Chapter

The Use of Allelochemicals of Aquatic Macrophytes to Suppress the Development of Cyanobacterial “Blooms”

Evgeny Kurashov, Julia Krylova and Elena Protopopova

Abstract

Harmful algal “blooms”, or HABs, is a hazardous natural phenomenon that often occurs under the influence of anthropogenic factors, for example, during the anthropogenic eutrophication of water bodies. An increase in the frequency and duration of cyanobacterial “blooms” carries a number of serious threats, including local and global degradation of water resources and the impact of cyanotoxins. There are various methods of fighting cyanobacterial “blooms” - physical, chemical, the use of bacterial preparations, etc. However, these methods are not effective enough and, most importantly, do not allow effectively solving the problem of suppressing HABs in water bodies without damage to other components of the aquatic ecosystem. Allelopathy is a natural phenomenon for both stimulatory and inhibitory effects of one plant upon another including microorganisms that resolves this problem. Allelochemicals of macrophytes can be considered as natural algacides and become the basis of a nature-like convergent technology to suppress the development of plankton cyanobacteria and prevent HABs in water bodies. In our work, we used some allelochemicals of aquatic macrophytes to create a combined algicide of the new generation for suppressing the development of cyanobacteria. The effectiveness of suppressing cyanobacterial “blooms” is demonstrated by the example of field experiments with mesocosms and natural phytoplankton.

Keywords: harmful algal “blooms”, phytoplankton, cyanobacteria, allelopathy, allelochemicals, field experiments, mesocosms

1. Introduction

Harmful algal “blooms”, or HABs, is a hazardous natural phenomenon that often occurs under the influence of anthropogenic factors, for example, during the anthropogenic eutrophication of water bodies. An increase in the frequency and duration of cyanobacterial “blooms” carries many serious threats, including local and global degradation of water resources and the impact of cyanotoxins [1–3]. This problem is especially relevant and acute for millions of small reservoirs widely used for various types of water consumption: fisheries and aquaculture, water supply for various industries, including agricultural, drinking, and domestic water supply, recreational purposes, including sporting events. HABs occur when algae or
cyanobacteria (most often they are) develop beyond measure and produce harmful effects on other hydrobionts, fish, aquatic and terrestrial animals, and birds as well as people [4, 5]. HABs disrupt the esthetics of water bodies and render the water unsuitable for various kinds of water uses. Economic damage due to HABs can be millions of dollars [6, 7].

Widespread HABs is a phenomenon to which special attention should be drawn since such “blooms” pose a number of serious threats, including local and global degradation of water resources and exposure to cyanotoxins [8–14].

Cyanobacterial “blooms” of water bodies are officially recognized as a global problem of modern ecology. Seasonal intense cyanobacterial “blooms” of reservoirs bring additional undesirable properties to natural and drinking water, such as a specific smell, taste, and the presence of toxins (microcysts). In some regions, the importance of this problem has been increasing recently [15]. The Working Group on the Evaluation of Carcinogenic Risks to Humans listed cyanotoxins as a carcino-genic substance harmful to humans [16].

The introduction of biotechnological methods into the practice of water body management that have maximum efficiency is one of the tasks of modern science. These include, first of all, the so-called convergent nature-like technologies, i.e. technologies that are based on any natural mechanisms causing this or that effect. These are precisely technologies that may be intended to ensure the sustainable development of modern countries [17–19].

Such technologies, aimed at managing the development of plankton communities in general and phytoplankton communities, in particular, may be based on such a phenomenon as allelopathy. This natural phenomenon can be very useful for effectively preventing and stopping the development of cyanobacterial “blooms” in water bodies [20–22]. Many existing methods of combating cyanobacteria [23] do not effectively solve the problem of “blooms” of water bodies without damage to other components of the ecosystem [3]. Usually, they are associated with serious adventitious effects on aquatic organisms and ecological systems [24].

At the same time, the application of the method of metabolic allelopathic control of HABs in water bodies during eutrophication is an effective and innovative solution to this problem. This approach preserves and restores water quality in water bodies, makes them suitable for multifunctional use, and natural allelochemicals (metabolites of macrophytes and their synthetic analogs) can be an effective alternative to existing algicides [20, 22, 25].

In reservoirs where macrophytes are developed (as a rule, at least 30% of the projective cover of the water area), water “bloom” is almost never observed. These circumstances are the causal basis for the development of nature-like technologies for the prevention and suppression of HABs with the help of new generation algicides based on allelochemical substances characteristic of aquatic macrophytes.

It has become apparent that metabolites-allelochemicals may be functioning in the processes of chemical suppressing of planktonic cyanobacteria in the aquatic ecosystems. However, data from field experiments are few concerning the effect of aquatic macrophyte allelochemicals on cyanobacteria, which is necessary for the development of nature-like technologies for preventing and suppressing cyanobacterial “blooms”, and therefore they are the objects of “hottest” areas of research. Utilization of allelochemicals from aquatic macrophytes or using their synthetic analogs to inhibit cyanobacterial overgrowth is an environment-friendly technology for suppressing HABs.

Some reviews are focusing on the practice of the application of allelochemicals in agriculture [26, 27], but the field of using nature-like allelopathic technology to manage aquatic ecosystems is still poorly developed.
In the present study, we aimed to provide the information on the suppressing of cyanobacteria by macrophytes allelochemicals and the possibility to develop an algaecide of the new generation as a convergent nature-like technology for preventing and stopping the development of HABs in water bodies based on such a phenomenon as allelopathy.

2. Suppression of the development of cyanobacteria by aquatic macrophytes

Allelopathy as a natural phenomenon had been repeatedly recorded for a very long time in the 3rd century BC in ancient Chinese literature [28]. The term “allelopathy” was coined comparatively recently, in 1937 by Austrian plant physiologist Hans Molisch [29], who can be named as the father of allelopathy [30]. In general, we can consider allelopathy as an area of science, which investigates inhibitory or stimulatory biochemical interactions between the two plant/plant or plant/microorganism species.

The recent history of the study of low molecular weight organic compounds, which are small molecules (less than 900 amu) and constitute the low molecular weight metabolic profiles of organisms, should apparently begin with the discovery of the inhibitory effect of volatile plant excreta on microorganisms by Tokin Boris Petrovitch during the experimental work of 1928–1930 [31]. The research resulted in a number of publications, in one of which (“Bactericides of plant origin (phytoncides)”) [32], the term “phytoncides” appeared. In the future, the doctrine of phytoncides was developed, which was reflected in the publication of several monographs. The history of research on phytoncides of aquatic and coastal plants began in the 40s of the XX century with the works of Gurevich Faiva Abramovich (1918–1992) [33], a student of B.P. Tokin. These studies ended in 1973 with the defense of a doctoral dissertation “Phytoncides of aquatic and coastal plants, their role in biocenoses” [34]. In particular, it was F.A. Gurevich who showed that the phytoncoidal activity of aquatic plants is closely related to the macrophyte species and peculiarities of its development. He also showed that phytoncides are a very significant factor in the distribution of hydrobionts in a water body, including invertebrates.

At present, we can say that the macrophyte and algal allelopathy is paid much less attention than allelopathy in terrestrial ecosystems. Macrophytes and cyanobacteria are known to have an antagonistic relationship in different natural and experimental aquatic ecosystems [25, 35, 36].

It is a recognized fact that phytoplankton is poorly developed in macrophytic lakes. Even if we take into account the opinion that this is due to such factors as winning competition for nutrients and shading, then in the overwhelming number of cases, the main factor providing suppression of phytoplankton development is undoubtedly allelopathic suppression [37]. Apparently, the competition for nutrients cannot be recognized as a decisive factor in the outcome of the struggle between macrophytes and cyanobacteria, including considering that most aquatic macrophytes are rooted, and they usually obtain the main part of the necessary nutrients from the bottom sediments, which is characterized by high nutrient concentrations [38].

It is well known the phenomenon when shallow-water lakes can change their trophic status and the type of lake ecosystem, being either a pure water body with well-developed aquatic vegetation or a water body with low transparency, high turbidity, and intensive phytoplankton (mainly cyanobacteria) development. In other words, they can shift from one state to another [36, 39–43]. As this takes place, the
mutual inhibitory allelopathic activities of macrophytes and phytoplankton may lead to the dominance of either macrophytes or phytoplankton [44].

We observed a similar effect in a floodplain lake with a changing trophic state in the Volga-Akhtuba interfluve, when cyanobacteria and macrophytes dominated in the same water body in different years [36]. Some evidence exists [45–48] that allelopathy is a factor affecting the development of phytoplankton (including cyanobacteria) in shallow lakes at the projective cover of macrophytes from 20 to 100%.

The importance of allelopathy as a powerful regulatory mechanism initiates a lot of studies devoted to the study of the inhibitory (sometimes stimulating) allelopathic effect of macrophytes on cyanobacteria and algae in aquatic ecosystems [49–58]. More than 60 species (67) of macrophytes are known to exhibit allelopathic activity against cyanobacteria. They are presented in Table 1.

According to the principle of allelopathic action, it is possible to prevent or mitigate the massive development of Cyanobacteria (blue-green algae), which leads to the HABs in water bodies. The implementation of this research direction promises huge benefits since it will solve the problem of the “blooms” of water bodies without negative consequences for other components of the ecosystem. [20, 22, 25].

As follows from Table 1, data from laboratory studies, in general, prevail in the observation and proof of the effect of macrophyte allelopathy on cyanobacteria. These studies are based on laboratory-scale experiments using the co-cultures systems, adding plant extracts, or leachate collection. This state of affairs is associated with a more complex organization and interpretation of field studies. In this regard, data from field experiments and observations, for example with mesocosms, are of particular value. Numerous studies (including those included in Table 1) strongly suggest that allelopathy might thus be relevant in natural waters and suppress cyanobacteria and algae.

There are observations on the differentiation of the inhibitory effect of macrophytes on various species of cyanobacteria and algae. For example, it was concluded that the extracts, exudates, and live material of macroalgae Chara australis (Charophyta) exhibited strong inhibitory effects on the cyanobacterium Trichormus variabilis (formerly Anabaena variabilis), but no effect was observed on the growth of the green alga Scenedesmus quadricauda [82].

The available data allow us to speak about the selective inhibition of various species of cyanobacteria by allelochemicals of various species of macrophytes. As a result, the allelopathic effect of macrophyte association on cyanobacteria (and all phytoplankton) seems to be stronger than the effect of one macrophyte species. This is evidenced by the fact that, as has been shown, the allelopathic effect of excretions of the association of macroalgae (Chara hispida, C. baltica, C. vulgaris, Nitella hyaline) and Myriophyllum spicatum is characterized by a significantly stronger effect than the effect of monoculture of macrophytes [83]. Such a combination of selective inhibition of macrophyte allelochemicals and a more strong impact of macrophyte assemblages toward the undesired cyanobacteria may be useful for biocontrol of HABs in water bodies as well as in aquaculture to remove harmful cyanobacteria and leave other algae to be used as food for hydrobionts and fish. The author [83] suggested that different allelochemicals produced by different macrophytes may exhibit a synergistic effect concerning cyanobacteria. It was also noted in [128] that different plants produce different types of allelochemicals and in different quantities. These summarized findings are therefore provided with more probability the basis for an effective strategy for reducing cyanobacterial biomass by introducing into water bodies with mixtures of submerged or floating native macrophytes for both restorations of aquatic ecosystems and mitigation of the HABs.
| Species of macrophytes | Ecological form | Study scale | Cyanobacteria inhibited Study Scale | Source |
|------------------------|----------------|-------------|-------------------------------------|--------|
| Acorus tatarinowii, Acorus calamus, Acorus gramineus | EM | L | Cyanobacteria as a whole | [59, 60] |
| Arundo donax | EM | L | Microcystis aeruginosa | [51, 57, 61–63] |
| Brasenia schreberi | FM | L | Anabaena flos-aquae | [64] |
| Cabomba caroliniana | SM | L | Microcystis aeruginosa, Dolichospermum flos-aquae (formerly Anabaena flos-aquae), Leptolyngbya tenuis (formerly Phormidium tenue), Cyanobacteria as a whole | [65, 66] |
| Canna generalis | EM | L | Microcystis aeruginosa | [67] |
| Ceratophyllum demersum | SM | L, F | Microcystis aeruginosa, Pseudanabaena limnetica (formerly Oscillatoria limnetica), Oscillatoriales. Anabaena sp., Trichormus variabilis (formerly Anabaena variabilis), Aphanizomenon flos-aquae, Synechococcus elongatus, Cyanobacteria as a whole | [58, 68–78]; Our data |
| Chara aspera | SM | L | Anabaena cylindrica, Anabaena torulosa, Anabaenopsis elenkinii, Microcystis aeruginosa, Microcystis flos-aquae, Synechococcus sp., Cyanobacteria as a whole | [37, 79–81] |
| Chara australis | SM | L | Trichormus variabilis (formerly Anabaena variabilis) | [82] |
| Chara baltica, C. canescens | SM | L | Synechococcus sp. | [81, 83] |
| Chara contraria | SM | L | Anabaena cylindrica, Microcystis aeruginosa, Cylindrospermum sp., Cyanobacteria as a whole | [79] |
| Chara fragilis | SM | L’ | Oscillatoria limnetica, Cyanobacteria as a whole | [71] |
| Chara globularis | SM | L | Anabaena cylindrica, Anabaena torulosa, Anabaenopsis elenkinii, Planktothrix rubescens, Microcystis aeruginosa, Microcystis flos-aquae, Cylindrospermum sp., Aphanizomenon flexuosum, Cyanobacteria as a whole | [68, 72, 79, 84] |
| Chara hispida | SM | L, F | Cyanobacteria as a whole | [83, 85] |
| Chara rudis, Chara tomentosa, Chara delicatula | SM | L | Anabaena cylindrica, Anabaena torulosa, Anabaenopsis elenkinii, Planktothrix agaridii, Planktothrix rubescens, Microcystis aeruginosa, Microcystis flos-aquae, Cylindrospermum sp., Aphanizomenon flexuosum, Cyanobacteria as a whole | [79] |
| Chara vulgaris | SM | L, F | Anabaena torulosa, Anabaenopsis elenkinii, Microcystis aeruginosa, Cyanobacteria as a whole | [79, 83, 86, 87] |
| Cyperus alternifolius | EM | L | Microcystis aeruginosa | [67] |
| Species of macrophytes | Ecological form | Study scale | Cyanobacteria inhibited | Source |
|------------------------|----------------|-------------|-------------------------|--------|
| *Eichhornia crassipes* | FM             | L           | Microcystis aeruginosa, Microcystis sp., Raphidiopsis raciborskii (formerly Cylindrospermopsis raciborskii), Arthrospira platensis (formerly Spirulina platensis), Nostoc linckia (formerly Nostoc piscinale), Cyanobacteria as a whole | [88–91] |
| *Eleocharis acicularis* | SM             | L           | Cyanobacteria as a whole | [66]   |
| *Eleocharis microcarpa* | SM             | L           | Anabaena flos-aquae, Oscillatoria tenuis | [92, 93] |
| *Eleodea canadensis, Eleodea nuttallii, Eleodea sp.* | SM             | L, F        | Microcystis aeruginosa, Anabaena spp., Cyanobacteria as a whole | [35, 68, 78, 94, 95] |
| *Hydrilla verticillata* | SM             | L           | Dactylococcopsis sp., Microcystis aeruginosa | [56, 58, 96] |
| *Egeria densa*         | SM             | L           | Microcystis aeruginosa, Dolichospermum floaqua (formerly Anabaena flos-aquae), | [66]   |
| *Limnophila sessiliflora* | SM             | L           | Microcystis aeruginosa | [66]   |
| *Myriophyllum aquaticum* | SM             | L           | Microcystis aeruginosa | [97]   |
| *Myriophyllum brasiliense, Myriophyllum alterniflorum, Myriophyllum heterophyllum* | SM             | L           | Microcystis aeruginosa, Dolichospermum floaqua (formerly Anabaena flos-aquae) | [98]   |
| *Myriophyllum elatinoides* | SM             | L           | Microcystis aeruginosa | [99]   |
| *Myriophyllum spicatum* | SM             | L, F        | Microcystis aeruginosa, Dolichospermum floaqua (formerly Anabaena flos-aquae), Leptolyngbya tenuis (formerly Phormidium tenuis); Cyanobacteria as a whole | [54, 65, 71, 78, 83, 100–104] |
| *Myriophyllum verticillatum* | SM             | L           | Cyanobacteria as a whole | [105, 106] |
| *Najas marina*         | SM             | L           | Anabaena sp., Trichormus variabilis (formerly Anabaena variabilis), Synechococcus elongates, Cyanobacteria as a whole | [74, 94] |
| *Nasturtium officinale* | EM             | L           | Microcystis aeruginosa | [107]   |
| *Nelumbo nucifera*     | FM             | L, F        | Microcystis aeruginosa, Cyanobacteria as a whole | [108, 109] |
| *Nitella gracilis, Nitella opaca, Nitellopsis obtusa, Nitella hyaline, Nitella sp.*, | SM             | L, F        | Nitzschia palea, Anabaena cylindrica, Anabaena torulosa, Anabaenopsis elenkinii, Microcystis flora-aquae, Cylindrospermum sp., Aphanizomenon flexuosa, Cyanobacteria as a whole | [68, 79, 83] |
| *Nuphar lutea*         | FM             | L, F        | Cyanobacteria as a whole | [110]; Our data |

Our data
Lombardo et al. [129] suggested that lake trophic state and extent of submerged vegetation coverage maybe the most important factors during formation in situ macrophyte–phytoplankton patterns at a large scale of natural water bodies. In this case, with a larger projective cover, a greater allelopathic effect will be achieved [45–48].

Not all macrophytes have the same allelopathic effect on cyanobacteria. Macrophytes that have the greatest suppressive effect on cyanobacteria (taking into account, among other things, information from Table 1) are such species

| Species of macrophytes | Ecological form | Study scale | Cyanobacteria inhibited | Study Scale | Source |
|------------------------|----------------|-------------|-------------------------|-------------|--------|
| Nymphaea candida       | FM             | F           | Cyanobacteria as a whole|             | Our data |
| Oryza sativa          | EM             | L           | Microcystis aeruginosa, | Phormidium sp. | [108, 112] |
| Phragmites communis    | EM             | L           | Microcystis aeruginosa, |             | [108, 112] |
| Pistia stratiotes      | FM             | L           | Synechococcus leopoliensis, Microcystis aeruginosa, | | [113–115] |
| Potamogeton crispus    | SM             | L, F        | Trichormus variabilis (formerly Anabaena variabilis), Cyanobacteria as a whole | | [82, 116, 117] |
| Potamogeton cristatus  | SM             | L           | Microcystis aeruginosa | | [58] |
| Potamogeton oxyphyllus | SM             | L           | Microcystis aeruginosa | | [66] |
| Potamogeton lucens     | SM             | L, F        | Microcystis aeruginosa, Cyanobacteria as a whole | | [58, 71], Our data |
| Potamogeton maackianus | SM             | L           | Microcystis aeruginosa | | [58, 118, 119] |
| Potamogeton malaianus  | SM             | L, F        | Microcystis aeruginosa, Oscillatoria sp. | | [118–120] |
| Potamogeton natans     | SM             | L, F        | Microcystis aeruginosa, Cyanobacteria as a whole | | [78], Our data |
| Potamogeton pectinatus | SM             | L           | Microcystis aeruginos, Oscillatoria tenuis | | [76, 118, 121] |
| Ranunculus aquatilis   | SM/FM          | L           | Microcystis aeruginosa | | [107] |
| Ruppia maritima        | SM             | L           | Microcystis aeruginosa | | [122, 123] |
| Stratiotes aloides     | FM             | L, F        | Synechococcus elongatus, Microcystis aeruginosa, Cyanobacteria as a whole | | [49, 68, 71] |
| Typha latifolia, Typha minima, Typha angustata | EM | L | Dolichospermum flouaquae (formerly Anabaena flouaquae), Romeria leopoliensis (formerly Synechococcus leopoliensis), Microcystis aeruginosa | | [57, 124–126] |
| Vallisneria denserurulata, Vallisneria spiralis, Vallisneria spinulosa | SM | L | Microcystis aeruginosa | | [58, 66, 75, 127] |

Table 1. The number and relative content (% of total essential oil) of the fatty acids in some species of freshwater macrophytes and macroalgae from different water bodies.
and groups as *Cabomba caroliniana*, *Myriophyllum spicatum*, *Ceratophyllum demersum*, *Elodea canadensis*, *Nuphar lutea*, *Stratiotes aloides*, and family Characeae ([22, 36, 49, 65, 71, 103, 130], etc).

In the study [131], it was concluded that of all the 15 tested aquatic macrophytes, *Nymphaea odorata* and *Brasenia schreberi* have the highest allelopathic potential. However, this conclusion was obtained in experiments with lettuce sprouts, and not with cyanobacteria. These macrophytes inhibited 78% and 82% of lettuce seedling radicle growth and 98% and 68% of *L. minor* frond production respectively. Elakovich S. D. and Wooten J. W. [132] also reported that *Nuphar lutea* has high allelopathic activity.

Similar results were obtained with the macrophytes *Potamogeton maackianus*, *Potamogeton wrightii*, and *Potamogeton crispus*, which exhibited different inhibitory effects on the two species of algae [128]. There is a view that most allelochemicals are released during the early developmental stage of plants. It is assumed that during this period, plants are most dependent on stress conditions and competition with other surrounding plants for resources such as light, nutrients, and water [133]. However, in our studies, we found that the active synthesis of allelochemicals in aquatic macrophytes can continue even at later stages of plant development [22].

For the sake of completeness, it should be noted that some terrestrial plant materials (for example, barley straw) exhibit a strong allelopathic effect on cyanobacteria under certain conditions [134–136], which is no coincidence, since terrestrial plants also contain numerous allelochemicals [28]. It was shown in [137] that salcolin (two enantiomers that differ in their anti-cyanobacterial abilities) is the key allelochemical in barley straw’s which exhibits an inhibitory effect on cyanobacteria and could be used as an agent in the control of cyanobacterial HABs. A review of typical terrestrial allelopathic plants with algistatic or algicidal effects is presented in [24].

### 3. Anti-cyanobacterial allelochemicals produced by aquatic macrophytes

Low-molecular-weight anti-cyanobacterial allelochemicals produced by aquatic macrophytes are very diverse. They belong to different classes of chemical compounds and are functionally diverse. Allelochemicals from the following groups of chemical compounds are the most important [22, 30, 55]: aldehydes, ketones, ethers, terpenes and terpenoids, phytoecdysteroids, fatty acids, sulfur-containing compounds, nitrogen-containing compounds, alcohols, lactones, polyacetylenes, quinines, phenolics, cinnamic acid and its derivatives, coumarins, flavonoids, tannins. These groups include hundreds of allelochemicals inhibiting cyanobacteria and algae [24], which should be discussed in detail in a special review.

These allelochemicals can be extracted from the plant biomass, but also their synthetic counterparts can be produced and used. This will reduce the consumption of natural plant resources. The effectiveness of synthetic allelochemicals can be similar to their natural counterparts. Thus, synthetic allelochemicals are a hopeful alternative to the use of natural metabolites-allelochemicals against HAB-forming cyanobacteria [20, 21].

Realizing that it is impossible to consider all groups of allelochemicals, here we will focus on considering only fatty acids and phenolic compounds as the most promising (in our opinion) for biotechnological use in the fight against HABs.

Studies of potential biological activities of major low molecular weight organic compounds of aquatic macrophytes using the QSAR method [138, 139] have shown that fatty acids and gallic acid are characterized by various types of bioactivity with
the highest probability of manifestation (Pa > 0.9) that can induce cyanobacteria growth suppression. Further studies based on the results obtained suggest clarifying experimental studies of the reaction of various species of cyanobacteria to the effects of selected allelochemicals.

As it was received in laboratory experiments conducted with fatty acids for their effect on the cyanobacteria *Synechocystis aquatilis* and *Aphanizomenon flos-aquae*, and which are described in detail in [140], selected allelochemicals (linoleic, heptanoic, octanoic, tetradecanoic, hexadecanoic, and gallic acids) possess inhibitory allelopathic activity against cyanobacteria. However, their inhibitory effect was different. The highest values of the Suppression index (SI, defined as the cyanobacterial density in control divided by the cyanobacterial density in an experiment with allelochemicals) (SI > 10) were recorded (in ascending order) for hexadecanoic, linoleic, tetradecanoic, gallic acids, and a mixture of four allelochemicals (heptanoic, octanoic, tetradecanoic and gallic acids).

The highest SI values for *Synechocystis aquatilis* were obtained when the culture of cyanobacteria was exposed to gallic acid (SI = 30) and a mixture of heptanoic, octanoic, tetradecanoic, and gallic acids (SI = 35.3). *Aphanizomenon flos-aquae* was found to be more sensitive to the effect of the given mixture of allelochemicals. SI for it on the 23rd day of the experiment was 17495 [140].

In works [141, 142] problems have been raised concerning effective algal inhibitors and control HABs. To address these issues, the authors suggested using unsaturated fatty acid (linoleic acid) in conjunction with alginate – chitosan microcapsule technology. They demonstrated that the linoleic acid microsphere had good encapsulation efficiency and release property. Besides, linoleic acid sustained-released microspheres could inhibit *Microcystis aeruginosa* (Cyanobacteria) growth to the non-growth state, and thus linoleic acid microsphere may be used as a potential candidate for HABs control.

Studies on the use of microgranules saturated with an allelochemical or a combination of allelochemicals (for example, a combination of fatty acids and phenolic compounds) to suppress cyanobacteria look very promising. The inhibitory agent, gradually releasing from the microgranules, prolongs its allelopathic effect on cyanobacteria. A sustained-release time of allelochemicals can range from 40 to 120 days [142–144]. A review of the studies carried out in this direction is presented in [128]. Results obtained in different investigations open up new promising areas for scientific research and practical use of allelochemicals of aquatic macrophytes.

According to results received in [112], nonanoic acid can inhibit the growth of cyanobacteria *Leptolyngbya tenuis* (formerly *Phormidium tenue*) and *M. aeruginosa*, whereas, no inhibitory effects of stearic, and palmitic acids was found.

In earlier works [113, 125], it was also found, that three fatty acids ($\alpha$ – linolenic, linoleic, and an unidentified C8: 2) inhibited cyanobacteria (particularly T 625 *Romeria leopoliensis* (formerly *Synechococcus leopoliensis*) and T 1444 *Dolichospermum flosaquae* (formerly *Anabaena flosaquae*)).

The essential oil of some allelopathic plants (*Potamogeton cristatus*, *Potamogeton maackianus*, *Potamogeton lucens*, *Vallisneria spinulosa*, *Ceratophyllum demersum*, and *Hydrilla verticillata*) was demonstrated to inhibited *Microcystis aeruginosa*, during which fatty acids constituted an important part of the essential oils isolated.

Recently, Wang et al. [95] reported the inhibitory effects of some fatty acids on *Microcystis aeruginosa*. The authors stated that pentadecanoic acid, linoleic acid, alpha-linolenic acid, and stearic acid were the most potent allelochemicals from *Elodea nuttallii* along with dihydroactinidiolide and beta-ionone.

We showed [140] that such plants as *Potamogeton natans*, *Nuphar lutea*, *Nymphaea alba*, *Myriophyllum spicatum*, *Persicaria amphibia* are the most active producers of allelochemical fatty acids, and therefore they can have a significant
allelopathic effect on cyanobacteria and phytoplankton in total. In these plants, the proportion of fatty acids in the content of volatile organic compounds can exceed 60–70%.

Our studies of the metabolome of *Potamogeton perfoliatus* from different habitats in Lake Ladoga show that the abundance of cyanobacteria in the associations of this macrophyte depends on the content of carboxylic acids in a given plant (Figure 1).

The study by Gao et al. [145] demonstrates that nonanoic acid may be involved in synergistic interactions with other allelochemicals, demonstrating a stronger allelopathic effect against *Microcystis aeruginosa*.

Similar results were obtained for octadecanoic acid [146], which may participate in synergistic, antagonistic, and additive allelopathic interactions. These findings led to the conclusion that joint effects of different allelochemicals depend on various factors such as the chemicals used, their respective proportions, the total concentration of the mixture, and the receptor species [146].

In addition to fatty acids, among allelochemicals, special attention should be paid to phenolic compounds.

As early as in 1981 [100], the results were published, which demonstrated that phenolic compounds extracted from *Myriophyllum spicatum* exhibit algicidal activity against cultured algae and natural phytoplankton assemblages. Later, it was found that such aquatic macrophytes as representatives of the genus *Myriophyllum* are able to excrete polyphenol-like allelochemicals to inhibit the growth of green algae and cyanobacteria [98]. A number of identified polyphenols (ellagic, gallic, pyrogallic, and catechin) and fatty acids (hexadecanoic acid, stearic acid, α-linolenic acid) were shown to significantly suppress the development of HAB-forming cyanobacteria species [147, 148].

Additionally, a study [78] has revealed that the major allelochemicals identified in tested macrophyte ethyl acetate extract of *Nasturtium officinale* included quercetin, tannic acid, and gallic acid. Also, findings are the combinations of different types of polyphenols, such as pyrogallic acid, gallic acid, and ellagic acid may have

![Figure 1.](image)

*Dependence of the concentration of cyanobacteria (BGA, cells/ml) on the concentration of fatty acids (Cca, μg/g.driw.) in *Potamogeton perfoliatus* in Lake Ladoga.*
an additive or synergistic effect on cyanobacterium *Microcystis aeruginosa* and the joint action of phenolic allelochemicals may be an important allelopathic pattern of submerged macrophytes to inhibit the growth of HAB-forming cyanobacteria in natural aquatic ecosystems [53, 146, 148–150].

In a study [54] during the investigation of contributions of five allelochemicals, (+) catechin, eugeniin, and ellagic, gallic, and pyrogallic acid, in the allelopathic effects of *Myriophyllum spicatum* on the cyanobacterium *M. aeruginosa* it was observed that these compounds, on average, may provide up to 50% of the allelopathic effects of *M. spicatum*. According to results received in [112], four phenols (sinapic, syringic, caffeic, and gallic acids) inhibited the growth of cyanobacteria *Leptolyngbya tenuis* (formerly *Phormidium tenue*) and *M. aeruginosa*. The inhibitory effect of pyrogallic acid and gallic acid produced by *M. spicatum* in relation with cyanobacteria was also demonstrated in [53, 114].

It is beyond question that there is a huge amount of scientific material regarding the allelopathic properties of fatty acids and gallic acid ([52, 54, 56, 67, 88, 103, 112, 113, 118, 119, 124–126, 146, 148, 151–166], etc.). This circumstance gives every reason to use them to create a new generation of algicides based on allelochemical substances of aquatic macrophytes. The use of this information, as well as the results of our researches [36, 138, 140], formed a prerequisite for the development of a new generation algicide based on allelochemicals of aquatic macrophytes against cyanobacteria. It is precisely fatty acids (heptanoic, octanoic, tetradecanoic acids) and gallic acid that were included in its composition [167].

4. Mesocosm study of the effects of allelochemicals on cyanobacteria

Evidence of suppression of the development of phytoplankton, including planktonic cyanobacteria, in real natural conditions by traditional observations, even in the most obvious cases [36], is nevertheless indirect and often contradictory [48, 168]. Taking this into account, the way of assessing the effect of allelochemicals on cyanobacteria in experiments with mesocosms in natural conditions is more promising and makes it possible to obtain results corresponding to natural aquatic ecosystems.

A good example is a field study by Hilt et al. [169] in which the authors found an allelopathic effect of the macrophyte *Myriophyllum verticillatum* on natural phytoplankton (including cyanobacteria) in Lake Krumme Lake (Berlin, Germany). In a mesocosm study [170] in Laguna Blanca lake in Manantiales (Maldo-nado, Uruguay) it was observed that macrophytes species (*Egeria densa* and *Potamogeton illinoensis*) seem to exert strong biological effects on phytoplankton biomass, and they are able to keep phytoplankton biomass low through allelopathic influence, even in the absence of zooplankton grazing.

In another mesocosm study [171], similar results were obtained, demonstrating that another species of the genus *Myriophyllum* (*Myriophyllum spicatum*) under conditions of 85 l mesocosms during 13 days of exposure had an only short-term inhibitory effect on total phytoplankton and green algae, whereas consistent negative effects (allelopathic) were detected concerning *M. aeruginosa*.

After the development of an algicide containing fatty acids (heptanoic, octanoic, tetradecanoic acids) and gallic acid, the rationale for the use of which is presented in detail in [140], we conducted the first experiments with this algicide with natural phytoplankton communities under conditions mesocosms.

In the field experiments, mesocosms with a volume of 700 liters were used. The experiments were carried out on two ponds on the territory of St. Petersburg (Russia): at Pulkovo Pond (pond 1; coordinates 59.835899, 30.328642) and Aviator’s
Pond (Pond 2; coordinates 59.868343, 30.300443). The depth of the ponds at the location of the experiments was about 3 m. The mesocosms were filled with water from the pond, then algicide was added to them in an amount so that its concentration in the water of the mesocosms was 1 mg/l.

In Pulkovo Pond, the experiment was carried out from June 25 to July 5, 2019. In the Aviatorov Pond, the experiment was carried out from July 2 to July 16, 2019. The temperature and light conditions in the mesocosms corresponded to those in the water of the pond outside the mesocosms. The change in water temperature in the surface layer of the studied ponds is shown in Figure 2.

The results of the algicide impact on the phytoplankton of pond 1 are shown in Figures 3-6.

As can be seen from Figure 3, in the water of pond 1, both the abundance and the biomass of all phytoplankton increased during the experiment. At the same time, this was not observed in the mesocosm. In the first three days, a decrease in phytoplankton biomass without a change in its abundance occurred. Subsequently, the abundance and biomass of phytoplankton in the mesocosm remained approximately at the same level as they grew in the pond. By the end of the experiment (on the 11th day), the phytoplankton biomass in the pond exceeded that in the mesocosm by about 5 times, and the abundance - by almost 12 times. The greatest differences were observed on the 8th day of the experiment; the difference in biomass and abundance was 7 and 20 times, respectively. Thus, the action of an algicide based on fatty acids and gallic acid inhibited the growth of phytoplankton.

The data of phytoplankton analysis are confirmed by the data on the measurement of optical density in the pond and the mesocosm (Figure 4). By the end of the experiment, an increase in optical density in the pond and a significant decrease in optical density in the mesocosm were observed (Figure 4). By the end of the experiment, the difference was about 2.3 times. This was also noticeable visually: the water in the mesocosm was more transparent than the water in the pond surrounding the mesocosm (Figure 5).

It is interesting to trace how the quantitative indicators of cyanobacteria in the pond and the mesocosm changed. Dolichospermum solitarium (formerly Anabaena solitaria) was the dominant cyanobacterial species in the pond (and at the beginning of the experiment in the mesocosm). This species belongs to cyanobacteria

---

Figure 2.
Change in water temperature (°C) in the surface layer of the investigated ponds.
capable of causing the phenomenon of HABs [172]. A decrease in both the number and biomass of cyanobacteria both in the pond and in the mesocosm was observed on the third day of the experiment. Moreover, in the mesocosm, this decrease was more pronounced. Subsequently, an increase in the number and biomass of cyanobacteria both in the pond and in the mesocosm was observed. However, it was more intense in the pond. By the end of the experiment (on the 11th day), the biomass of cyanobacteria in the pond exceeded that in the mesocosm by about 2.5 times, and the number - by 1.5 times. The greatest differences were observed on the 8th day of the experiment, the difference in biomass and abundance was 4.4 and 39 times, respectively. At the end of the experiment, the same species *Dolichospermum solitarium* remained the dominant species in the composition of cyanobacteria. At the same time, *Cuspidothrix ussaczevii* (formerly *Aphanizomenon elenkinii*) began to dominate in the mesocosm among cyanobacteria. This species is also included in
the bloom-forming Cyanobacteria from water bodies of the North-Western Russia list [173]. However, *C. ussaczevii* is less toxic than *D. solitarium*, for which toxigenic strains producing delayed-action toxins have been isolated [174].

Thus, the action of an algicide based on fatty acids and gallic acid prevented the growth of the number of cyanobacteria and changed their species structure.

In pond 2, the beginning of the experiment coincided with an intense cyanobacterial “bloom” (Figure 7), while their biomass was more than 55 mg/l. At the same time, in the surface layer of the pond, the maximum water temperature (20.5°C) for the entire duration of the experiment was noted (Figure 2). The cyanobacteria *Aphanizomenon flos-aquae*, *C. ussaczevii*, and *Dolichospermum affine* (formerly *Anabaena affinis*) dominated in phytoplankton. *Aphanizomenon flos-aquae* is one of the most widespread species that form HABs in ponds and lakes in Northwest Russia [173]. The species is capable of synthesizing dangerous (including for humans) toxins [173]. *Cuspidothrix ussaczevii* also often causes water
“bloom” in water bodies of St. Petersburg and the Leningrad Region, being the dominant or subdominant in bloom-forming cyanobacteria [173].

By the fourth day of the experiment, the water temperature in the pond dropped to about 18°C. This led to a decrease in the number and biomass of cyanobacteria, apparently, mainly due to their sinking into the lower layers of the reservoir. However, an even greater decrease in the development of cyanobacteria was observed in the mesocosm, in which cyanobacteria could not sink so deeply (Figure 8). This is also confirmed by data on the optical density of water in the pond and in the mesocosm, where a more significant decrease was noted (Figure 9). Subsequently, the optical density slightly decreased to approximately the same level in the pond and mesocosm and almost did not change in the pond and mesocosm.
At the same time, the control of the development of cyanobacteria from pond 2 in the laboratory, where there was no decrease in temperature, showed their significant growth in the control. With that, under the influence of allelochemicals, significant suppression of plankton growth was observed, recorded by optical density (Figure 10).

By the 8th day of the experiment, a further decrease in the optical density of plankton under the influence of algicide was noted in the laboratory. At the same time, a decrease in optical density and the control was observed, obviously, due to the inability of natural plankton to laboratory conditions (the experiment was carried out in 0.5-liter jars).

By July 8, the species of cyanobacteria *Aphanizomenon flos-aquae* and *Cuspidothrix ussachevii* in the mesocosm dropped out of the dominant composition, although they continued to dominate in the pond water. As our laboratory experiments with this algicide have shown [140], this species of cyanobacteria was especially sensitive to the used mixture of allelochemicals. So, a complete suppression of the development of the culture of *Aphanizomenon flos-aquae* was observed in the experiment with the combined effect of heptanoic, octanoic, tetradecanoic, and gallic acids at various concentrations (0.1, 1, and 10 mg/l).

![Figure 9](image1.png)

*Figure 9.* Change in the optical density of the water mass in pond 2 and the mesocosm when exposed to algicide with a concentration of 1 mg/l.

![Figure 10](image2.png)

*Figure 10.* Change in the optical density of the water mass in pond 2 and the mesocosm when exposed to algicide with a concentration of 1 mg/l during exposure in the laboratory.
In the last phase of the experiment (from July 12), representatives of Cryptophyta - Cryptomonas sp., Komma caudata (formerly Chroomonas acuta) dominated the pond in the composition of phytoplankton (Figure 11). Among the cyanobacteria, Aphanizomenon flos-aquae and Aphanocapsa conferta dominated. In the mesocosm at this time (especially toward the end of the experiment) cryptophyte algae (98% of the total phytoplankton biomass) with the dominant Cryptomonas sp. reached a very high development (with biomass of more than 42 mg/l) (Figure 11). Cyanobacteria were represented by the species Dolichospermum affine, Aphanocapsa conferta with very little quantitative development.

It is noteworthy that by the end of the experiment in the mesocosm, the total phytoplankton biomass returned to almost the same high values as at the beginning of the experiment.

Figure 11.
Changes in the abundance and biomass of cyanobacteria (a) and Cryptophyta (B) in pond 2 and the mesocosm under the influence of algicide at a concentration of 1 mg/l.
experiment. However, if at the beginning of the experiment cyanobacteria prevailed (about 99% of the total biomass of phytoplankton), then by the end of the experiment cryptophyte algae accounted for more than 98% of the biomass of phytoplankton. Cryptomonas sp. dominated among cryptophyte algae. That is, the replacement of dangerous toxicogenic species of cyanobacteria with cryptophyte algae occurred, which can be consumed by aquatic organisms and which are safe for other organisms, including humans. If we project this result to entire aquatic ecosystems, then we can get a very beneficial ecosystem effect, expressed in the suppression of HABs and the development of algae, whose production can be consumed, for example by zooplankton and planktivorous fish.

Thus, the main results of the experiments carried out on the effect of an algicide of four allelochemical components (heptanoic, octanoic, tetradecanoic, and gallic acids) on the phytoplankton of natural water bodies can be considered the following results, indicating that allelochemical substances of aquatic macrophytes: 1) are able to effectively reduce phytoplankton development and suppress even intense HABs; 2) may lead to the replacement of dangerous cyanobacteria in phytoplankton with safe algae, whose production can be used in the food chains of aquatic organisms.

5. Conclusions and perspectives

In this way, available data show that the use of allelochemicals from aquatic macrophytes to inhibit cyanobacterial overgrowth is an environment-friendly and perspective technology for suppressing HABs. Allelochemicals can be considered as natural algaecides and become the basis of a nature-like convergent technology to mitigate the development of plankton cyanobacteria and prevent HABs in water bodies.

One can quite agree with the conclusion of work [24] that allelopathy is a promising strategy to control HABs as the effectiveness of allelochemicals on inhibiting microalgae cells has been discovered, investigated, and confirmed in many works and for many years [175]. However, there are several problems that must be investigated in order to understand what determines the strength of the manifestation of the allelopathic effect. One of these problems is undoubtedly the action of various environmental factors.

Another problem is the resistance of allelochemicals in the aquatic environment and their chemical or biochemical (under the influence of bacteria) changes [26, 74, 168, 176]. In this regard, very promising are works in which systems are being developed that allow dosing and prolonging the release of allelochemicals into the aquatic environment [141–143].

The development and research of allelopathy and its application for suppressing the HABs are striving toward a future for sustainable, rational, and effective using the water resources worldwide. The algicides of the new generation developed based on the phenomenon of allelopathy can definitely reduce the amount of synthetic algicides and herbicides used.

While allelochemicals have shown growth inhibition of planktonic cyanobacteria, there is still insufficient knowledge of the impact on various species of cyanobacteria (especially their action in real aquatic ecosystems), the influence of various factors on the action of allelochemicals, and the molecular mechanisms of their action. These gaps may limit their use as conventional biotechnology for the mitigation and prevention of HABs in aquatic ecosystems.

All the laboratory studies can propose only the potential for allelopathy of macrophytes metabolites toward cyanobacteria, its real use as biotechnology for the management of planktonic communities and HABs will be possible only after convincing field studies using mesocosms and entire ecosystems.
In addition, if we are to understand more about the mechanisms of allelochemicals actions that cyanobacterial cells respond to, more cognizance needs to be taken of the molecular peculiarities of interactions between allelochemicals and cyanobacterial cells.

Acknowledgements

The work was performed within the framework of the state task of the Russian Academy of Sciences on topic 0154-2019-0002. The authors thank Dr. Alexandr Rusanov and Mr. Denis Bardinskij as well as Ms. Elena Fisak for their kind help in the field experiments.

Conflict of interest

The authors declare that there is no conflict of interest.

Author details

Evgeny Kurashov¹,²*, Julia Krylova² and Elena Protopopova¹

1 Institute of Limnology, A Separate Subdivision of the St. Petersburg Federal Research Center of the Russian Academy of Sciences, 9 Sevastyanova street, Saint Petersburg, 196105, Russia

2 Saint-Petersburg Branch of the Federal State Budgetary Scientific Institution “All-Russian Research Institute of Fisheries and Oceanography” (“GosNiorch” by L.S. Berg), 26 Makarova Nab., Saints Petersburg, 199053, Russia

*Address all correspondence to: evgeny_kurashov@mail.ru

IntechOpen

© 2021 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
References

[1] Anderson D. HABs in a changing world: a perspective on harmful algal blooms, their impacts, and research and management in a dynamic era of climactic and environmental change. Harmful Algae. 2012 (2012). 2014;2012:3-17

[2] Šulčius S, Montvydienė D, Mazur-Marzec H, Kasperovičienė J, Rulevičius R, Cibulskaitė Ž. The profound effect of harmful cyanobacterial blooms: From food-web and management perspectives. Science of The Total Environment. 2017;609:1443-1450. DOI:10.1016/j.scitotenv.2017.07.253

[3] Huisman J, Codd GA, Paerl HW, Ibelings BW, Verspagen JMH, Visser PM. Cyanobacterial blooms. Nat Rev Microbiol. 2018;16:471-483. DOI:10.1038/s41579-018-0040-1

[4] Hallegraeff GM. A review of harmful algal blooms and their apparent global increase. Phycologia. 1993;32(2):79-99. DOI:10.2216/i0031-8884-32-2-79.1

[5] Amorim CA, Moura AN. Ecological impacts of freshwater algal blooms on water quality, plankton biodiversity, structure, and ecosystem functioning. Science of The Total Environment, Available online 17 November 2020. DOI: 10.1016/j.scitotenv.2020.143605

[6] Hoagland P, Anderson D M, Kaoru Y, White AW. The Economic Effects of Harmful Algal Blooms in the United States: Estimates, Assessment Issues, and Information Needs. Estuaries. 2002;25(4b):819-837

[7] Wolf D, Georgic W, Klaiber HA. Reeling in the damages: Harmful algal blooms’ impact on Lake Erie’s recreational fishing industry. Journal of Environmental Management. 2017;199:148-157. DOI:10.1016/j.jenvman.2017.05.031

[8] Brock TD. A Eutrophic Lake: Lake Mendota, Wisconsin. Ecological Studies. Springer-Verlag New York Inc. 1985;55. 308 p. DOI: 10.1007/978-1-4419-8700-6

[9] Landner L, Wahlgren U. Eutrophication of lakes and reservoirs in warm climates. Copenhagen; World Health Organization. Regional Office for Europe; 1988. 121 p.

[10] Harper D. Eutrophication of freshwaters, principles, problems and restoration. Chapman and Hall, London; 1992. 327 p.

[11] Lam AKY, Prepas LEE, Spink D, Hrudey SE. Chemical control of hepatotoxic phytoplankton blooms: Implications for human health. Water Res. 1995;29(8):1845-1854

[12] Ansari AA, Gill SS, Lanza GR, Rast W, editors. Eutrophication: Causes, Consequences and Control. Springer, Dordrecht; 2011. 394 p. DOI: 10.1007/978-90-481-9625-8

[13] Chislock MF, Doster E, Zitomer RA & Wilson AE. Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. Nature Education Knowledge. 2013;4(4):10

[14] Yanagi T. Eutrophication and Oligotrophication in Japanese Estuaries: A Synthesis. In: Yanagi T, editor. Eutrophication and Oligotrophication in Japanese Estuaries. Estuaries of the World. Springer, Dordrecht. 2015. p. 1-4. DOI:10.1007/978-94-017-9915-7_1

[15] Rivasa EJG, Pérezb GR, Tundisic JG, Vammend K, Örmecie B, Fordef M. Eutrophication: A growing problem in the Americas and the Caribbean. Braz. J. Biol. 2020;80(3). DOI:10.1590/1519-6984.200001

[16] IARC Monographs on the Evaluation of Carcinogenic Risks to
Humans. Ingested Nitrate and Nitrite, and Cyanobacterial Peptide Toxins. Vol.94. Lyon, France, 450 p.

[17] Koval’chuk MV, Naraikin OS. Nature-Like Technologies—New Capacities and New Challenges. Ind. Bezop. 2017;22(3-4):118-119

[18] Zhironkin S, Demchenko S, Kayachev G, Taran E, Zhironkina O. Convergent and Nature-Like Technologies as the Basis for Sustainable Development in the 21st Century. IVth International Innovative Mining Symposium. E3S Web of Conferences 105, 03008. 2019. DOI:10.1051/e3sconf/201910503008

[19] Nature-like and Convergent Technologies Driving the Fourth Industrial Revolution. United Nations Industrial Development Organization. Vienna; 2019. 79 p.

[20] Hu H, Hong Y. Algal-bloom control by allelopathy of aquatic macrophytes—a review. Frontiers of Environmental Science & Engineering in China. 2008;2(4):421-438

[21] Macías FA, Galindo JLG, García-Díaz MD, Galindo JCG. Allelopathic agents from aquatic ecosystems: potential biopesticides models. Phytochem Rev. 2008;7:155-178. DOI: 10.1007/s11101-007-9065-1

[22] Kurashov EA, Krylova JV, Mitrukova GG, Chernova AM. Low-molecular-weight metabolites of aquatic macrophytes growing on the territory of Russia and their role in hydroecosystems. Contemporary Problems of Ecology. 2014;7(4):433-448. DOI: 10.1134/S1995425514040064

[23] Burford MA, Gobler CJ, Hamilton DP, Visser PM, Lurling M, Codd GA. Solutions for managing cyanobacterial blooms: A scientific summary for policy makers. IOC/UNESCO, Paris; 2019. 17 p. (IOC/INF-1382)

[24] Zhu X, Dao G, Tao Y, Zhan X, Hu H. A review on control of harmful algal blooms by plant-derived allelochemicals. Journal of Hazardous Materials. 2021;401:123403. DOI:10.1016/j.jhazmat.2020.123403

[25] Mohamed ZA. Macrophytes-cyanobacteria allelopathic interactions and their implications for water resources management—a review. Limnologica - Ecology and Management of Inland Waters. 2017;63:122-132. DOI:10.1016/j.limno.2017.02.006

[26] Cheng F, Cheng ZH. Research progress on the use of plant allelopathy in agriculture and the physiological and ecological mechanisms of allelopathy. Front. Plant Sci. 2015;6:16. DOI:10.3389/fpls.2015.01020

[27] Saraf M, Pandya U, Thakkar A. Role of allelochemicals in plant growth promoting rhizobacteria for biocontrol of phytopathogens. Microbiol. Res. 2014;169:18-29. DOI: 10.1016/j.micres.2013.08.009

[28] Kong Ch. Allelopathic Research in China. Allelopathy Journal [Internet]. 2005. Available from: https://www.researchgate.net/publication/271885916_Alelopathy_in_China. [Accessed: 2020-11-23]

[29] Molisch H. Der Einfluss einer Pflanze auf die andere-Allelopathie. Fischer: Jena, Austria; 1937. 116 p

[30] Li Z-H, Wang Q, Ruan X, Pan C-D, Jiang D-A. Phenolics and Plant Allelopathy. Molecules. 2010;15(12):8933-8952. DOI:10.3390/molecules15128933

[31] Tokin BP. Über die mitogenetischen Strahlen und die Lisegangschen Ringe. Biol. Zentralblatt. 1930;50(11):641-671

[32] Tokin BP. Vegetable bactericides (phytoncides). Moscow: Medgiz; 1942. 108 p. [Bakteritsidy rastitel’nogo proiskhozhdeniya (fitontsidy)] (In Russ.)
[33] Gurevich FA. Relationship between the plants and freshwater animal embryos. Dokl. Akad. Nauk SSSR. 1948;59(3):569-572

[34] Gurevich FA. Phytoncides of aquatic and coastal plants, their role in hydrobiocenoses: dissertation abstract of Dr. Biol. Sciences: 030018 / Gurevich Faiva Abramovich; scientific consultant B. P. Tokin. Irkutsk; 1973. 29 p.

[35] Hasler AD, Jones E. Demonstration of the antagonistic action of large aquatic plants on algae and rotifers. Ecology. 1949;30:359-364. DOI:10.2307/1932616

[36] Kurashov EA, Mitrukova GG, Krylova JV. Interannual variability of low-molecular metabolite composition in Ceratophyllum demersum (Ceratophyllaceae) from a Floodplain lake with a changeable trophic status. Contemporary Problems of Ecology. 2018;11(2):179-194. DOI: 10.1134/S1995425518020063

[37] Van Donk E, van de Bund WJ. Impact of submerged macrophytes including charophytes on phyto- and zooplankton communities: Allelopathy versus other mechanisms. Aquat. Bot. 2002;72:261-274

[38] Seto M, Takamura N, Iwasa Y. Individual and combined suppressive effects of submerged and floating-leaved macrophytes on algal blooms. Journal of Theoretical Biology. 2013;319:122-133. DOI:10.1016/j.jtbi.2012.11.016

[39] Scheffer M, Hosper SH, Meijer M-L, Moss B, Jeppesen E. Alternative equilibria in shallow lakes. Trends Ecol. Evol. 1993;8:275-279

[40] Scheffer M. Alternative Attractors of Shallow Lakes. The Scientific World. 2001;1:254-263. DOI 10.1100/tsw.2001.62

[41] Scheffer M, Carpenter S, Foley JA, Folke C, Walker B. Catastrophic shifts in ecosystems. Nature. 2001;413:591-596

[42] Scheffer M, Szabo S, Gragnani A, van Nes EH, Rinaldi S, Kautsky N, Norberg J, Roijackers RMM, Franken RJM. Floating plant dominance as a stable state. Proc. Nat. Acad. Sci. 2003;100(7):4040-4045

[43] Jackson LJ. Macrophyte-Dominated and Turbid States of Shallow Lakes: Evidence from Alberta Lakes. Ecosystems. 2003;6:213-223. DOI: 10.1007/s10021-002-0001-3

[44] Scheffer M. Ecology of Shallow Lakes. Springer US; 1998. 358 p.

[45] Mjelde M, Faafeng BA. Ceratophyllum demersum hampers phytoplankton development in some small Norwegian lakes over a wide range of phosphorus concentrations and geographical latitude. Freshwater Biol. 1997;37:355-365

[46] Van den Berg MS, Coops H, Meijer ML, Scheffer M, Simons J. Clear water associated with a dense Chara vegetation in the shallow and turbid lake Veluwemeer, The Netherlands. In: Jeppesen E, Sondergaard Ma, Sondergaard Mo and Christoffersen K, editors. The Structuring Role of Submerged Macrophytes in Lakes. New York: Springer; 1998. p. 339-352

[47] Blindow I, Hargeby A, Andersson G. Seasonal changes of mechanisms maintaining clear water in a shallow lake with abundant Chara vegetation. Aquat. Bot. 2002;72:315-334

[48] Hilt S, Gross EM. Can allelopathically active submerged macrophytes stabilize clear water states in shallow lakes? Basic Appl. Ecol. 2008;9:422-432

[49] Mulderij G, Mau B, van Donk E, Gross EM. Allelopathic activity of Stratiotes aloides on phytoplankton-towards identification of allelopathic substances. Hydrobiologia. 2007;584:89-100. DOI:10.1007/s10750-007-0602-0
[50] Shao JH, Wu ZX, Yu GL, Peng X, Li RH. Allelopathic mechanism of pyrogallol to Microcystis aeruginosa PCC7806 (Cyanobacteria): from views of gene expression and antioxidant system. Chemosphere. 2009;75:924-928

[51] Hong Y, Hu H, Xie X, Sakoda A. Gramine-induced growth inhibition, oxidative damage and antioxidant responses in freshwater cyanobacterium Microcystis aeruginosa. Aquat. Toxicol. 2009;91(3):262-269

[52] Mohamed ZA, Al-Shehri AM. Differential responses of epiphytic and planktonic toxic cyanobacteria to allelopathic substances of the submerged macrophyte Stratiotes aloides. Int. Rev. Hydrobiol. 2010;95:224-234

[53] Zhu J, Liua B, Wang J, Gao Y, Wu Z. Study on the mechanism of allelopathic influence on cyanobacteria and chlorophytes by submerged macrophyte (Myriophyllum spicatum) and its secretion. Aquat. Toxicol. 2010;98 (2):196-203. DOI:10.1016/j.aquatox.2010.02.011

[54] Nakai S, Yoshihara T, Yamada S, Hosomi M. The allelochemicals accounting for the allelopathic effects of Myriophyllum spicatum on the cyanobacterium Microcystis aeruginosa [Internet]. 2005. Available from: http://www.regional.org.au/au/allelopathy/2005/2/1/2244_nakais.htm#TopOfPage [Accessed: 2020-11-23]

[55] Nakai S, Zou G, Okuda T, Nishijima W, Hosomi M, Okada M. Polyphenols and fatty acids responsible for anti-cyanobacterial allelopathic effects of submerged macrophyte Myriophyllum spicatum. Water Sci. Technol. 2012;66:993-999

[56] Wang LX, Zhang L, Zhang YX, Jin CY, Lu CM, Wu GR. The inhibitory effect of Hydrilla verticillata culture water on Microcystic aeruginosa and its mechanism. J. Plant Physiol. Mol. Biol. 2006;32(6):672-678

[57] Wang HQ, Liang F, Qiao N, Dong JX, Zhang LY, Guo YF. Chemical composition of volatile oil from two emergent plants and their algae inhibition activity. Pol. J. Environ. Stud. 2014;6:2371-2374

[58] Wang H, Liang F, Zhang L. Composition and anti-cyanobacterial activity of essential oils from six different submerged macrophytes. Pol. J. Environ. Stud. 2015;24(1):333-338. DOI: https://doi.org/10.15244/pjoes/26383

[59] He CQ, Ye JX. Inhibitory effects of Acorus tatarinowii on algae growth. Acta Ecol. Sin. 1999;19(5):754-758

[60] Greca MD, Monaco P, Previtera L, Aliotta G, Pinto G, Pollio A. Allelochemical activity of phenylpropanes from Acorus gramineus. Phytochemistry. 1989;28(9):2319-2321 DOI:10.1016/s0031-9422(00)97975-5

[61] Foguel D, Chaloub RM. Effects of the alkaloid gramine on the light-harvesting, energy transfer, and growth of Anabaena sp. (PCC 7119). Plant Physiol. 1993;101:633-639

[62] Hong Y, Hu HY. Effects of the aquatic extracts of Arundo donax L. on the growth of freshwater algae. Allelopathy J. 2007;20:315-325

[63] Hong Y, Hu H-Y, Sakoda A, Sagehashi M. Isolation and characterization of antialgal allelochemicals from Arundo donax L. Allelopathy Journal. 2010;25(2):357-368

[64] Elakovich SD, Wooten JW. An examination of the phytotoxicity of the water shield Brasenia schreberi. J. Chem. Ecol. 1987;13(9):1935-1940. DOI:10.1007/bf01014676

[65] Nakai S, Inoue Y, Hosomi M, Murakami A. Growth inhibition of blue-green algae by allelopathic effects of macrophytes. Japanese Journal of Water Treatment Biology. 1997;33(4):215-222. DOI:10.2521/jswtb.33.215
[66] Nakai S, Inoue Y, Hosomi M. Growth inhibition of blue-green algae by allelopathic effects of macrophytes. Water Sci. Tech. 1999;39(8):47-53

[67] Zhou L, Chen G, Cui N, Pan Q, Song X, Zou G. Allelopathic effects on Microcystis aeruginosa and allelochemical identification in the culture solutions of typical artificial floating-bed plants. Bull. Environ. Contam. Toxicol. 2019;102(1):115-121. DOI:10.1007/s00128-018-2486-2

[68] Wium-Andersen S. Allelopathy among aquatic plants. Archiv für Hydrobiologie, Beiheft Ergebnisse der Limnologie. 1987;27:167-172

[69] Kogan SI, Chinnova GA. Relations between Ceratophyllum demersum L. and some blue-green algae. Hydrobiol. J. 1972;8:14-19

[70] Jasser I. Influence of Ceratophyllum demersum on phytoplankton community in experimental conditions. Verh. Internat. Verein. Limnol. 1994;25:2291-2295

[71] Jasser I. The influence of macrophytes on a phytoplankton community in experimental condition. Hydrobiologia. 1995;306:21-32. DOI:10.1007/BF00007855

[72] Korner S, Nickisch A. Allelopathic growth inhibition of selected phytoplankton species by submerged macrophytes. Journal of Phycology. 2002;38(5):862-871. DOI:10.1046/j.1529-8817.2002.t01-1-02001.x

[73] Wium-Andersen S, Anthoni U, Houen G. Elemental sulphur, a possible allelopathic compound from Ceratophyllum demersum. Phytochemistry. 1983;22:2613

[74] Gross EM, Erhard D, Iványi E. Allelopathic activity of Ceratophyllum demersum L. and Najas marina sp. intermedia (Wolfgang) Casper.

Hydrobiologia. 2003;506-509(1-3):583-589. DOI:10.1023/b:hydr.000008539.32622.91

[75] Qiming X, Haidong C, Huixian Z, Daqiang Y. Allelopathic activity of volatile substance from submerged macrophytes on Microcystin aeruginosa. Acta Ecologica Sinica. 2006;26(11):3549-3554

[76] Ghobrial MG, Nassr HS, Kamil AW. Bioactivity effect of two macrophyte extracts on growth performance of two bloom-forming cyanophytes. The Egyptian Journal of Aquatic Research. 2015;41(1):69-81. DOI:10.1016/j.ejar.2015.01.001

[77] Amorim CA, de Moura-Falcão RH, Valença CR, de Souza VR, Moura AN. Allelopathic effects of the aquatic macrophyte Ceratophyllum demersum L. on phytoplankton species: contrasting effects between cyanobacteria and chlorophytes. Acta Limnol. Bras. 2019;31. DOI: 10.1590/s2179-975x1419

[78] Tazart Z, Douma M, Caldeira AT, Tebaa L, Mouhri K, Loudiki M. Highlighting of the antialgal activity of organic extracts of Moroccan macrophytes: potential use in cyanobacteria blooms control. Environ Sci Pollut Res. 2020;27:19630-19637. DOI:10.1007/s11356-020-08440-w

[79] Berger J, Schagerl M. Allelopathic activity of Characeae. Biologia. 2004;59:9-15

[80] Berger J, Schagerl M. Allelopathic activity of Chara aspera. Hydrobiologia. 2003;501:109-115

[81] Złoch I, Śliwińska-Wilczewska S, Kucharska M, Kozłowska W. Allelopathic effects of Chara species (C. aspera, C. baltica, and C. canescens) on the bloom-forming picocyanobacterium Synechococcus sp. Environ Sci Pollut Res. 2018;25:36403-36411. DOI:10.1007/s11356-018-3579-5
[82] Pakdel FM, Sim L, Beardall J, Davis J. Allelopathic inhibition of microalgae by the freshwater stonewort, Chara australis, and a submerged angiosperm, Potamogeton crispus. Aquatic Botany. 2013;110:24-30. DOI:10.1016/j.aquabot.2013.04.005

[83] Rojo C, Segura M, Rodrigo MA. The allelopathic capacity of submerged macrophytes shapes the microalgal assemblages from a recently restored coastal wetland. Ecol. Eng. 2013;58:149-155. DOI:10.1016/j.ecoleng.2013.06.019

[84] Wium-Andersen S, Anthoni U, Christophersen C, Houen G. Allelopathic effects on phytoplankton by substances isolated from aquatic macrophytes (Charales). Oikos. 1982;39:187-190

[85] Horecka M. The significant role of Chara hispida grown in water regions of a gravel pit lake. Senec. Arch. Protistenkd. 1991;139:275-278

[86] Crawford SA. Farm pond restoration using Chara vulgaris vegetation. Hydrobiologia. 1979;62(1):17-31. DOI:10.1007/bf00012559

[87] Zhang T, He M, Wu A, Nie L. Allelopathic effects of submerged macrophyte Chara vulgaris on toxic Microcystis aeruginosa. Allelopath. J. 2009;23(2):391-401

[88] Yang SY, Sun WH. Isolation and identification of antialgal compounds from root system of water hyacinth. Acta Photophysiol. Sin. 1992;18(4):399-402

[89] Shanab SMM, Shalaby EA, Lightfoot DA, El-Shemy HA. Allelopathic effects of water hyacinth [Eichhornia crassipes]. PLoS ONE. 2010;5(10):e13200. DOI:10.1371/journal.pone.0013200

[90] Liu R, Ran X, Bai F, Xu J, Yang S, Shi J, Wu Z. Use of chlorophyll a fluorescence to elucidate the toxicity target of N-phenyl-2-naphthylamine on photosynthetic system of Cylindrospermopsis raciborskii (Cyanobacteria). Phycologia. 2015;54:12-19

[91] Pei Y, Liu L, Hilt S, Xu R, Wang B, Li C, Chang X. Root exuded algicide of Eichhornia crassipes enhances allelopathic effects of cyanobacteria Microcystis aeruginosa on green algae. Hydrobiologia. 2018;823:67-77. DOI:10.1007/s10750-018-3696-7

[92] Proctor VW. Some controlling factors in the distribution of Haematococcus pluvialis. Ecology. 1957;38:457-462

[93] Van Aller RT, Pessoney GF, Rogers VA, Watkins EJ, Leggett HG. Oxygenated fatty acids: A class of allelochemicals from aquatic plants. ACS Symp. Ser. 1985;268:387-400. DOI: 10.1021/bk-1985-0268.ch026

[94] Erhard D, Gross EM. Allelopathic activity of Elodea canadensis and Elodea nuttallii against epiphytes and phytoplankton. Aquatic Botany. 2006;85(3):203-211. DOI:10.1016/j.aquabot.2006.04.002

[95] Wang HQ, Zhu HJ, Zhang LY, Xue WJ, Yuan B. Identification of antialgal compounds from the aquatic plant Elodea nuttallii. Allelopathy J. 2014;34:207-213

[96] Gao H, Song Y, Lv C, Chen X, Yu H, Peng J, Wang M. The possible allelopathic effect of Hydrilla verticillata on phytoplankton in nutrient-rich water. Environmental Earth Sciences. 2015;73(9):5141-5151. DOI:10.1007/s12665-015-4316-8

[97] Cheng W, Xuexiu C, Hongjuan D, Difu L, Junyan L. Allelopathic inhibitory effect of Myriophyllum aquaticum (Vell.) Verdc. on Microcystis aeruginosa and its physiological mechanism. Acta Ecologica Sinica. 2008;28(6):2595-2603

[98] Saito K, Matsumoto M, Sekine T, Murakoshi I,Morisaki N,
Iwasaki S. Inhibitory substances form Myriophyllum brasiliense on growth of bluegreen algae. J. Nat. Prod. 1989;52(6):1221-1226. DOI:10.1021/np50066a004

[99] Bi YL, Wu SM, Zhou SN, Wu SH, Xu SJ. Allelopathic effects and allelochemicals of Myriophyllum elatinoides on Microcystis aeruginosa and Selenastrum capricornutum. Environ. Sci. 2019;40:2265-2270. DOI: 10.13227/j.hjkx.201810064

[100] Planas D, Sarhan F, Dube L, Godmaire H. Ecological significance of phenolic compounds of Myriophyllum spicatum. Verh. Internat. Verein. Limnol. 1981;21:1492-1496

[101] Gross EM, Sütfeld R. Polyphenols with algicidal activity in the submerged macrophytes Myriophyllum spicatum L. Acta Hortic. 1994;381:710-716

[102] Nakai S, Yamada S, Hosomi M. Anticyanobacterial fatty acids released from Myriophyllum spicatum. Hydrobiologia. 2005;543:71-78

[103] Gross EM, Meyer H, Schilling G. Release and ecological impact of algicidal hydrolysable polyphenols in Myriophyllum spicatum. Phytochemistry. 1996;41(1):133-138

[104] Gross EM. Allelopathy in benthic and littoral areas: case studies on allelochemicals from benthic cyanobacteria and submerged macrophytes. In: Inderjit Dakshini KMM, Foy CL, editors. Principles and Practices in Plant Ecology: Allelochemical Interactions. CRC Press, Boca Raton, FL; 1999. p. 179-199

[105] Aliotta G, Molinari A, Monaco P, Pinto G, Previtera L. Three biologically active phenylpropanoid glucosides from Myriophyllum verticillatum. Phytochemistry. 1992;31(1):109-111

[106] Pollio A, Pinto G, Ligrone R, Aliotta G. Effects of the potential allelochemical a-asarone on growth, physiology and ultrastructure of two unicellular green algae. J. Appl. Phycol. 1993;5:395-403

[107] Tazart Z, Caldeira AT, Douma M, Salvador C, Loudiki M. Inhibitory effect and mechanism of three macrophytes extract on Microcystis aeruginosa growth and physiology. Water and Environment Journal. 2020. DOI:10.1111/wej.12653

[108] Li FM, Hu HY. Isolation and characterization of a novel antialgal allelochemical from Phragmites communis. Applied and Environmental Microbiology. 2005;71(11):6545-6553. DOI:10.1128/aem.71.11.6545-6553.2005

[109] He L, Meng F-L, Meng R, Huang C-H, Li Y-W, Xi B-D, Shu J-M. In Situ Enclosure Experiment on Nelumbo nucifera for Eutrophication Control in Baiyang dian Lake. Wetland Science. 2013;11(2):282-285

[110] Balanda OV, Sakevich AI. Alkaloids of Nuphar lutea (L.) Smith. and their Influence on the Vital Activity of Cyanobacteria and Algae. Hydrobiological Journal. 2004;40(6):108-120. DOI: 10.1615/HydrobJ.v40.i6.100

[111] Ahluwalia AS, Ghawana VK. Allelopathic interactions among cyanobacteria and rice and their potential role in biotechnology. In: Subramanian G, Kaushik BD, Venkataraman GS, editors. Cyanobacterial Biotechnology. India: Oxford and IBH Publishing;1998. p. 403-408

[112] Nakai S, Zhou S, Hosomi M, Tominaga M. Allelopathic growth inhibition of cyanobacteria by reed. Allelopathy J. 2006;18(2):277-286

[113] Aliotta G, Monaco P, Pinto G, Pollio A, Previtera L. Potential allelochemicals from Pistia stratiotes L. J. Chem. Ecol. 1991;17(11):2223-2234. DOI:10.1007/bf00988003
[114] Wu X, Wu H, Chen J, Ye J. Effects of allelochemical extracted from water lettuce (Pistia stratiotes Linn.) on the growth, microcystin production and release of Microcystis aeruginosa. Environmental Science and Pollution Research. 2013;20(11):8192-8201. DOI:10.1007/s11356-013-1783-x

[115] Wu X, Wu H, Ye J, Zhong B. Study on the release routes of allelochemicals from Pistia stratiotes Linn., and its anti-cyanobacteria mechanisms on Microcystis aeruginosa. Environmental Science and Pollution Research. 2015;22(23):18994-19001. DOI:10.1007/s11356-015-5104-4

[116] Zhou Y, Zhou X, Han R, Xu X, Wang G, Liu X, Feng D. Reproduction capacity of Potamogeton crispus fragments and its role in water purification and algae inhibition in eutrophic lakes. Science of The Total Environment. 2017;580:1421-1428. DOI:10.1016/j.scitotenv.2016.12.108

[117] Kang LJ, Xu H, Zou W, Zhu MY, Ji PF, Chen J. Influence of Potamogeton crispus on Lake Water Environment and Phytoplankton Community Structure. Environmental Science. 2020;41(9):4053-4061. DOI: 10.13227/j.hjkx.202002006

[118] Zhang S, Cheng S, Wang HQ, He F, Wu ZB. Allelopathic interactions between the Potamogeton spp and toxic cyanobacteria (Microcystis aeruginosa). Allelopathy Journal. 2009;23(2):379-390

[119] Zhang S, Sun P, Ge F, Wu Z. Different Sensitivities of Selenastrum capricornutum and Toxic Strain Microcystis aeruginosa to Exudates from Two Potamogeton Species. Pol. J. Environ. Stud. 2011;20(5):1359-1366

[120] Zhang W, Shen H, Zhang J, Yu J, Xie P, Chen J. Physiological differences between free-floating and periphytic filamentous algae, and specific submerged macrophytes induce proliferation of filamentous algae: A novel implication for lake restoration. Chemosphere. 2020;239:124702. DOI:10.1016/j.chemosphere.2019.124702

[121] Dehui C, Yongding L, Lirong S. The allelopathy of macrophyte Potamogeton pectinatus L on chlorophyta (Scenedesmus obliquus) and cyanobacteria (Microcystis aeruginosa) and calculation of allelopathic parameter. Acta Hydrobiologica Sinica. 2004;28(2):163-168

[122] Zhang X, Lu X, Wang L. Allelopathic effect of Ruppia maritima on Chlorella vulgaris and Microcystis aeruginosa. China Environmental Sciencece. 2019; 39(4): 1589-1595

[123] Greca MD, Fiorentino A, Isidori M, Monaco P, Zarrelli A. Antialgal ent-labdane diterpenes from Ruppia maritime. Phytochemistry. 2000;55:909-913

[124] Dai SG, Zhao F, Jin ZH, Zhuang YY, Yuan YC. Allelopathic effect of plant’s extracts on algae and the isolation and identification of phytotoxins. Environ. Chem. 1997;16(3):268-271

[125] Aliotta G, Greca MD, Monaco P, Pinto G, Pollio A, Previtera L. In vitro algal growth inhibition by phytotoxins of Typha latifolia L. J. Chem. Ecol. 1990;16(9):2637-2646. DOI: 10.1007/BF00988075

[126] Greca MD, Mangoni L, Molinaro A, Monaco P, Previtera L. (20S)-4α-methyl-24-methylenecholest-7-en-3β-ol, an allelopathic sterol from Typha latifolia . Phytochemistry. 1990;29:1797-1798. DOI:10.1016/0031-9422(90)85019-c

[127] Xian QM, Chen HD, Liu HL, Zou RX, Yin DQ. Isolation and identification of antialgal compounds from the leaves of Vallisneria spiralis L. by activity-guided fractionation. Environ. Sci. Pollut. Res. 2006;13(4):233-237
[128] Li B, Yin Y, Kang L, Feng L, Liu Y, Du Z, Tian Y, Zhang L. A review: Application of allelochemicals in water ecological restoration - algal inhibition. Chemosphere. 2020;128869. DOI:10.1016/j.chemosphere.2020.128869

[129] Lombardo P, Mjelde M, Källqvist T, Brettum P. Seasonal and scale-dependent variability in nutrient- and allelopathy-mediated macrophyte–phytoplankton interactions. Knowledge and Management of Aquatic Ecosystems. 2013;409:10. DOI:10.1051/kmae/2013055

[130] Mulderij G, Mooij WM, Smolders AJP, Van Donk E. Allelopathic inhibition of phytoplankton by exudates from Stratiotes aloides. Aquatic Botany. 2005;82:284-296. DOI:10.1016/j.aquabot.2005.04.001

[131] Elakovich, SD. Allelopathic aquatic plants for aquatic weed management. Biol Plant. 1989;31:479. DOI:10.1007/BF02876221

[132] Elakovich SD, Wooten JW. Allelopathic potential of Nuphar lutea (L.) Sibth. & Sm. (Nymphaeaceae). J Chem Ecol. 1991;17:707-714. DOI:10.1007/BF00994194

[133] Dekker J, Meggitt WF. Interference between velvetleaf (Abutilon theophrasti Medic.) and soybean (Glycine max (L.) Merr.). I. Growth. Weed Res. 1983;23:91-101

[134] Ball AS, Williams M, Vincent D. Algal growth control by a barley straw extract. Bioresource Technol. 2001;77:177-181

[135] Everall NC, Lees DR. The identification and significance of chemical released from decomposing barley straw during reservoir algal control. Water Res. 1997;31:614-620

[136] Ferrier MD, Butler BR Sr, Terlizzi DE. The effects of barley straw (Hordeum vulgare) on the growth of freshwater algae. Bioresource Technol. 2005;96:1788-1795

[137] Xiao X, Huang H, Ge Z, Rounge TB, Shi J, Xu X, Li R, Chen Y. A pair of chiral flavonolignans as novel anti-cyanobacterial allelochemicals derived from barley straw (Hordeum vulgare): characterization and comparison of their anti-cyanobacterial activities. Environ. Microbiol. 2014;16 (5):1238-1251. DOI:10.1111/1462-2920.12226

[138] Kurashov EA, Fedorova EV, Krylova JV, Mitrukova GG. Assessment of the potential biological activity of low molecular weight metabolites of freshwater macrophytes with QSAR. Scientifica. 2016; Article ID 1205680. DOI:10.1155/2016/1205680

[139] Kurashov EA, Fedorova EV, Krylova JV. Using the QSAR method to identify the most promising allelochemics against cyanobacteria. [Ispol’zovaniye metoda QSAR dlja vyyavleniya naiboleye perspektivnykh allelokhemikov v otnoshenii tsianobakteriy]. Russian Journal of Applied Ecology. 2018;4(16):56-61 (In Russ.)

[140] Kurashov E, Kapustina L, Krylova J, Mitrukova G. The use of fluorescence microscopy to assess the suppression of the development of cyanobacteria under the influence of allelochemicals of aquatic macrophytes. In: Natalia Grigoryeva, editor. Fluorescence Methods for Investigation of Living Cells and Microorganisms. IntechOpen; 2020. 28 p. DOI: 10.5772/intechopen.92800

[141] Ni LX, Jie XT, Wang PF, Li SY, Wang GX, Li YP, Li Y Acharya K. Effect of linoleic acid sustained-release microspheres on Microcystis aeruginosa antioxidant enzymes activity and microcystins production and release.
The Use of Allelochemicals of Aquatic Macrophytes to Suppress the Development...
DOI: http://dx.doi.org/10.5772/intechopen.95609

Chemosphere. 2015;121:110-116. DOI: 10.1016/j.chemosphere.2014.11.056

[142] Ni LX, Jie XT, Wang PF, Li SY, Hu SZ, Li YP, Li Y Acharya K. Characterization of unsaturated fatty acid sustained-release microspheres for long-term algal inhibition. Chemosphere. 2015b;120:383-390. DOI:10.1016/j.chemosphere.2014.07.098

[143] Ni LX, Acharya K, Ren GX, Li SY, Li YP, Li Y. Preparation and characterization of anti-algal sustained-release granules and their inhibitory effects on algae. Chemosphere. 2013;91:608-615. DOI:10.1016/j.chemosphere.2012.12.064

[144] Huang HM, Xiao X, Lin F, Grossart HP, Nie ZY, Sun LJ, Xu C, Shi JY. Continuous-release beads of natural allelochemicals for the long-term control of cyanobacterial growth: preparation, release dynamics and inhibitory effects. Water Res. 2016;95:113-123. DOI:10.1016/j.watres.2016.02.058

[145] Gao Y, Liu B, Ge FJ, He Y, Lu Z, Zhou Q, Zhang YY, Wu ZB Joint effects of allelochemical nonanoic acid, N-phenyl-1-naphthylamine and caffeic acid on the growth of Microcystis aeruginosa. Allelopathy Journal. 2015; 35(2):249-258

[146] Zuo S, Zhou S, Ye L, Ma S. Synergistic and antagonistic interactions among five allelochemicals with antialgal effects on bloom-forming Microcystis aeruginosa. Ecological Engineering. 2016;97:486-492. DOI:10.1016/j.ecoleng.2016.10.013

[147] Wang HQ, Zhang LY. Allelopathic activity of ethyl acetate extracts from typical emergent plants against Microcystis aeruginosa Kütz. Bangladesh J. Bot. 2017;46: 025-1029

[148] Nakai S, Inoue Y, Hosomi M, Murakami A. myriophyllum spicatum-released allelopathic polyphenols inhibiting growth of blue-green algae Microcystis aeruginosa. Water Res. 2000;34(11):3026-3032. DOI:10.1016/S0043-1354(00)00039-7

[149] Nakai S, Inoue Y, Hosomi M. Algal growth inhibition effects and inducement modes by plant-producing phenols. Water Res. 2001;35:1855-1859. DOI:10.1016/S0043-1354(00)00444-9

[150] Gao Y-N, Liu B-Y, Xu D, Zhou Q-H, Hu C-Y, Ge F-J, Zhang L-P, Wu Z-B. Phenolic compounds exuded from two submerged freshwater macrophytes and their allelopathic effects on Microcystis aeruginosa. Polish J. Environ. Stud. 2011;20:1153-1159

[151] Greca MD, Lanzetta R, Mangoni L, Monaco P, Previtera L. A bioactive benzoinendone from Eichhornia crassipes. Solms. Bioorg. Med. Chem. Lett. 1991;1:599-600

[152] Greca MD, Lanzetta R, Molinaro A, Monaco P, Previtera L. Phenalene metabolites from Eichhornia crassipes. Bioorg. Med. Chem. Lett. 1992; 2:311-314

[153] Greca MD, Fiorentino A, Monaco P, Pinto G, Pollio A, Previtera L. Action of antialgal compounds from Juncus effusus L. on Selenastrum capricornutum. J. Chem. Ecol. 1996; 22(3):587-603

[154] Greca MD, Fiorentino A, Monaco P, Pinto G, Previtera L, Zarrelli A. Synthesis and antialgal activity of dihydrophenanthenes and phenanthenes II: Mimics of naturally occurring compounds in Juncus effusus. J. Chem. Ecol. 2001;27(2):257-271

[155] Sun WH, Yu SW, Yang SY, Zhao BW, Yu ZW, Wu HL, Huang SY, Tang CS. Allelochemicals from root exudates of water hyacinth (Eichhornia crassipes). Acta Photophysiol. Sin. 1993;19(1):92-96
Plankton Communities

[156] Sutfeld R, Peterit F, Nahrstedt A. Resorcinol in exudates of Nuphar lutea. J. Chem. Ecol. 1996;22:2221-2231

[157] Sutfeld R. Polymerization of resorcinol by a cryptophycean exoenzyme. Phytochemistry. 1998;49: 451-459

[158] Gallardo MT, Martin BB, Martin DF. Inhibition of water fern (Salviana minima) by cattail (Typha domingensis) extracts and by 2-chlorophenol and salicylaldehyde. J. Chem. Ecol. 1998;24:1483-1490

[159] Della GM, Ferrara M, Fiorentino A, Monaco P, Prevertera L. Antialgal compounds from Zantedeschia aethiopica. Phytochemistry. 1998;49 (5):1299-1304

[160] Choe S, Jung IH. Growth inhibition of freshwater algae by ester compounds released from rotted plants. J. Ind. Eng. Chem. 2002;8(4):297-304

[161] Nakai S, Hosomi M. Allelopathic inhibitory effects of polyphenols released by Myriophyllum spicatum on algal growth. Allopath. J. 2002;10(2):123-131

[162] Wu ZB, Deng P, Wu XH, Luo S, Gao YN. Allelopathic effects of the submerged macrophyte Potamogeton malaianus on Scenedesmus obliquus. Hydrobiologia. 2007;592: 65-474

[163] Liu H, He L, Gao J, Ma Y, Zhang X, Peng H, Chen J. Chemical constituents from the aquatic weed Pistia stratiotes. Chem. Nat. Compd. 2008;44(2):236-238

[164] Liu G, Zhou C, Sun L, Zhu W, Jiang H, Wang H, An S. Effects of Eichhornia crassipes allelochemicals on the growth of two mono- and co-cultured algae Microcystis aeruginosa and Scenedesmus obliquus. Acta Scientiae Circumstantiae. 2011;31(10):2303-2311

[165] Huang H, Xiao X, Ghadouani A, Wu J, Nie Z, Peng C, Shi J. Effects of Natural Flavonoids on Photosynthetic Activity and Cell Integrity in Microcystis aeruginosa. Toxins. 2015;7(1):66-80. DOI:10.3390/toxins7010066

[166] Dong J, Chang M, Li C, Dai D, Gao Y. Allelopathic effects and potential active substances of Ceratophyllum demersum L. on Chlorella vulgaris Beij. Aquatic Ecol. 2019;53(4):651-663

[167] Kurashov EA, Krylova JV, Bataeva YuV, Rusanov AG, Sukhenko LT. Algicide for suppressing the development of cyanobacteria and green algae based on metabolites—allelochemicals of aquatic plants. Patent for invention RU 2709308 C1, 17.12.2019. Application No. 2019104959 dated 02.21.2019. [Internet] 2019. Available from: https://patents.s3yandex.net/RU2709308C1_20191217.pdf [Accessed: 2020-11-23]

[168] Gross EM, Hilt S, Lombardo P, Mulderij G. Searching for allelopathic effects of submerged macrophytes on phytoplankton-state of the art and open questions. Hydrobiology. 2007;584:77-88

[169] Hilt S, Ghoebial M, Gross EM. In situ allelopathic potential of Myriophyllum verticillatum (Haloragaceae) against selected phytoplankton species. J. Phycol. 2006;42:1189-1198

[170] Vanderstukken M, Mazzeo N, Van Colen W, Declerck SAJ, Muylaert K. Biological control of phytoplankton by the subtropical submerged macrophyte Egeria densa and Potamogeton illinoensis: a mesocosm study. Freshwater Biology. 2011;56(9):1837-1849. DOI:10.1111/j.1365-2427.2011.02624.x

[171] Švanys A, Paškauskas R, Hilt S. Effects of the allelopathically active macrophyte Myriophyllum spicatum on a natural phytoplankton community: a mesocosm study. Hydrobiologia. 2013;737(1):57-66. DOI:10.1007/s10750-013-1782-4

[172] Patova EN. Bloom-forming Cyanoprokaryotes in Kharbeyksie Lakes of
Bolshezemelskaya Tundra. Journal of Siberian Federal University. Biology. 2014;7(3):282-290

[173] Beljakova RN. Bloom forming cyanoprokaryota from water bodies of North-Western Russia. Novitates Systematicae Plantarum Non Vasculararium. 2005;39:12-36. (In Russ.)

[174] Skulberg OM, Underdal B, Utkilen H. Toxic waterblooms with cyanophytes in Norway — current knowledge. Algological Studies. 1994;75:279-289

[175] Willis RJ. The History of Allelopathy. Springer, Dordrecht; 2007. 316 p. DOI: 10.1007/978-1-4020-4093-1

[176] Bauer N, Grossart HP, Hilt S. Effects of bacterial communities on the sensitivity of Stephanodiscus minutulus and Desmodesmus armatus to tannic acid. Aquat. Microb. Ecol. 2010;59: 295-306