



Photoprotective Potential of Mycosporine-Like Amino Acids in Red Algae (Rhodophyta) from San Andrés and Providencia Islands, Colombian Caribbean

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Abstract

Ten samples of common red macroalgae (Rhodophyta) were collected from San Andrés and Providencia Islands (Colombia) to evaluate the potential as sources of photoprotective compounds. Aqueous extracts were analyzed for sun protection factor, UVA protection factor, and critical wavelength (λ_c). Mycosporine-like amino acids, known for their strong UV-absorbing properties, were identified and quantified using ultra-high-performance liquid chromatography coupled with diode array detection and tandem mass spectrometry (UHPLC-DAD-MS/MS), and quantified with diode array detection (UHPLC-DAD), respectively. Six mycosporine-like amino acids were detected: shinorine, palythine, asterine-330, porphyra-334, palythine-threonine, and palythanol. Among the tested species, *Laurencia obtusa* showed the highest total mycosporine-like amino acid content ($1.54 \text{ mg g}^{-1} \text{ DW}$) and the strongest UVB protection (SPF 23.14 at $20 \text{ mg ml}^{-1} \text{ DW}$). *Acanthophora spicifera* collected in October 2023 exhibited the highest porphyra-334 levels and provided broad-spectrum protection, meeting the European Commission criteria for UVA coverage. Heatmap analyses revealed a positive correlation between mycosporine-like amino acid concentration and photoprotective performance. These results demonstrate the potential of Caribbean red marine macroalgae as sustainable sources of mycosporine-like amino acids for use in natural sunscreen formulations.

Keywords Bioprospecting · Sun protection factor (SPF) · Marine natural products · Photoprotection

Introduction

Mycosporine-like amino acids (MAAs) are widely recognized as important photoprotective compounds in red algae, due to their capacity to absorb ultraviolet (UV) radiation across both UVA and UVB spectra, in addition to their antioxidant properties (Huovinen et al. 2004; Korbee et al. 2006). These characteristics make MAAs highly desirable for their incorporation into sunscreens and anti-aging

products, some of which are already commercially available as UVB photoprotective solutions (Moh et al. 2014). To date, more than 74 MAAs have been identified, with 22 of those found in red macroalgae (Rhodophyta), the most abundant being shinorine, porphyra-334, palythine, and asterine-330 (Sun et al. 2020).

In Colombia, marine areas cover approximately 45% of the territory, with a coastline stretching about 3100 km (Bautista et al. 2022). Over 621 macroalgal taxa have been reported in the country, including 351 species of red algae (Rincón et al. 2020). In the Archipelago of San Andrés, Providencia and Santa Catalina, located within the Seaflower Biosphere Reserve in the Colombian insular Caribbean, 325 macroalgal species have been reported, 153 of which are red algae (Corrales Castilla 2019; Reyes-Gómez et al. 2021). This rich algal diversity underscores the potential of exploring these species as potential sources of compounds with photoprotective properties, especially since studies on the chemistry of marine algae as potential sources of compounds

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with cosmetic value remain limited in the country (Bautista et al. 2022).

Materials and Methods

Reagents, Solvents, and Equipment

Reagents used for chemical analyses included ultrapure water Type I (Milli-Q Merck Millipore, 2.2 µm membrane), HPLC-grade acetonitrile (ACN), MS-grade formic acid (Sigma-Aldrich Inc., USA) and MS-grade ammonium formate (Sigma-Aldrich Inc., USA).

For the extraction process, an ultrasonic bath (Elmasonic Easy 37 kHz, Germany) and a refrigerated centrifuge (MPR115 Advanced Multipurpose Refrigerated, 8000 rpm, Cole-Parmer Inc., USA) were employed. For the evaluation of photoprotection parameters (SPF, UVA_r, λ_c) of the aqueous extracts, a Thermo Scientific™ Multiskan™ GO Microplate Spectrophotometer was used, featuring a monochromator and xenon lamp with 96-well flat-bottom polystyrene plates. Metabolic profiling of the extracts was conducted using a UHPLC-DAD system (Shimadzu Nexera X2, Shimadzu, Japan) equipped with a photodiode array detector (SPD M240) and a Synergi Hydro-RP 80 Å column (4 µm, 150 × 2.0 mm) protected by a SecurityGuard pre-column.

Sample Collection

Algal samples were manually collected by snorkel on sand flats and rocky bottoms as well as in the intertidal zone at various sites on the islands of San Andrés and Providencia, concentrating our efforts in sites with high densities of red algae. Algal samples were carefully detached from the substrate and stored in mesh bags, collecting approximately 2 kg of algae per morphotype. Following collection, algal samples were rinsed with fresh water, placed in resealable bags, and frozen at −20 °C prior to transportation to the laboratories at Universidad Nacional de Colombia in Bogotá, where they were stored in a freezer at −20 °C to prevent sample decomposition. Prior to chemical analyses, all samples were lyophilized (freeze-dried; $n = 3$).

Samples were identified by Mónica Puyana, Natalia Rincón, and Vanessa Urrea-Victoria based on morphological characters following Littler & Littler and other specialized literature. Voucher specimens were deposited in the herbarium at Pontificia Universidad Javeriana (HPUJ) and Jiwukori (JIW) herbarium at the Universidad

Nacional de Colombia, in Bogotá. Algal nomenclature and taxonomy follow AlgaeBase (Guiry and Guiry 2024) (Table SM1).

Assessment of Photoprotective Activity Parameters

Lyophilized macroalgae ($n = 3$) were extracted with deionized water and prepared at different concentrations of 5, 10, and 20 mg ml^{−1}. For extract preparation, samples were vortexed at room temperature, then centrifuged at 2383 × *g* for 10 min, and the supernatants were used for spectrophotometric analysis. From these solutions, 500 µl was analyzed in semi-micro quartz square cuvettes of 0.5 ml, using deionized water as a blank. Absorbance measurements were recorded across the ultraviolet spectral range of 290–400 nm. As a positive control: benzophenone-3 (BP-3).

The sun protection factor (SPF) was determined in vitro following Mansur et al. (1986). This method uses an equation that correlates sample absorbance in the UVB region (290–320 nm) (Eq. 1).

$$SPF = CF * \sum_{290}^{320} EE(\lambda) * I(\lambda) * Abs(\lambda) \quad (1)$$

where Abs (λ): absorbance of the product at wavelength λ; CF: correction factor equal to 10, determined using two photoprotective substances with known SPF; *I* (λ): solar intensity at wavelength λ; *EE* (λ): erythemal effect of radiation at wavelength λ.

The UVA/UVB protection ratio (UVA_r) was evaluated in the 290 to 400 nm range, following Eq. 2 (Rojas et al. 2015).

$$UVA_r = \frac{\int_{320}^{400} Abs(\lambda)}{\int_{290}^{320} Abs(\lambda)} \quad (2)$$

Critical wavelength (λ_c) (Eq. 3) was calculated as the balance between UVB and UVA protection. It determines the wavelength at which 90% of the integrated area under the absorbance curve of the filter or preparation is reached (European Commission 2009; FDA 2021).

$$UVA_r = \frac{\int_{320}^{400} Abs(\lambda)}{\int_{290}^{320} Abs(\lambda)} \quad (3)$$

Identification and Quantification of Mycosporine-Like Amino Acids

Characterization and quantification of mycosporine-like amino acids (MAAs) were performed following Urrea-Victoria et al. (2025). In brief, 5 mg of freeze-dried samples

($n = 3$) was mixed with 1 ml of acidified water (containing 0.25% formic acid and 20 mM ammonium formate), sonicated for 15 min (Elmasonic Easy 37 kHz ultrasonic bath, Germany) at room temperature, and subsequently analyzed via UHPLC-DAD. Representative chromatograms are provided in Supplementary Information Figure SM1. The chromatographic separation was carried out using a Synergi Hydro-RP 80 A column (4 μm , 150 $\times$ 2 mm), with a Security Guard pre-column. Flow rate was set at 0.3 ml min⁻¹ and kept at 22 °C. The gradient mobile phase consisted of aqueous solvent A (0.25% formic acid and 20 mM ammonium formate) and acetonitrile (solvent B), with a gradient profile of 100% solvent A (0–3 min), 95% solvent A (3–7 min), and 20% solvent A (7–8 min). A 7-min re-equilibration was allowed between runs, and detection occurred at a wavelength of 330 nm.

For MAA identification, the same chromatographic conditions were used in conjunction with a Shimadzu Nexera X2 UHPLC system (Japan) coupled with a qTOF-MS detector. Mycosporine-like amino acid analysis was performed in Multiple Reaction Monitoring (MRM) mode for target compounds, supplemented by a full scan (DIA mode) to confirm the presence of additional potential MAAs. The mass spectrometer conditions were previously reported by Urrea-Victoria et al. (2025).

MAAs quantification was carried out following the calibration curve equation calculated by Urrea-Victoria et al. (2025), with $Y = 33276x + 13,308$, where x is the MAA concentration ($\mu\text{g ml}^{-1}$) and y is the absorbance at 330 nm; $R^2 = 0.9995$; LOQ: 0.1460 $\mu\text{g ml}^{-1}$; LOD: 0.0438 $\mu\text{g ml}^{-1}$. Results were expressed as milligrams of MAAs per gram of dry weight (DW) of the alga. Concentrations of the MAAs shinorine, palythine, asterine-330, palythine-threonine, and palythanol were calculated using the same calibration equation. Quantification areas for these compounds were determined at their respective maximum absorption wavelengths and corrected using their molar extinction coefficients (ϵ): shinorine (332 nm) = 44,668 M⁻¹ cm⁻¹, palythine (320 nm) = 36,200 M⁻¹ cm⁻¹, asterine-330 (330 nm) = 43,800 M⁻¹ cm⁻¹, palythine-threonine (320 nm) = 36,200 M⁻¹ cm⁻¹, and palythanol (320 nm) = 43,500 M⁻¹ cm⁻¹, relative to the extinction coefficient of porphyra-334 (334 nm) = 42,300 M⁻¹ cm⁻¹ (Carignan et al. 2009; Vega et al. 2021; Moreira et al. 2022). A standard solution of porphyra-334, isolated in the laboratory by Vanessa Urrea-Victoria, was used as control.

Photoprotection and Mycosporine-Like Amino Acids Content Comparison

A heatmap was created to visually relate photoprotective capacity and MAAs concentration in the extracts of red algal samples ($n = 9$; where MAAs were quantified; *Spyridia*

filamentosa (Wulfen) Harvey 1833 was excluded as no MAAs were detected in this study). The integrated variables included SPF, UVA_r, λ_c , porphyra-334 concentration (5 mg ml⁻¹) and total MAAs concentration. Data was organized into a matrix averaging all variables and converted into a CSV file for analysis in RStudio®. Libraries such as Ggplot2, Colorspace, Pheatmap, and RcolorBrewer were used. Data normalization involved scaling and centering, and cluster analysis was performed to group samples based on variable similarities.

Results and Discussion

Macroalgae sampling focused on abundant specimens, yielding a total of 10 red macroalgae samples collected in 2021 and 2023 from various locations across the Archipelago of San Andrés, Providencia, and Santa Catalina. A summary of the sampling data is presented in Table SM1. Of these, eight samples were collected from San Andrés Island, while two samples were obtained from Providencia Island.

Photoprotective Activity of Aqueous Extracts

Red macroalgae are recognized as sources of photoprotective compounds, including chlorophylls, phycobiliproteins, polyphenols, sulfated polysaccharides, carotenoids, and MAAs (Pangestuti et al. 2018). Aqueous extracts were obtained from each algal sample, and their photoprotective parameters were evaluated. Sun protection factor (SPF) was measured at extract concentrations of 5, 10, and 20 mg ml⁻¹, while UVA radiation protection (UVA_r) and critical wavelength (λ_c) were assessed at a concentration of 5 mg ml⁻¹. Benzophenone-3 (BP-3) as a positive control was tested at a concentration of 5 mg ml⁻¹ in all experiments.

At the highest concentration evaluated (20 mg ml⁻¹), SPF values ranged from 3.56 for the extract of *Gracilaria* sp. Greville, 1830 to 23.14 for the extract of *Laurencia obtusa* (Hudson) J.V.Lamouroux, 1813 to 20 mg ml⁻¹. The extract of *L. obtusa* showed the highest photoprotective activity and was classified as a medium photoprotector in the UVB range, according to the EC classification (European Commission 2009). In contrast, the extract of *Gracilaria* sp. displayed the lowest SPF value and was considered inactive (Fig. 1).

When tested at lower concentrations (5 mg ml⁻¹), only the extract of *L. obtusa* exhibited UVB protection based on the EC classification (European Commission 2009). Species of this genus are well known for producing MAAs, compounds with high photoprotective potential (Stein et al. 2013).

Tested at extract concentrations of 5 mg ml⁻¹, UVA_r values ranged from 0.49 (*Gracilaria* sp.) to 1.15 (*Ceramium* sp. 1 Gaertner ex Stackhouse, 1797), with 9 out of 10 samples meeting the criteria for maximum protection labelling. Similarly, λ_c critical wavelength values ranged from 360.9 nm

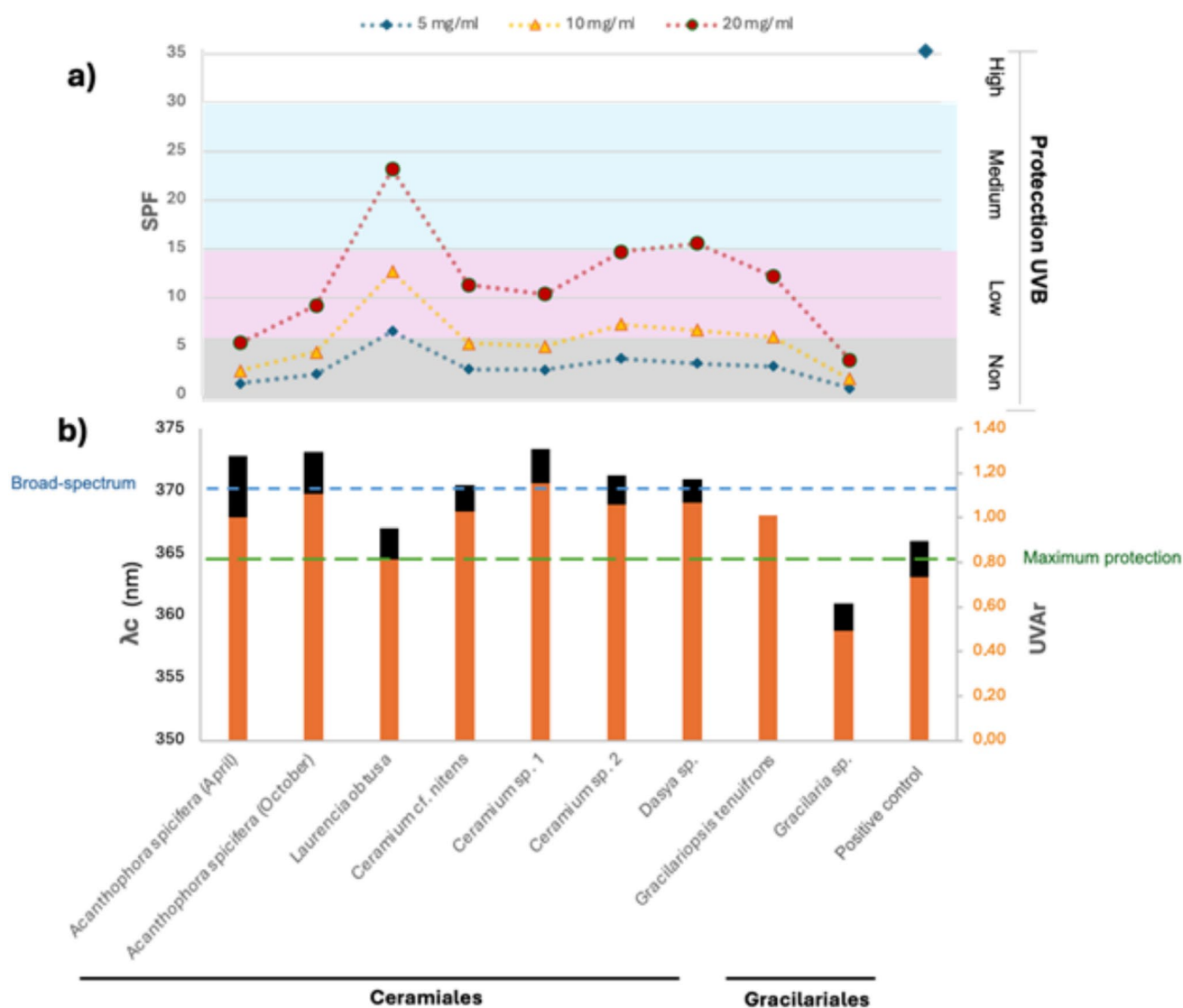


Fig. 1 Photoprotection parameters (SPF, UVA, λ_c) of aqueous extracts of red algae from San Andrés and Providencia Islands. **a** SPF measured at extract concentrations of 20 mg ml⁻¹ (red circles), 10 mg ml⁻¹ (yellow triangles) and 5 mg ml⁻¹ (blue diamonds), joined by dashed lines for visual support. UVB protection scale: high (white),

medium (blue), low (pink); none (gray). **b** UVA protection (orange columns) evaluated at extract concentrations of 5 mg ml⁻¹ and λ_c critical wavelength (black columns) evaluated at extract concentrations of 5 mg ml⁻¹

(*Gracilaria* sp.) to 373.3 nm (*Ceramium* sp. 1), with 8 out of 10 extracts fulfilling the broad-spectrum photoprotection criteria established by EC standards (European Commission 2009; Padera 2015). The UVA showed that 9 out of 10 samples had values above 0.8, indicating optimal UVA protection, which could be promising for cosmetic formulations offering both UVB and UVA protection.

De la Coba et al. (2019) demonstrated that topical formulations containing MAAs enhance UVA and UVB protection through different biological effective protection factors (BEPFs). Their findings highlight the role of MAAs in

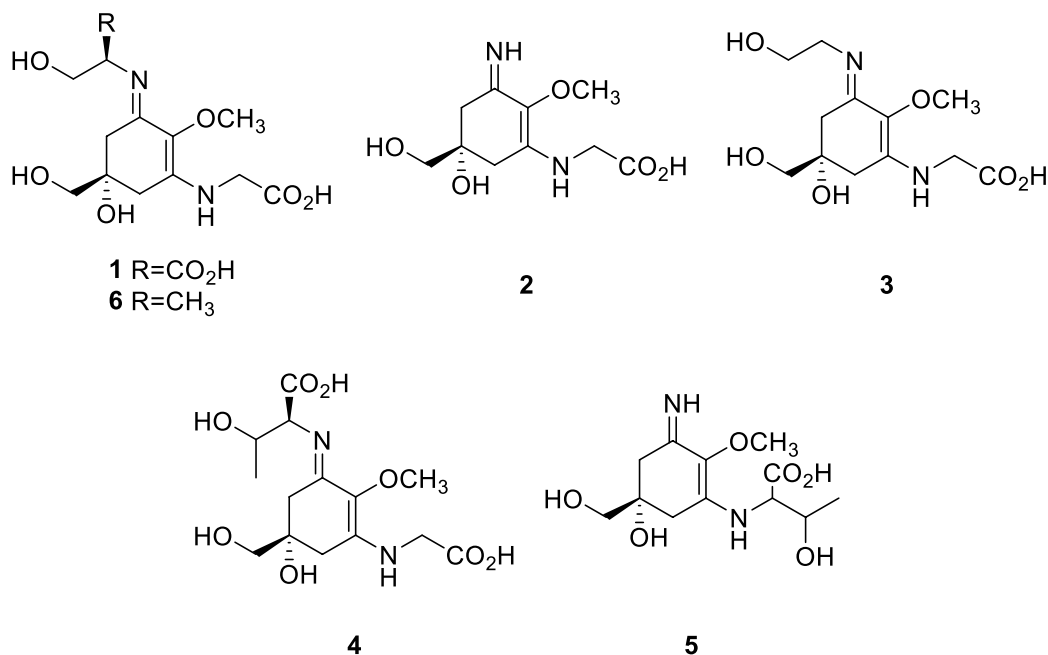
mitigating UV-induced damage, reinforcing the hypothesis that these compounds contribute significantly to photoprotection in marine organisms. In this context, the MAA content of each extract was characterized to correlate the photoprotective activity parameters (SPF, UVA, λ_c) of algal aqueous extracts.

Identification and Quantification of Mycosporine-Like Amino Acids in Red Algae

The MAA content in the 10 algal extracts evaluated revealed the presence of six known MAAs, shinorine (**1**), palythine

(2), asterine-330 (3), porphyra-334 (4), palythine-threonine (5) and palythanol (6). Additionally, a minor signal corresponding to an unidentified MAA (unID1) was detected. The retention time, maximum absorbance wavelength,

protonated molecular ion mass ($[M + H]^+$), MS/MS fragmentation patterns, and identification details of these compounds are summarized in Table SM2.



From extracts of red algae collected at San Andrés Island, four common MAAs (shinorine (1), palythine (2), asterine-330 (3), and porphyra-334 (4)) were identified in *Gracilariopsis* cf. *tenuifrons* (C.J.Bird & E.C.Oliveira) Fredericq & Hommersand, 1989, *Dasya* sp. C. Agardh, 1824 and *Ceramium* sp. 2. Additionally, palythine-threonine (5) was detected in *Acanthophora spicifera* (Vahl) Børgesen, 1910, collected in April of 2023 (*A. spicifera* sample 1) and October of 2023 (*A. spicifera* sample 2). Palythanol (6) was identified in *L. obtusa*, while an unidentified MAA (unID1) was detected in *Ceramium* cf. *nitens* (C.Agardh) J.Agardh, 1851 and *Ceramium* sp.1. Extracts from *Gracilaria* from Providencia Island contained shinorine (1), palythine (2), asterine-330 (3), and porphyra-334 (4), and palythanol (6). In contrast, no MAAs were detected in *Spyridia filamentosa*.

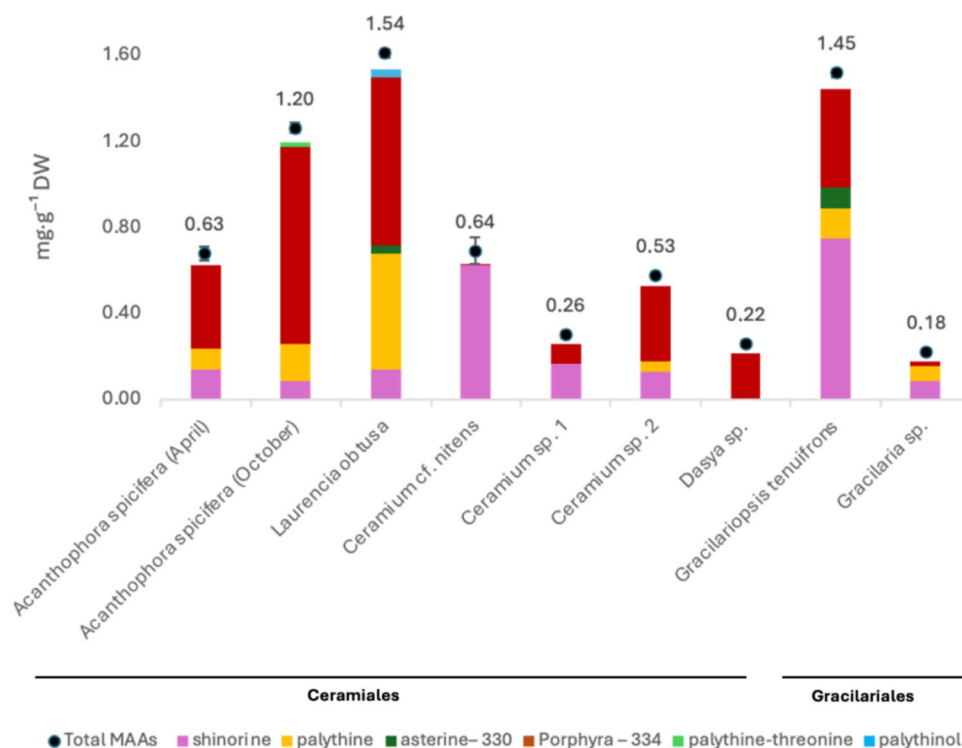
The quantitative data obtained in this study (Fig. 2) indicate that total MAA content in the analyzed samples ranged from 0.18 to 1.54 mg g⁻¹ DW. These values align with the expected concentrations for species within the orders Ceramiales and Gracilariales, which typically exhibit MAA levels ranging from 1 to 2 mg g⁻¹ DW, while some members of the Gracilariales may exceed 2 mg g⁻¹ DW of MAAs.

However, several species of macroalgae have been contain significantly lower MAA concentrations, even below 0.1 mg g⁻¹ DW (Sun et al. 2020).

Life habits of algae as well as their location in the intertidal zone may explain differences in MAA profile, with lower concentrations in algae thriving in the infralittoral and greater concentrations in algae from the supralittoral zone as these are more exposed to intense sunlight. These differences suggest that specific habitat conditions may influence MAA production, although it remains unclear how local environmental conditions impact the biosynthesis of these compounds.

The highest MAA concentrations were detected in *L. obtusa* (1.54 mg g⁻¹ DW) and *A. spicifera* both collected in October 2023 (1.20 mg g⁻¹ DW). These values are higher than those reported for the same species in Brazil, where *L. dendroidea* exhibited MAA concentrations ranging from 0.06 to 1.36 mg g⁻¹ DW and *A. spicifera* from 0.04 to 0.44 mg g⁻¹ DW (Briani et al. 2018). However, these values are lower than concentrations reported for other samples collected in the Colombian Caribbean in 2022, where *A. spicifera* reached 2.50 mg g⁻¹ DW and *L. obtusa* exhibited values

Fig. 2 Quantification of mycosporine-like amino acids in extracts of red algae from San Andrés and Providencia Islands



as high as 6.49 mg g⁻¹ DW of MAAs (Urrea-Victoria et al. 2025). This variation in MAA concentrations may be attributed to environmental differences, genetic variability within populations, or physiological responses to local stressors. Future studies should further evaluate these factors to better understand the underlying causes of these fluctuations.

Similarly, samples of *Gracilariopsis cf. tenuifrons* from San Andrés Island exhibited a high MAA content (1.45 mg g⁻¹ DW), comparable to *G. longissimi* (0.80–1.62 mg g⁻¹ DW) reported in other regions (Álvarez-Gómez et al. 2019). *Gracilariopsis cf. tenuifrons*, as reported by Torres et al. (2015), demonstrated significant variation in MAA content when cultured under different levels of photosynthetically active radiation (PAR). Under higher PAR conditions (600 and 1000 μmol m⁻² s⁻¹), total MAA content increased by approximately 20%, with a notable rise in palythanol (6) concentration, which showed a strong correlation with increased irradiance. These findings suggest that *G. tenuifrons* under laboratory conditions exhibits a remarkable capacity to accumulate MAAs, similar to other *Gracilariopsis* species. This further supports the role of MAAs in photoprotection against high irradiance and can explain high values of MAA concentration in *Gracilariopsis cf. tenuifrons*.

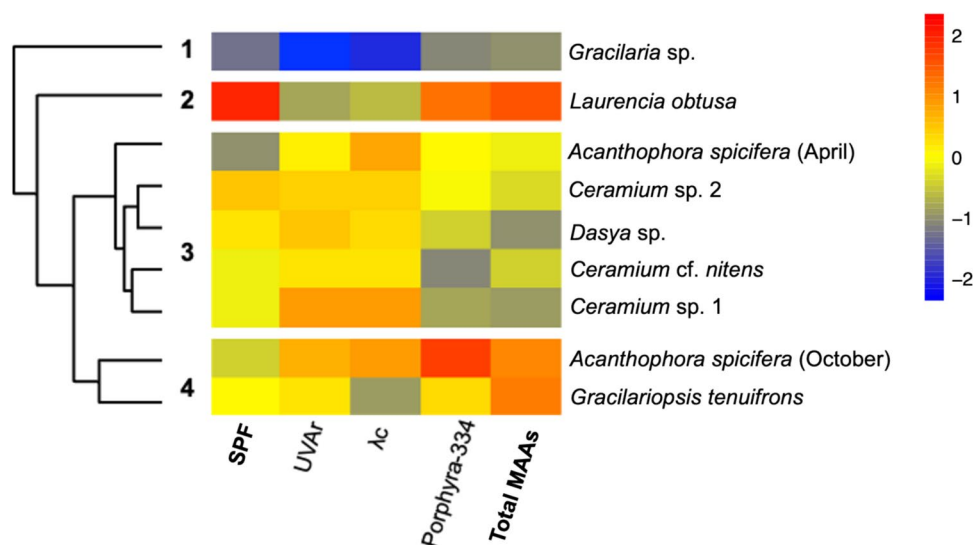
In relation to the concentrations of individual MAAs (Fig. 2), shinorine (1) concentrations ranged from 0.01 to 0.75 mg g⁻¹ DW, with the highest values found in *Gracilariopsis cf. tenuifrons* and *Ceramium cf. nitens*, while

Gracilaria sp. and *Dasya sp.* exhibited the lowest levels of this compound. Palythine (2) concentrations ranged from 0.05 to 0.54 mg g⁻¹ DW, with the highest value detected in *L. obtusa*, and the lowest in the *Ceramium sp. 2*. Asterine-330 (3) levels ranged from 0.04 to 0.10 mg g⁻¹ DW, with the highest concentration in *G. tenuifrons*, while *L. obtusa* had the lowest concentration (Fig. 2). Porphyra-334 (4) concentrations ranged from 0.01 to 0.92 mg g⁻¹ DW, with the highest values observed in *A. spicifera*, *L. obtusa*, and *G. tenuifrons*, while *Gracilaria sp.* and *Ceramium cf. nitens* had the lowest concentrations of this MAA. The sample of *A. spicifera* collected in October 2023 had 0.02 mg g⁻¹ DW of palythine-threonine. Additionally, palythanol was identified in the *L. obtusa* sample (0.04 mg g⁻¹ DW).

Photoprotective Potential of Mycosporine-Like Amino Acids in Red Algae

A heatmap (Fig. 3) was created to compare the results of SPF, UVA_r, λ_c, porphyra-334 (4) concentration, and total MAAs at a concentration of 5 mg ml⁻¹. Red colors indicate values above average, while blue colors reflect values below average, allowing a visual interpretation of the relationship between MAA concentration and photoprotective activity. The heatmap grouped into four clusters: Cluster 1, which included only *Gracilaria sp.*, exhibited the lowest values for SPF, UVA_r, and λ_c, with a low content of MAAs. Cluster 2

Fig. 3 Heatmap of photoprotective properties of aqueous extracts from red algae tested at a concentration of 5 mg ml⁻¹. Variables shown include SPF, UVA_r, λ_c , porphyra-334 concentration, and total mycosporine-like amino acids content. Highlighted bold numbers correspond to each cluster



featured *L. obtusa*, which showed the highest UVB photoprotection values and the highest MAA concentrations, highlighting its potential for cosmetic applications. Cluster 3, the largest group, displayed average photoprotection values and low MAA concentrations. Finally, Cluster 4, including *G. tenuifrons* and *A. spicifera*, also exhibited high MAAs concentrations and important photoprotection parameters, suggesting this species as promising for its photoprotective properties.

In the heatmap, species of *L. obtusa* and *A. spicifera* collected in October 2023 as well as *G. tenuifrons* showed high photoprotection and significant MAA concentrations among the evaluated samples due to their high exposure to sunlight. The Archipelago of San Andrés, Providencia, and Santa Catalina receives high levels of UV radiation annually (5313.1 Wh m⁻² per day); according to official data (IDEAM et al. 2017), algae from the intertidal zone are expected to produce high concentrations of MAAs as means of protection against solar radiation.

Species such as *Gracilaria* sp., *Ceramium* cf. *nitens*, *Ceramium* sp. 1, and *Ceramium* sp. 2 showed lower MAAs concentration. Concentrations of MAAs are highly dependent on algal species, as it has been reported in various studies (Korbee et al. 2006; Pliego-Cortés et al. 2019; Geraldés et al. 2020). Other opportunities to obtain MAAs from red algae would be through cultures since optimized cultivation methods for obtaining MAAs have shown that increasing nitrogen availability and UV radiation can yield MAA concentrations as high as 8.9 mg g⁻¹ DW (Peinado et al. 2020). This suggests that cultivating macroalgae under controlled conditions could enhance MAA content, increasing their potential for commercial applications.

UVA_r values above 0.8 indicate that the extract is ranged as maximum UVA protection, which is particularly advantageous for cosmetic formulations designed to provide both

UVB and UVA protection. When correlating MAA content with UVA_r and λ_c parameters, it was observed that despite high Porphyra-334 (4) levels in *L. obtusa* and *G. tenuifrons*, extracts from these species did not meet the broad-spectrum protection criteria based on λ_c . This suggests that other compounds may contribute to UVA_r and λ_c . Furthermore, photoprotective formulations containing MAAs such as shinorine (1), asterine-330 (3), and porphyra-334 (4), which strongly absorb in the UVA region, have not been classified as UVA sunscreen filters (Médice et al. 2023). These findings indicate that the mere presence of MAAs does not necessarily ensure UVA protection, as exemplified by the extract of *Laurencia obtusa* sample, which exhibited high UVB protection but relatively low UVA protection.

Commercial products such as Helionori™, Algamarine™, and Helioguard™ 365 sunscreens already use marine-derived MAAs like porphyra-334 (4) as active ingredients. The use of polymeric gels with Pluronic F-127® in formulations with MAAs has also demonstrated photoprotection in vivo tests (Tosato et al. 2015). In response to the growing demand for natural and environmentally friendly products, MAAs obtained from red macroalgae are potentially valuable as promising ingredients for the cosmetic industry.

In conclusion, this study allowed the identification and quantification of six known MAAs from Caribbean algae. Aqueous extracts from *L. obtusa* showed the highest concentration of MAAs (1.54 mg g⁻¹ DW), with porphyra-334 (4) being the predominant compound. Heatmap analysis revealed a significant correlation between MAA concentration and photoprotective capacity, with *L. obtusa* showing a direct association between high MAA levels and UVB protection, achieving a SPF of 23.14. Additionally, *A. spicifera*, characterized by a high porphyra-334 (4) content, exhibited broad-spectrum photoprotection. These findings align with

previous reports from algae belonging to the Gracilariales and Ceramiales orders. However, due to their low local abundance and biomass, the studied macroalgae cannot be considered optimal candidates as sustainable sources of bioactive metabolites for photoprotective cosmetic applications.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s43450-025-00663-7>.

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Author Contribution EA-N conceived the idea and developed the methodology under the supervision of VU-V, FARR, GMC, and LC. NR-D, MP-H, and VU-V were responsible for collecting and identifying algal samples. EA-N, VU-V, LC, and FAR-R led the manuscript writing, with support from all the authors. All authors contributed to the reviewing and editing of the manuscript.

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Data Availability The datasets generated and/or analyzed during this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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