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BRIEF REPORT

Phytomelatonin contents in macroalgae

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Abstract

Phytomelatonin is an indoleamine with clearly established antioxidant, regulatory, and signalling actions in vascular plants and also several studies have highlighted its presence in macroalgae. Despite this, its quantitative distribution in macroalgae remains insufficiently investigated and documented. In this study, phytomelatonin was quantified in six seaweeds (*Cystoseira compressa*, *Carpodesmia tamariscifolia*, *Halopteris scoparia*, *Sargassum vulgare*, *Ulva intestinalis* and *Ulva linza*) using high-performance liquid chromatography coupled with fluorescence detection (HPLC-FLD). The phytomelatonin content in the six seaweeds ranged from 27.96 ± 4.28 to 639.33 ± 36.61 ng g^{-1} fresh weight (FW). These results emphasize the potential of these macroalgae as a natural source of phytomelatonin for sustainable agricultural and biotechnological applications, and give rise to the hypothesis that the phytomelatonin content of these algae may contribute independently and/or synergistically to their biostimulant and bioprotectant effects on plants, but further studies are required to confirm this hypothesis and investigate phytomelatonin fluctuations in these seaweeds.

Keywords Bioprotectants · Biostimulants · Macroalgae · Melatonin · Phytomelatonin · Seaweeds

Introduction

The agricultural sector is affected by environmental stresses arising from escalating global warming and climate change. The growing frequency and intensity of abiotic stresses such as salinity, extreme temperature, heavy metals toxicity and drought leads to a decline in crops productivity and quality. As a result, one of the main challenges facing food security is maximizing global food production while guaranteeing crop quality and reducing the environmental effects of agricultural practices (Ben Mrid et al. 2021; Han et al. 2024). To enhance crop yield, the World Food and Agriculture - Statistical Yearbook 2024, published by the Food and Agriculture Organization of the United Nations (2024), forecasts agricultural use of synthetic fertilizers at 185 million tonnes, and global use of pesticides at 3.7 million tonnes in 2022. However, excessive and inappropriate use of fertilizers and pesticides can induce imbalances in soil nutrients, influencing soil productivity and the quality of the agrarian ecosystems (Tripathi et al. 2020), around 24 billion tonnes of fertile soils are being lost annually worldwide (UNCCD 2017). For the purpose of ensuring food security for the succeeding generations, the sustainability of natural agro-ecosystems must be secured while improving the health and yield of the crops

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that we produce for ourselves, by increasing the nutrient uptake and efficiency of use, and by enhancing plants natural defence mechanisms against biotic and abiotic stresses, simultaneously reducing the dependence on chemical inputs (Costa et al. 2019; Singh et al. 2020; Ben Mrid et al. 2021; Han et al. 2024). Accordingly, biostimulants and bioprotectants are steadily being appreciated as vital agents for boosting plant growth as well as yield and reducing the effect of stresses (Ben Mrid et al. 2021).

Phytomelatonin is the melatonin (N-acety-5-methoxytryptamine) derived from algae and plants (Arnao et al. 2023). A naturally occurring, ubiquitous molecule (Nawaz et al. 2016), melatonin was first discovered in the pineal gland of a bovine in 1958 (Lerner et al. 1958) and much later in 1995 its presence in plants was reported (Dubbels et al. 1995; Hattori et al. 1995). Since its first discovery in plants, phytomelatonin has received a great deal of attention, although it has been quantified in various plants for its multiple functions in plants biochemistry and physiology (Dubbels et al. 1995; Hattori et al. 1995; Manchester et al. 2000; Hernandez-Ruiz et al. 2004; Zhang et al. 2015; Arnao and Hernández-Ruiz 2019; Ahmad et al. 2023). Melatonin biosynthesis in plants involves multi-step enzymatic pathways that begin with the decarboxylation of tryptophan to tryptamine by tryptophan decarboxylase, preceding the resulting tryptamine being hydroxylated by tryptamine 5-hydroxylase to form serotonin. Unlike the biosynthesis of melatonin from tryptophan in animals, the sequence of reactions is reversed: hydroxylation precedes decarboxylation. These steps are followed by the acetylation of serotonin into N-acetylserotonin, catalysed by the enzyme arylalkylamine N-acetyltranserase. Finally, N-acetylserotonin is methylated by N-acetylserotonin o-methytransferase to form melatonin (Tan et al. 2012).

Phytomelatonin is found in all parts of plants, including roots, shoots, seeds, fruits, leaves and flowers (Arnao and Hernández-Ruiz 2014). As a regulator of a wide range of physiological process, it is implicated in the regulation of plant growth and development (Sun et al. 2021), its amphiphilic properties allow it to penetrate cell membranes readily and functions as a powerful antioxidant, by neutralizing reactive oxygen species (ROS) and reactive nitrogen species (RNS) while stimulating antioxidant enzymes (Himanshu et al. 2024), thereby increasing the efficiency of photosynthesis and the accumulation of osmolytes (Fan et al. 2018).

The aim of this study was to assess the presence of phytomelatonin in six macroalgae by quantifying it using optimised analytical techniques, namely high-performance liquid chromatography coupled with fluorescence detection (HPLC-FLD). Given its pleiotropic role in plant physiology, including antioxidant activity, protection against stress and regulation of plant growth, phytomelatonin may contribute considerably to the biostimulant and bioprotectant characteristics recorded in seaweed extracts. Phytomelatonin could therefore represent a key bioactive molecule responsible, at least in part, for the improvement of plant growth, plant resilience and enzymatic activation induced by seaweed-based biostimulants and bioprotectants as agro-chemicals.

Materials and methods

Chemicals

All reagents and solvents (ethyl acetate, acetonitrile and methanol, HPLC grade) used were from Sigma-Aldrich (Spain). Standard melatonin (99%) was provided by Acros Organics Co. (Geel, Belgium). Ultra-pure water from Milli-Q system (Milli-Q Corp, Merck, Germany) was utilized.

Algal materials

The algae used in the current investigation are the Phaeophyceae *Cystoseira compressa* (Esper) Gerloff & Nizamuddin, *Carpodesmia tamariscifolia* (Hudson) Orellana & Sansón, *Halopteris scoparia* (L.) Sauvageau, and *Sargassum vulgare* C. Agardh, and the Chlorophyceae *Ulva intestinalis* L. and *Ulva linza* L. These algae were selected based on the checklist published by Moussa et al. (2018), which reveals the wide distribution of the above-mentioned species on the Moroccan Mediterranean coast, specifically in the marine protected area of Al Hoceima national park.

Algae samples were hand-gathered from the Mediterranean littoral of Al Hoceima (35°14'41"N 3°57'56"W) in March 2025 during ebb tide. The samples were carefully washed with seawater to remove any sand debris or epiphytes, after which the algae biomass were transported to the laboratory in an isothermal box. The samples were than rewashed to remove any excess salt and blotted before being stored at −20°C for further use.

Phytomelatonin extraction

The extraction process was performed following the protocol of Arnao and Hernández-Ruiz (2009) with slight modifications. Generally, 400 mg of fresh alga from each sample was added to 4 mL of ethyl acetate. The mixtures were kept in the dark under continuous shaking using a rotary agitator at room temperature (20°C) for 15 hours. The extraction procedure was conducted in triplicate in PVPP tubes. The mixtures then were centrifuged at 9,130 ×*g* for 10 min The ethyl acetate was removed under a vacuum thermo-centrifuge SpeedVac (ThermoSavant SPD111V, Thermo-Fisher, USA) over 4 h at 45°C. The obtained samples were resuspended in 1 mL of acetonitrile using a vortex mixer to ensure complete

homogenisation and total dissolution of the residual material and then filtered through a 0.22 µm PTFE filter.

Phytomelatonin quantification

Phytomelatonin levels in the macroalgae samples were quantified using high-performance liquid chromatography coupled with fluorescence detection as previously described (Arnao and Hernández-Ruiz 2009; Losada et al. 2022; Kaabi et al. 2025). The instrument used was a Jasco model 2000 HPLC (Jasco Co., Tokyo, Japan), comprising an online degasser, quaternary pump, autosampler and thermo-stated column. A Phenomenex-Luna ODS2 S5 (150 × 4.6 mm) column was used to accomplish the separation under an isocratic mobile phase composed of acidified water (85%) and methanol (15%) with a flow rate of 0.5 mL min^{-1}, and a column operating temperature of 36°C. The detection was carried out employing an in-line fluorescence detector (Jasco FP-2020-Plus) at an excitation wavelength of 280 nm and an emission wavelength of 350 nm. The identification of phytomelatonin in algal samples is achieved by comparing retention times with those of standard melatonin (t_R = 11.2 min) and analysing excitation and emission spectra using in-line fluorescence analysis with Jasco ChromNav 2.0 software. To ensure accurate identification, an Agilent LC-chromatograph TOF mass spectrometer (LC/QTOF-MS) (Agilent Technologies, USA) was used to determine the precise phytomelatonin determination of the samples analysed.

Statistical analysis

Statistical analysis was performed using RStudio software (v.2025.05.1+513; Posit Software, USA). Employing an in-line fluorescence detector (Jasco FP-2020-Plus) values were compared using Kruskal-Wallis test at a 5% probability level, followed by Dunn's post hoc test with Holm-Bonferroni correction. The normality of the data was first checked using the Shapiro-Wilk test.

Results

The peak corresponding to phytomelatonin was identified using HPLC-FLD at 11.2 min, which corresponded to the retention time of standard melatonin. In addition, a calibration curve for standard melatonin was prepared in the range of 0 to 0.5 ng of injected melatonin and demonstrated excellent linearity (R^2= 0.991) (Arnao and Hernández-Ruiz 2009; Kaabi et al. 2025). The phytomelatonin content of the studied macroalgae is shown in Table 1.

Phytomelatonin levels varied considerably among the six algae species (Kruskal-Wallis test, p = 0.0083), but the difference was statistically significant only between *C. tamariscifolia* and *C. compressa* based on the Dunn test results. *Carpodesmia tamariscifolia* had the highest phytomelatonin concentration, reaching 639.33 ± 36.61 ng g^{-1} FW, while *C. compressa* had the lowest level, with only 27.96 ± 4.28 ng g^{-1} FW. The other species had intermediate values, such as *S. vulgare* (160.86 ± 12.59 ng g^{-1} FW), *H. scoparia* (140.7 ± 5.34 ng g^{-1} FW), *U. intestinalis* (123.73 ± 11.48 ng g^{-1} FW) and *U. linza* (57.96 ± 4.82 ng g^{-1} FW).

Discussion

Algal extracts derived from species such as *C. compressa*, *C. tamariscifolia*, *H. scoparia*, *S. vulgare*, *U. intestinalis* and *U. linza* have exhibited significant effects in agricultural applications. For example, *C. compressa* extract contains high levels of amino acids (e.g., L-alanine ~23 mg (100 g)$^{-1}$ extract and L-glutamic acid ~19 mg (100 g)$^{-1}$ extract), sugars (e.g., arabinose ~4 g (100 g)$^{-1}$ extract and sucrose ~3.6 g (100 g)$^{-1}$), and zeatin (~244 mg (100 g)$^{-1}$ extract) as the most abundant phytohormone, all of which contribute to reinforcing the nutritional balance of plants and promoting their growth (Rabhi et al. 2025).

Sargassum vulgare and *C. tamariscifolia* extracts are recognized for enhancing plant growth and salt tolerance

Table 1 Phytomelatonin content in seaweeds

Family	Specie	Phytomelatonin content (ng g^{-1} FW)
Phaeophyceae (brown algae)	*Cystoseira compressa*	27.96 ± 4.28 [b] *
	Carpodesmia tamariscifolia	639.33 ± 36.61 [a]
	Halopteris scoparia	140.7 ± 5.34 [ab]
	Sargassum vulgare	160.86 ± 12.59 [ab]
Chlorophyceae (Green algae)	*Ulva intestinalis*	123.73 ±11.48 [ab]
	Ulva linza	57.96 ± 4.82 [ab]

*Results are presented as mean ± standard deviation (n = 3). Different letters indicate significant differences between the species (phytomelatonin levels) according to Dunn's post hoc test with Holm-Bonferroni correction.

by increasing the activities of antioxidant enzymes such as superoxide dismutase (SOD), glutathione S-transferase (GST), and glutathione peroxidase (GPx), in addition to the regulation of carbon and nitrogen metabolism by boosting the activities of several key enzymes implicated in carbon and nitrogen assimilation as malate dehydrogenase (MDH), phosphoenolpyruvate carboxylase (PEPC), aspartate aminotransferase (AAT), glutamate dehydrogenase (GDH), and glutamine synthetase (GS). The increased activity of antioxidant enzymes played an important role in reducing hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) levels in plants subjected to salt stress (Krid et al. 2024a, b). Antifungal evaluations also revealed significant efficacy of *S. vulgare* extracts against *Pythium aphanidermatum*, the agent responsible for pythium leak in potatoes (Ammar et al. 2017).

Treatments with *H. scoparia* extracts have been shown to activate the phenylpropanoid defence pathway in tomato seedlings. This response is reflected in a noticeable increase in the activity of phenylalanine ammonia-lyase (PAL) and the accumulation of phenolic compounds. Since PAL, a key enzyme in polyphenol biosynthesis, its induced expression highlights the potential of *H. scoparia* to improve plant resistance to both biotic and abiotic stresses (Hadjkacem et al. 2023).

Green algae such as *U. linza* and *U. intestinalis* exhibit biostimulant and bioprotectant effects. Foliar spray treatments with *U. intestinalis* greatly upped the levels of salicylic acid and its β-glucoside in parsley, which in basil induced the accumulation of jasmonic and abscisic acids, indicating preparation for defensive responses and changes in metabolism (Paulert et al. 2021).

Although there are no straightforward measurements of phytomelatonin in these species, their levels of antioxidants, osmolytes, and phytohormones match the mechanisms often triggered by phytomelatonin in stress tolerance and growth regulation processes in plants. The complex biochemical profiles of these algae strongly suggest that phytomelatonin may also contribute synergistically to the biostimulant and bioprotectant activities of the extracts.

The quantification of phytomelatonin in seaweeds has been the subject of only a limited number of studies until now, underlining the scarcity of research in this field in comparison with vascular plants. However, the first published evidence was provided by Fuhrberg et al. (1996) who established phytomelatonin production in the juvenile sporophytes of the brown alga *Pterygophora californica* by reverse-phase HPLC with on-line electrochemical detection and the confirmation was assessed using radioimmunoassay, linking phytomelatonin to the regulation of growth under light-dark cycles. Subsequently, Pape and Luning (2006) have developed and validate a robust HPLC-ELISA (Enzyme-Linked Immunosorbent Assay) method for quantifying phytomelatonin in phototrophic organisms, reporting around 12 pg g^{-1} fresh weight in the green alga *Ulva lactuca*. More recently, the presence of phytomelatonin in *Ulva* sp. was confirmed and quantified using thin layer chromatography (TLC) followed by fluorescence detection and gas chromatography/mass spectroscopy (GC/MS) by Tal et al. (2011) highlighting its role as an antioxidant and its semi-lunar rhythmic fluctuations in responses to environmental stresses.

Exogenous melatonin has proven to be a potent bioactive compound in plant physiology, capable of improving plant growth and tolerance to a wide range of stresses (Arnao and Hernández-Ruiz 2014). When applied externally, melatonin acts simultaneously as a biostimulant, enhancing crop growth and yield, and as a bioprotectant, strengthening the natural defence systems of plants against biotic and abiotic stresses (Arnao et al. 2022; Aghdam and Arnao 2024; Khan et al. 2024)

Melatonin treatments promote the development of plants at several stages: germination, vegetative growth and reproductive phase. During germination, it has been demonstrated that priming seeds in melatonin for 12 h breaks seed dormancy and stimulates root formation and vitality under water stress conditions (Zhang et al. 2013). Furthermore, melatonin pre-treatment of seeds mitigates the inhibitory effects of NaCl-induced stress by upregulating abscisic acid (ABA) catabolism genes and downregulating ABA biosynthesis genes, in addition to upregulating gibberellin (GA) biosynthesis genes, which contributes to a significant increase in GA content (Zhang et al. 2014). These effects are not limited to cucurbits: similar results have been observed in soybean, wheat, maize and alfalfa subjected to flooding stress (Luo et al. 2024). An extensive study on melatonin effects in germination also has been conducted (Wang et al. 2024).

The first use of melatonin in plant agriculture from its potently antioxidative properties showed that treatment with melatonin reduces oxidative damage in tomato seedlings under salt stress by raising the activity of antioxidant enzymes (SOD, catalase, ascorbate peroxidase, glutathione reductase, among others), boosting the photosynthetic mechanisms, and improving osmoregulation through an increase in proline and carbohydrate metabolism. The mitigation of salt toxicity induced by melatonin is reflected in a greater increase in growth indicators, relative water content, membrane stability index and gas exchange attributes. Melatonin application also led to a reduction in MDA and H_2O_2 levels, as well as significant decrease in Na^+ absorption at root interface of tomato plants. Overall, melatonin-induced stress tolerance linked to improved water relationship, increased antioxidant defences and photosynthetic capacity, maintaining ionic homeostasis (Altaf et al. 2021; Arnao and Hernández-Ruiz 2021b, a; Arnao et al. 2022; Bhardwaj et al. 2022).

Besides its role in alleviating abiotic stresses, exogenous melatonin also boosts resistance to biotic stresses, like pathogen attacks. Melatonin stimulates the immune responses of plants via the activation of signalling pathways linked with JA and SA, which are crucial hormonal regulators of plant immunity, as well as nitric oxide (NO), which is an

important signalling modulator in plant defence (Arnao and Hernández-Ruiz 2018; Moustafa-Farag et al. 2019; Arnao and Hernández-Ruiz 2021; Hernández-Ruiz et al. 2023).

The identification of phytomelatonin, for the first time, in these macroalgae opens a door to rethink the mode of action of treatments with algae-based biostimulants to improve crops, being a first step in the search for optimal sources of phytomelatonin in macroalgae, and also for investigating fluctuations in phytomelatonin levels in macroalgae depending on different environmental conditions and/or algae growth stage and/or the algae's biological rhythms.

Conclusion

The presence of phytomelatonin in *C. compressa*, *C. tamariscifolia*, *H. scoparia*, *S. vulgare*, *U. intestinalis* and *U. linza* reinforces the hypothesis that the biostimulant and bioprotectant effects of this seaweed extracts can be partially ascribed to the presence of this compound. It should be noted that the documented physiological and biochemical responses of these macroalgae extracts, such as improving seed germination, stimulating root system and shoot system development, activating antioxidant defence systems, and boosting tolerance to abiotic and biotic stresses, are surprisingly well matched to reported actions when exogenous melatonin supplied to plants. This high degree of similarity indicates the potential role of exogenous melatonin as a key bioactive compound responsible for the beneficial impacts of seaweeds extracts on plant performance. Accordingly, these results lay the foundation for in-depth research on the beneficial on specific contributions of melatonin derived from algae to sustainability in agriculture practices, facilitating a better understanding of their action mechanisms, the optimization of application approaches, and potentially synergistic effects with other phycocompounds. These finding could eventually lead to the development of novel innovative, eco-friendly biostimulant and bioprotectant formulations to crop growth, resiliency, and productivity in an environmentally sustainable way.

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Data availability For any additional data contact the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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