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Allelopathic effect of macroalgae *Fucus vesiculosus* (Ochrophyta) and *Coccotylus brodiei* (Rhodophyta) on the growth and photosynthesis performance of Baltic cyanobacteria

Introduction

The term "allelopathy" was introduced to science by Hans Molisch (Molisch, 1937), who used this appellation to describe the chemical interaction between plants. With the development of allelopathic research, this definition includes negative and positive effects of compounds secreted by various plant and animal organisms (Rice, 1984). Inderjit and Dakshini (1994) have also shown allelopathic activity in aquatic environments between cyanobacteria (*Aphanizomenon gracile* (Lemmerm.) Lemmerm.) and microalgae (*Pediastrum boryanum* (Turpin) Menegh., *Cosmarium lundellii* Delp., *Micrasterias* sp.) (Guiry, Guiry, 2021). With the end of the 20th century, the definition of allelopathy was standardised by the International Allelopathy Society (*IAS*, 1996), describing any process in which bioactive metabolites (so-called allelochemicals or allelopathic compounds) secreted by organisms affect the development of other plant and animal species (Legrand et al., 2003). Currently, allelopathy is considered to be a unique strategy to deter or eliminate competitors and predators coexisting in the same ecosystem (Granéli et al., 2008; Gomes et al., 2017; Śliwińska-Wilczewska et al., 2021).

In aquatic ecosystems, the allelopathy of donor organisms depends on the production and secretion of active allelopathic compounds and their efficient dispersal to target organisms affected by these compounds (Śliwińska-Wilczewska et al., 2021). For photoautotrophic organisms, the production of active allelopathic compounds becomes a crucial adaptation in achieving a competitive advantage over other primary producers (Legrand et al., 2003). Red and brown macroalgae are the important source of many biologically active metabolites (El Gamal, 2010). For instance, the tichocarpols A and B isolated from the red alga *Tichocarpus crinitus* (Gmel.) Rupr. exhibit antifeedant activity against the sea urchin (Ishii et al., 2004). On the other hand, dictyterepenoids A and

B isolated from the brown algae *Dilophus okamurae* E.Y.Dawson display antifeedant activity against the abalone (Suzuki et al., 2002).

In benthic communities, organisms are often located at shorter distances from each other. Thus, direct contact between donor and target cells may occur. This also leads to constant competition for space, nutrients, and light. Competition for resources may then be crucial in the occurrence of allelopathic interactions (Gross, 2003). It has been found that target organisms can be inhibited, resisted, or even stimulated by allelopathic compounds present in water (Suikkanen et al., 2004; Śliwińska-Wilczewska et al., 2021). Consequently, allelopathic interactions may contribute to changes in phytoplankton and phytobenthic structure in aquatic ecosystems.

Compared to the intensive and extensive research on allelopathic interactions among terrestrial plants, knowledge of allelopathy in aquatic plant communities is still not fully demonstrated. This is partly because it is difficult to provide direct evidence for allelopathic interactions in water ecosystems under natural conditions. It is challenging to study allelopathic effects among aquatic organisms under natural conditions because factors such as competition for nutrients and light, temperature, and pH change can mask allelopathic effects (Legrand et al., 2003). Therefore, it is important that attempts to identify allelopathic interactions among aquatic organisms be conducted in a controlled system, such as by conducting a series of laboratory experiments. Therefore, in the present study, the allelopathic effect of aqueous extracts from the Baltic red alga *Coccotylus brodiei* (Turner) Kütz. and the brown alga *Fucus vesiculosus* L. (Guiry, Guiry, 2021) on the growth and chlorophyll fluorescence of two bloom-forming cyanobacteria from the genus *Aphanizomenon* and *Nostoc* were investigated.

Material and methods

Material and place of sampling

The material used in the experiments consisted of strains of Baltic cyanobacteria *Aphanizomenon* sp. (CCBA-69) and *Nostoc* sp. (CCBA-81) (Fig. 1). Strains of cyanobacteria were isolated from the natural phytoplankton communities of the coastal waters of the Gulf of Gdansk (southern Baltic Sea: 54°30'53.7"N 18°54'23.5"E). Currently, these strains are maintained as monocultures in the Culture Collection of Baltic Algae (CCBA) at the Laboratory of Marine Plant Ecophysiology at the University of Gdańsk (Latała et al., 2006). The macroalgae used in the study were collected from the coastal zones of the Gulf of Gdańsk (54°30'08.7"N 18°33'32.3"E). Determination of macroalgae based on the examination of morphological features. The herbarium sheets were deposited at the Institute of Oceanography, University of Gdansk (Poland) and are available on the website (https://zielnik.ug.edu.pl/en/home/).

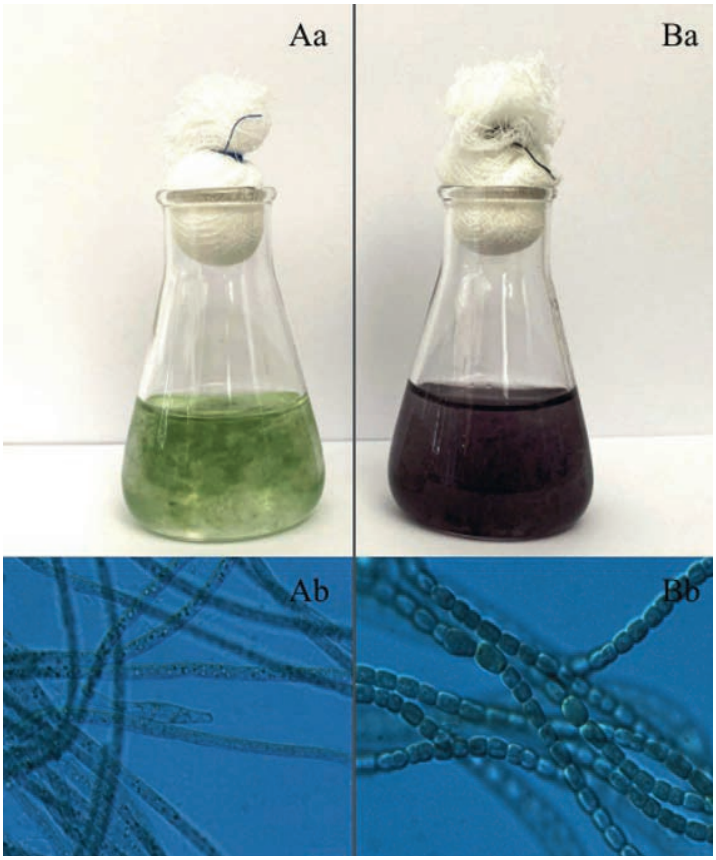

Fig. 1. Photographs of the cyanobacterial culture in 25-mL Erlenmeyer flasks (a) of strain: CCBA-69 *Aphanizomenon* sp. (Aa) and CCBA-81 *Nostoc* sp. (Ba); light microscope photographs (b) of cyanobacterial strain; scale = 10 μm, (Photo. S. Śliwińska-Wilczewska)

Cyanobacteria cultivation

The studied cyanobacteria were cultured on sterile mineral medium f/2 (Guillard, 1975) prepared with Baltic Sea water filtered through glass fiber filters (Whatman GF/C) and autoclaved. The salinity was 8 PSU as measured with a salinometer (inoLab Cond Level 1, Weilheim in Oberbayern, Germany). The cyanobacterial strains used in the experiments was maintained in 25mL glass Erlenmeyer flasks. Cyanobacteria were cultured at a PAR intensity of 10 μmol photons $m^{-2}s^{-1}$ (16:8 h light: dark cycle) and a temperature of 18°C. Photosynthetically active irradiance (PAR) was measured using a quantum meter (LI-COR, Nebraska, USA). The light sources used in the experiment were lamps (Cool White 40W, Sylvania, USA). The culture was acclimated to these conditions for 7 days, and these growth conditions were used for the experiments.

Determination of the allelopathic effect of an aqueous extract obtained from macroalgae

The allelopathic effect of Baltic macroalgae was investigated by adding different concentrations of aqueous extract to the target cyanobacteria monocultures. The allelopathic effect was examined according to the method proposed by Złoch et al. (2018) with modifications. First, dried macroalgae material was mechanically ground to powder in a mortar. In the next step, 50 g of dry matter was weighed and filtered in 50 mL of culture medium. Finally, the extract was filtered with a glass fibre filter (Whatman GF/C) using a vacuum pump (400 mbar) to remove suspended particles. The concentration of major nutrients in the control and experimental samples were adjusted to the same level as in the f/2 standard. Therefore, the influence of nutrients, micronutrients and vitamins on the experimental result can be excluded.

Target cyanobacterial strains were maintained in 25-mL Erlenmeyer flasks. In all experiments, the starting concentration of chlorophyll *a* in cyanobacterial cultures was 0.4 μg chl *a* mL^{-1}. The experiment was conducted by adding 100, 500, and 1000 μL of macroalgae extract to Erlenmeyer flasks containing 20 mL of the target cyanobacteria. Thus, the final extract concentrations were: 5, 25, and 50 μL mL^{-1}. Control cultures were prepared analogously, but f/2 medium was added instead of extract at 100, 500, and 1000 μL. After 7 days of the exposure, the cells concentration as well as chlorophyll *a* fluorescence parameters were determined. Each experiment was performed in triplicate.

Determination of cyanobacterial number of cells

The number of cells (N) in *Aphanizomenon* sp. and *Nostoc* sp. cultures was estimated with previously determined linear correlations between cell abundance (N mL^{-1}) and optical density (OD). N was counted using a Bürker chamber (48 squares per count) and light microscope following a procedure according to Guillard and Sieracki (2005), and the OD was measured spectrophotometrically at 750 nm with a Multiskan GO UV-VIS spectrophotometer (Thermo Scientific, Massachusetts, USA). The linear correlation between N and OD for *Aphanizomenon* sp. was described by Śliwińska-Wilczewska et al. (2017) whereas for *Nostoc* sp. was examined by Budzałek et al. (2018). OD measurements were performed on the 7^{th} days of the experiment and control and converted to cyanobacteria cells.

Determination of the chlorophyll *a* fluorescence

In the conducted experiments, the Pulsed Amplitude Modulation (PAM) method was used to measure the chlorophyll *a* fluorescence (FMS1, Hansatech). This method is widely used to measure chlorophyll *a* fluorescence in cyanobacteria, both in the laboratory and in the natural environment (Schreiber et al., 1995; Campbell et al., 1998). Samples were taken for chlorophyll fluorescence analysis after the 7^{th} days of the ex-

periment. About 5 mL of target cyanobacteria were filtered through 13-mm glass fiber filters (Whatman GF/C). In the next step, the filters were placed in holders. The samples were kept in the dark for 5 min before measurement. In this study, the maximum PSII quantum efficiency (F_v/F_m) and the effective quantum yield of PSII photochemistry (ΦPSII) were determined (Campbell et al., 1998).

Statistical analysis

To confirm the effect of the extracts obtained from macroalgae on the number of cells and chlorophyll *a* fluorescence parameters of target cyanobacteria, a *t*-test was performed at three levels of significance: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$. Data are reported as the means ± standard deviations (SD). The statistical analyses were performed using Statistica® 13.1 software.

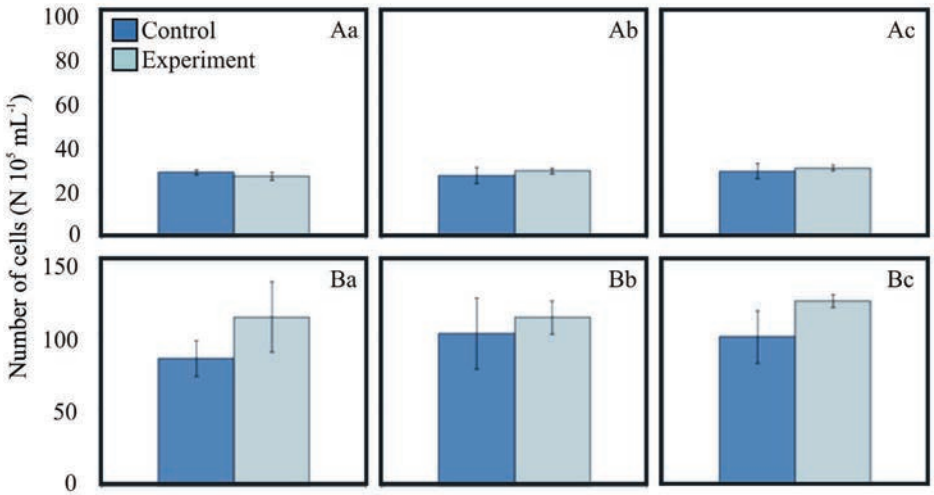

Fig. 2. The number of cells (N 10^5 mL^{-1}) of *Aphanizomenon* sp. (A) and *Nostoc* sp. (B) in controls and cultures to which were added: 5 (a), 25 (b), and 50 (c) (μL mL^{-1}) of aqueous extract obtained from *Fucus vesiculosus* L. after 7 days of the experiment. The values shown are mean (n = 3, mean ± SD). * indicates statistically significant differences compared to control based on *t*-test at: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Allelopathic effect of aqueous extract on cyanobacterial abundances

In this work, the number of cells (N 10^5 mL^{-1}) of *Aphanizomenon* sp. and *Nostoc* sp. in controls and cultures to which were added: 5, 25, and 50 (μL mL^{-1}) of aqueous extract obtained from *Fucus vesiculosus* and *Coccotylus brodiei* after 7 days of the experiment were determined. It was found that aqueous extracts obtained from *F. vesiculosus* had no statistically significant effect on the number of cells of the cyanobacteria *Aphanizomenon* sp. and *Nostoc* sp. (Fig. 2A–B). On the other hand, it was examined a stimulating effect of 5, 25, and 50 μL mL^{-1} of the aqueous extract obtained from *C. brodiei* on the number of

Nostoc sp. cells which constituted 108% ($p < 0.01$), 140% ($p < 0.01$), and 147% ($p < 0.001$), respectively, relative to the control treatment (Fig. 3 Ba-Bc). Moreover, the *C. brodiei* extracts had no significant effect on the growth of *Aphanizomenon* sp. (Fig. 3Aa–Ac).

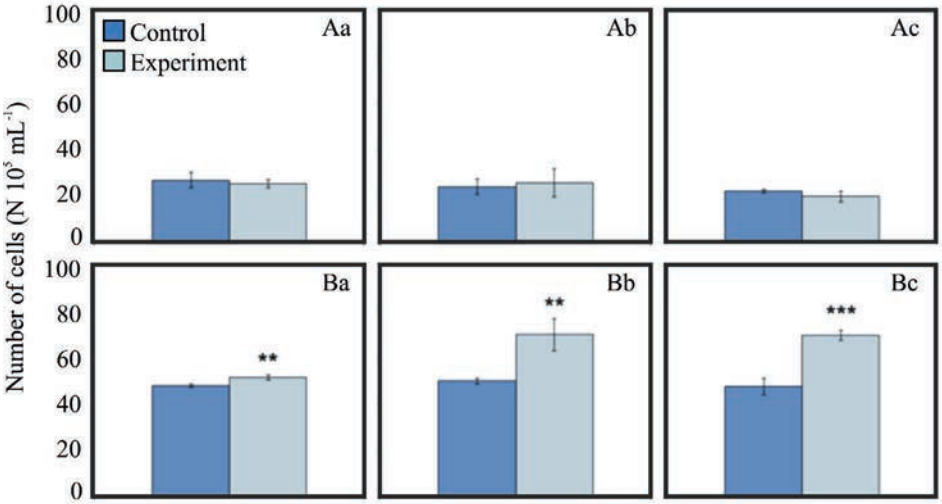

Fig. 3. The number of cells (N 10^5 mL^{-1}) of *Aphanizomenon* sp. (A) and *Nostoc* sp. (B) in controls and cultures to which were added: 5 (a), 25 (b), and 50 (c) (µL mL^{-1}) of aqueous extract obtained from *Coccotylus brodiei* (Turner) Kütz. after 7 days of the experiment. The values shown are mean (n = 3, mean ± SD). * indicates statistically significant differences compared to control based on *t*-test at: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Allelopathic effect of an aqueous extract on fluorescence parameters

The values of the fluorescence parameter F_v/F_m (the maximum PSII quantum efficiency) and ΦPSII (the effective quantum yield of PSII photochemistry) for *Aphanizomenon* sp. and *Nostoc* sp. in control and cultures to which were added a different concentrations (5, 25, and 50 µL mL^{-1}) of aqueous extract obtained from *F. vesiculosus* and *C. brodiei* after 7 days of experiment were examined.

A stimulating effect of concentrations of 5 and 25 µL mL^{-1} of *F. vesiculosus* extract on the values of fluorescence parameters of cyanobacteria *Aphanizomenon* sp. were observed and in this conditions these parameters constituted 119% (*t*-test, $p < 0.01$) and 113% (*t*-test, $p < 0.05$), respectively, for F_v/F_m and 122% (*t*-test, $p < 0.001$) and 118% ($p < 0.001$), respectively, for ΦPSII, relative to the control culture (Fig. 4Aa–Ab). Moreover, a stimulatory effect of 25 and 50 µL mL^{-1} of *F. vesiculosus* extract on fluorescence parameters F_v/F_m and ΦPSII of tested cyanobacterium *Nostoc* sp. was observed. It was found that the values of F_v/F_m was 109% (*t*-test, $p < 0.01$) at 25 µL mL^{-1} and 109% (*t*-test, $p < 0.05$) at 50 µL mL^{-1}, relative to the control culture (Fig. 4Bb–Bc). Furthermore, in the same experiment conditions, the values of ΦPSII were 111% (*t*-test, $p < 0.01$) and

116% (*t*-test, $p < 0.001$), respectively, compared to control (Fig. 4Bb–Bc). On the other hand, an inhibitory effect of 50 μL mL^{-1} of *F. vesiculosus* extract on F_v/F_m was noted for cyanobacteria *Aphanizomenon* sp. which was 92% (*t*-test, $p < 0.01$) relative to the control (Fig. 4Ac). Similarly, an inhibitory effect of this brown alga extract at a concentration of 5 μL mL^{-1} on *Nostoc* sp. was observed. In this condition, the F_v/F_m constituted 92% (*t*-test, $p < 0.01$) relative to the control (Fig. 4Ba).

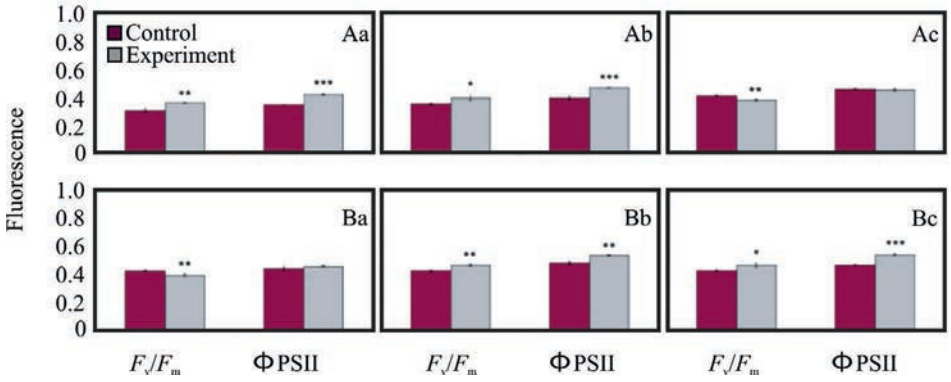

Fig. 4. The values of the fluorescence parameter F_v/F_m and ΦPSII for *Aphanizomenon* sp. (A) and *Nostoc* sp. (B) in control and cultures to which were added: 5 (a), 25 (b), and 50 (c) (μL mL^{-1}) of aqueous extract obtained from *Fucus vesiculosus* L. after 7 days of the experiment. The values shown are mean (n = 3, mean ± SD). * indicates statistically significant differences compared to control based on *t*-test at: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

It was found a stimulating effect of concentrations of 5 μL mL^{-1} of *C. brodiei* extract on the F_v/F_m and ΦPSII parameters of cyanobacteria *Aphanizomenon* sp. In these conditions these parameters constituted 133% (*t*-test, $p < 0.001$) and 130% (*t*-test, $p < 0.001$), respectively, relative to the control culture (Fig. 5Aa). A stimulatory effect of 5 and 25 μL mL^{-1} of *C. brodiei* extract on fluorescence parameter F_v/F_m of *Nostoc* sp. was also examined. It was found that the values of F_v/F_m was 147% (*t*-test, $p < 0.001$) and 106% (*t*-test, $p < 0.01$), respectively (Fig. 5Ba–Bb). Furthermore, a stimulating effect of concentrations of 5, 25, and 50 μL mL^{-1} of *C. brodiei* extract on the ΦPSII values of cyanobacteria *Nostoc* sp. was observed and in these conditions these parameters constituted 164% (*t*-test, $p < 0.001$), 121% (*t*-test, $p < 0.001$), and 107% (*t*-test, $p < 0.001$), respectively, relative to the control culture (Fig. 5Ba–Bc). On the other hand, an inhibitory effect of 25 and 50 μL mL^{-1} of *C. brodiei* extract on F_v/F_m was demonstrated for *Aphanizomenon* sp. which was 72% (*t*-test, $p < 0.001$) and 93% (*t*-test, $p < 0.01$), respectively, of the control (Fig. 5Ab–Ac). Furthermore, an inhibitory effect of the highest concentration of the *C. brodiei* extract (50 μL mL^{-1}) on the ΦPSII values of the cyanobacterium *Aphanizomenon* sp. was noted and constituted 88% ($p < 0.001$) of control (Fig. 5Ac).

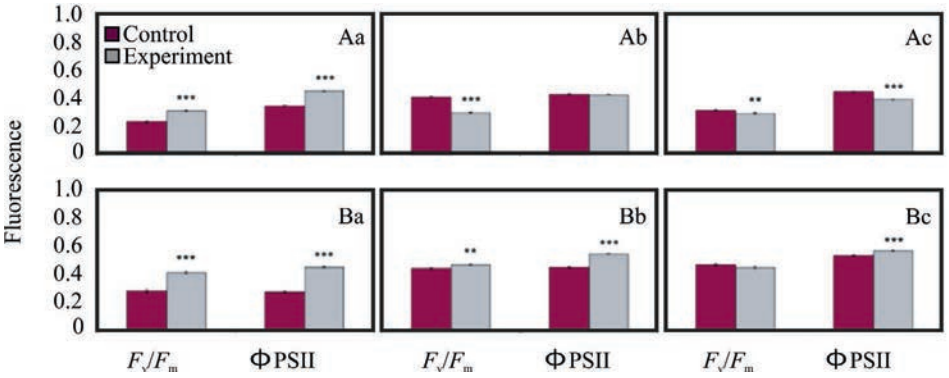

Fig. 5. The values of the fluorescence parameter F_v/F_m and ΦPSII for *Aphanizomenon* sp. (A) and *Nostoc* sp. (B) in control and cultures to which were added: 5 (a), 25 (b), and 50 (c) (μL mL^{-1}) of aqueous extract obtained from *Coccotylus brodiei* (Turner) Kütz. after 7 days of the experiment. The values shown are mean (n = 3, mean ± SD). * indicates statistically significant differences compared to control based on *t*-test at: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Discussion

Allelopathic activity of red and brown algae on cyanobacteria growth

In the present study, the allelopathic effect of Baltic red alga *Coccotylus brodiei* and brown alga *Fucus vesiculosus* extract on growth and chlorophyll fluorescence of two cyanobacteria *Aphanizomenon* sp. and *Nostoc* sp. was investigated. It was noted that aqueous extracts obtained from *F. vesiculosus* had no effect on the change in cell concentrations of the cyanobacteria *Aphanizomenon* sp. and *Nostoc* sp. Additionally, there was no significant effect of extract from *C. brodiei* on the cell abundance of cyanobacteria *Aphanizomenon* sp. Only a stimulating effect of each of the three tested concentrations (5, 25, and 50 μL mL^{-1}) of the aqueous extract of *C. brodiei* on the cell abundance of *Nostoc* sp. was observed. It is worth noting here that the slightest effect was observed when the allelopathic effect was tested at the lowest extract concentration (5 μL mL^{-1}), while the ‚most substantial effect was observed at the highest tested concentration of 50 μL mL^{-1}. It may be due to the fact that the extract obtained from the dry thallus of tested macroalgae contained certain mineral compounds that stimulated the growth of Baltic cyanobacteria.

It should be emphasized here that there are very few studies on the allelopathic activity of brown and red algae on associated cyanobacteria and microalgae species. Kakisawa et al. (1988) showed inhibition or no significant effect of the brown alga *Cladosiphon okamuranus* Tokida which depended on the target species (Cyanobacteria: *Microcyctis wesenbergii* (Komárek) Komárek ex Komárek, *Oscillatoria raciborskii* Woloszynska; Rhodophyta: *Cyanidium caldarium* (Tilden) Geitler; Bacillariophyta: *Aulacosira ambiqua* (Grunow) Sim., *Chaetoceros debilis* P.T. Cleve, *Coscinodiscus granii*

L.F. Gough, *Skeletonema costatum* (Greville) P.T. Cleve, *Tabellaria flocculosa* (Roth) Kütz.; Miozoa: *Gymnodinium nagasakiense* H. Takayama & M. Adachi, *G. sanguineum* K. Hirasaka, *Heterocapsa triquetra* (Ehrenb.) F. Stein, *Prorocentrum micans* Ehrenb.; Ochrophyta: *Chattonella antiqua* (Y. Hada) C. Ono, *C. marina* (Subrahmanyan) Y. Hara & M. Chihara, *Olisthodiscus luteus* N. Carter, *Heterosigma akashiwo* (Y. Hada) Y. Hada ex Y. Hara & M. Chihara; Haptophyta: *Cricosphaera roscoffensis* (P.A. Dangeard) Gayral & Fresnel; Cryptophyta: *Cryptomonas* sp.; Chlorophyta: *Hafniomonas reticulata* (Korshikov) Ettl & Moestrup, *Nephroselmis* sp., *Pterosperma cristatum* Schiller, *Plymnesium parvum* N. Carter, *Pyramimonas* sp., *Tetraselmis cordiformis* (H.J. Carter) F. Stein, *Tetraselmis chui* Butcher, *Chlamydomonas augustae* Skuja, *Chlamydomonas* sp., *Chlorella pyrenoidosa* H. Chick, *Chlorosarcinopsis* sp., *Chlorosarcinopsis delicata* Shin Watanabe, *Haematococcus lacustris* (Girod-Chantrans) Rostafinski, *Oltmannsiella* sp., *Scenedesmus quadricauda* (Turpin) Bréb. in Bréb. & Godey, *Volvox aureus* Ehrenb., *Closterium acerosum* Ehrenb. ex Ralfs, and also Euglenozoa: *Euglena gracilis* G.A. Klebs, *Eutreptia* sp.) (Guiry, Guiry, 2021).

On the other hand, Nagayama et al. (2003) investigated the effect of the extract of brown alga *Ecklonia kurome* Okamura on bloom-forming dinoflagellates *Karenia mikimotoi* (Miyake & Kominami ex Oda) Gert Hansen & Moestrup, *Cochlodinium polykrikoides* Margalef, and *Chattonella antiqua*. The authors showed a very high inhibition of dinoflagellate growth, morphological changes, and even complete cell death. In turn, Suzuki (1998) studied the inhibitory effect of extract obtained from red alga *Lithophyllum* sp. on dinoflagellate *Heterosigma akashiwo*. Wang et al. (2007) investigated the inhibitory effects of extract, filtrate, and live thallus of the brown alga *Sargassum thunbergii* (Mertens ex Roth) Kuntze and the red alga *Corallina pilulifera* Postels & Ruprecht on the growth of two dinoflagellates *Heterosigma akashiwo* and *Alexandrium tamarense* (Lebour) Balech. Live material from both macroalgae caused lysis of *H. akashiwo* cells. Growth of *A. tamarense* was inhibited, but cells were not lysed. The filtrate caused an overall decrease in both macroalgae, but only the filtrate from *Corallina* caused lysis of *H. akashiwo* cells. The extract caused the least effect on the cell concentration of the tested dinoflagellates. An exception was an experiment where the influence of *S. thunbergii* filtrate on *H. akashiwo* was tested where cells were lysed after the first day of culture. Later, Lu et al. (2011) demonstrated both inhibitory and stimulatory effects of the extract obtained from red alga *Gracilaria lemaneiformis* (Bory) Greville on the diatom *Skeletonema costatum*. To the best of the author's knowledge, there are no more papers confirming the allelopathic activity of brown and red algae on phytoplankton representatives. The results obtained in this work constitute an important contribution to the knowledge on the allelopathic activity of Baltic red and brown algae on certain bloom-forming species of filamentous cyanobacteria.

Effects of allelopathic compounds produced by Baltic macroalgae on photosynthesis performance

Analysis of chlorophyll a fluorescence parameters allows for the assessment of photosynthetic activity (Machado et al., 2015; Song et al., 2017). Fluorescence measurements are a useful tool in physiological studies and are a highly sensitive method of studying photosynthetic reactions in cyanobacteria (Campbell et al., 1998).

In this study, we investigated the effect of the allelopathic effect of macroalgal extracts on the maximum PSII quantum efficiency (F_v/F_m) and the effective quantum yield of PSII photochemistry (ΦPSII). It was found that *Fucus vesiculosus* and *Coccotylus brodiei* had the allelopathic effect on fluorescence parameters of tested cyanobacteria. The low and medium concentrations of aqueous extract (5 and 25 μL mL^{-1}) from *F. vesiculosus* stimulated the values of F_v/F_m and ΦPSII of cyanobacterium *Aphanizomenon* sp. compared to the control. The inhibitory effect of the highest concentration of aqueous extract (50 μL mL^{-1}) on the F_v/F_m parameter of *Aphanizomenon* sp. was demonstrated. Moreover, a stimulating effect of medium and high extracts concentrations of *F. vesiculosus* on cyanobacterium *Nostoc* sp. on the fluorescence parameters F_v/F_m and ΦPSII was observed. In addition, the inhibitory effect of this brown alga at the lowest extract concentration on F_v/F_m of *Nostoc* sp. was demonstrated. On the other hand, the stimulatory effect of the lowest extract concentration (5 μL mL^{-1}) obtained from *C. brodiei* on the fluorescence parameter F_v/F_m and ΦPSII of cyanobacterium *Aphanizomenon* sp. was noted. In addition, the inhibitory effect of 25 and 50 μL mL^{-1} extracts on fluorescence parameters of this cyanobacterium was demonstrated. It was also shown that all tested extract concentrations obtained from *C. brodiei* stimulated the ΦPSII parameter of *Nostoc* sp. In our study it has been demonstrated that brown alga *F. vesiculosus* and red alga *C. brodiei* can release some allelopathic substances which affect the fluorescence parameters of cyanobacteria *Nostoc* sp. and *Aphanizomenon* sp. Similarly, as in the case of cyanobacterial growth, the stimulation of the fluorescence parameters may be caused by additional mineral compounds contained in the macroalgal extracts. Moreover, the high values of the fluorescence parameters indicate a relatively high potential efficiency of photosystem II in the studied cyanobacteria. The low level of these parameters indicates certain disturbances in the photosynthesis process.

Three years earlier, Budzałek et al. (2018) demonstrated that the dry powder of *Ulva intestinalis* L. contains water-soluble allelochemical(s) is capable of restricting the fluorescence parameter F_v/F_m of cyanobacterium *Nostoc* sp. The authors noted that the highest decrease in F_v/F_m for *Nostoc* sp. was observed after the first, third and seventh day of the experiment, after the addition of 100 μL mL^{-1} extracts obtained from *U. inestinalis* with a magnitude of 69%, 59%, and 49% respectively, compared to the control treatment. To the best of the author's knowledge, no more works confirm the allelopathic effects of macroalgal extracts on the fluorescence parameter F_v/F_m of cyanobacteria. Moreover,

this work is the first to indicate the allelopathic effect of macroalgal aqueous extracts on the effective quantum yield of PSII photochemistry (ΦPSII) of Baltic cyanobacteria. Therefore, these studies indicate the need to study the photosynthesis performance in target organisms that are exposed to contact with Baltic macroalgae in more detail.

The characterisation of the allelopathic compounds is a time-consuming task. Some studies have described novel secondary metabolites, produced by marine red (Rhodophyta) and brown (Ochrophyta) macroalgae, which have significant biological activity on target organisms (El Gamal, 2010) however, to the best of the authors knowledge, there is no information about the allelopathic compounds produced by *F. vesiculosus* and *C. brodiei*. Only Kristinsson and Jónsdóttir (2015) described that *F. vesiculosus* showed antioxidant activity however, the chemical structure of this compound has not been studied. Thus, demonstrating the composition of the these macroalgal allelochemicals should become a priority for future work.

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Conflict of interest

The authors declare no conflict of interest related to this article.

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Abstract

In aquatic ecosystems, allelopathic activity depends on the production and secretion of allelopathic compounds and their effective dispersal in the environment. In addition, macroalgae have been found to produce active metabolites that affect other organisms that compete with them for nutrients. However, the allelopathic activity of Baltic red and brown macroalgae on filamentous cyanobacteria is still insufficiently understood. Therefore, the main objective of this study was to demonstrate and compare the allelopathic effects of macroalgae *Fucus vesiculosus* L. and *Coccotylus brodiei* (Turner) Kütz. on the growth and photosynthetic activity of two Baltic cyanobacteria *Aphanizomenon* sp. and *Nostoc* sp. It was found a stimulating effect of different concentrations (5, 25, and 50 µL mL–1) of the aqueous extract obtained from *C. brodiei* on the number of cells of *Nostoc* sp. which constituted 108%, 140%, and 147%, respectively, relative to the control treatment. On the other hand, extracts obtained from *F. vesiculosus* had no statistically significant effect on the number of cells of the cyanobacteria Aphanizomenon sp. and *Nostoc* sp. Moreover, the *C. brodiei* extracts had no significant impact on the growth of *Aphanizomenon* sp. Furthermore, Baltic macroalgae *F. vesiculosus* and *C. brodiei* was able to exert allelopathic effects on photosynthesis performance of *Nostoc* sp. and *Aphanizomenon* sp. and compounds produced by them had inhibitory, stimulatory, or no significant effect on the maximum PSII quantum efficiency (Fv/Fm) and the effective quantum yield of PSII photochemistry (ΦPSII). The results obtained in this work constitute an important contribution to the knowledge on the allelopathic activity of Baltic red and brown algae on certain bloom-forming species of filamentous cyanobacteria.

Key words: allelopathy, aqueous extract, brown algae, cyanobacteria, fluorescence, growth, macroalgae, red algae

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Oddziaływanie allelopatyczne *Fucus vesiculosus* (brunatnica) i *Coccotylus brodiei* (krasnorost) na wzrost oraz aktywność fotosyntetyczną bałtyckich sinic

Streszczenie

Aktywność allelopatyczna w ekosystemach wodnych zależy od produkcji i uwalniania związków allelopatycznych oraz ich skutecznego rozprzestrzeniania się w środowisku. Stwierdzono, że makroglony wytwarzają aktywne metabolity, które wpływają na inne organizmy, konkurując z nimi o światło i składniki odżywcze. Jednak aktywność allelopatyczna bałtyckich krasnorostów i brunatnic na nitkowate sinice jest nadal niedostatecznie poznana. Dlatego głównym celem niniejszej pracy było wykazanie i porównanie aktywności allelopatycznej makroglonów *Fucus vesiculosus* L. (brunatnica) i *Coccotylus brodiei* (Turner) Kütz. (krasnorost) na wzrost i aktywność fotosyntetyczną dwóch bałtyckich sinic *Aphanizomenon* sp. i *Nostoc* sp. W pracy stwierdzono stymulujący wpływ różnych stężeń (5, 25 i 50 µL mL–1) wodnego ekstraktu otrzymanego z *C. brodiei* na liczebność komórek *Nostoc* sp., które wynosiły odpowiednio: 108%, 140% i 147%, w stosunku do grupy kontrolnej. Z drugiej strony ekstrakty uzyskane z *F. vesiculosus* nie miały istotnego statystycznie wpływu na liczebność komórek sinic *Aphanizomenon* sp. i *Nostoc* sp. Wykazano także, że ekstrakty z *C. brodiei* nie miały istotnego wpływu na wzrost *Aphanizomenon* sp. Ponadto bałtyckie makroglony *F. vesiculosus* i *C. brodiei* wpływały allelopatycznie na aktywność fotosyntetyczną u *Nostoc* sp. i *Aphanizomenon* sp., a wydzielane przez nie związki wykazywały hamujący, stymulujący lub brak wpływu na maksymalną wydajność kwantową drugiego fotosystemu (PSII) w ciemności (Fv/Fm) oraz na rzeczywistą wydajność kwantową PSII w świetle (ΦPSII). Wyniki uzyskane w niniejszej pracy stanowią ważny wkład w stan wiedzy na temat aktywności allelopatycznej bałtyckich krasnorostów i brunatnic na wybrane gatunki nitkowatych sinic, zdolnych do tworzenia masowych zakwitów.

Słowa kluczowe: allelopatia, brunatnice, ekstrakt wodny, fluorescencja, krasnorosty, makroglony, sinice, wzrost

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