Effect of Ultraviolet-C Radiation on the Morphology of Cyanobacteria *Nostoc* sp.
LBALBR-2 Isolated from Supply Reservoir (Belém, Pará, Brazil)

Efeito da Radiação Ultravioleta-C na Morfologia da Cianobactéria *Nostoc* sp. LBALBR-2 Isolada do Reservatório de Abastecimento (Belém, Pará, Brasil)

Efecto de la Radiación Ultravioleta-C sobre la Morfología de la Cianobacteria *Nostoc* sp. LBALBR-2 Aislado del Embalse de Abastecimiento (Belém, Pará, Brasil)

Received: 22/08/2022 | Revisado: 09/09/2022 | Aceptado: 12/09/2022 | Publicado: 20/09/2022

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Abstract
Cyanobacteria are photosynthetic prokaryotic organisms that in aquatic environments can compose the phytoplankton and phytobenthos, being important in the primary production of these ecosystems. The objective of this work was to identify the main morphological variations of the cells, filaments and thallus of the cyanobacterium *Nostoc* sp. LBALBR-2 submitted to ultraviolet radiation (UV-C) in microcosm systems. The cyanobacteria *Nostoc* sp. was subjected to four treatments: 1- control treatment in nutrient medium; 2- treatment in nutrient medium with exposure to UV-C radiation; 3- control treatment in medium without nutrients and 4- treatment in medium without nutrients with exposure to UV-C radiation. Optical density and chlorophyll-a analyses were performed to determine the growth of *Nostoc* populations and microscopic analyses to characterize the morphological development of the species. Lack of nutrients generated short trichomes with terminal heterocytes, scattered solitary akinetes and appearance of hormogonia. On nutrient medium the trichomes of *Nostoc* sp. showed predominantly the vegetative serial form. Cultures exposed to UV-C produced anomalous cells, thick mucilage, fragmented trichomes and hormogonia. It is concluded that *Nostoc* sp. LBALBR-2 grew well under eutrophic conditions and although it showed cell deformation it was resistant to UV-C radiation.

Keywords: Cyanobacteria; Bloom; Microcosm.

Resumo
As cianobactérias são organismos procarióticos fotossintetizantes que no ambiente aquático podem compor o fitoplâncton e os fitobentos apresentando importância na produção primária destes ecossistemas. O objetivo deste trabalho foi identificar as principais variações morfológicas das células, dos filamentos e talo da cianobactéria *Nostoc* sp. LBALBR-2 submetida à radiação ultravioleta (UV-C) em sistemas de microcosmos. A cianobactéria *Nostoc* sp. foi submetida a quatro tratamentos: 1- tratamento controle em meio nutritivo; 2- tratamento em meio nutritivo com exposição à radiação UV-C; 3- tratamento controle em meio sem nutrientes e 4- tratamento em meio sem nutrientes...
com exposição à radiação UV-C. Foram realizadas análises de densidade óptica e clorofila-\textit{a} para determinar o crescimento das populações de \textit{Nostoc} e análises microscópicas para caracterizar o desenvolvimento morfológico da espécie. A falta de nutrientes gerou tricomas curtos com heterócitos terminais, acinetos solitários dispersos e aparecimento de hormogônios. Em meio nutritivo os tricomas de \textit{Nostoc} apresentaram predominantemente a forma seriada vegetativa. Culturas expostas a UV-C produziram células anómalas, mucilagem espessa, tricomas fragmentados e hormogônios. Conclui-se que \textit{Nostoc} sp. LBALBR-2 se desenvolveu bem em condições de eutrofização e apesar de apresentar deformações celulares mostrou-se resistente às radiações UV-C.

**Palavras-chave:** Cianobactéria; Floração; Microcosmo.

**Resumen**

Las cianobacterias son organismos procarióticos fotosintéticos que en el medio acuático pueden componer fitoplanción y fitobentos, presentando importancia en la producción primaria de estos ecosistemas. El objetivo de este trabajo fue identificar las principales variaciones morfológicas de células, filamentos y talos de la cianobacteria \textit{Nostoc} sp. LBALBR-2 sometido a radiación ultravioleta (UV-C) en sistemas de microcosmos. La cianobacteria \textit{Nostoc} sp. se sometió a cuatro tratamientos: 1- tratamiento testigo en medio nutritivo; 2- tratamiento en medio nutritivo con exposición a radiación UV-C; 3- tratamiento control en medio sin nutrientes y 4- tratamiento en medio sin nutrientes con exposición a radiación UV-C. Se realizaron análisis de densidad óptica y clorofila-\textit{a} para determinar el crecimiento de las poblaciones de \textit{Nostoc} y anályses microscópicos para caracterizar el desarrollo morfológico de la especie. La falta de nutrientes generó tricomas cortos con heterócitos terminales, acinetos solitarios dispersas y aparición de hormonas. En medio nutritivo, los tricomas de \textit{Nostoc} presentaron predominantemente la forma seriada vegetativa. Los cultivos expuestos a UV-C produjeron células anómalas, mucilago espeso, tricomas fragmentados y hormonas. Se concluye que \textit{Nostoc} sp. LBALBR-2 se desarrolló bien en condiciones de eutrofización y, a pesar de mostrar deformaciones celulares, fue resistente a la radiación UV-C.

**Palabras clave:** Cianobacterias; Floração; Microcosmo.

1. **Introduction**

Cyanobacteria are oxygenic photosynthetic Gram negative prokaryotes that in the aquatic environment can compose the phytoplankton and phyto - benthos, being important in the primary production of this ecosystem (Komárek, 2013; Silva et al., 2020).

\textit{Nostocaceae C. A. Agardh (ex Kirchner)} constitute a family of filamentous, heterocystic, isopolar cyanobacteria with unbranched uniseriate trichomes, or false branches, which inhabit diverse environments (Komárek, 2013; Komárek et al., 2014). These cyanobacteria present importance to the global scientific Community because they have a significant number of strains producing amino acids, fatty acids, polysaccharides, flavonoids, vitamins, and many types of minerals that have antitumor, antiviral, antibacterial, and anti-inflammatory effects (Gheda & Ismail, 2020; Khalifa et al., 2021; Deyab et al., 2020; Mazur-Marzec et al., 2021).

In addition, \textit{Nostocaceae} fix atmospheric nitrogen and contribute to the fertility of agricultural soils worldwide, and some species behave as harmful microorganisms in aquatic ecosystems due to toxic bloom events (Huisman et al. 2018).

\textit{Nostoc} Vaucher ex Bornet et Flahault is a genus of \textit{Nostocaceae} well distributed worldwide and has more than 300 recognized species, however, the genus is heterogeneous and certainly divided into several generic clusters and most species need revision at the morphological and molecular level (Komárek, 2013). In Brazil, 12 species are recognized (Werner et al., 2015) and only one species is cited for the state of Pará, Brazilian Amazon (Costa et al., 2014).

In recent decades, increasing research on cyanobacteria in simulated environments (mesocosm and microcosm) is observed in an attempt to evaluate their behavior in relation to different environmental factors, such as exposure to heavy metals (Mota et al., 2015), nitrogen and phosphorus concentrations (Hughes & Marion, 2021), stimulation to different conditions of temperatures, light, photoperiod (Huisman et al. 2018) and ultraviolet-UV light (Rastogi et al., 2014).

Regarding UV, studies address the behavior of cyanobacteria in the face of light as a stressor of biochemical processes (Jantaro et al., 2011). Cyanobacterial cells react and produce some photoprotective and antioxidant compounds such as
mycosporine-like amino acids- MAAs that have been researched for application in sunscreens and anti-aging products (Soule et al., 2016; Latifi et al., 2009; Geraldes, 2019).

On the other hand, there are studies on the behavior, morphogenesis and toxin production by cyanobacteria when exposed to UV projecting a future climate change scenario due to the sharp increase in solar ultraviolet radiation (UVR) caused by the continuous depletion of the ozone layer, fueling serious concerns about the ecological consequences for all living organisms, including cyanobacteria (Rastogi et al., 2014). UV-C used for germicidal purposes is artificial and is an alternative to prevent cyanobacterial blooms in lakes and reservoirs (Tao et al., 2010; Skai et al., 2009; Usepa, 2006; Jiang et al., 2020), as shortwave UV-C radiation has shown effect on cyanobacterial cells by inhibiting their growth and reducing cyanotoxin concentration through repression of photosynthetic activity and DNA damage (Ou et al., 2012), but no effect on green algae (Tao et al., 2010).

Few studies show the changes that occur in the morphology of cyanobacteria under the effects of UV-C radiation, especially cyanobacteria from Amazonian environments. The objective of this study was to identify the main morphological variations of the cells, filaments and thallus of the cyanobacteria Nostoc sp. LBALBR-2 submitted to ultraviolet radiation (UV-C) in a simulated environmental system.

2. Methodology

2.1 Culture

The cyanobacteria Nostoc sp. LBALBR-2 was isolated from roots of the decomposed aquatic macrophyte Eichhornia crassipes Mart. (Solms) on the banks of Bolonha reservoir (1°25'14.6"S and -48°25'58.4"W), which belongs to the water supply system of Belém Metropolitan Region (Pará, Brazil). The species was isolated in May/2018 and is cultured in BG-11 medium (Rippka et al., 1979) in triplicate in non-continuous culture with repotting every 15 days. The incubation temperature is 30°C ± 5°, luminosity of approximately 20-60 µmol.photon.m⁻².s⁻¹ and photoperiod of 12 h light.

2.2 Experimental Design

Four experimental treatments were used in microcosm to verify their effects on the cyanobacteria Nostoc sp. LBALBR-2 (Table 1). Experiments 1 and 2 contain nutrients (BG-11 medium) and experiments 3 and 4 contain ultrapure water type I.

Table 1. Experimental design submitted to Nostoc sp. LBALBR-2, cyanobacteria isolated from the roots of macrophytes from Bolonha reservoir (Belém, Pará, Brazil).

| Experiment                     | Temperature (°C) | Humidity (%) | Light (µmol.photon.m⁻².s⁻¹) | Photoperiod (h) | UV-C (h. day⁻¹) | Medium   |
|--------------------------------|-----------------|--------------|-----------------------------|----------------|----------------|----------|
| Experiment 1 (nutrient control)| 20 ± 5          | 60 ± 2       | 40 - 60                     | 12             | Absent         | BG-11    |
| Experiment 2 (nutrient UV-C)   | 20 ± 5          | 60 ± 2       | 40 - 60                     | 12             | 1 a 3          | BG-11    |
| Experiment 3 (water control)   | 20 ± 5          | 60 ± 2       | 40 - 60                     | 12             | Absent         | Absent   |
| Experiment 4 (water UV-C)      | 20 ± 5          | 60 ± 2       | 40 - 60                     | 12             | 1 a 3          | Absent   |

Source: Authors.

For each experiment, samples were taken daily for microscopic analysis, aliquots for chlorophyll-α and optical density analysis until the fourth day, then the withdrawals occurred at 3-day intervals until day 22nd. All treatments took place in a
climatic chamber for plant growth (Humidity, Panasonic). The radiation source was a 30W UV-C germicidal tubular lamp, Redy.

2.3 Morphological and Morphometric Characterization

The species was observed and analyzed using an inverted microscope (Axiovert A1, Zeiss Germany) at each time point of the experiments. Morphometric measurements were recorded with a camera (Axio Cam MRc, software Axio Vision, Zeiss Germany) with measurements in micrometers (µm), measuring cell diameters and lengths (width and height), length of filaments and the presence/absence of specialized cells (akinetes and heterocytes), morphological changes, presence of mucilage, among others. Staining was established according to the Faber Castell palette (1761).

2.4 Chlorophyll - a and Optical Density

Chlorophyll-a analysis was performed according to the 10200 H method of SWWM (APHA, 2017) using 90 % acetone in a HANNA 2000 spectrophotometer. Optical density were analyzed at wavelengths 680, 650 and 750 nm (Śliwińska-Wilczewka et al., 2016; Ortiz-Moreno et al., 2020).

2.5 Data Analysis

The cellular values, chlorophyll-a and optical density were submitted to parametric ANOVA one way (F) and non-parametric Kruskal-Wallis (H) analysis of variance to verify the differences between the times and types of experiments, considering as significant variation \( p<0.05 \) and the post hoc tests of Tukey and Dunn, parametric and non-parametric, respectively, both performed in Past 4.03 software (Hammer et al., 2001).

3. Results

3.1 Growth

We suggest that all the wavelengths analyzed express the growth of the species Nostoc sp. There was a significant difference between the times (F= 168.2; df= 9; \( p= 0.0005 \)), where the curves start to differ from day 4 (T4) (Figure 1).

For the experiments in nutrient medium (experiments 1 and 2) the exponential phase started on day 10th (T6), suggesting a decline from day 19th (T9) (Figures 1A and 1B). The species showed slower growth in the absence of nutrients (experiments 3 and 4), in which only the exponential phase was evident (T5 to T10), and in T6 outliers were observed in both experiments (Figures 1C and 1D).
Figure 1. Growth curve of *Nostoc* sp. LBALBR-2 at different optical densities (650 nm, 680 nm and 750 nm) and in the different treatments: A- experiment 1, nutrient control; B- experiment 2, nutrient UV-C; C- experiment 3, water control; D- experiment 4, water UV-C.

The experiments were different (F= 6.0; df= 3; p= 0.0004), with the lack of nutrients being a limiting factor for the growth of the species, as experiments 3 and 4 had the lowest growth than experiments grown on nutrient medium (experiments 1 and 2), regardless of exposure to UV-C radiation (Figure 2).
Figure 2. Growth variation of *Nostoc* LBALBR-2 at different optical densities (650 nm, 680 nm, and 750 nm) and experimental treatments (box plot showing: maximum, third quartile, median, first quartile and minimum).

There was no difference in chlorophyll-*a* between times (H= 3.7; p= 0.89). However, experiments 1 and 2 showed a slight increase in chlorophyll-*a* concentrations from day 13\textsuperscript{th} (T7) and day 7\textsuperscript{th} (T5), respectively (Figure 3).

Figure 3. Growth curve of *Nostoc* sp. LBALBR-2 from chlorophyll-*a* concentrations at different times and experimental treatments.
The chlorophyll-a concentrations also showed significant differences among experiments (F= 4.7; df= 3; p= 0.004), being experiments 3 (58.0 ± 40.0 µg.L⁻¹) and 4 (45.0 ± 46.0 µg.L⁻¹) with chlorophyll-a lower than the nutrient medium, which had mean concentrations of 198.5 µg.L⁻¹ and 187.0 µg.L⁻¹, in experiments 1 and 2, respectively (Figure 4).

**Figure 4.** Variation of chlorophyll-a concentration of *Nostoc* sp. LBALBR-2 in the different experimental treatments (box plot showing: maximum, third quartile, median, first quartile and minimum).

| Experiment | Chlorophyll-a (µg.L⁻¹) |
|------------|-------------------------|
| Experiment 1 | 58.0 ± 40.0           |
| Experiment 2 | 45.0 ± 46.0            |
| Experiment 3 | 198.5                  |
| Experiment 4 | 187.0                  |

Source: Authors (2022).

### 3.2 Morphology: Filament, Trichomes and Cells

There was no difference in average diameter cell *Nostoc* (F= 0.24; df= 3.0; p= 0.8) and length (F= 0.5; df= 3.0; p=0.7) between experiments, but diameter (F= 10.7; df= 9; p=0.002) and cell length (F= 5.0; df= 9; p=0.005) increased significantly over time.

The average cell diameter ranged from 1.6 µm to 3.3 µm and the average cell length ranged from 3.3 to 3.8 µm between day 1 and day 22, respectively, for all experiments (Figure 5).
**Figure 5.** Temporal variation of cell morphometry of *Nostoc* sp. LBALBR-2: A- cell length (height) and B- cell diameter (width).

![Temporal variation of cell morphometry](image)

3.3 Thallus Morphology

The thallus of *Nostoc* LBALBR-2 presented as a thick, foliaceous, dark green mass (color palette 059) in the nutrient cultures (experiments 1 and 2) (Figure 6A). The fouling started with a thin film on the microcosm wall and a thicker layer on the surface with the appearance of gas, usually after one week of colonization (Figures 6B and 6C).

On the other hand, cultures without nutrients (experiments 3 and 4) presented a thin, lemon yellow mass (color palette 004) (Figures 6D and 6E). It was found that after 30 days of incubation the stalk acquired a gelatinous consistency, especially in samples without nutrients (Figure 6F).
For all experiments, starting on day 4th of cultivation the thallus changed from amorphous colonies, with vegetative cells overlapping in irregular layers, to multiple trichomes with cells arranged in uniseriate sequences (Figures 6G to 6I).

In cultures with nutrients (experiments 1 and 2) the trichomes were longer, on average 300 µm long (Figures 6J to 6L). In cultures without nutrients (experiments 3 and 4), the final cells had terminal heterocytes and the trichomes were short, on average 105 µm (Figure 6M), and in the final times of the experiment, akinetes appeared, measuring 2.5-3.0 µm in height by 1.6-2.0 µm in diameter (Figure 6N).

In cultures exposed to UV radiation (experiments 2 and 4), the filaments were surrounded by a dense mucilaginous sheath that was dark green in nutrient-depleted cultures and yellowish in nutrient-free cultures (Figures 6O and 6P).

Also, after 15 days of UV exposure, fragments and hormogonia appeared and increased over time. At the final times, the trichomes showed anomalous cells as a result of UV exposure (Figures 7A to 7E).
Figure 6 - Photomicrograph of *Nostoc* sp. LBALBR-2: A- Macroscopic appearance of the thallus; B, C, D and E- growth and colonization of the thallus evidencing the fouling after seven days of inoculation, respectively, for the experiments nutrient control, nutrient UV-C, water control, water UV-C; F- macroscopic appearance of the water UV-C strain after 30 days of colonization; G and H- young filaments with overlapping vegetative cells; I- young filaments in cultures exposed to UV-C; J- mucilaginous mass involving the filament (arrow); K- detail of filament visualized in epifluorescence; L- mucilaginous sheath evidenced by Nanquim ink pigmentation; M- detail of trichomes showing terminal heterocytes (arrows); N- scattered akinetes (arrows) in culture without nutrients; O- production of mucilaginous material in colonies under UV-C radiation exposure conditions; P- mucilage interferes in epifluorescence.

Source: Authors (2022).
Figure 7 - Photomicrograph of *Nostoc* sp. LBALBR-2: A and B- hormogonia in colonies grown without nutrients and exposed to UV-C; C to E- anomalous cells in trichomes exposed to UV-C.

Source: Authors (2022).

4. Discussion

The absence of nutrients and UV exposure were stressors to the *Nostoc* sp. LBALBR-2 population. According to Meeks et al. (2002), *Nostoc* cyanobacterial species mature into four forms, which are determined by environmental cues.

Multilayered vegetative cells, trichomes with vegetative cells, trichomes with akinetes and heterocytes and the hormogonia are the main differentiations observed in *Nostoc* (Silva et al., 2020). Thus, the population of *Nostoc* sp. in the present study developed better in nutrient crops generating longer trichomes. For the vegetative cycle is maintained when the amount of nutrients is sufficient for the growth of the species (Silva et al., 1989).

On the other hand, lack of nutrients generated short trichomes with terminal heterocytes and scattered solitary akinetes. On this, Dextro et al. (2018) observed that the absence of nutrients, especially nitrogen, induces heterocyte formation and low light intensity induces akinetes formation in *Nostoc* strains.

Akinetes are generally recognized as resistance cells, with thick walls, that accumulate protein reserves in the form of cyanophycin granules. Akinetes are produced when environmental conditions are unfavorable (Calijuri et al., 2006; Mehnert et al., 2014; Wood et al., 2021), with temperature being one of the main factors responsible for the formation of akinetes, as some cyanobacteria initiate the production of akinetes at temperatures between 20°C and 25°C, such as *Aphanizomenon ovalisporum* (Cirés et al, 2013), and the absence of this cell occurs at temperatures below 21°C, as in the cyanobacterium *Cylindrospermopsis raciborskii* (Bittencourt-Oliveira et al., 2012). However, other environmental factors should influence the formation of these cells including carbon depletion, phosphorus limitation and symbiotic interactions (Singh et al.; 2011; Allaf &Peerhossaini, 2022).
According to Legrand et al. (2016) akinetes are formed under various abiotic stress conditions, depending on the species and also the sampling season. Thus, the resistance of akinetes and their ability to germinate seem to follow a species-specific process and are so important for the maintenance of the species that they also carry the genes for toxin production.

Perez et al. (2016) found that the trigger for differentiation of akinetes of the planktonic species Anabaena variabilis is low luminosity and of the terrestrial or symbiotic species Nostoc punctiforme is lack of phosphate. These authors suggest that at the time of akinetes differentiation there is a decrease in photosynthesis and respiration in both species, and this remains low in the mature akinetes, this may indicate a reduction in growth of Nostoc sp. LBALBR-2, from the present study, in the absence of nutrients, as many dispersed acini were formed.

The occurrence and quantity of heterocytes in cyanobacterial populations depend on different environmental factors, such as aerobic fixation of atmospheric nitrogen (N₂), concentration and lack of nitrate, organic components, temperatures, X-rays, irradiation, etc. Nitrogen metabolism and environmental nitrogen concentration are considered the crucial factors in their development (Rippka et al., 1979; Komarek, 2013), thus their highest abundance was in the trichomes grown in nutrient-free medium.

We suggest that hormogonia arose in response to lack of nutrients and UV exposure, although there are few studies confirming UV stress on hormogonia formation. UV is known to cause trichome fragmentation in Nostoc sp. (Singh et al., 2011). Hormogonia is a process of dispersal, phototaxis, reproduction and establishment of nitrogen-fixing symbioses and constitutes part of the life cycle of filamentous cyanobacteria, especially in Nostoc.

According to Zuniga et al. (2020) light quality and quantity, nutrient concentrations, and autogenic repressors are factors that induce hormogonia formation, which according to Gonzales et al. (2019) occurs through a regulatory network of sigmas genes that works in a cascade, coupled with specific genes that induce changes in cell architecture.

Regarding the stresses promoted by UV-C, the most significant were the production of a thick mucilaginous sheath around the Nostoc filaments and anomalous cells, which appeared at the end of UV exposure.

Studies have shown that Nostoc sp. creates enzymatic and non-enzymatic defense mechanisms to counteract the damaging effects of UV radiation, such as the production of antioxidant enzymes and mycosporin-like amino acids capable of performing UV screening, yet it dies if continuously exposed to this radiation (Richa & Sinha, 2015) or recovers when the radiation source is ceased (Phukan & Syiem, 2019). Thus, we suggest that the mucilaginous sheath that appeared on Nostoc in the present study is the production of these compounds in response to UV-C exposure.

Phukan & Syiem (2019) evaluated the oxidant and antioxidant homeostasis responses of the cyanobacteria Nostoc muscorum exposed to UV radiation and evidenced a complex defense organization developed by this species, which after being subjected to doses of UV-C radiation exhibited ultrastructural cell damage, produced reactive oxygen species (ROS) and consequently significantly induced enzymatic and non-enzymatic antioxidant production.

In the present study, we show the morphological alterations of UV-C exposure that we suppose are consequences of the biochemical and ultrastructural alterations suffered by the exposed cells. It is worth noting that not all cells showed malformations, due to the organization of the Nostoc tallus that takes place by the superposition of cells, allowing some cell layers to be more exposed than others which was also observed by Phukan & Syiem (2019).

The Amazon microbiota is poorly known when compared to its estimated high diversity. The behavior and development of the species can be studied from models made in Nostoc cultures, and their potential in biopharmaceutical production is important in contemporary scientific research. Thus, we suggest that future studies should better highlight the sequences of events identified in the present study, especially at the intracellular and biochemical level to potentiate their use as a model of cyanobacteria development.
Furthermore, the study contributes to strengthening the knowledge about the defense mechanisms of cyanobacteria and also to improving the processes of reducing blooms using UV-C radiation.

5. Conclusion

The effect of the radiation on the species occurred in the initial development of the thallus, the color of the colony, the shape of the cells and the length of the filaments. The nutrient cultures allowed the cyanobacteria population to develop further and the cells did not change in diameter and length, but UV-C exposure caused anomalous cells, the appearance of a thick mucilage and numerous fragmented trichomes and hormogonia, which we suggest are adaptive strategies to UV-C light stress and especially the lack of nutrients.

References

Allaf, M. M. & Peerhossaini, H. (2022). Cyanobacteria: Model Microorganisms and Beyond. Microorganisms. 10, 696. 2022 Mar 24,10(4):696.

American Public Health Association. (APHA), American WWAAWE, Federation (WEF) (2017) Standard methods for the examination of water and wastewater. 23th ed. Washington, DC: American Public Health Association.

Bittencourt-Oliveira, M., Piccin-Santos, V., Moura, A. N., Aragão-Tavares, N. K. C. & Cordeiro-Araújo, M. K. (2014). Cyanobacteria, microcystins and cylindrospermopsin in public drinking supply reservoirs of Brazil. Anais da Academia Brasileira de Ciências, 86(1), 297-310.

Calijuri, M. C., Alves, M. S. A. & Santos, A. C. A. (2006). Cianobactérias e cianotoxinas em águas continentais. São Carlos: RiMa. 108 p

Cirés, S., Wörmer, L., Agha, R. & Quesada, A. (2013). Overwintering populations of Anabaena, Aphanizomenon and Microcystis as potential inocula for summer blooms. Journal of Plankton Research, 35 (6), p. 1254–1266.

Costa, S. D., Martins-da-Silva, R. C. V., Bicudo, C. E. M., Barros, K. D. N. & Oliveira, M. E. C. (2014). Algas e Cianobacterias Continentais no Estado do Pará, Brasil. Belém, PA: Embrapa Amazônia Oriental, 2014. 351 p.

Dextror, R. B., Moutinho, F. H. M. & Nordi, C. S. F. (2018). Growth and special structures production of Nostoc paludosum (Nostocaceae, Cyanobacteria) under nutrient starvation and different light intensities. Revista Ambiente & Água, 13(6), e2191.

Deyab, M., Mofeed, J., El-Bilawy, E. & Ward, F. (2020). Antiviral activity of five filamentous cyanobacteria against coxsackievirus B3 and rotavirus. Arch Microbiol. 2020 Mar,202(2):213-223. doi: 10.1007/s00203-019-01734-9.

Gerald, V., Jacinavicius, F. R., Genuário, D. B. & Pinto, E. (2020). Identification and distribution of mycosporine-like amino acids in Brazilian cyanobacteria using ultrahigh-performance liquid chromatography with diode array detection coupled to quadrupole time-of-flight mass spectrometry. Rapid Commun Mass Spectrom, 34 (S3), e8634.

Gheda, S. F. & Ismail, G. A. (2020). Natural products from some soil cyanobacterial extracts with potent antimicrobial, antioxidant and cytotoxic activities. Anais da Academia Brasileira de Ciência. 92(2), e20190934.

Gonzalez, A., Riley, K. W., Harwood, T. V., Zuniga, E. G. & Risser, D. D. (2019). A Tripartite, hierarchical sigma factor cascade promotes hormogonium development in the filamentous cyanobacterium Nostoc punctiforme. mSphere. May 1,4(3):e00231-19. doi: 10.1128/mSphere.00231-19.

Hammer, Ø., Harper, D. A. T. & Ryan, P. D. (2001). Past: Paleontological statistics software package for education and data analysis. Palaeontologia Electronica, 4(1), 1-9.

Harwood, T. V. & Risser, D. D. (2021). The primary transcriptome of hormogonia from a filamentous cyanobacterium defined by cappable-seq. Microbiology (Reading), 167(11), 167:00111

Hughes, S. E. & Marion, J. W. (2021). Cyanobacteria Growth in Nitrogen- & Phosphorus-Spiked Water from a Hypereutrophic Reservoir in Kentucky, USA. Journal of Environmental Protection, 12, 75-89.

Huisman, J., Codde, G. A., Paerl, H. W., Ibelings, B. W., Verspunen, J. M. H. & Visser, P. M. (2018). Cyanobacterial blooms. Nature Reviews Microbiology, 16(8), 471-483.

Jantaro, S., Pothipongsa, A., Khanthasuwon, S. & Incharoensakdi, A. (2011). Short-Term UV-B and UV-C Radiations Preferentially Decrease Spermidine Contents and Arginine Decarboxylase Transcript Levels of Synechocystis sp. PCC 6803. Current Microbiology. 62:420–426.

Jiang, Y., Liu, Y. & Zhang, J. (2020). Antibiotic contaminants reduced the treatment efficiency of UV-C on Microcystis aeruginosa through hormesis. Environmental Pollution, 261, 114193.

Jodlowska, S. & Latala, A. (2013). Combined effects of light and temperature on growth, photosynthesis, and pigment content in the mat-forming cyanobacterium Geitlerinema amphibium. Photosynthetica, 51, 202-214.
Khalifa, S. A. M., Shedid, E. S., Saied, E. M., Jassbi, A. R., Jamebozghi, F. H., Rateb, M. E., Du, M., Abdel-Daim, M. M., Kai, G. Y., Al-Hammady, M. A. M., Xiao, J., Guo, Z. & El-Seedi, H. R. (2021). Cyanobacteria - From the Oceans to the Potential Biotechnological and Biomedical Applications. Marine Drugs, 19, 241.

Komárek J. (2013). Cyano-prokaryota. 3. Heterococcus generas. – In: Büdèl, B., Gärtner, G., Krienitz, L. & Schagerl, M. (eds), Süßwasserflora von Mitteleuropa/Freshwater flora of Central Europe, p. 1130, Springer Spectrum Berlin, Heidelberg.

Komárek, J., Kaštovský, J., Mareš, J. & Johansen, J. R. (2014). Taxonomic classification of cyano-prokaryotes (cyanobacterial genera) 2014, using a polyphasic approach. Preslia 86: 295–335.

Latifi, A., Ruiz, M. & Zhang, C. (2009). Oxidative stress in cyanobacteria. FEMS Microbiology Reviews 33, 258–278.

Legrand, B., Lamarque, A., Sabart, M. & Latour, D. (2016). Characterization of akinetes from Cyanobacterial Strains and Lake Sediment: A Study of Their Resistance and Toxic Potential. Harmful Algae, 59, 42-50.

Mazur-Marzec, H., Cegłowska, M., Konkel R. & Pyrć, K. (2021). Antiviral Cyanometabolites-A Review. Biomolecules. 11(3):474. doi: 10.3390/biom11030474.

Meeks, J. C., Campbell, E. L., Summers, M. L. & Wong, F. C. (2002). Cellular differentiation in the cyanobacterium Nostoc punctiforme. Archives of Microbiology, 178, 395–403.

Mehnert, G., Rucker, J. & Wiedner, C. (2014). Population dynamics and akinete formation of an invasive and a native cyanobacterium in temperate lakes. Journal of Plankton Research 36 (2): 378–387.

Mota, R., Pereira, S. B., Meazzini, M., Fernandes, R., Santos, A., Evans, C. A., Philippis, R., Wright, P. C. & Tamagnini, P. (2015). Differential proteomes of the cyanobacterium Cyanotheca sp. CCY 0110 upon exposure to heavy metals. Data in Brief, 4, 152-158.

Ortiz-Moreno, M. L., Poblador, J. C., Agredo, J. & Solarte-Murillo, L. V. (2020). Modeling the effects of light wavelength on the growth of Nostoc ellipso- sporum. Universitas Scientiarum, 25(1), 1-14.

Ou, H., Gao, N., Deng, Y., Qiao, J. & Wang, H. (2012). Immediate and long-term impacts of UV-C irradiation on photosynthetic capacity, survival and microcystin-LR release risk of Microcystis aeruginosa. Water Research, 46(4), 1241-1250.

Perez, R., Forchhammer, K., Salerno, G. & Maldener, I. (2016). Clear differences in metabolic and morphological adaptations of akinetes of two Nostocales living in different habitats. Microbiology (Reading). 162(2), 214-223.

Phukan, T. & Syiem, M. B. (2019). Modulation of oxidant and antioxidant homeostasis in the cyanobacterium Nostoc muscorum Meg1 under UV-C radiation stress. Aquatic Toxicology, 213, 105228.

Rastogi, P. R. & Incharoensakdi, A. (2014). UV radiation-induced biosynthesis, stability and antioxidant activity of mycosporine-like amino acids (MAAs) in a unicellular cyanobacterium Gloecapsa sp. CU2556. Journal of Photochemistry and Photobiology B: Biology, 130, 287-292.

Rica, R. P. S. (2015). Biochemical characterization of sun-screening mycosporine-like amino acids from two Nostoc species inhabiting diverse habitats. Prototaxisma, 252(1), 199-208.

Rippka, R., Deruelles, J., Waterbury, J. B., Herdman, M. & Stanier, R. Y. (1979). Generic assignments, strain histories and properties of pure cultures of cyanobacteria. Microbiology, 111(1), 1-61.

Sakai, H., Katayama, H., Oguma, K. & Ohgaki, S. (2009). Kinetics of Microcystis aeruginosa Growth and Intracellular Microcystins Release after UV Irradiation. Environmental Science & Technology, 43, 896–901.

Silva, G. M., Gomes, A. L., Cunha, C. J. S., Costa Tavares, V. B., Pinheiro, S. C. C. & Sousa, E. B. (2020). Caracterização de Nostoc sp. LBALBR-2 (Cianobacteria) isolada das raízes de macrófitas do reservatório Bolonha (Belém-Pará) sob diferentes condições de temperatura, luz e umidade. Brazilian Journal of Animal and Environmental Research, 3(4), 4242-4256.

Silva, H. J., Cortiñas, T. I. & Ertola, R. J. (1989). Effect of nutritional factors on the culture of Nostoc sp. as a source of phycobiliproteins. Applied Microbiology and Biotechnology 31, 293–297.

Singh, S. P. & Montgomery, B. L. (2011). Determining cell shape: adaptive regulation of cyanobacterial cellular differentiation and morphology. Trends in Microbiology, 19 (6), 278-285.

Singh, Y., Khattar, J. I. S., Singh, D. P., Rahi, P. & Gulati, A. (2014). Limnology and cyanobacterial diversity of high altitude lakes of Lahaul-Spiti in Himachal Pradesh, India. Journal of Biosciences, 39, 643–657.

Śliwińska-Wileczewska, S., Gergella, K. & Latala, A. (2016). Allelopathic activity of the Synechococcus sp. (Cyanobacteria, Chroococcales) on selected cyanobacteria species. Annales Universitatis Paedagogicae Cracoviensis Studia Naturae, 1: 115–126.

Soule, T., Shipe, D. & Lothamer, J. (2016). Extracellular Polysaccharide Production in a Scytonemin-Deficient Mutant of Nostoc punctiforme Under UVA and Oxidative Stress. Curr Microbiol. 73(4): 455-62.

Tao, Y., Zhang, X. & Du, D. W. T., Mao, X. & Yuan, K. (2010). The effects of sub-lethal UV-C irradiation on growth and cell integrity of cyanobacteria and green algae. Chemosphere, 78, 541–547.

USEPA (2006). Environmental Protection Agency of Ground Water and Drinking Water Standards and Risk Management Division. Distribution System Indicators of Drinking Water Quality. Pennsylvania Ave., NW Washington DC.
Werner, V. R., Cabezudo, M. M., Neuhaus, E. B., Caires, T. A., Sant'Anna, C. L., Azevedo, M. T. P., Malone, C., Gama Jr., W. A., Santos, K. R. S. & Menezes, M. (2015). Cyanophyceae in Lista de Espécies da Flora do Brasil. Jardim Botânico do Rio de Janeiro. (http://floradobrasil2015.jbrj.gov.br/FRB108051)

Wood, S. M., Kremp, A., Savela, H., Akter, S., Vartti, V. P., Saija Saarni, S. & Suikkanen, S. (2021). Cyanobacterial Akinete Distribution, Viability, and Cyanotoxin Records in Sediment Archives From the Northern Baltic Sea. Front Microbiol, 15, 12:681881. doi: 10.3389/fmicb.2021.681881

Zucchi, M. R. & Necchi O., Jr. (2001). Effects of Temperature, Irradiance and Photoperiod on Growth and Pigment Content in some Freshwater Red Algae in Culture. Phycological Research, 49 (2), 103-114, Disponível em: <http://hdl.handle.net/11449/66556>.

Zuniga, E. G., Figueroa, N. M., Gonzalez, A., Pantoja, A. P. & Risser, D. D. (2020). The Hybrid Histidine Kinase HrmK Is an Early-Acting Factor in the Hormogonium Gene Regulatory Network. Journal of Bacteriology. 202:e00675-19.