined (7z,7aa)
Palytoxin poisoning	Palytoxin and congeners	Ostreopsis, zoanthids, and some marine organisms	Disruption of Na+/K+-ATPase (16j,7bb)

Footnotes: PSP, ASP, DSP, CFP, NSP, and AZP are the principal human seafood poisoning syndromes caused by marine phycotoxins. The listed source organisms are representative and not exhaustive. Molecular targets summarize the dominant toxic mechanism most relevant to human disease.

The broader significance of algal toxins becomes clearer when viewed against the scale and interconnectedness of contemporary food and water systems. The World Health Organization estimates that unsafe food causes approximately 600 million illnesses and 420,000 deaths globally each year and emphasizes that increasingly globalized food chains allow local contamination events to escalate rapidly into international concerns [8]. In the United States, commonly cited federal estimates attribute roughly 48 million foodborne illnesses, 128,000 hospitalizations, and 3,000 deaths annually to foodborne hazards overall [9]. Although these figures are not specific to algal toxins, they underscore the central point advanced here: hazards that begin as localized environmental events can become supply-chain and public-trust crises when they intersect with centralized processing, interstate commerce, and essential water infrastructure. For that reason, toxin-mediated hazards should be incorporated into preventive food-safety and defense systems rather than treated solely as episodic environmental anomalies.

Seafood safety programs are central to algal-toxin prevention. The National Shellfish Sanitation Program promotes public health protection for bivalve molluscan shellfish moving in interstate commerce through cooperation among state agencies, the FDA, the EPA, NOAA, and the shellfish industry [10,11]. This cooperative structure is important because shellfish can concentrate marine biotoxins even when the surrounding water appears safe to consumers. State officials may close harvest areas when monitoring shows unsafe levels of toxic algae or shellfish toxins, and consumers are advised to follow local shellfish, fishing, and swimming advisories [10,12].

Drinking-water systems require similar attention. Cyanobacterial toxins are among the most hazardous substances widely found in bodies of water, and the World Health Organization emphasizes that managing lakes, reservoirs, and rivers is critical to preventing cyanobacterial blooms and protecting public health [13]. EPA notes that harmful algal blooms that produce cyanotoxins can pose risks through drinking-water exposure and that severe blooms require proactive planning and active management to reduce risk in potable water supplies [14,15]. EPA has also issued drinking-water health advisories for microcystins and cylindrospermopsin; although these advisories are not legally enforceable federal standards, they provide technical guidance for protecting public health during contamination events [16]. The contrast between marine and freshwater toxin systems is summarized in Table 2, which shows how environmental setting, exposure pathway, and physicochemical behavior shape public health risk (16a).

 doi:10.20944/preprints202606.1989.v1

Table 2. Freshwater and Marine Algal Toxins: Distribution, Physicochemical Tendencies, and Public Health Relevance.

Environmental setting	Major toxin groups	Dominant physicochemical tendency*	Principal exposure pathway	Public health relevance
Marine	PSP, ASP, DSP, CFP, NSP, palytoxin-related toxins	Mixed; hydrophilic toxins often produce rapid systemic effects; lipophilic toxins show broader tissue distribution (7b,7c,16c-16j)	Seafood consumption; in some cases, aerosol inhalation	Shellfish and fish safety; coastal respiratory events
Freshwater	Microcystins, nodularin, cylindrospermopsin, saxitoxin, anatoxin-a, guanitoxin, dermatotoxins	Many are hydrophilic (16k,16L); some are membrane-active irritants	Drinking water, recreation, animal ingestion, skin contact	Municipal water safety; livestock and wildlife mortality
Mixed coastal systems	Brevetoxins, ciguatoxins, palytoxin-like compounds	Often lipophilic and persistent (16c-16j,7f)	Seafood, aerosols, marine contact	Beach-related illness; seafood advisories; fishery impacts

*From PubChem, NIH, National Library of Medicine, National Center for Biotechnology Information.
Footnotes: Physicochemical behavior influences tissue distribution, clearance, and persistence of toxicity. Hydrophilic toxins often act quickly and may be cleared faster, whereas lipophilic toxins may distribute more widely and persist longer. The route of exposure is a major determinant of the clinical syndrome.

Water-system preparedness is also a security issue. Under America's Water Infrastructure Act, community drinking-water systems serving more than 3,300 people must develop or update risk and resilience assessments and emergency response plans [16]. These plans are directly relevant to algal toxins because cyanotoxin contamination can affect source-water quality, treatment decisions, public notification, alternative water supplies, healthcare preparedness, and public trust. Together with seafood controls, these water-system requirements clarify why algal toxins belong within a broader food-and-water defense framework, rather than solely within routine environmental or public health management.

From a food-defense perspective, algal toxins are concerning not only because they can contaminate seafood and other food inputs, but also because they challenge conventional assumptions about control. A vulnerability-based approach asks where an attacker—or a system failure—could introduce, concentrate, misclassify, or distribute toxin-contaminated material to achieve the greatest public health impact. In practice, that means focusing on high-risk points such as harvest-area verification, raw-material approval, receiving, bulk liquid handling, storage, blending, labeling, and distribution. Under the FDA's food-defense framework, facilities are expected to identify significant vulnerabilities, establish mitigation strategies at actionable process steps, monitor those controls, and verify that they function as intended. For algal-toxin hazards, this perspective underscores the need for restricted access, chain-of-custody controls, supplier verification, product-hold procedures, and rapid traceback capability for seafood, algal ingredients, and water-dependent foods [3,17].

The main analytical and regulatory tools used to detect, evaluate, and manage algal-toxin risk are outlined in Table 3.

 doi:10.20944/preprints202606.1989.v1

Table 3. Analytical and Regulatory Approaches for Algal Toxins.

Approach	Use	Strengths	Limitations	Representative application
Mouse bioassay [18,19]	Historical regulatory screening	Detects overall biological toxicity	Ethical concerns, low specificity, variability	Legacy screening for shellfish toxins
Chemical analysis [20–24]	Toxin identification and quantitation	High specificity, supports congener profiling	Requires standards and instrumentation	LC-MS/MS detection of marine and freshwater toxins
Immunoassays [18,25]	Screening for selected toxins	Rapid, relatively simple	May miss analogs or structurally divergent toxins	Shellfish monitoring
Receptor-binding assays [18,25]	Functional detection of bioactive toxin classes	Detects biologically active analogs	Limited to toxins with known binding targets	Saxitoxin and brevetoxin screening
Functional cell-based assays [26]	Assessment of physiological toxicity	Captures integrated cellular response	Cell-line sensitivity varies; interpretation can be complex	Neuronal or hepatocyte toxicity testing
Primary neuronal culture / MEA systems [27–30]	Mechanistic neurotoxicity assessment	Sensitive, dynamic, non-invasive electrophysiology	Technically specialized	Early detection of toxin effects on neuronal firing

From a water-defense perspective, algal toxins demonstrate that source-water protection and treatment resilience are inseparable from security planning. America's Water Infrastructure Act requires many community water systems to assess risks to source water, treatment processes, storage, distribution, monitoring practices, and emergency-response capacity. These requirements align closely with cyanotoxin preparedness. A defensible strategy includes source-water surveillance, clear trigger points for intensified sampling, treatment adjustments, redundancy for critical operations, alternative-water planning, and communication protocols that can be activated quickly if finished water is threatened. Because cyanotoxin incidents can resemble naturally occurring blooms yet still cause high-consequence disruptions, utilities also need detection, decision-making, and incident command systems that enable rapid coordination with public health agencies, laboratories, and emergency managers [4,5,12,16].

Food and Water Defense Implications

These considerations lead to a clear defense conclusion: algal toxins are not merely environmental contaminants or episodic public health curiosities, but operational hazards that expose vulnerabilities in both food and water systems. In food systems, this means protecting points at which contaminated seafood, algal ingredients, or process water could be introduced, concentrated, mislabeled, blended, or distributed at scale. In water systems, it means treating cyanotoxin events not only as water-quality incidents, but also as disruptions that can affect treatment performance, continuity of service, public communication, healthcare demand, and institutional trust. Across both domains, the same principle applies: effective prevention depends on identifying high-consequence failure points before exposure occurs and integrating monitoring, access control, traceback, emergency planning, and public health response within a single preparedness architecture.

Operationalizing that framework requires an integrated approach that combines food safety, water safety, environmental monitoring, and emergency planning. In practice, this includes monitoring harvest waters and source water, testing when indicated, optimizing treatment and control measures, maintaining traceback and communication systems, and applying food-defense safeguards at high-risk points such as sourcing, receiving, processing, storage, blending, and water

 doi:10.20944/preprints202606.1989.v1

inputs [3,17]. Recent international guidance reinforces this operational approach. The 2026 joint FAO/IOC-UNESCO/IAEA guidance on algal toxins in bivalve mollusks emphasizes harmful-algae monitoring, management of harvesting and production areas, pre-harvest monitoring, post-harvest batch testing, and microalgal monitoring as components of a risk-based system for preventing toxin-contaminated shellfish from entering commerce (38b).

Novelty and Significance of the Review

The significance of this review lies in explicitly reframing algal toxins as food-and-water defense hazards rather than treating them only as environmental contaminants, seafood syndromes, or drinking-water quality problems. This framing is novel because algal toxins occupy an unusual position among defense-relevant hazards: they are naturally occurring and biologically derived, yet their potency, concealment, resistance to routine consumer mitigation, uncertain attribution, and capacity to disrupt high-volume food and water systems create challenges similar to those considered in intentional-contamination planning. The defense question is therefore not limited to whether contamination is deliberate. It is whether the food and water system can rapidly detect, contain, trace, communicate, and recover from high-consequence toxin events before avoidable exposures occur.

This integrated framing also clarifies the practical value of the review. It brings together topics that are often managed separately--harmful algal bloom ecology, toxin mechanisms, seafood controls, drinking-water resilience, clinical recognition, laboratory testing, climate change, intentional-adulteration preparedness, and emergency communication--and organizes them around operational vulnerability. That approach supports a preparedness model in which seafood authorities, water utilities, laboratories, poison centers, clinicians, emergency managers, and food-sector operators can plan from a shared risk architecture rather than responding through disconnected programs.

Surveillance and Clinical Recognition

Harmful algal bloom-related illnesses may present with gastrointestinal, neurologic, respiratory, dermatologic, or hepatic effects, depending on the toxin and route of exposure. CDC notes that treatment for cyanotoxin-associated illnesses and foodborne illnesses caused by harmful algal bloom toxins is generally supportive and symptom-directed, and that no specific antidotes exist for many of these toxins [4]. This reality increases the importance of prevention, early reporting, poison-control consultation, public health notification, and laboratory coordination when contaminated seafood, drinking water, or algal products are suspected.

Recent U.S. outbreak surveillance reinforces the operational importance of this prevention-first approach. During 2011-2023, CDC identified 402 foodborne disease outbreaks associated with marine toxins, resulting in 1,280 illnesses, 96 hospitalizations, and one death; ciguatoxin alone caused 189 outbreaks, 619 illnesses, and 67 hospitalizations [41]. Although the CDC marine-toxin category also includes non-algal etiologies such as scombroid toxin, the report is directly relevant to algal-toxin preparedness because it emphasizes that ciguatoxin and shellfish-associated algal toxins are tasteless, odorless, and resistant to cooking or freezing once aquatic animals are contaminated [41]. These features reinforce the core defense argument of this review: consumer-level detection and routine preparation cannot be relied on as the final safety barrier. The range of human illnesses associated with these toxins is summarized in Table 4 to link exposure pathways to the syndromes most relevant to clinical and public health responses.

 doi:10.20944/preprints202606.1989.v1

Table 4. Human Syndromes Associated with Algal Toxins, Exposure Routes, and Hallmark Clinical Findings.

Syndrome	Typical toxins	Common exposure route	Hallmark clinical findings	Typical clinical concern
PSP (7b,7c)	Saxitoxins (4a)	Contaminated shellfish	Perioral numbness, paresthesia, weakness, paralysis	Respiratory failure
ASP (16c-16g)	Domoic acid	Shellfish, occasionally other seafood	Confusion, disorientation, amnesia, seizures	Persistent neurologic injury
DSP (7x)	Okadaic acid, dinophysistoxins	Shellfish	Diarrhea, abdominal cramps, nausea, vomiting	Dehydration, transient illness
CFP (7d-7h,16i)	Ciguatoxins	Reef fish	GI symptoms, paresthesia, temperature reversal, fatigue	Prolonged neurologic symptoms
NSP (7g,16i)	Brevetoxins	Shellfish; aerosol near blooms	Paresthesia, dizziness, bronchial irritation, respiratory complaints	Neuro-respiratory toxicity
Cyanobacterial hepatotoxicity (7i-7L)	Microcystins, nodularin, cylindrospermopsin	Drinking water, recreation, food	Nausea, vomiting, abdominal pain, liver dysfunction	Hepatic injury
Cyanobacterial neurotoxicity (7m,7n)	Saxitoxin, anatoxin-a, guanitoxin	Drinking water, animal exposure, recreation	Tremor, weakness, fasciculations, paralysis	Respiratory compromise
Cyanobacterial dermatitis (7o-7q)	Lyngbyatoxins, aplysiatoxins	Skin contact, aerosols	Rash, erythema, blistering, irritation	Local tissue injury

Footnotes: Clinical manifestations vary with dose, route, toxin combination, and host factors. Some toxins produce overlapping syndromes, and sublethal exposures may still be clinically significant. Aerosol exposure is particularly relevant for brevetoxins and some cyanobacterial irritants.

Climate Change and Emerging Risk

Climate change is not simply an environmental backdrop to harmful algal blooms; it is a force multiplier for food-and-water defense risk. Warmer surface waters, altered precipitation patterns, intensified stratification, nutrient runoff, eutrophication, drought-flood cycles, marine heatwaves, and changing circulation patterns can increase bloom frequency, extend bloom duration, expand geographic range, and shift species composition across freshwater, estuarine, and marine systems [31–35,38–40]. These changes matter operationally because the public health threat posed by harmful algal blooms depends not only on whether blooms occur, but also on which organisms dominate, what toxins they produce, how those toxins move through food and water systems, and whether surveillance systems can recognize changing exposure profiles.

Recent literature strengthens the evidence base for this risk. A 2024 review in Nature Reviews Earth & Environment reported that global inland harmful algal bloom occurrence has risen since the 1980s, including a 44% increase from the 2000s to the 2010s, and emphasized nutrient pollution, climate warming, legacy nutrients, integrated monitoring networks, and data-sharing frameworks as central to forecasting and mitigation [35]. In high-latitude coastal systems, modeling and observational work show that warming and freshening can change not only bloom frequency but also seasonality and toxin profiles. Along the Norwegian coast, a 3 °C warmer scenario was projected

 doi:10.20944/preprints202606.1989.v1

to increase Dinophysis acuta bloom frequency and reduce Alexandrium tamarense-complex blooms, implying a shift in relative exposure from paralytic to diarrhetic shellfish toxins in some settings [36].

Field evidence also links climate-related ocean change to food-web exposure. A 2025 Nature study quantified domoic acid and saxitoxin in bowhead whale samples collected over 19 years and found that algal-toxin prevalence and concentrations were correlated with ocean heat flux, open-water area, wind velocity, and atmospheric pressure, supporting a mechanistic link between warming conditions and increasing algal-toxin concentrations in Arctic food webs [37]. These findings are especially important for food-and-water defense because they connect environmental change to food security, subsistence harvesting, wildlife health, and the need for surveillance systems capable of detecting northward and seasonal shifts in toxin risk.

A One Health perspective further underscores the significance of algal toxins as sentinel hazards. A 2026 study of a harmful algal bloom in Golfo Nuevo, Argentina, documented phycotoxin transfer from phytoplankton to mesozooplankton, mussels, fish, whales, and sea lions; it also described sea-lion mortality, evidence of maternal toxin transfer, and gastrointestinal illness in approximately 10% of the local population during the bloom period [42]. In the Arctic, rapid detection and risk communication during a large Alexandrium catenella bloom demonstrated the value of near-real-time monitoring, interdisciplinary coordination, and stakeholder engagement in remote regions where routine laboratory capacity and public-health infrastructure may be limited [43]. Together, these studies show that climate-driven algal-toxin risks are not confined to environmental monitoring; they affect seafood safety, public communication, emergency preparedness, wildlife conservation, subsistence food security, and confidence in food and water systems.

Conclusion

In conclusion, algal toxins should be understood as a consequential component of modern food-and-water defense rather than as a marginal subset of environmental health. Their ability to contaminate seafood, drinking water, algal ingredients, and other water-dependent food pathways, to evade sensory detection, to resist routine preparation, and to disrupt interconnected supply systems makes them important hazards for preventive planning. The novelty of this review is its integration of algal-toxin toxicology, harmful algal bloom ecology, seafood safety, drinking-water protection, intentional-adulteration preparedness, climate change, and emergency response into a single defense-oriented framework. This perspective does not imply that most algal-toxin events are deliberate. Rather, it emphasizes that high-consequence toxin incidents require preparedness systems capable of functioning regardless of whether contamination is ultimately classified as natural, accidental, or intentional.

Credible preparedness, therefore, requires more than bloom awareness alone. It requires coordinated surveillance of source waters and harvest areas, risk-based testing, supplier and chain-of-custody controls, product-hold and traceback capacity, treatment resilience for drinking-water systems, clinical and poison-control recognition, public advisories, and emergency communication across the food and water continuum. As climate change, global seafood trade, expanding aquaculture, changing recreational and subsistence harvesting patterns, and water-system vulnerabilities alter exposure profiles, algal toxins provide a practical test case for whether contemporary food and water defense systems can manage biologically derived hazards that are environmentally driven, operationally complex, and socially disruptive.

 doi:10.20944/preprints202606.1989.v1

Author Contributions: AN: writing-review and editing, reviewed all drafts, and approved the final manuscript. MTF-S: writing-review and editing, reviewed all drafts, and approved the final manuscript. AM: Conceptualization, worked on the original draft, writing-review and editing, reviewed all drafts and approved the final manuscript. PP: Conceptualization, enhanced original draft; writing-review and editing, reviewed all subsequent drafts and approved the final manuscript. AWH: Conceptualization, writing original draft, writing-review and editing, supervision, project administration, and approved the final manuscript. All authors have read and agreed to the published version of the paper.

Funding: This research received no funding (external or internal).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: None of the authors has a conflict of interest to declare.

References

1. Centers for Disease Control and Prevention. (2025, April 23). Food poisoning from marine toxins. In CDC Yellow Book: Health Information for International Travel. No DOI assigned.
2. U.S. Environmental Protection Agency. (2025). Common toxins produced by cyanobacteria, dinoflagellates, and diatoms. No DOI assigned.
3. U.S. Food and Drug Administration. (2024). Natural toxins in food. No DOI assigned.
4. Centers for Disease Control and Prevention. (2024, January 9). Harmful algal blooms and your health. No DOI assigned.
5. Cusick KD, Sayler GS. An overview on the marine neurotoxin saxitoxin: Genetics, molecular targets, methods of detection, and ecological functions. Mar Drugs. 2013;11(4):991-1018. doi:10.3390/md11040991.
6. Centers for Disease Control and Prevention. (2024). Preventing illnesses caused by harmful algal blooms. No DOI assigned.
7. Federal Select Agent Program. (2025). Select agents and toxins list. No DOI assigned.
8. Buratti FM, Manganelli M, Vichi S, Stefanelli M, Scardala S, Testai E, Funari E. Cyanotoxins: Producing organisms, occurrence, toxicity, mechanism of action, and human health toxicological risk evaluation. Arch Toxicol. 2017;91:1049-1130. doi:10.1007/s00204-016-1913-6.
9. Federal Select Agent Program. (2025). Permissible toxin amounts. No DOI assigned.
10. Anderson DM, Cembella AD, Hallegraeff GM. Progress in understanding harmful algal blooms: Paradigm shifts and new technologies for research, monitoring, and management. Annu Rev Mar Sci. 2012;4:143-176. doi:10.1146/annurev-marine-120308-081121.
11. Suleiman M, Jelip J, Rundi C, Chua TH. Case report: Paralytic shellfish poisoning in Sabah, Malaysia. Am J Trop Med Hyg. 2017;97(6):1731-1736. doi:10.4269/ajtmh.17-0589.
12. Taylor FJR. Artificial respiration saves two. Harmful Algae News. 1992;3:5.
13. Lewis RJ. The changing face of ciguatera. Toxicon. 2001;39(1):97-106. doi:10.1016/S0041-0101(00)00161-6.
14. Soliño L, Costa PR. Differential toxin profiles of ciguatoxins in marine organisms: Chemistry, fate, and global distribution. Toxicon. 2018;150:124-143. doi:10.1016/j.toxicon.2018.05.005.
15. Murray TF. Neurotoxins: Ciguatoxin and brevetoxin—from excitotoxicity to neurotherapeutics. In: Advances in Neurotoxicology. Vol 6. Elsevier; 2021:89-104. doi:10.1016/bs.ant.2021.03.003.
16. Dechraoui MY, Naar J, Pauillac S, Legrand AM. Ciguatoxins and brevetoxins, neurotoxic polyether compounds active on sodium channels. Toxicon. 1999;37(1):125-143. doi:10.1016/S0041-0101(98)00169-X.
17. L'Herondelle K, Talagas M, Mignen O, Misery L, Le Garrec R. Neurological disturbances of ciguatera poisoning: Clinical features and pathophysiological basis. Cells. 2020;9(10):2291. doi:10.3390/cells9102291.
18. Zurawell RW, Chen H, Burke JM, Prepas EE. Hepatotoxic cyanobacteria: A review of the biological importance of microcystins in freshwater environments. J Toxicol Environ Health B Crit Rev. 2005;8(1):1-37. doi:10.1080/10937400590889412.

 doi:10.20944/preprints202606.1989.v1

19. Melaram R, Newton AR, Chafin J. Microcystin contamination and toxicity: Implications for agriculture and public health. Toxins (Basel). 2022;14(5):350. doi:10.3390/toxins14050350.
20. Runnegar MT, Kong SM, Zhong YZ, Lu SC. Inhibition of reduced glutathione synthesis by cyanobacterial alkaloid cylindrospermopsin in cultured rat hepatocytes. Biochem Pharmacol. 1995;49(2):219-225. doi:10.1016/S0006-2952(94)00466-8.
21. Runnegar MT, Xie C, Snider BB, Wallace GA, Weinreb SM, Kuhlenkamp J. In vitro hepatotoxicity of the cyanobacterial alkaloid cylindrospermopsin and related synthetic analogues. Toxicol Sci. 2002;67(1):81-87. doi:10.1093/toxsci/67.1.81.
22. Colas S, Marie B, Lance E, Quiblier C, Tricoire-Leignel H, Mattei C. Anatoxin-a: Overview on a harmful cyanobacterial neurotoxin from the environmental scale to the molecular target. Environ Res. 2021;193:110590. doi:10.1016/j.envres.2020.110590.
23. Christensen VG, Khan E. Freshwater neurotoxins and concerns for human, animal, and ecosystem health: A review of anatoxin-a and saxitoxin. Sci Total Environ. 2020;736:139515. doi:10.1016/j.scitotenv.2020.139515.
24. Fujiki H, Mori M, Nakayasu M, Terada M, Sugimura T, Moore RE. Indole alkaloids: Dihydroteleocidin B, teleocidin, and lyngbyatoxin A as members of a new class of tumor promoters. Proc Natl Acad Sci U S A. 1981;78(6):3872-3876. doi:10.1073/pnas.78.6.3872.
25. Willey JC, Moser CE Jr, Harris CC. Effects of aplysiatoxin and debromoaplysiatoxin on growth and differentiation of normal human bronchial epithelial cells. Cell Biol Toxicol. 1984;1(1):145-154. doi:10.1007/BF00125571.
26. Ueyama H, Sasaki I, Shimomura K, Suganuma M. Specific protein interacting with a tumor promoter, debromoaplysiatoxin, in bovine serum is alpha 1-acid glycoprotein. J Cancer Res Clin Oncol. 1995;121(4):211-218. doi:10.1007/BF01366964.
27. Noda M, Suzuki H, Numa S, Stühmer W. A single point mutation confers tetrodotoxin and saxitoxin insensitivity on the sodium channel II. FEBS Lett. 1989;259(1):213-216. doi:10.1016/0014-5793(89)81531-5.
28. Terlau H, Heinemann SH, Stühmer W, et al. Mapping the site of block by tetrodotoxin and saxitoxin of sodium channel II. FEBS Lett. 1991;293(1-2):93-96. doi:10.1016/0014-5793(91)81159-6.
29. Penzotti JL, Fozzard HA, Lipkind GM, Dudley SC. Differences in saxitoxin and tetrodotoxin binding revealed by mutagenesis of the Na+ channel outer vestibule. Biophys J. 1998;75(6):2647-2657. doi:10.1016/S0006-3495(98)77710-0.
30. Walker JR, Novick PA, Parsons WH, et al. Marked difference in saxitoxin and tetrodotoxin affinity for the human nociceptive voltage-gated sodium channel (Nav1.7). Proc Natl Acad Sci U S A. 2012;109(44):18102-18107. doi:10.1073/pnas.1206952109.
31. Biscoe TJ, Evans RH, Headley PM, Martin M, Watkins JC. Domoic and quisqualic acids as potent amino acid excitants of frog and rat spinal neurones. Nature. 1975;255(5504):166-167. doi:10.1038/255166a0.
32. Wright JL, Bird CJ, de Freitas AS, Hampson D, McDonald J, Quilliam MA. Chemistry, biology, and toxicology of domoic acid and its isomers. Can Dis Wkly Rep. 1990;16(Suppl 1E):21-26.
33. Valdiglesias V, Prego-Faraldo M, Pásaro E, Méndez J, Laffon B. Okadaic acid: More than a diarrheic toxin. Mar Drugs. 2013;11(11):4328-4349. doi:10.3390/md11114328.
34. Fu L-ling, Zhao X-yu, Ji L-dan, Xu J. Okadaic acid (OA): Toxicity, detection, and detoxification. Toxicon. 2019;160:1-7. doi:10.1016/j.toxicon.2018.12.007.
35. Woods Hole Oceanographic Institution. (n.d.). AZP (azaspiracid poisoning). No DOI assigned.
36. Yang J, Sun W, Sun M, Cui Y, Wang L. Current research status of azaspiracids. Mar Drugs. 2024;22(2):79. doi:10.3390/md22020079.
37. Rossini GP, Bigiani A. Palytoxin action on the Na(+),K(+)-ATPase and the disruption of ion equilibria in biological systems. Toxicon. 2011;57(3):429-439. doi:10.1016/j.toxicon.2010.09.011.
38. World Health Organization. WHO Estimates of the Global Burden of Foodborne Diseases: Foodborne Disease Burden Epidemiology Reference Group 2007–2015. Geneva, Switzerland: World Health Organization; 2015.
39. FoodSafety.gov. (n.d.). Food poisoning. No DOI assigned.

 doi:10.20944/preprints202606.1989.v1

40. U.S. Food and Drug Administration. (2025). National Shellfish Sanitation Program Centennial. No DOI assigned. https://www.fda.gov/food/federal-state-local-tribal-and-territorial-cooperative-human-food-programs/national-shellfish-sanitation-program-nssp-centennial
41. U.S. Food and Drug Administration and Interstate Shellfish Sanitation Conference. National Shellfish Sanitation Program (NSSP) Guide for the Control of Molluscan Shellfish: 2023 Revision. Silver Spring, MD: U.S. Food and Drug Administration; 2023. No DOI assigned.
42. Centers for Disease Control and Prevention. (2024, May 6). Clinical overview of harmful algal bloom-associated illnesses. No DOI assigned.
43. World Health Organization. (2021). Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management (2nd ed.). No DOI assigned for the WHO webpage; corresponding book DOI: 10.1201/9781003081449.
44. U.S. Environmental Protection Agency. (2025). Managing algal toxins in drinking water. No DOI assigned.
45. U.S. Environmental Protection Agency. (2025). EPA drinking water health advisories for cyanotoxins. No DOI assigned.
46. U.S. Environmental Protection Agency. 2026. Drinking water health advisory documents for cyanobacterial toxins. No DOI assigned.
47. Chorus I, Welker M, eds. Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management. 2nd ed. CRC Press; 2021. doi:10.1201/9781003081449.
48. Proceedings of a Symposium: Domoic Acid Toxicity. Ottawa, Ontario; April 11-12, 1989.
49. Perl TM, Bédard L, Kosatsky T, Hockin JC, Todd ECD, Remis RS. An outbreak of toxic encephalopathy caused by eating mussels contaminated with domoic acid. N Engl J Med. 1990;322(25):1775-1780. doi:10.1056/NEJM199006213222504.
50. Teitelbaum JS, Zatorre RJ, Carpenter S, et al. Neurologic sequelae of domoic acid intoxication due to the ingestion of contaminated mussels. N Engl J Med. 1990;322(25):1781-1787. doi:10.1056/NEJM199006213222505.
51. Wright JL, Bird CJ, de Freitas AS, Hampson D, McDonald J, Quilliam MA. Chemistry, biology, and toxicology of domoic acid and its isomers. Can Dis Wkly Rep. 1990;16(Suppl 1E):21-26.
52. Novelli A, Fernández-Sánchez MT, Pérez-Gómez A, Cabrera-Garcia D, Salas-Puig J, Lipsky R, Marini AM. Marine toxins, neurodegeneration and neuroprotection. Am J Neuroprotect Neuroregen. 2011;3(1):21-31. doi:10.1166/ajnn.2011.1030.
53. Loeffler CR, Spielmeyer A, Blaschke V, Bodi D, Kappenstein O. Ciguatera poisoning in Europe: A traceback to Indian Ocean-sourced snapper fish (Lutjanus bohar). Food Control. 2023;151:109799. doi:10.1016/j.foodcont.2023.109799.
54. Onuma Y, Satake M, Ukena T, Roux J, Chanteau S, Rasolofonirina N, Ratsimaloto M, Naoki H, Yasumoto T. Identification of putative palytoxin as the cause of clupeotoxism. Toxicon. 1999;37(1):55-65. doi:10.1016/S0041-0101(98)00133-0.
55. McCord J, Lang JR, Hill D, Strynar M, Chernoff N. pH-dependent octanol-water partitioning coefficients of microcystin congeners. J Water Health. 2018;16(3):340-345. doi:10.2166/wh.2018.257.
56. Zurawell RW, Chen H, Burke JM, Prepas EE. Hepatotoxic cyanobacteria: A review of the biological importance of microcystins in freshwater environments. J Toxicol Environ Health B Crit Rev. 2005;8(1):1-37. doi:10.1080/10937400590889412.
57. U.S. Food and Drug Administration. (2016). Mitigation strategies to protect food against intentional adulteration. Federal Register, 81(103), 34166–34297. No DOI assigned.
58. Campàs M, Alkassar M, Gaiani G, Leonardo S, Rambla-Alegre M, Diogène J. The wide spectrum of methods available to study marine neurotoxins. In: Advances in Neurotoxicology. Vol 6. Elsevier; 2021:275-315. doi:10.1016/bs.ant.2021.03.005.
59. Dillon M, Zaczek-Moczydlowska MA, Edwards C, et al. Current trends and challenges for rapid SMART diagnostics at point-of-site testing for marine toxins. Sensors (Basel). 2021;21(7):2499. doi:10.3390/s21072499.
60. Alshannaq AF, Yu JH. A liquid chromatographic method for rapid and sensitive analysis of aflatoxins in laboratory fungal cultures. Toxins (Basel). 2020;12(2):93. doi:10.3390/toxins12020093.

 doi:10.20944/preprints202606.1989.v1

61. Sulyok M, Suman M, Krska R. Quantification of 700 mycotoxins and other secondary metabolites of fungi and plants in grain products. NPJ Sci Food. 2024;8(1):49. doi:10.1038/s41538-024-00294-7.
62. Khan R, Ghazali FM, Mahyudin NA, Samsudin NIP. Chromatographic analysis of aflatoxigenic Aspergillus flavus isolated from Malaysian sweet corn. Separations. 2021;8:98. doi:10.3390/separations8070098.
63. Gbashi S, Njobeh PB. Enhancing food integrity through artificial intelligence and machine learning: A comprehensive review. Appl Sci. 2024;14(8):3421. doi:10.3390/app14083421.
64. Wijayawardene NN, Boonyuen N, Ranaweera CB, de Zoysa HKS, Padmathilake RE, Nifla F, Dai DQ, Liu Y, Suwannarach N, Kumla J, Bamunuarachchige TC, Chen HH. OMICS and other advanced technologies in mycological applications. J Fungi (Basel). 2023;9(6):688. doi:10.3390/jof9060688.
65. Louzao MC, Vilariño N, Vale C, Costas C, Cao A, Raposo-Garcia S, et al. Current trends and new challenges in marine phycotoxins. Mar Drugs. 2022;20(3):198. doi:10.3390/md20030198.
66. LePage KT, Dickey RW, Gerwick WH, Jester ELE, Murray TF. On the use of Neuro-2a neuroblastoma cells versus intact neurons in primary culture for neurotoxicity studies. Crit Rev Neurobiol. 2005;17(1):27-50. doi:10.1615/CritRevNeurobiol.v17.i1.20.
67. Hogberg HT, Sobanski T, Novellino A, Whelan M, Weiss DG, Bal-Price AK. Application of micro-electrode arrays (MEAs) as an emerging technology for developmental neurotoxicity: Evaluation of domoic acid-induced effects in primary cultures of rat cortical neurons. Neurotoxicology. 2011;32(1):158-168. doi:10.1016/j.neuro.2010.10.007.
68. Hogberg HT, Sobanski T, Novellino A, Whelan M, Weiss DG, Bal-Price AK. Application of micro-electrode arrays (MEAs) as an emerging technology for developmental neurotoxicity: Evaluation of domoic acid-induced effects in primary cultures of rat cortical neurons. Neurotoxicology. 2011;32(1):158-168. doi:10.1016/j.neuro.2010.10.007.
69. Domínguez HJ, Cabrera-García D, Cuadrado C, Novelli A, Fernández-Sánchez MT, Fernández JJ, Daranas AH. Prorocentroic acid, a neuroactive super-carbon-chain compound from the dinoflagellate Prorocentrum hoffmannianum. Org Lett. 2021;23(1):13-18. doi:10.1021/acs.orglett.0c03437.
70. Novelli A, Hernandez-Daranas A, Cabrera-García D, Ascencio Salazar F, Fernández-Sánchez MT. Potential neurotoxins: Okadaic acid and analogs. In: Advances in Neurotoxicology. Vol 6. Elsevier; 2021:193-221. doi:10.1016/bs.ant.2021.04.001.
71. U.S. National Office for Harmful Algal Blooms. (n.d.). Distribution of HABs throughout the world. No DOI assigned.
72. Wells ML, Karlson B, Wulff A, Kudela R, Trick C, Asnaghi V, Berdalet E, Cochlan W, Davidson K, De Rijcke M, Dutkiewicz S, Hallegraeff G, Flynn KJ, Legrand C, Paerl H, Silke J, Suikkanen S, Thompson P, Trainer VL. Future HAB science: Directions and challenges in a changing climate. Harmful Algae. 2020;91:101632. doi:10.1016/j.hal.2019.101632.
73. Anderson DM. Approaches to monitoring, control and management of harmful algal blooms (HABs). Ocean Coast Manag. 2009;52(7):342. doi:10.1016/j.ocecoaman.2009.04.006.
74. Sanseverino I, Conduto D, Pozzoli L, Dobricic S, Lettieri T. Algal bloom and its economic impact. Publications Office of the European Union; 2016.
75. Feng L, Wang Y, Hou X, Qin B, Kutser T, Qu F, Chen N, Paerl HW, Zheng C. Harmful algal blooms in inland waters. Nat Rev Earth Environ. 2024;5:631-644. doi:10.1038/s43017-024-00578-2.
76. Silva E, Counillon F, Brajard J, Davy R, Outten S, Pettersson LH, Keenlyside N. Warming and freshening coastal waters impact harmful algal bloom frequency in high latitudes. Commun Earth Environ. 2025;6:445. doi:10.1038/s43247-025-02421-y.
77. Lefebvre KA, Charapata P, Stimmelmayr R, et al. Bowhead whale faeces link increasing algal toxins in the Arctic to ocean warming. Nature. 2025;644:693-698. doi:10.1038/s41586-025-09230-5.
78. Hennon GMM, Dyhrman ST. Progress and promise of omics for predicting the impacts of climate change on harmful algal blooms. Harmful Algae. 2020 Jan;91:101587. doi: 10.1016/j.hal.2019.03.005.
79. Carmichael, W. W. (2001). Health effects of toxin-producing cyanobacteria: "The CyanoHABs." Human and Ecological Risk Assessment, 7(5), 1393–1407. https://doi.org/10.1080/20018091095087.

 doi:10.20944/preprints202606.1989.v1

80. Food and Agriculture Organization of the United Nations, Intergovernmental Oceanographic Commission of UNESCO, & International Atomic Energy Agency. (2026). Joint FAO/IOC-UNESCO/IAEA guidance on monitoring of algal toxins in bivalve molluscs: Including monitoring of harmful algae and management of harvesting and production areas (Food Safety and Quality Series No. 34). FAO. doi:10.4060/cd8990en.
81. Gerssen, A., Pol-Hofstad, I. E., Poelman, M., Mulder, P. P. J., van den Top, H. J., & de Boer, J. (2010). Marine toxins: Chemistry, toxicity, occurrence and detection, with special reference to the Dutch situation. Toxins, 2(4), 878–904. doi:10.3390/toxins2040878.
82. Huisman, J., Codd, G. A., Paerl, H. W., Ibelings, B. W., Verspagen, J. M. H., & Visser, P. M. (2018). Cyanobacterial blooms. Nature Reviews Microbiology, 16(8), 471–483. doi:10.1038/s41579-018-0040-1.
83. Paerl, H. W., & Otten, T. G. (2013). Harmful cyanobacterial blooms: Causes, consequences, and controls. Microbial Ecology, 65, 995–1010. doi:10.1007/s00248-012-0159-y.
84. Testai, E., Buratti, F. M., Funari, E., Manganelli, M., Vichi, S., Arnich, N., Biré, R., Fessard, V., & Sialehaamoa, A. (2016). Review and analysis of occurrence, exposure and toxicity of cyanobacteria toxins in food. EFSA Supporting Publications, 13(2), 998E. doi:10.2903/sp.efsa.2016.EN-998.
85. Visser, P. M., Verspagen, J. M. H., Sandrini, G., Stal, L. J., Matthijs, H. C. P., Davis, T. W., Paerl, H. W., & Huisman, J. (2016). How rising CO_2 and global warming may stimulate harmful cyanobacterial blooms. Harmful Algae, 54, 145–159. doi:10.1016/j.hal.2015.12.006.
86. Havens KE, Paerl HW. Climate Change at a Crossroad for Control of Harmful Algal Blooms. Environ Sci Technol. 2015 Nov 3;49(21):12605-6. doi: 10.1021/acs.est.5b03990.
87. Hartley CM, Hoang ST, Roberts VA, Chard AN. Foodborne Disease Outbreaks Associated with Marine Toxins--Foodborne Disease Outbreak Surveillance System, United States, 2011-2023. MMWR Surveill Summ. 2026;75(No. SS-3):1-13. doi:10.15585/mmwr.ss7503a1.
88. D'Agostino VC, Degrati M, Arregui M, Nocera AC, Guinder V, Ferronato C, Krock B. Marine mammal mortality during a harmful algal bloom in the Southwestern Atlantic reveals trophic phycotoxin transfer and fetal exposure in sea lions. Commun Earth Environ. 2026;7:512. doi:10.1038/s43247-026-03493-0.
89. Fachon E, Pickart RS, Sheffield G, Pate E, Pathare M, Brosnahan ML, et al. Tracking a large-scale and highly toxic Arctic algal bloom: Rapid detection and risk communication. Limnol Oceanogr Lett. 2025;10(1). doi:10.1002/lol2.10421.