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The effect of UVA radiation on the production of photoprotective compounds and carotenoids in terrestrial cyanobacteria strains

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ABSTRACT

Cyanobacteria constitute a diverse group of photosynthetic prokaryotes with significant metabolic complexity, capable of synthesizing bioactive pigments and compounds with potential applications as natural bioproducts, including carotenoids, scytonemin, and mycosporine-like amino acids (MAAs). The study aimed to explore the potential of terrestrial cyanobacteria isolated from the Brazilian Atlantic Forest to produce photoprotective (anti-UV) substances and to investigate the effect of UVA radiation on this production. Six strains of terrestrial cyanobacteria were isolated from the Brazilian Atlantic Forest and subjected to 24 hours of UV-A irradiation. Afterward, the output of photoprotectors (scytonemim and MAAs) and carotenoids was evaluated by maceration with 100% acetone and 20% methanol, then measured by spectrophotometry. The investigation revealed significant production of scytonemin under UV-A irradiation in the *Aphanothece* sp. CCIBt 3609 and *Plectolyngbya* sp. CCAPE 79 strains. This study provides unprecedented data on scytonemin production in the genus *Plectolyngbya* and solidifies *Aphanothece* as a potential source of the anti-UV compound scytonemin.

Keywords: Anti-UV, Atlantic Forest, bioactive compounds, scytonemin, secondary metabolites.

Introduction

Cyanobacteria are ancient photosynthetic prokaryotes comprising approximately 8,000 species, grouped into 150 genera, and exhibit vast morphological diversity, ranging from unicellular to colonial and filamentous forms, including specialized cells such as heterocytes (Hachicha et al., 2022). Having existed for approximately 3.5 billion years, they played a crucial role in the Great Oxidation Event, which occurred between 2.4 to 3.2 billion years ago (Urrejola et al., 2020). This long evolutionary history exposed cyanobacteria to diverse environmental pressures, leading to their adaptation to a wide range of habitats, including aquatic environments (e.g., lakes, seas, and rivers), terrestrial habitats (e.g., soils and biofilms colonizing various surfaces), and extreme conditions such as deserts, hot springs, and polar regions globally (Guerreiro et al., 2020). The evolutionary success of cyanobacteria is attributed to their biosynthesis of secondary metabolites, which enable these organisms to thrive in various extreme conditions (Nowruzi et al., 2020). These compounds have garnered significant biotechnological attention for potential applications in cosmetics and pharmaceuticals (Morone et al., 2019). Despite the predominant focus on marine cyanobacteria, molecules synthesized by terrestrial cyanobacteria also exhibit pharmacological activity (Nowruzi et al., 2020; Toribio et al., 2020; Khalifa et al., 2021).

Cyanobacteria produce a variety of bioactive compounds, including anti-UV molecules such as scytonemin and mycosporine-like amino acids (MAAs), which have potential applications in pharmaceutical products. MAAs are a group of more than 20 small (<400 Da), water-soluble, colorless molecules found in the cytoplasm of cyanobacteria, fungi, macroalgae, and microalgae (Singh et al., 2023). These compounds function as photoprotectors and antioxidants, with maximum absorption

wavelengths ranging from 310 to 362 nm (Rosic, 2019; Kumari et al., 2021). Scytonemin is a lipophilic biomolecule exclusively found in the extracellular sheath of cyanobacteria, with a yellowish color and a photoprotective role against long-wavelength UV radiation (315-400 nm), with a maximum absorption at 384 nm. It is prevalent in cyanobacteria inhabiting high-light incidence extreme environments (Rastogi & Incharoensakdi, 2014; Rastogi et al., 2015; Singh et al., 2023). Carotenoids are tetraterpene pigments known for their vibrant yellow, orange, red, and purple colors. These are among nature's most abundantly distributed pigments, found in various organisms, including photosynthetic bacteria, some Archaea, fungi, algae, plants, and animals (Maoka, 2020). In cosmetics, non-protein amino acids such as mycosporines and cyanopeptides have been recognized for their considerable potential as natural bioproducts. They hold promises for applications in skin care, notably in sunscreens and anti-aging formulations (Garlapati et al., 2019; Geraldes et al., 2020).

The Atlantic Forest Domain is a tropical forest mostly held along the Brazilian coast, rich in biodiversity, and home to numerous endemic species (Lima et al., 2020). Many new cyanobacterial genera and species were described in this forest, and some have shown significant biotechnological potential (Genuário et al., 2019; Caires & Affe, 2021). However, reports on the ability of terrestrial tropical cyanobacteria to synthesize bioactive metabolites are limited (Geraldes et al., 2020). This study aimed to explore the potential of terrestrial cyanobacteria isolated from the Brazilian Atlantic Forest to produce photoprotective (anti-UV) substances and to investigate the effect of UVA radiation on this production.

Material and Methods

Cyanobacteria strains and growth conditions

Six strains of terrestrial cyanobacteria were selected for this study based on the locations where they were initially sampled, from habitats exposed to sunlight in the Brazilian Atlantic Forest across the states of Pernambuco, Rio de Janeiro, and São Paulo, as listed in Table 1. Initially, three of these strains were housed at the Coleção de Cultura de Algas, Cianobactérias e Fungos do Instituto de Botânica (CCIBt), within the Instituto de Pesquisas Ambientais, Unidade Jardim Botânico, São Paulo, before being donated to the Coleção de Cultura de Cianobactérias e Algas de Pernambuco (CCAPE), established at the Universidade Federal Rural de Pernambuco (UFRPE). Concurrently, the remaining three strains are also maintained at the CCAPE. The cultures were grown in ASM-1 medium at room temperature (23°C ± 2) with a 12/12-h light/dark cycle, illuminated with cool white LED lights at approximately 30 µmol photons m^{-2} s^{-1}, following the guidelines established by Jacinavicius et al. (2013)

Experimental setup

The experimental procedure involved cultivating cyanobacterial strains according to the protocols outlined by Jacinavicius et al. (2013), with cultures grown to a volume of 1,000 mL. Subsequently, the culture volume underwent centrifugation (Bench centrifuge 5,000 rpm K14-5,000 m Kasvi. Paraná/Brazil) to remove most of the liquid phase, leaving behind a pellet/biomass, which was then weighed and evenly distributed in Petri dishes containing solid medium (ASM-1 + 1% agar) in triplicate for both treatment and control groups. Following this, the Petri dishes, each kept open and containing the biomass, were subjected to different conditions: exposure to UV-A radiation (treatment) using actinic lamps (400 - 320 nm) and to LED white lights (control) for 24 hours, in line with the standard conditions of CCAPE. Subsequently, the biomass from each set of triplicates was lyophilized, and the resulting dried biomass was weighed using a Lyophilizer L101 Liobras (São Paulo, Brazil).

Extraction and screening

The extraction of carotenoids and scytonemin followed the methodology outlined by Garcia-Pichel & Castenholz (1991). The biomass of each triplicate was macerated in a pestle and mortar made of agate using 8 mL of 100% acetone, followed by centrifugation at 5,000 g for 9 minutes. The resulting supernatant was collected and used to qualify pigments by spectrophotometry: scytonemin (384 nm), carotenoids (490 nm), and chlorophyll a (663 nm) were measured using a Bel UV-M51 UV-Vis spectrophotometer (Monza/Italy). Then, 8 mL of 20% methanol was added to the samples, which were centrifuged at 5,000 g for 4 min and left overnight at 4°C. Following this, they were incubated at 45°C in a water bath (Heidolph OB 4000, Germany) for 2.5 hours, then centrifuged at 5,000 g for 2 minutes to collect the supernatant for screening MAAs using the spectrophotometric method described by Browne et al. (2023). Photoprotectors Mycosporine-like amino acids (MAAs) were analyzed at wavelengths 309, 310, 323, 325, 326, 330, and 332 nm.

Statistical analysis

All data were assessed for normality and homoscedasticity using the Shapiro-Wilk test and then compared using the T-test to observe differences between the control and treatment groups regarding photoprotectors and carotenoid production. A nonparametric test was employed if the data did not follow a normal distribution. Values with $p < 0.05$ were considered statistically significant. The statistical analyses were performed using GraphPad Prism® software (GraphPad Software, Boston, USA).

Table 1. List of strains for the evaluation of the production potential of photoprotectors. CCIBt Culture Collection of Algae, Cyanobacteria, and Fungi of the Institute of Botany; CCAPE: Culture Collection of Cyanobacteria and Algae of Pernambuco. Font: Gama et al. (2024).

Strains	Sampling Location	Substrate	Identification
CCAPE 75	Tapacurá Ecological Station/PE (8°02'26.8"S 35°11'43.1"W)	Tree bark	*Chlorogloea* sp.
CCAPE 79	Tapacurá Ecological Station/PE (8°02'26.8"S 35°11'43.1"W)	Clay brick	*Plectolyngbya* sp.
CCAPE 80	Tapacurá Ecological Station/PE (8°02'26.8"S 35°11'43.1"W)	Concrete	*Scytonema* sp.
CCIBt 3588	Serra do Mar State Park, Santa Virgínia Unit/SP (23°20'05.1"S 45°08'01.5"W)	Rooftop	*Nostoc* sp.
CCIBt 3601	Prainha/RJ (23°02'27.9"S 43°30'19.9"W)	Rock	*Gloeothece* sp.
CCIBt 3609	Jureia-Itatins Ecological Station/SP (24°21'24.6"S 47°00'48.7"W)	Rock	*Aphanothece* sp.

Results

Morphological identification

The taxonomic analysis was conducted using microscopic identification with a Zeiss Light Microscope. Identifications were based primarily on Strunecký et al. (2023). Only morphological characteristics of light microscopy can be used for identification, and these are insufficient to identify cyanobacterial species; therefore, the strains used in this study are identified only to the genus. Cyanobacteria strains are shown in Figure 1.

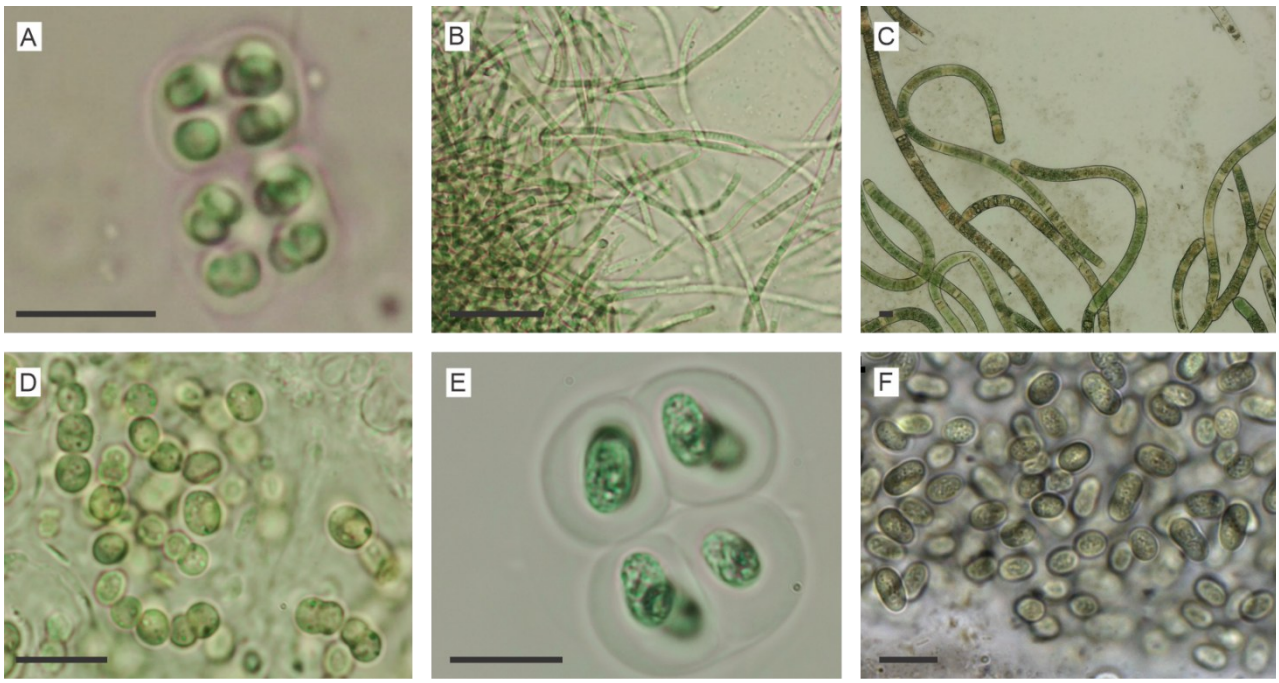


Figure 1. The strains analyzed in this study. A. *Chlorogloea* sp. (CCAPE-75); B. *Plectolyngbya* sp. (CCAPE-79); C. *Scytonema* sp. (CCAPE-80); D. *Nostoc* sp. (CCIBt 3588); E. *Gloeothece* sp. (CCIBt 3601); F. *Aphanothece* sp. (CCIBt 3609). Bars = 10µm. Font: Gama et al. (2024).

Photopigments and anti-UV compounds evaluation

The content of carotenoids was constant between the strains and the treatments, and no significant statistical difference ($p<0.05$) was observed. The accumulation of carotenoids was detected in the strains exposed to white light and

UV-A radiation (Figure 2B). Thus, our results revealed constant carotenoid content across all strains and treatments, with no significant differences.

After statistical analysis, it was possible to identify that the UV-A irradiation enhances the biosynthesis of the photoprotector scytonemin (Figure 3A) in two tested strains. This behavior was demonstrated by the strain *Aphanothece* sp. CCIBt 3609 under the UV-A irradiation treatment showed a significant difference ($p<0.0001$) in comparison with the white light (control).

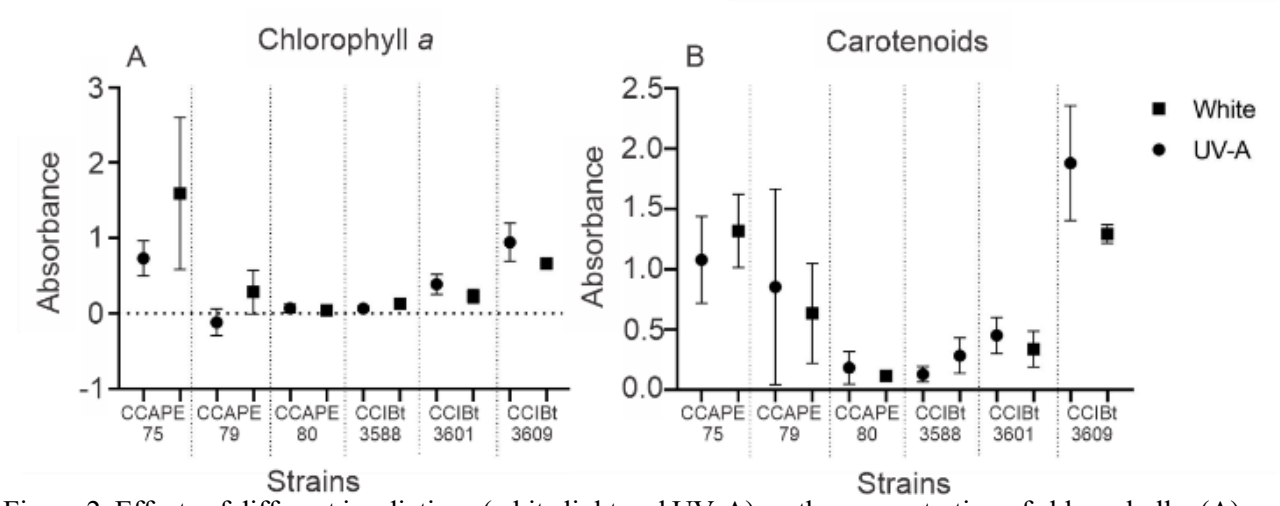
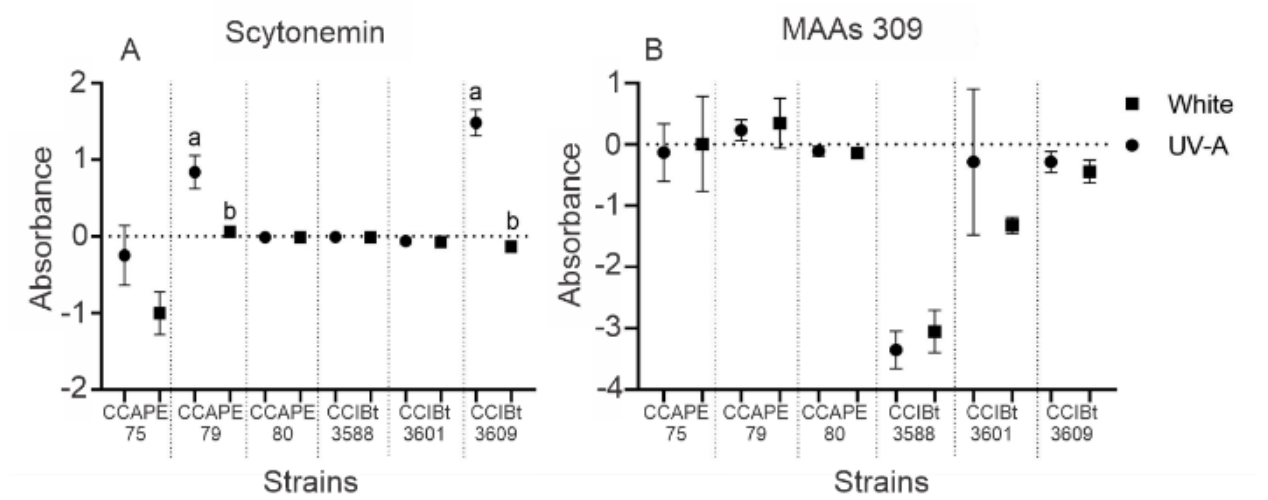


Figure 2. Effects of different irradiations (white light and UV-A) on the concentration of chlorophyll *a* (A) and carotenoids (B) in terrestrial cyanobacteria strains. Font: Gama et al. (2024).

The strain *Plectolyngbya* sp. CCAPE 79 also showed increased scytonemin production after exposure to UV-A radiation, which was significantly different from the control ($p=0.0039$). The discussion must be restricted to the significance of the data presented and to comparisons with data from the literature, without any conclusions based on them.

None of the strains exhibited significant differences between control and treatment in the production of MAAs at any wavelength (Figures 3 and 4). However, the strain *Plectolyngbya* sp. CCAPE 79 displayed accumulations of MAAs of 309 nm (Figure 3B) and 310 nm (Figure 3C), and the strain *Chlorogloea* sp. CCAPE 75 exhibited accumulations of MAAs at 310 nm (Figure 3C).



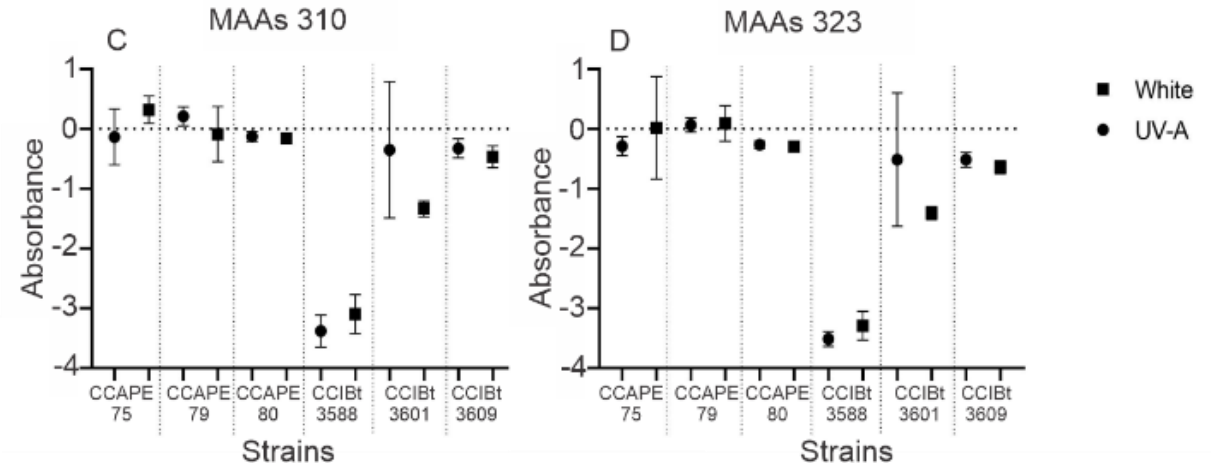


Figure 3. Effects of different irradiations (white light and UV-A) on the concentration of scytonemin (A) and mycosporine-like amino acids: 309 nm (B), 310 nm (C), and 323 nm (D) in the terrestrial cyanobacteria strains analyzed. Distinct letters represent significant differences. Font: Gama et al. (2024).

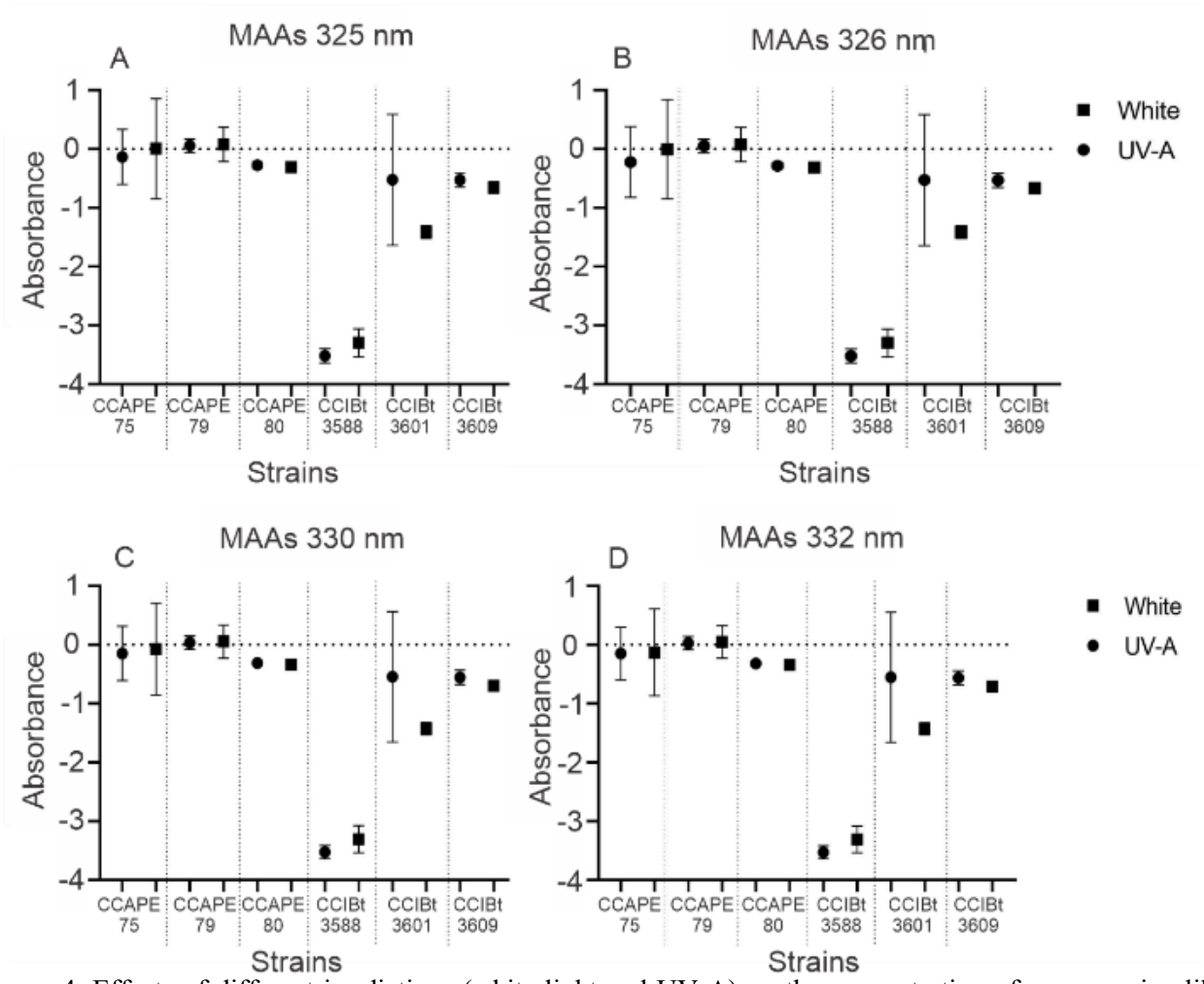


Figure 4. Effects of different irradiations (white light and UV-A) on the concentration of mycosporine-like amino acids: 325 nm (A), 326 nm (B), 330 nm (C), and 332 nm (D) in the terrestrial cyanobacteria strains analyzed. Font: Gama et al. (2024).

Discussion

The current investigation aimed to assess the capacity of six terrestrial cyanobacterial strains isolated from the Brazilian Atlantic Forest to produce sunscreen and photopigments. Carotenoids, a critical pigment in photosynthesis responsible for light capture, play a crucial role in photoprotection (Fabrowska et al., 2018). It is noted that prolonged exposure to UV-B radiation has been associated with decreased Chlorophyll *a*

content and increased total carotenoid levels in cyanobacteria, possibly due to UV-B-induced damage to photosynthetic pigments, resulting in reduced photosynthetic rates (Kannaujiya & Sinha, 2017; Pandey et al., 2020). This pattern is reflected in the data from our study, as indicated by the notably lower Chlorophyll *a* concentration compared to carotenoids (Figure 1AB).

The strains exposed to UV-A radiation exhibited an increase in carotenoid concentration, consistent with the typical response of photosynthetic organisms to heightened light exposure. Exposure to UV-A radiation may produce secondary carotenoids, which are more effective antioxidants than primary carotenoids. These have potential applications in cosmetics, nutrition, and aquaculture (Cezare-Gomes et al., 2019; Novoveská et al., 2019).

Among the six strains, only *Aphanothece* sp. (CCIBt 3609) and *Plectolyngbya* sp. (CCAPE 79) displayed a significant concentration of the yellow-brown pigment scytonemin, attributed to their capability to fix atmospheric nitrogen and synthesize scytonemin as a defense against UV radiation (Kokabi et al., 2019; Nowruzi et al., 2020). Notably, the production of scytonemin is known to increase in response to UV-A radiation and temperature fluctuations (Abed et al., 2011; Tamre & Fournier 2022), providing a shielding effect against UV-A radiation (Gao et al., 2021). The findings regarding *Plectolyngbya* sp. (CCAPE 79) are particularly noteworthy, as this genus is relatively understudied in its capacity to produce bioactive metabolites. The accumulation of scytonemin in *Plectolyngbya* strains following UV-A exposure indicates their potential for pharmaceutical applications (Orellana et al., 2020).

In contrast, the analysis revealed no significant concentration of mycosporine-like amino acids (MAAs) across all strains studied. Although MAAs are known for their UV-shielding properties, this study's findings suggest that their biosynthesis was not notably triggered by the UV-A radiation employed, raising questions about their production under standard culture conditions. This aligns with prior investigations that have demonstrated the potential for MAAs production in the absence of UV radiation while stressing the role of UV stress in enhancing their synthesis (Nazifi et al., 2015; Singh et al., 2023). Mansouri & Talebizadeh (2017) also proposed broader functional roles for MAAs beyond UV protection. This study's lack of MAA production may be related to the specific UV wavelength, as these compounds are typically associated with UV-B irradiation.

Conclusion

The dynamic responses of cyanobacterial photopigments to different light conditions highlight the significant impact of UV-A radiation on scytonemin production in select strains. UV-A irradiation significantly enhanced the production of the photoprotective pigment scytonemin in two tested strains, *Aphanothece* sp. CCIBt 3609 and *Plectolyngbya* sp. CCAPE 79. None of the strains showed significant differences in mycosporine-like amino acid (MAA) production between the control and treatment conditions at any wavelength. Also, carotenoids were consistently produced across all treatments, with no statistical difference.

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