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REVIEW

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The eco-physiology of harmful algal blooms

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ABSTRACT

Harmful algal blooms (HABs) can occur in freshwater and marine environments, caused by various species of planktonic algae spanning a wide taxonomic range. The occurrence of these algal blooms encompasses a diverse array of organisms, bloom dynamics, and impact mechanisms. There are two primary factors that lead to algal bloom: natural mechanisms like circulation, relaxation of upwelling, river flow, and anthropogenic inputs, which result in eutrophication. Unfortunately, there is a common assumption that anthropogenic factors are solely responsible for recent blooms in stagnant waters and coastal areas, which is not always true. This review highlights the ecological and environmental factors contributing to the formation and development of algal blooms, focusing on nutrient enrichment, temperature, light availability, and grazing pressure. By investigating the physiological and molecular responses of bloom-forming species to changing ecological conditions, the review aims to provide insights into the factors influencing the size and duration of algal blooms. Ultimately, it contributes to developing more efficient management and mitigation strategies for harmful algal blooms.

KEYWORDS

Harmful algal blooms; Ecology; Physiology; Molecular biology; Toxins

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Introduction

Earth is the only known planet capable of supporting life, accommodating a wide spectrum of life forms ranging from the tiniest prokaryotes to the largest eukaryotes. Scientific research indicates that the origins of life on our planet trace back to a primordial environment characterized by a lack of oxygen, with oxygen being present solely in the form of compounds such as oxides, hydroxides, peroxides, superoxides, and the like. These early life forms likely contributed to the emergence of oxygen gas by breaking these compounds and engaging in anoxygenic photosynthesis, ultimately paving the way for developing more complex organisms. Algae represent one such primitive life form within this context. The term "algae" encompasses a diverse array of organisms endowed with the ability to generate oxygen through photosynthesis. These organisms display a remarkable range of diversity in pigmentation and their capacity to perform photosynthesis under varying environmental conditions. However, they share certain defining characteristics that set them apart from other major groups of photosynthetic organisms [1]. Planktonic algal species exhibit a wide spectrum of sizes, spanning from a few nanometres to several micrometers in diameter, primarily classified into three categories: pico-sized (<2 μm), nano-sized (2-20 μm), and microplankton (>20 μm). Together, they significantly contribute, accounting for an estimated 60% of the global oceans' primary production. Microplankton is the primary producers in coastal oceans and estuaries, while nano and picoplankton assume this role in the open ocean regions.

The review aims to the ecological, physiological, and molecular aspects of algal blooms, particularly emphasizing the genetic and physiological basis underlying their formation and development. It provides a multifaceted analysis of these complex oceanic phenomena by integrating insights from molecular and cell biology, fieldwork, numerical modeling, and remote sensing. Through interdisciplinary research, this contributes to a deeper understanding of the complicated mechanisms governing algal blooms, including the factors influencing their growth, the role of nutrients, the impact of grazing pressure, and the molecular characteristics of bloom-forming species.

Importance of Algae in Aquatic Ecosystem

As a long-term photosynthesis generator, algae make an important contribution to the environment and health. This vital process has been ongoing for millions of years. Planktonic algae, which dominate the oceanic ecosystem, play a crucial role as the largest reservoir for CO_2 absorption through photosynthesis. When examining the ancient history of biofuels, it is suggested that petroleum may have partially originated from ancient algae deposits. Some of the oldest oil reserves are linked to cyanobacteria, although the exact identification of the mechanism remains unknown [2]. More recent oil deposits likely stem from eukaryotic marine green algae, coccolithophorids, and other microscopic marine phytoplankton. Various microalgal species, including green algae, diatoms, and cyanobacteria, are recognized as promising candidates for biofuel production. All types of algae possess the capability to synthesize energy-rich oils, and numerous microalgal species naturally accumulate significant oil content in their dry mass. Furthermore, algae are distributed across various habitats and are known for their rapid reproduction rates [3].

Role of Algae in Oceanic Food Chain and Ecology

Algae play a crucial role in the world's ecosystems as they contribute to the formation of clouds and ocean food webs.

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Phytoplankton, the microscopic algae, establish the primary trophic level in the oceanic food web [4]. Phytoplankton serve as the primary nutritional source for smaller fish and crustaceans, which subsequently constitute prey for larger species at the trophic level. This trophic transfer extends through successive levels of the food chain, ultimately reaching the largest predators and human consumption of algae, with specific varieties employed for numerous commercial and industrial applications. Algae synthesize organic nutrient molecules by utilizing carbon dioxide and water in the process of photosynthesis, a mechanism by which they capture solar energy. Additionally, to synthesize organic compounds, algae generate oxygen as a byproduct during the process of photosynthesis. Algae are estimated to contribute approximately 30 to 50 percent of the total global oxygen supply available to humans and other terrestrial animals for the purpose of respiration [5].

Algal Blooms

When favorable environmental conditions arise, specific algal species can experience rapid population growth, leading to the proliferation of their numbers, often reaching several million cells per liter. This abundance of algae can manifest as visible patches on the water's surface or a noticeable change in the water's color. This dense and rapid algal growth is referred to as a 'bloom,' which can be either persistent (commonly observed in polluted freshwater systems) or seasonal (typically seen in mesotrophic lakes and coastal ocean regions). The coloration of these blooms corresponds to the types of algae present within them. Many of the species responsible for bloom formation are planktonic and produce toxins, resulting in disruptions to the ecological balance of oceans and freshwater bodies. However, it's worth noting that green algal blooms are generally non-toxic [6].

In oceanic environments, the primary species responsible for bloom formation are certain types of dinoflagellates and diatoms. In freshwater systems, blooms are primarily caused by cyanobacteria and planktonic green algae. Under specific estuarine conditions, planktonic green algae can also reach bloom levels, albeit typically for a brief duration. In natural settings, algae produce toxins as a defense mechanism to deter consumption by small organisms, requiring only a minimal quantity to ensure their protection [7]. The "bloom" concentrations differ across species; e.g., 10^5 cells/L constitutes a bloom of *Protogonyuulux*, while blooms of *Aureococcus unophugefleruns* occur at the concentration of 10^9 cells/L [8]. In freshwater bodies, *Microcystis* attains a population as high as 10^9 cells/L, forming the dense bloom, but bloom condition appears with a cell density of 10^5 cells/L. Blooms are typically visible occurrences that can take on a variety of colors, such as green, red, brown, or bluish-green, depending on the dominant species within the population. While a few species may form blooms together, most standing blooms are generated by a combination of 2 to 5 species. These blooms may or may not be visible, and their coloration can vary. Interestingly, some of the most destructive blooms in recent history have been brown in color [7,9].

In most cases, red water blooms are caused by wind and currents on the water's surface. It is supported by the incidents that nearly all significant blooms initiate within the open ocean rather than in the bay environment [10]. Such blooms can either be toxigenic, producing specific toxins, or harmful, leading to anoxia due to the decay process, or, in certain cases, they can basically obstruct the gill structures of filter-feeding organisms. Additionally, algal blooms can emerge suddenly and induce the rapid development of shellfish toxicity within a short period. There is a threat of Harmful algal blooms (HABs), and the presence of harmful algal species has the potential to impact aquaculture negatively. These outbreaks not only represent a public health hazard, with numerous fatalities historically linked to paralytic shellfish poisoning but also lead to substantial mortality among shellfish populations and significant economic challenges for coastal fisheries and aquaculture enterprises. The challenges linked to toxic algal blooms are no longer confined to dinoflagellates and are increasingly evolving into a worldwide concern. Various research investigations and symposia have concentrated on the most prevalent species of toxic dinoflagellates [11]. The existence of toxic algal species and the potential for blooms have clear, negative impacts on aquaculture development. Table 1 summarises different algal species and their blooming environments.

Table 1. List of blooming species and their environmental condition.

Sl. No.	Genus	Phylum	Bloom Condition	Reference
1	*Alexandrium*	Dinoflagellates	Marine	[12,13]
2	*Amphidoma*	Miozoa	Marine	[14,15]
3	*Anabaena*	Cyanobacteria	Fresh water	[16-19]
4	*Anabaenopsis*	Cyanobacteria	Fresh water and Marine	[18,20,21]
5	*Aphanizomenon*	Cyanobacteria	Fresh water	[17,18,21]
6	*Aphanocapsa*	Cyanobacteria	Fresh water	[17,19,22]
7	*Aureococcus*	Heterokonta	Estuaries and marine	[23,24]
8	*Botryococcus*	Chlorophyta	Fresh water	[17,25,26]
9	*Ceratium*	Pyrrhophyta (Dinophyta)	Fresh water	[17,27,28]
10	*Chlorococcus*	Chlorophyta	Fresh water	[17,29,30]

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11	*Chromulina*	Chrysophyta	Fresh water	[17,31]
12	*Chrysochromulina*	Chrysophyta	Fresh water	[17,32,33]
13	*Cryptomonas*	Cryptophyta	Fresh water	[17,34]
14	*Cylindrospemopsis*	Cyanobacteria	Fresh water	[17,18,21]
15	*Dictyocha*	Heterokonta	Marine	[35,36]
16	*Dinobryon*	Chrysophyta	Fresh water	[17,37,38]
17	*Dinophysis*	Myzozoa	Marine	[39,40]
18	*Gloeotrichia*	Cyanobacteria	Fresh water	[17,18]
19	*Gonyaulax*	Dinoflagellata	Fresh water and Marine	[41,42]
20	*Gymnodinium*	Dinoflagellata	Fresh water and Marine	[43,44]
21	*Gyrodinium*	Miozoa	Marine water	[45,46]
22	*Lyngbya*	Cyanobacteria	Marine	[17,18,21]
23	*Mallomonas*	Chrysophyta	Fresh water	[17,47]
24	*Microcystis*	Cyanobacteria	Fresh water	[17,18,21]
25	*Nodularia*	Cyanobacteria	Fresh water	[17,18,21]
26	*Nostoc*	Cyanobacteria	Fresh water and Marine	[17,18,21]
27	*Oscillatoria*	Cyanobacteria	Fresh water	[17;18]
28	*Peridinium*	Pyrrhophyta (Dinophyta)	Fresh water	[17,48]
29	*Prymnesium*	Prymnesiophyta	Marine	[46,49]
30	*Phaeocystis*	Prymnesiophyte	Marine	[46,50]
31	*Phormidium*	Cyanobacteria	Fresh water	[18,51]
32	*Planktothrix*	Cyanobacteria	Fresh water	[18,21]
33	*Prorocentrum*	Pyrrhophyta (Dinophyta)	Fresh water	[18,46]
34	*Prymnesium*	Chrysophyta	Fresh water	[17,52]
35	*Pseudoanabaena*	Cyanobacteria	Fresh water	[18,53]
36	*Pyrodinium*	Dinoflagellata	Marine	[46,54]
37	*Raphidiopsis*	Cyanobacteria	Fresh water	[18,21]
38	*Rhizosolenia*	Ochrophyta	Marine and Brackish water	[46,55]
39	*Rhodomonas*	Cryptophyta	Fresh water	[17,56]

Causes of algal bloom

It is widely acknowledged that the increase in human activities and the expansion of coastal populations have played a role in the rise of toxic and harmful micro and macro-algae over the past two decades [61-63]. This surge in HABs poses a significant threat to our valuable marine ecosystems. What makes this situation particularly concerning is that, unlike chemical pollution, HABs, a form of 'biological pollution' have the potential to proliferate and thus become more frequent and severe. HABs have detrimental and swift effects on both natural ecosystems and aquaculture systems, including factors like temperature and chemical imbalances and drastic fluctuations in hydrogen, oxygen, and carbon dioxide levels. They also have enduring impacts, such as changes in chemical dynamics and disruptions in food chains. These consequences can limit the use of resources and negatively impact commercial fishing and shellfish production. The most alarming aspect is that certain HABs produce toxic substances that harm and even kill marine organisms, including mammals, fish, and birds while posing substantial health risks to humans [64-66].

Furthermore, some microalgae generate taste and odor compounds that are undesirable, although not toxic. These compounds lead to substantial losses in aquaculture production and raise concerns about the safety of water resources containing them. Consequently, marine resource administrators, public health authorities, commercial fishing enterprises, and industries such as aquaculture, potable water production, and processed food and beverages have identified

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algal-derived toxins and compounds associated with taste and odor as serious issues [67-69]. In light of these concerns, this review will examine the ecology, physiology, and molecular biology of algal blooms.

Ecological factors

The main ecological factor for the bloom is the excess enrichment of nutrients in both freshwater and marine ecosystems [17,70-72]. Nitrogen inputs are often cited as controlling "new" production in the marine environment [73], while phosphorus is thought to limit primary productivity in freshwater ecosystems [74]. Estuarine ecosystems often exhibit intermediate nutrient limitation “paradigms” where P-limited conditions are characteristic in the low salinity oligohaline regions (salinity <5), upstream regions, and N limitation typifying more saline (salinity >5), downstream waters [73]. Elevated levels of phosphorus, particularly in relation to nitrogen, can promote the development of algal blooms, particularly favoring N_2 fixing cyanobacterial genera. These cyanobacteria have the capacity to meet their own nitrogen requirements by enzymatically converting atmospheric nitrogen (N_2) to biologically available ammonia (NH_3) [75]. Water bodies enriched with nutrients are particularly susceptible to bloom formation, particularly when they exhibit prolonged residence times (low flushing rates), experience periodic water temperatures exceeding 20 °C in the subtropics and temperature conditions, and remain at around 30 °C in the tropical water bodies, calm surface waters, and persistent vertical stratification [76]. Elevated phosphorus (in relation to nitrogen) loading is not a universal “trigger” for forming algal blooms.

Nutrient inputs from agricultural, urban, and industrial sources have undergone rapid acceleration in recent decades, and nitrogen loads often surpass phosphorus inputs [77]. As a result of increased N-fertilizer application, human and agricultural wastes, stormwater runoff, groundwater discharge, and atmospheric deposition, which are all high in nitrogen relative to P, water bodies already impacted by nutrient depletion are being loaded with nitrogen [78]. Aquatic ecosystems with elevated nitrogen levels (high N:P ratios) can also experience the occurrence of blooms, particularly those comprised of non-N_2-fixing genera. This category primarily includes species belonging to *Microcystis* and *Planktothrix*, although various non-N_2-fixing genera, such as *Aphanocapsa, Raphidiopsis*, and *Woronochinia*, possess the capacity of aggressive expansion in nitrogen-enriched aquatic environments. In numerous cases, maximum daily loads for phosphorus have been defined and implemented; however, nitrogen inputs are subject to less strict regulation, resulting in their increase in many ecosystems. N augmentation in both developed and developing regions has raised concerns that excessive N loading is accelerating eutrophication and promoting standing algal blooms in downstream freshwater and marine ecosystems [77,79,80]. Hence, the “P-only” paradigm for blooms control [81] needs to be revised [82]. Recent research, however, has demonstrated that cyanobacterial N_2 fixation does not meet the nitrogen requirements of phytoplankton or the ecosystem [82,83] for various factors, including (1) the high energy demands of N_2 fixation, (2) the inhibition of this anaerobic process by production of oxygen in blooms through photosynthesis, (3) disruption of N_2 fixation by turbulence and wind mixing, and (4) potential limitations imposed by other cofactors such as Fe, Mo, and/or other trace metals [84]. In aquatic environments where N_2 fixation fails to meet the ecosystem's nitrogen demands, external nitrogen inputs play a vital role in augmenting nutrient availability, with excessive nitrogen inputs frequently resulting in undesirable and excessive algal production. Thus, eutrophic systems that are already subjected to HAB occurrences are prone to further expansion of these blooms due to supplementary nitrogen inputs, particularly when they already possess adequate autochthonous phosphorus. Certainly, eutrophic systems on a global scale demonstrate the ability to absorb increasing amounts of nitrogen as they progress through higher trophic states [77,85]. An evaluation of algal productivity under nutrient enrichment in geographically diverse eutrophic lakes, reservoirs, estuarine and coastal waters, as well as a range of experimental enclosures (<1L to over 10,000L), showed that the strongest stimulation was found for both nitrogen and phosphorous additions, indicating widespread nutrient colimitation [72,86,87].

Nutrient regulation of algal blooms

Nitrogen often serves as the principal limiting nutrient for phytoplankton formation in several freshwater habitats, particularly in the tropics, subtropics, high-altitude regions, and various large lake ecosystems [88]. In contrast, some marine ecosystems in both the tropics and the subtropics can display P-limited conditions [89]. There are rare occurrences of blooms of temporary nature in the marine systems of the temperate, but freshwater bodies have no problem of bloom appearance.

Blooms of freshwater cyanobacteria are commonly linked to water bodies characterized by eutrophic conditions and limited water exchange [76,90]. A significant number of cyanobacteria exhibit the capacity for nitrogen fixation [17,76], and given that numerous freshwater ecosystems experience phosphorus limitation [89], there has been a prevalent assumption that phosphorus loading fosters the development of toxic cyanobacterial blooms [76]. The exact effect of phosphorus on cyanobacterial development is complex and varies between taxa. According to laboratory studies, increasing phosphorus concentration can result in increased, decreased, or unaltered growth, as well as toxin levels in cyanobacteria [91]. Similarly, the presence of microcystin can exhibit either positive or negative correlations with varying levels of phosphorus loading in freshwater [92]. Nitrogen loading may hold equal significance in the occurrence of toxic cyanobacterial blooms, especially in the case of non-N_2-fixing cyanobacteria, such as *Microcystis* spp., *Oscillatoria* spp. [93,94].

Toxic cyanobacteria have been shown in field and laboratory investigations to disturb grazing by some zooplankton [95,96]. Mesozooplankton (>200mm), such as cladocerans and copepods, can be harmed in various systems that have dense and/or toxic algal blooms, experiencing reduced feeding rate, impaired food assimilation, or even mortality [95,96]. Many factors determine how much zooplankton feed on cyanobacteria, including the levels of toxins, the specific cyanobacterial strains, zooplankton species, and ecological conditions [95-97]. Organisms that have lived in isolated environments rich in nutrients, where they likely encountered harmful cyanobacteria over extended

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periods, exhibit enhanced resilience when it comes to feeding on and thriving alongside toxic *Microcystis* sp. cultures compared to individuals without prior exposure to such blooms. This suggests their capacity to withstand toxins and adapt to life within these blooming species [98]. While these studies indicate the adaptive potential of *Daphnia* in response to toxic cyanobacteria, other research findings have shown that these grazers may remain unable to feed on cyanobacteria despite repeated exposure [99]. It has been proposed that microzooplankton (20-200 mm) consume harmful cyanobacteria [17,100].

A potentially stimulatory nutritional effect may be diminished or eliminated by other elements like suspended sediments or grazing pressure. In turbid lakes and reservoirs characterized by light limitations and frequent water turnover, elevated phosphorus loading may not necessarily stimulate phytoplankton blooms. This phenomenon is particularly notable in water bodies subject to substantial episodic sediment inputs and featuring relatively rapid flushing rates [101]. Cyanobacteria have the capacity to proliferate in environments with reduced light availability by positioning themselves towards the water's surface during the intervals between episodic sediment loading episodes or by utilizing buoyancy regulation systems [101]. The grazing pressure from macrozooplankton can drastically diminish the populations of most phytoplankton species in lakes characterized by low to moderate nutrient loading, counteracting the effect of nutritional stimulation [102]. The Pearl River Estuary, the South China Sea, Victoria Harbour, and regions to the east have all reported similar phenomena in coastal waterways and estuaries. The high sediment loads in such estuaries and oceans, according to Tang et al.'s hypothesis, cause the negative relationship between nutrient loading and algal biomass [103]. Limitations in light would inhibit phytoplankton from fully utilizing the nutrients that were provided to them.

The grazing pressure

The formation, growth, and development of the algal bloom are significantly influenced by the grazing pressure. The quality of the available biomass generally determines the grazing rate and directs it towards specific palatable species, which are typically not the bloom-forming ones. Grazers may reduce the growth of phytoplankton biomass (of species other than the bloom-forming ones) by feeding, but they may also promote the regeneration of nutrients by releasing and excreting waste products. This will consequently change the ratio of reduced to oxidized forms of nitrogen that are available to the phytoplankton for utilization [104].

Physiological adaptation of algal blooms

The rate of nutrient delivery may not consistently align with the rate of nutrient uptake by the algae responsible for bloom formation, as the latter process is influenced by factors such as nutritional selectivity, uptake capacities, and physiological or nutritional conditions. This complicates the physiological responses of bloom-forming species to modified ecological conditions. Numerous other elements, like as interactions with grazers and physical forcings (such as turbulence), affect how the entire phytoplankton population and various species within it react [104,105]. The ability of phytoplankton to assimilate nutrients depends on environmental parameters such as light, temperature, and the stability of the water column, with various environmental effects having varying effects on various nutritional substrates. According to Glibert et al., the assimilation of ammonium and urea is typically believed to exhibit a lower dependency on light than nitrate uptake [105]. Additionally, the temperature dependency of ammonium uptake may differ from that of nitrate [105]. The stability of the water column is yet another important aspect that affects species composition.

The ability to utilize available light efficiently and the development of physiological tolerance to low light provide blooming species an edge over competing species in terms of growth. In contrast to other species, they are more favored by low grazing pressure to expand in density quickly and utilize all resources effectively. Warm, stable weather has been linked to *Karenia mikimotoi* blooms, which can endure long periods of low light and nutrients [106]. These blooms begin in Norwegian waters at the pycnocline in the summer or the first few weeks of fall, then gather at hydrographic fronts within close proximity to the shoreline [106]. A link between the formation of blooms and decreasing day length has been seen in Tunisian lagoons, where blooms of *G. aureolum* have repeatedly killed fish [107]. This aligns with the higher frequency of these blooms occurring during the late summer and autumn periods. When assessing the potential consequences of nutrient stimulation on HAB biomass or productivity, it is imperative to consider the physiological and ecological tolerances of the particular species under examination.

For the regulation and management of algal blooms, research on the physiological mechanisms employed by various groups of organisms to obtain their nutrients has become crucial. Because marine diatoms, owing to the physiological adaptations that enable them to take advantage of nitrate-enriched circumstances, there has been a strong correlation between rapidly growing marine diatoms and substantial and/or frequent nitrate inputs [108]. There are many flagellate species, including some HAB species, that are capable of obtaining both nitrogen and carbon by consuming particles or up taking dissolved organic molecules [108]. As a result of such mixotrophic or heterotrophic tendencies, these cells can bloom when non-organic nutrients or light are insufficient for their nutritional needs. Numerous *Dinophysis* species, particularly those that cause diarrhetic shellfish poisoning, are now thought to depend on mixotrophy for their survival and growth. *Heterosigma carterae*, A. *tamarense* [109], and *Gyrodinium galatheanum* [21] have all been proven to be mixotrophic.

Numerous organisms that produce planktonic blooms possess the physiological capacity to obtain some of their nutrients through extracellular oxidation or hydrolysis. Extracellular amino acid oxidation has been demonstrated to occur in various flagellates and ecosystems, but it seems to be more pronounced when ambient inorganic nutrient levels are at or close to depletion [9]. At the cell surface, proteins and peptides can also undergo hydrolysis, resulting in smaller molecules that the cells can absorb. In addition to the N or P that HAB cells need, organic substances may help to meet their C needs as well [9].

Molecular biology

Since they all belong to the same family, the molecular biology

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characteristics of bloom-forming species are not significantly different from those of non-blooming species. However, the presence of toxin-producing genes distinguishes bloom-forming species from non-blooming species. Although not a uniform trait of HABs, synthesizing hazardous chemicals is a typical aspect. Unexpectedly, only a small number of HAB toxins have been identified, and they are produced by a small number of algal species [9]. As toxins affect a wide variety of organisms' survival, growth, fecundity, and recruitment, toxic algae may thus have a large impact on ecological dynamics. The diarrhoeic, paralytic, neurotoxic, and amnesic shellfish poisoning symptoms are caused by the most well-known marine HAB toxins. The toxins linked to each of these poisoning incidents are created by planktonic dinoflagellates, with the exception of the ASP toxin, domoic acid, which is largely made by diatoms. The fifth form of marine HAB toxin event, ciguatera fish poisoning, is brought on by benthic dinoflagellates [110].

Alkaloids, polyethers, or substituted amines are the three main chemical types of marine HAB toxins. However, other toxins, including superoxide and/or hydroxyl radicals, lipoteichoic acids with hemagglutinin activity, and pentacyclic derivatives with a fused azine, have also been linked to HAB species [111]. Toxins found in freshwater differ from those found in marine environments in two ways. First, cyanobacteria almost always produce freshwater HAB toxins rather than dinoflagellates [112]. In addition, freshwater poisons have a wider range of chemical structures, including alkaloids, phosphate esters, macrolides, chlorinated diary lactones, and penta- and heptapeptides. According to Ferreira et al., these cyanobacterial toxins can be neurotoxic, hepatotoxic, or dermatotoxic [113]. Saxitoxins, the main cause of paralytic shellfish poisoning (PSP), are interestingly produced by cyanobacteria in freshwater, whereas dinoflagellates and bacteria do so in marine settings [113]. According to research to date, HAB poisons have intricate chemical structures. These toxins appear to result from complex metabolic processes, and some of the enzymatic reactions probably involve extremely particular and specialized reactions. As a result, our understanding of the biology involved in toxin production is quite limited.

Discussion

Algal blooms are intricate oceanic phenomena that need interdisciplinary research in fields like molecular and cell biology, as well as extensive fieldwork, numerical modeling, and remote sensing. Bilateral and multilateral initiatives are working to unite scientists from various nations and fields in a coordinated attempt to address this intricate and multifaceted problem. As our understanding of these processes grows, so do the technologies and management strategies that can lessen the incidence and effects of harmful blooms. One significant result of the rising investment in the Global Ocean Observing System will undoubtedly be more efficient HAB management. Increasing concern has been expressed about the damaging effects of excessive nutrient enrichment on surface waterways and aquaculture waterways. Groundwater, row crops, and atmospheric deposition are all sources of 'nonpoint source' nutrient loading. Large-scale animal feed lots and aquaculture farms are also sources of 'point source-like' nutrient inputs, fueling concerns about their environmental sustainability [114]. According to numerous studies, microalgae directly and frequently distinguishably respond to such environmental changes in many physiological processes (such as photophysiological regulation, respiration, protein and enzyme kinetics, secondary metabolite synthesis, etc.) [90,115]. Such physiological reactions serve as the foundation for cell maintenance, growth, and, eventually the expansion of an undesirable phytoplankton population. Additionally, the molecular and/or cellular regulation of physiological processes firmly controls the size and duration of a given reaction [116-118].

Conclusions

In order to effectively manage algal blooms and related metabolites, it is important to understand their genetic and physiological basis. It is crucial to know these kinds of details to understand phenomena such as why certain taxa displace others in taxon assemblages, how some taxa sustain long-term competitive dominance, and why some taxa (and usually different strains of a taxon) produce harmful metabolites and alter their habitats directly or indirectly. Over the past ten years, the rapid development of new computer-based technologies has nearly "leaped-frogged" the ability of scientists to evaluate such instrumentation and analysis. The general consensus in society is that algae are undesirable and should be removed whenever possible. However, this misconception is false because only a few species pose a threat, with *Homo sapiens* being the worst of these. Algae produce oxygen, fish are a significant food supply for aquatic life, and many other benefits. HABs are a necessary evil that we must deal with but cannot completely eradicate, even if algal blooms are detrimental and dangerous for human society. This is because algae have more good effects than negative ones, making HABs a necessary evil that we must deal with but cannot completely eradicate. There is a widespread perception that algae are toxic and should be eliminated at every opportunity. There are many kinds of animals that benefit from the presence of algae and fish, but only a few species pose a threat to the environment, and the worst of these is the *Homo sapiens*. Though algal blooms are harmful and are problematic to human society but still algae cannot be eradicated worldwide only for their harmful property as they have many positive effects as compared to some negative ones, so HABs are a necessary evil that we have to cope with but cannot eliminate them.

Disclosure statement

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