Food Chemistry Advances 8 (2025) 101062

Contents lists available at ScienceDirect

Food Chemistry Advances

journal homepage: www.elsevier.com/locate/focha

Seaweed bioprospecting in the Mediterranean Sea and the potential exploitation

Loredana Stabili [a,b,*], Maria Immacolata Acquaviva [a], Ester Cecere [a], Carmela Gerardi [c], Antonella Petrocelli [a,b], Elisa Quarta [a,b]

[a] Institute of Water Research (IRSA) - C.N.R, Taranto 74123, Italy
[b] National Biodiversity Future Center (NBFC), Palermo 90133, Italy
[c] Institute of Sciences of Food Production, U.O.S. di Lecce, Lecce 73100, Italy

ARTICLE INFO

Keywords:
Antibacterial activity
Antioxidant activity
Lipidic extract
Fatty acids
Seaweeds

ABSTRACT

Algae attract interest as a source of bioactive compounds with diverse properties. In this study, we conducted a comparative analysis of the potential of nine seaweeds collected in the Mediterranean Sea investigating their antibacterial, antioxidant, and nutritional properties. The species analyzed were: *Chaetomorpha linum, Rama rupestris, Gracilaria dura, Gracilaria gracilis, Gracilariopsis longissima, Grateloupia turuturu, Hypnea corona, Gongolaria barbata* and *Undaria pinnatifida*. All lipidic extracts exhibited antibacterial activity against different *Vibrio* species. Lipidic extracts from *H. corona, G. barbata, R. rupestris* and *U. pinnatifida* inhibited some antibiotic-resistant human pathogens. Palmitic and linoleic acids appear to be involved in these activities. The extracts also showed antioxidant activity with the highest value recorded for *G. barbata* (1009.560±115.174 mmol Trolox equivalent/g extract). Gas chromatography revealed the presence of free saturated (SAFAs), monounsaturated (MUFAs), polyunsaturated (PUFAs) fatty acids with SAFAs prevailing in *G. longissima* (67.30±13.10%) and PUFAs in *C. linum* (71.97±13.48%). The seaweeds showed a noteworthy ω6/ω3 ratio. The results are discussed in the light of the biotechnological applications indicating that *C. linum, G. turuturu* and *U. pinnatifida* have the highest quality fatty acid profiles useful in nutraceuticals. *Hypnea corona, G. barbata, R. rupestris* and *U. pinnatifida* are more promising for pharmaceutical use.

1. Introduction

Seaweeds are marine primary producers widely distributed in the world oceans, numbering several hundred species. They provide a wide range of ecosystem services producing almost half of the world's O_2 and providing shelter and food to many animals. In addition, seaweeds are considered excellent indicators of environmental quality and can treat pollutants from wastewater as they are able to absorb both inorganic and organic pollutants (Cotas et al., 2023; Guo et al., 2022; Theobald et al., 2024). Seaweeds have also a high value in food production, both for their nutrient content and health benefits. Finally, algal biomass contains a wide range of bioactive compounds, which can find application in various industrial fields due to their antimicrobial (e.g., antibacterial, antiviral and antifungal) and antioxidant activities. Among them, polysaccharides, phlorotannins, proteins, terpenoids, pigments, peptides, lipids, phenolic compounds, vitamins are included (Rengasamy et al., 2020). These potential drugs, especially antibiotics, make seaweeds appealing for the pharmaceutical industries (Guedes et al., 2024) since the emergence of antibiotic-resistant bacteria necessitates the development of new antibiotics to combat infections that are no longer effectively treated by conventional medications (Larsson & Flach, 2022; Pancu et al., 2021). Significant progress has been made in the field of engineered biosynthetic antimicrobials, but nature still remains the source offering the most attractive variety of new antibiotics (Álvarez-Martínez et al., 2020; Cook & Wright, 2022). In particular, seaweeds have been recognized for millennia in traditional medicine, as having therapeutic value (Pérez-Lloréns et al., 2023), but only in recent years the attention has focused on the identification of secondary metabolites with antibacterial activity thanks to modern screening methods. In vitro antimicrobial activity against bacteria, viruses, fungi was assessed in extracts of several species of red, green and brown seaweeds, mainly against human pathogens (Francavilla et al., 2015;

---

* Corresponding author at: Institute of Water Research (IRSA) - C.N.R, Taranto 74123, Italy.
E-mail addresses: loredana.stabili@irsa.cnr.it (L. Stabili), maria.acquaviva@irsa.cnr.it (M.I. Acquaviva), ester.cecere@irsa.cnr.it (E. Cecere), carmela.gerardi@ispa.cnr.it (C. Gerardi), antonella.petrocelli@cnr.it (A. Petrocelli), elisaquarta@cnr.it (E. Quarta).

https://doi.org/10.1016/j.focha.2025.101062
Received 17 April 2025; Received in revised form 10 July 2025; Accepted 15 July 2025

Katiyar et al., 2021; Lomartire & Gonçalves, 2022; Masarin et al., 2016; Noorjahan et al., 2022; Trivedi et al., 2016). Detection and evaluation of the efficacy of algal antibacterial substances on fish pathogens is still limited (Siddik et al., 2023). The present paper represents a contribution on this topic since we investigated the antimicrobial activity of nine seaweed species collected in the Mediterranean area also against vibrios which include several species pathogens to fish and marine organisms (Manchanayake et al., 2023; Gracinda et al., 2022). The attention was focused on the following seaweed species: *Chaetomorpha linum* (O.F. Müller) Kützing (Chlorophyta, Cladophorales), *Rama rupestris* (Linnaeus) Boedeker, M.J. Wynne & Zuccarello (Chlorophyta, Cladophorales), *Gracilaria dura* (C. Agardh) J. Agardh (Rhodophyta, Gracilariales), *Gracilaria gracilis* (Stackhouse) Steentoft, L.M. Irvine et Farnham (Rhodophyta, Gracilariales), *Gracilariopsis longissima* (S.G. Gmelin) Steentoft, L.M. Irvine *et* Farnham (Rhodophyta, Gracilariales), *Grateloupia turuturu* Y. Yamada (Rhodophyta, Halymeniales), *Hypnea corona* Huisman & Petrocelli (Rhodophyta, Gigartinales), *Gongolaria barbata* (Stackhouse) Kuntze (Heterokontophyta, Fucales) and *Undaria pinnatifida* (Harvey) Suringar (Heterokontophyta, Laminariales). Since the industry requires large amounts of biomass to obtain bioactive compounds, some of these nine species were selected because they are particularly abundant along the Northern Ionian Sea (Mar Piccolo of Taranto) and easily available (e.g., *G. barbata, R. rupestris*) (Petrocelli et al., 2019); others were selected because they proved to be easily cultivable with large biomass production (e.g., *C. linum, G. dura, G. gracilis, G. longissima*) (Giangrande et al. 2020; Petrocelli & Cecere, 2019; Stabili et al., 2019a). The remaining species (*G. turuturu, H. corona, U. pinnatifida*) are non-indigenous species (NIS), introduced into the Northern Ionian Sea (Mar Piccolo of Taranto) in different years, that have formed more or less stable populations in the basin (Cecere et al., 2000; Petrocelli et al., 2020). Their exploitation thanks to the presence of bioactive compounds, recorded in this study, could transform a potential invasion into a valuable resource, effectively allowing the control of these populations (Pacheco et al., 2020).

Antimicrobial activity of the here investigated seaweeds on *Vibrio* was unknown (Lopes et al., 2021), thus, the present paper is a first insight into this bioprospecting. Seaweeds are also the main food in several Asian countries and are receiving increasing attention elsewhere in the world, where the growing population is making the availability of new healthy resources necessary. Algae are a novel and easily accessible feedstock that can be used in the food market, being a source of lipids beneficial to human health, especially essential unsaturated fatty acids (Lopes et al., 2021; Murai et al., 2021). The types and amounts of ω3 and ω6 fatty acids produced varies significantly between different algal species (Marques et al., 2021; Murai et al., 2021). On account of these features the introduction of these nutrients in the daily diet can represent an effective alternative to the consumption of unhealthy food, based on a high intake of saturated fatty acids, now recognised among the main causes of social metabolic diseases such as diabetes, hypercholesterolemia, obesity, and the resulting cardiovascular complications (Wali et al., 2020). Dietary fiber supplementation from seaweeds promotes the maintenance and growth of beneficial intestinal flora (Murai et al., 2021). The use of algal hydrocolloids in the food sector finds many applications both as stabilizers and nutraceuticals, with marked antimicrobial activity (Basir et al., 2024; Caneschi et al., 2023; Peñalver et al., 2020). In this scenario we investigated the above selected algal species as a source of beneficial compounds for humans and attention was focused on total lipid and fatty acid content. Although studies have already been carried out on some of the seaweeds here considered, a comparison has never been made among those collected in the Mediterranean Sea, and this study, therefore, represents a first attempt in this direction.

Finally, the antioxidant effect of several seaweed secondary metabolites is equally intriguing, since they could become a valid natural and safe alternative to synthetic antioxidants used such as GSH precursors, mitochondrially targeted antioxidants, NADPH oxidase inhibitors, which showed toxic effects (Halliwell et al., 2024; Kumar et al., 2021a; Kumar et al., 2021b). In this context, this study aims to examine the nine seaweed species collected in the Mediterranean Sea (i.e., Northern Ionian Sea) by performing a comparative analysis of their potential antibacterial and antioxidant activity and nutritional value. The importance of comparing these species lies in the evaluation of those most suitable for use in the nutraceutical, pharmaceutical and fortified food sectors. Therefore, the present study aims to develop, in Europe, new production chains related to the use and valorisation of seaweeds.

2. Materials and methods

2.1. Species description and collection

The seaweeds come from the Ionian Sea populations and were collected during the periods of maximum growth.

Chaetomorpha linum can live in coastal waters, in the attached form, and in transitional waters, mainly in the floating form (Cormaci et al., 2014). In the Mar Piccolo of Taranto (Ionian Sea, southern Italy), *C. linum* is present only in the floating form, reaching considerable biomass value in the range of a few dozen kilograms per square meters, throughout the year, with a preference for spring and summer (Petrocelli et al., 2019).

Rama rupestris prefers high hydrodinamism zones but commonly lives also in transitional waters (Cormaci et al., 2014), such as the Mar Piccolo of Taranto. Here, it was often observed blooming in early spring, forming surface floating populations in some areas (Stabili et al., 2014).

Gracilaria dura is a common species in lagoon environments. It is widely known to produce high-quality agar. In Mar Piccolo, it lives as a bentopleustophytic species at a depth up to 5 - 6 m, becoming one of the dominant species in summer (Cecere & Petrocelli, 2009).

Gracilaria gracilis is a marine agarophyte species, common also in transitional waters where it is often observed in the unattached form (Cormaci et al., 2020). In the Mar Piccolo of Taranto, it is present at the intertidal zone in the floating form, moderately abundant from autumn to spring.

Gracilariopsis longissima is a marine cosmopolitan species, distributed in sheltered sites at the intertidal zone (Cormaci et al., 2020). The attached habitus is the commonest, even though it is often present also in the floating form, mainly in transitional waters. In the Mar Piccolo of Taranto, *G. longissima* unattached thalli generally coexists with *G. gracilis.*

Grateloupia turuturu is a marine species, living both in exposed and sheltered areas in the intertidal zone and in the attached habitus (Cormaci et al. 2021). It is a non-indigenous species (NIS), introduced in the Mar Piccolo in 2007, where it was commonly observed settled also on plastic nets abandoned on the bottom (Petrocelli et al., 2020).

Hypnea corona is a carrageenophyte recently described in Australia (Huisman & Petrocelli, 2021). In Mar Piccolo it is a NIS, first reported in December 2000 and now become the summer dominant, without any impact on the populations of native species (Denti et al., 2024).

Gongolaria barbata lives attached on hard substrata with a variable morphology depending on the geographic area and the ecological conditions (Cormaci et al., 2012; Falace et al., 2024). This species is able to survive also in highly polluted waters, provided that there is enough oxygen (Sfrisoet al., 2011). In the Mar Piccolo of Taranto, *G. barbata* shows seasonal behavior, flourishing mainly during summer.

Undaria pinnatifida is an alginophyte commonly living in coastal waters, attached on hard substrata, up to 10 m depth. It is a NIS for the Mar Piccolo of Taranto, where it was introduced in 1998, through the importation of oysters (i.e. *Magallana gigas* (Thunberg, 1793)) from France (Cecere et al., 2000; Sfrisoet al., 2011) and showed a seasonal cycle, reaching its maximum growth in winter.

2.2. Reagent and standards

Reagents were acquired from various suppliers: Folin-Ciocalteu phenol reagent, Trolox [(*S*)-(-)-6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid], 2,2′-Azinobis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) from Sigma-Aldrich (St. Louis, MO, USA). The purified and deionized water, essential for making reagents and testing antioxidants was obtained through a Milli-Q water system (Merck Millipore, Darmstadt, Germany).

2.3. Preparation of lipidic extracts from the seaweeds

By using a mixture of ethanol (40 %) and sodium hypochlorite (1 %) for 10 s the seaweed samples were cleaned, in order to eliminate epiphytes and other marine organisms (Kientz et al., 2011). After removal of the necrotic parts, the same samples were rinsed with sterile sea water to eliminate any other associated debris. The cleaned material, after air-dried was pulverized. Extraction was carried out, with a Soxhlet apparatus, using 3 *g* of each sample and 150 mL of chloroform/methanol (2:1) at 55 - 60 °C for 24 hours (Ramola et al., 2019). Extraction solvents were removed under vacuum at controlled and constant temperature, then absolute ethanol (95 %, from J.T. Baker) was added to obtain a final concentration of 5 mg/mL of extract in ethanol. Finally, the antimicrobial and antioxidant activities were assayed as reported in Sections 2.5 and 2.6.

2.4. Test microorganisms

Seven human pathogenic microbial strains were used to test antibacterial activity (*Candida albicans, Candida famata, Candida glabrata, Enterococcus* sp., *Pseudomonas aeruginosa, Staphylococcus* sp. and *Streptococcus agalactiae*) in addition to several *Vibrio* strains isolated and identified from seawater samples of the Mar Piccolo of Taranto (*V. aestuarinus, Vibrio alginolyticus, V. cambelli, V. carchariae, Vibrio cholerae* non-O1*, V. diazotrophicus, V. fischeri, V. fluvialis, V. furnissii, V. harveyi, V. hollisae, V. inusitatus, V. litoralis, V. mediterranei, V. metschnikovii, V. natriegens, V. nereis, V. ordalii, V. orientalis, V. parahaemolyticus, V. salmonicida, V. splendidus* and *V. vulnificus*) (Cavallo & Stabili, 2002; Stabili et al., 2005).

2.5. Antimicrobial activity

Kirby Bauer method (Bauer et al., 1966) was used to evaluate the antimicrobial activity. Sterile 6 mm diameter paper discs (AA, Whatman International Ltd., Maidstone, Kent, United Kingdom) were impregnated with 100 μL of extract, then they were left to air-dry for 4 hours (Cavallo et al., 2013). For each test, three discs were prepared as controls: 1) the first one impregnated with carrier solvent, 2) the second one impregnated with an "extraction blank" represented by MeOH/$CHCl_3$ used as solvent in the extraction, then dried and resuspended in ethanol, 3) the third one was a positive control represented by the vibrio static agent O/129 at a concentration of 10 μg, for vibrios, and by lysozyme from chicken egg white at 0.76 mg/mL, for the other microbial strains.

100 μL of each microbial suspension (about 10^8 CFU/mL) were spreaded (Ely et al., 2004) under sterile conditions on specific agarized medium for each bacterial and fungal tested strain; the Petri dishes inoculated with *Vibrio* species were incubated at 30 °C, those with human pathogenic strains at 37 °C. The presence of a clear zone around the test discs was indicative of antimicrobial activity. Then, diameter of this clear zone was measured in millimetres. Since from the NMR and gas chromatography analyses the λ-linolenic acid resulted the most abundant fatty acid this pure compound ($\geq$ 99 Sigma–Aldrich) was employed in ethanol to determine its effective antimicrobial activity. In particular, 0.009, 0.018, 0.035, 0.051, 0.067, 0.082 mg/mL were tested for the antibacterial action (Stabili et al., 2019a).

2.6. Antioxidant activity

2.6.1. Oxygen radical absorbance capacity assay (ORAC)

For ORAC the method of Dávalos et al. (2004) was used. The ORAC procedure was carried out as per Gerardi et al. (2021). The reaction was carried out using a 96-well plate Infinite 200 Pro plate reader (Tecan, Männedorf, Switzerland), in 200 μL final reaction volume. Each sample was subjected to at least three independent assays. Seaweed extracts (20 μL) and fluorescein (120 μL; 70 nM, final concentration) were put into the microplate well and incubated at 37 °C for 15 min. Then, AAPH (2, 2′-Azobis-(2-methylpropionamidine) dihydrochloride) solution (60 μL; 12 mM, final concentration) was added and the fluorescence recorded at excitation of 485 nm and emission wavelength of 527 nm, every minute for 60 min. A blank using phosphate buffer was carried out. Decay curves (fluorescence intensity vs. time) were recorded for samples and for the antioxidant Trolox as a standard (1 – 6 μM were used to make a standard curve). The final ORAC values were indicated in terms of mmol Trolox equivalents/g of extract.

2.6.2. Trolox equivalent antioxidant capacity assay (TEAC)

The TEAC assay (Re et al., 1999) was performed adapting the method to a microplate reader as described by Gerardi et al. (2021). $ABTS^{\bullet+}$ was prepared by mixing potassium persulfate 2.45 mM (final concentration) and an aqueous solution of $ABTS^{\bullet+}$ 7 mM (final concentration) in the dark at room temperature for 12 - 16 hours. $ABTS^{\bullet+}$ solution was diluted in PBS (pH 7.4) to an absorbance of 0.40 at 734.00 ± 0.02 nm. A volume of 10 μL of Trolox or extracts diluted in PBS were added in the wells of a 96 well-plate (Costar) with 200 μL of diluted $ABTS^{\bullet+}$, choosing an absorbance of 734 nm within an Infinite 200 Pro plate reader (Tecan, Männedorf, Switzerland). The appropriate solvent blanks were tested in each plate. The lipidic extract was assayed in triplicate. The inhibition of absorbance at 734 nm of the lipidic extract was plotted as a function of concentration of Trolox and compared to a standard calibration curve of Trolox (0 – 16 μM). The control software Magellan v 7.2 was used to measure the TEAC value, expressed in terms of Trolox equivalent (in mmol)/g of lipidic extract.

2.7. Gas chromatographic analysis of fatty acid

The method reported by Folch et al. (1957) was used in order to extract total lipids from seaweeds. After homogenization of each sample, extraction was performed in methanol/chloroform/water (1/2/1) until reaching a final volume equal to 20 times the initial volume. Fatty acids composition was established according to Budge and Parrish (2003) and Couturier et al. (2020). Briefly, the fatty acids (FAs) of total lipids were transesterified to methyl esters accordingly to Stabili et al. (2019a, 2023a). The samples were cooled, and then 1 mL of distilled water was added, followed by a vigorous shaking. The fatty acid methyl esters (FAMEs) were collected in the upper benzene phase. The benzene phase was then transferred to a vial and then the drying was reached by a nitrogen stream. To avoid losing the sample, a very slow flow rate was used. FAME extracts were analysed through gas chromatography by using an HP 6890 series GC (Hewlett Packard, Wilmington, DE, USA) equipped with a flame ionization detector. FAMEs were separated with an Omegawax 250 capillary column (Supelco, Bellafonte, PA, USA) (30 m long, 0.25 mm internal diameter, and 0.25 mm film thickness). The column temperature program was as follows: 150 – 250 °C at 4 °C/min and then held at 250 °C. Helium was the carrier gas, and the injection volume was 1 mL. All assays were conducted in triplicate. FAMEs were identified by comparing retention times obtained with those of known standards (FAME mix, Supelco-USA) and the results were reported as percentages of total identified methyl ester fatty acids.

2.8. Statistical analysis

Analysis of variance (ANOVA) was performed by using STATISTICA

10.0 software in order to assess differences of the studied components in the same algal species as well as among species. Significance was set at a critical level of 95 % ($p < 0.05$). Furthermore, regression analysis and determination of Pearson's correlation coefficient R were used to examine the relationship between antioxidant activity and total lipid content.

3. Results

3.1. Antimicrobial activity

The in vitro assays highlighted the presence of an antimicrobial activity in the examined seaweed species. The diameters of inhibition zones were employed to measure the degree of the antimicrobial activity on each strain employing 100 µL of the algal extract (corresponding to 500 µg of dry extract) (Table 1).

As regard human pathogenic bacteria, the lipidic extracts of *R. rupestris* and *H. corona* were capable to inhibit the growth of *Enterococcus* spp. (diameter of inhibition 8.0 ± 0.2 mm). In the lipidic extract of *R. rupestris* an antibacterial activity against *Streptococcus agalactiae* was also observed. *Pseudomonas aeruginosa* was inhibited by the lipidic extract of *G. barbata* (diameter of inhibition 9.0 ± 0.3 mm). Finally, *U. pinnatifida* lipidic extract was capable of acting against *Staphylococcus* sp. (Fig. 1 i).

Many algal lipidic extracts showed antibacterial activity against several of the tested *Vibrio* species. In particular, the algal species *U. pinnatifida* was effective against several *Vibrio* strains such as *V. aestuarinus, V. fischeri, V. furnisii, V. inusitatus, V. litoralis* and *V. mediterranei*. The seaweeds *G. dura* (Fig. 1 ii), *G. gracilis, G. longissima* and *G. barbata* were effective against *V. alginolyticus* with *G. longissima* exerting the highest ($p < 0.05$) inhibition capability. Moreover, *G. dura, G. gracilis and G. longissima* were also capable to inhibit the growth of *V. cholerae* non-O1. *Gracilaria dura, G. gracilis, G. longissima* and *G. turuturu* resulted also active against *V. fluvialis*. The seaweeds *G. gracilis* and *G. longissima* exerted an antibacterial activity also against *V. salmonicida; G. longissima* and *G. barbata* were also active against *V. vulnificus. Rama rupestris* lipidic extract resulted active against *V. dizotrophicus, V. cholerae* non-O1, *V. fluvialis, V. metschnikovii, V. ordalii, V. salmonicida* and *V. vulnificus*. The algal species *H. corona* was active against *V. cholerae* non-O1 and *V. fluvialis*. Finally, *C. linum* was capable to inhibit the growth of *V. ordalii* and *V. vulinificus.* By contrast, the lipidic extracts of all the examined seaweed species were ineffective against *V. campbellii, V. carchariae, V. harveyi, V. hollisae, V. natriegens, V. nereis, V. orientalis, V. pelagius* I and *V. splendidus*, as well as against all the tested yeasts.

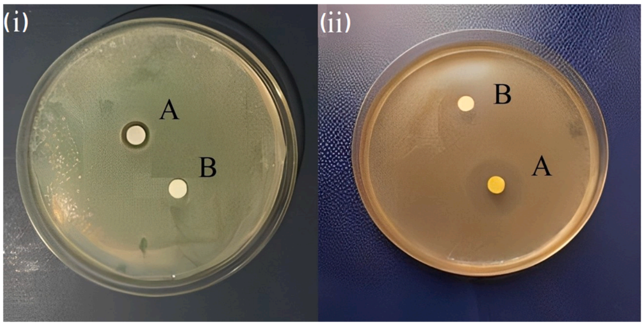

Fig. 1. Antibacterial disc diffusion assay. (i) *Undaria pinnatifida* lipidic extract showing antibacterial activity against *Staphilococcus* sp. (ii) *Gongolaria barbata* lipidic extract with antibacterial activity against *Vibrio alginolyticus*; (A) disc impregnated with 100 µL of algal extract; (B) negative control.

Table 1
Antimicrobial activity of the chloroform/methanol lipidic extracts (dried and ethanol resuspended; final concentration 5 mg/mL; 100 µL impregnated discs) of some seaweeds present along the Northern Ionian Sea (Italy).

Microbial Strain	**Diameter of Growth Inhibition (mm)**								
	C. linum	*R. rupestris*	*G. dura*	*G. gracilis*	*G .longissima*	*G. turuturu*	*H. corona*	*G. barbata*	*U. pinnatifida*
Yeasts									
Candida albicans	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Candida famata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Candida glabrata	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gram +									
Enterococcus sp.	0.0	8.0 ± 0.2	0.0	0.0	0.0	0.0	8.0 ± 0.2	0.0	0.0
Staphilococcus sp.	0.0	0.0	0.0	0.0	0.0	ND	0.0	ND	7.0 ± 0.2
Streptococcus agalactiae	0.0	8.0 ± 0.3	ND	ND	ND	ND	0.0	ND	0.0
Gram -									
Pseudomonas aeruginosa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0 ± 0.3	0.0
Vibrio aestuarinus	ND	ND	ND	ND	ND	ND	ND	ND	9.0 ± 0.2
V. alginolyticus	0.0	0.0	10.0 ± 0.4	10.0 ± 0.4	25.0 ± 1.2	0.0	0.0	15.0 ± 0.8	0.0
Vibrio campbellii	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio carchariae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V. cholerae nonO1	0.0	8.0 ± 0.2	8.0 ± 0.2	8.0 ± 0.2	10.0 ± 0.6	0.0	8.0 ± 0.2	0.0	0.0
Vibrio diazotrophicus	0.0	12.0 ± 1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio fischeri	ND	ND	ND	ND	ND	ND	ND	ND	10.0 ± 1.1
Vibrio fluvialis	0.0	9.0 ± 0.5	8.0 ± 0.2	8.0 ± 0.2	8.0 ± 0.2	8.0 ± 0.2	8.0 ± 0.2	0.0	0.0
Vibrio furnissii	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0 ± 0.2
Vibrio harveyi	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio hollisae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio inusitatus	ND	ND	ND	ND	ND	ND	ND	ND	10.0 ± 1.1
Vibrio litoralis	ND	ND	ND	ND	ND	ND	ND	ND	11.0 ± 1.0
Vibrio mediterranei	0.0	0.0	0.0	0.0	0.0	0.0	0.0	ND	9.0 ± 0.2
Vibrio metschnikovii	0.0	8.0 ± 0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio natriegens	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio nereis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio ordalii	12.0 ± 1.1	8.0 ± 0.2	ND	ND	ND	ND	ND	ND	ND
Vibrio orientalis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio pelagius I	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio salmonicida	0.0	9.0 ± 0.5	0.0	8.0 ± 0.3	8.0 ± 0.3	0.0	0.0	0.0	0.0
Vibrio splendidus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vibrio vulnificus	12.0 ± 1.2	9.0 ± 0.5	ND	ND	15.0 ± 1.3	ND	ND	6.0 ± 0.02	0.0

3.2. Antioxidant activity

The antioxidant activity of the lipidic extracts from the examined seaweeds, was determined by the ORAC (Oxygen Radical Absorbance Capacity) and TEAC (Trolox Equivalent Antioxidant Capacity) assays and is reported in Table 2.

In all the examined samples, the antioxidant capacity of the seaweed extract measured by the ORAC assay resulted higher than the activity measured by the TEAC assay ($p < 0.05$). In particular, in the case of the ORAC assay the highest antioxidant activity ($p < 0.05$), corresponding to 1009.560 ± 115.174 mmol Trolox equivalents/g extract, was recorded in *G. barbata* followed by *G. longissima* (525.610 ± 19.672 mmol Trolox equivalents/g extract) and then by *R. rupestris* (315.650 ± 51.647 mmol Trolox equivalents/g extract). The same trend was also observed in the case of the TEAC assay, except that *U. pinnatifida* showed a higher activity than *C. linum* and *R. rupestris* ($p < 0.05$). The antioxidant activity, as revealed by the values of the coefficient of correlation calculated for each algal species, was significantly related to the total lipid content of the seaweed extracts ($R > 0.9$, $p < 0.01$). In particular, the highest coefficient of correlation was observed in the case of *G. barbata* ($R = 0.9986$, $p < 0.01$) .

3.3. Total lipid content

Table 3 shows the data concerning the total lipid content of the investigated seaweeds. *Gongolaria barbata* showed the highest ($p < 0.05$) lipid content (30.20 ± 3.20 mg/g dw) followed by *G. turuturu* with 6.64 ± 0.81 mg/g dw and then by *G. dura* with 5.20 ± 0.15 mg/g dw and *R. rupestris* (4.84 ± 0.21 mg/g dw). The other seaweed species had a total lipid content of approximately 2.40 mg/g dw. As regards the lipid classes, phospholipids were the dominant class in *G. barbata, G. turuturu* and *H. corona*, whereas triglycerides prevailed in the case of *G. gracilis, G. longissima* and *G. dura*. By contrast, in the case of *C. linum* and *R. rupestris* the content of triglycerides and phospholipids was similar. A high cholesterol concentration was recorded in *G. dura* (21 %) and a low one in *R. rupestris* and *G. barbata.*

3.4. Fatty acid profile

Tables 4 and 5 report the fatty acid profiles of total lipids extracted from the examined seaweed species. Forty fatty acids, included in the range C8:0 - C22:6 ω3, and exceeding a minimum of 0.01 % of total fatty acids (FAs), were identified. The main fatty acid profiles of the examined algal species are shown in Fig. 2.

The percentages of saturated (SAFAs), monounsaturated (MUFAs) and polyunsaturated (PUFAs) fatty acids are reported in Fig. 3.

PUFAs were the most abundant in *C. linum* reaching a value of 71.97 ± 3.48 % ($p < 0.05$). In the case of *G. turuturu* and *G. gracilis* PUFAs were about 38.00 % in *U. pinnatifida* (33.80 ± 1.40 %), in *R. rupestris* 27.62 ± 4.42 %, *G. barbata* 26.14 ± 2.14 % and *H. corona, G. dura* and *G. longissima* about 15.00 % (Fig. 3 a). Among PUFAs, linoleic acid (C18:2 ω6) and Υ-linolenic acid (C18:3 ω6), were the most abundant, representing 38.46 ± 1.50 %, and 14.00 ± 0.38 % of total FAs, respectively in *C. linum* ($p < 0.05$) (Fig. 2). Instead, arachidonic acid (AA, C20:4 ω6) and eicosapentaenoic acid (EPA, C20:5 ω3) were abundant PUFAs in *G. turuturu* accounting for 9.30 ± 0.45 % and 16.98 ± 0.65 %, respectively and EPA reached in this algal species the highest values recorded in all the examined seaweeds ($p < 0.05$). Moreover, docosaesaenoic acid (C22:6 ω3) reached in *R. rupestris* the value of 3.14 ± 0.67 %.

Table 2

Antioxidant activity of the algal lipidic extracts assayed by Trolox Equivalent Antioxidant Capacity Assay (TEAC) and Oxygen Radical Absorbance Capacity Assay (ORAC) assays ($n = 3$). All values represent the mean ± standard deviation.

Algae Species	TEAC (mmol Trolox equivalents/g extract)	ORAC (mmol Trolox equivalents/g extract)
Chaetomorpha linum	37.987 ± 2.297	170.960 ± 16.829
Rama rupestris	37.365 ± 3.990	315.650 ± 51.647
Gracilaria dura	13.981 ± 0.881	84.815 ± 10.925
Gracilaria gracilis	16.296 ± 1.091	160.345 ± 21.248
Gracilariopsis longissima	112.257 ± 4.724	525.610 ± 19.672
Grateloupia turuturu	ND	ND
Hypnea corona	18.428 ± 1.078	79.755 ± 2.029
Gongolaria barbata	225.190 ± 10.981	1009.560 ± 115.174
Undaria pinnatifida	88.773 ± 15.599	± 20.469

Table 3

Total lipids (mg/g) dry weight, percentage content of triglycerides (TAG %), phospholipids (PL %) and cholesterol (CL %) of the analyzed seaweeds.

Algae Species	Total Lipid (mg/g)	TAG (%)	PL (%)	CL (%)
Chaetomorpha linum	ND	53.00	40.00	7.00
Rama rupestris	4.84 ± 0.21	47.05	37.90	3.80
Gracilaria dura	5.20 ± 0.15	54.30	24.60	21.00
Gracilaria gracilis	2.45 ± 0.25	61.65	31.81	6.54
Gracilariopsis longissima	2.35 ± 0.23	60.20	28.85	13.95
Grateloupia turuturu	6.64 ± 0.81	30.10	64.50	5.40
Hypnea corona	2.48 ± 0.00	26.30	65.70	7.90
Gongolaria barbata	30.20 ± 3.20	41.20	55.10	3.70
Undaria pinnatifida (Tabakaeva et al., 2017)	1.07 ± 0.05	ND	ND	ND

MUFAs accounted for 35.17 ± 4.41 % of total FAs in *G. dura*, 29.08 ± 2.67 % in *H. corona*, for about 23.00 % in *R. rupestris, G. turuturu* and *G. barbata*, for 20.34 ± 4.07 % in *G. gracilis*, 18.60 ± 0.70 % *in U. pinnatifida*, 16.16 ± 1.15 % in *G. longissima* and 4.20 ± 0.70 % in *C. linum* (Fig. 3 b) Oleic acid (C18:1 ω9) was the most represented within this class, reaching 16.70 ± 0.70 % in *U. pinnatifida* ($p < 0.05$). By contrast, the lowest value of oleic acid among the examined seaweeds was evidenced in *G. dura* ($p < 0.05$) (Fig. 2).

SAFAs were the most abundant ($p < 0.05$) in *G. longissima,* representing for 67.30 ± 3.10 % of total fatty acids (FAs) (Fig. 3 c); palmitic acid methyl ester (C16:0) was the prevalent SAFAs ($p < 0.05$) (41.67 ± 1.81 % of total FAs in this algal species) (Fig. 2). SAFAs reached values ranging from 55.49 ± 2.68 % to 23.83 ± 2.17 % in the other species examined and the myristic acid methyl ester prevailed ($p < 0.05$) in *R. rupestris* (16.63 ± 2.05 % of total FAs). Finally, the stearic acid (C18:0) was the most abundant fatty acid in *H. corona* (11.18 ± 0.85 %) compared to the other seaweeds ($p < 0.05$) (Fig. 2).

As regards the ratio between ω3 and ω6 fatty acids, a high value (1.72 %) was observed for *H. corona* and a low value (0.34 %) for *G. barbata* (Table 6).

4. Discussion

Recently, research attention has been directed to bio-based high-value products. Seaweeds are a reservoir of bioactive compounds with biotechnological application in various fields, including human nutrition, pharmaceuticals and nutraceuticals (Tahir et al., 2021). In the present study, we examined and compared the potential of nine seaweed species collected in the Mediterranean Sea (i.e., Northern Ionian Sea) as sources of new bioactive compounds in the light of marine bioprospecting (Tahir et al., 2021). The importance of algae as food sources is growing and their potential as sources of lipids, especially fatty acids (FA), makes them an interesting raw material for the food and nutraceutical industries since their functional benefits go beyond the simple nutritional content. Since different algal species have different lipidic profiles (Galloway et al., 2012; Rocha et al., 2021; Susanto et al., 2019), here we evaluated a few species collected in the Mediterranean Sea and

Table 4
Fatty acid profiles of total lipids extracted from the seaweed species examined, in particular the species: *Chaetomorpha linum, Rama rupestris, Gracilaria dura, Gracilaria gracilis* and *Gracilariopsis longissima.* Forty fatty acids were identified, ranging in the C8:0 - C22:6 ω3 range, and exceeding a minimum of 0.01 % of total fatty acids (FA). Sum of Saturated fatty acids (∑SAFA), Monounsaturated fatty acids (∑MUFA), Polyunsaturated fatty acids (∑PUFA), Saturated fatty acids Polyunsaturated fatty acids ratios (∑PUFA/∑SAFA).

	C. linum	*R. rupestris*	*G. dura*	*G. gracilis*	*G. longissima*
C8:0	–	0.94 ± 0.07	–	–	–
C10:0	–	0.05 ± 0.04	–	0.05 ± 0.01	–
C11:0	–	–	–	0.01 ± 0.01	–
C12:0	–	1.69 ± 0.78	–	0.31 ± 0.13	–
C13:0	–	–	–	0.05 ± 0.01	–
C14:0	9.00 ± 0.80	16.63 ± 2.05	4.98 ± 0.76	4.87 ± 1.04	9.45 ± 0.30
C15:0	–	–	0.36 ± 0.08	0.85 ± 0.22	2.31 ± 0.10
C16:0	13.83 ± 1.00	26.61 ± 2.58	39.86 ± 2.41	30.41 ± 2.10	41.67 ± 1.81
C17:0	–	0.28 ± 0.08	0.99 ± 0.05	0.57 ± 0.21	1.84 ± 0.20
C18:0	1.00 ± 0.10	0.72 ± 0.26	1.72 ± 0.63	2.78 ± 0.41	5.21 ± 0.31
C20:0	–	0.51 ± 0.18	1.88 ± 0.52	0.30 ± 0.12	3.62 ± 0.31
C21:0	–	0.59 ± 0.27	–	–	–
C22:0	–	–	1.08 ± 0.09	0.32 ± 0.12	1.45 ± 0.01
C23:0	–	–	1.33 ± 0.11	0.08 ± 0.02	1.75 ± 0.01
C24:0	–	–	–	0.20 ± 0.03	–
∑SAFA	**23.83 ± 2.17**	**48.02 ± 4.84**	**52.20 ± 4.45**	**40.80 ± 4.29**	**67.30 ± 3.10**
C14:1	–	0.38 ± 0.08	26.28 ± 2.20	0.56 ± 0.16	1.96 ± 0.20
C15:1	–	–	–	0.07 ± 0.02	–
C16:1	–	6.33 ± 0.19	2.32 ± 0.56	5.56 ± 1.66	2.91 ± 0.10
C16:1 ω7	–	–	–	–	–
C17:1	–	0.65 ± 0.08	–	0.43 ± 0.18	–
C18:1 ω9t	–	3.82 ± 1.90	–	3.73 ± 0.76	–
C18:1ω9c	4.10 ± 0.50	13.07 ± 0.68	2.86 ± 0.88	9.51 ± 1.83	8.47 ± 0.60
C18:1 ω7	–	–	1.11 ± 0.27	–	0.93 ± 0.01
C20:1	–	–	–	0.28 ± 0.03	–
C21:1	–	–	–	0.03 ± 0.01	–
C20:1 ω9	–	–	2.60 ± 1.75	–	1.89 ± 0.21
C24:1 ω9	–	0.11 ± 0.04	–	–	–
C24:1	–	–	–	0.17 ± 0.05	–
∑MUFA	**4.20 ± 0.70**	**24.36 ± 2.73**	**35.17 ± 4.41**	**20.34 ± 4.07**	**16.16 ± 1.15**
C18:2 ω6t	38.00 ± 1.50	1.83 ± 0.79	1.62 ± 0.42	–	1.60 ± 0.20
C18:2 ω6c	–	4.41 ± 0.79	–	3.15 ± 0.42	–
C18:3 ω3	–	11.25 ± 1.02	0.48 ± 0.17	1.51 ± 0.77	1.67 ± 0.10
C18:3 ω6	14.00 ± 0.38	0.89 ± 0.16	1.85 ± 0.45	–	1.46 ± 0.01
C18:4 ω3	–	-	–	–	–
C20:2 ω6	–	2.19 ± 0.18	–	–	–
C20:2	–	–	0.95 ± 0.12	0.24 ± 0.11	1.80 ± 0.32
C20:3 ω6	–	0.93 ± 0.12	0.95 ± 0.10	0.51 ± 0.09	–
C20:3 ω3 + C22:1	–	–	0.76 ± 0.12	2.12 ± 0.93	1.17 ± 0.32
C20:4 ω6	8.14 ± 0.70	0.90 ± 0.17	1.13 ± 0.25	30.61 ± 2.24	2.26 ± 0.11
C22:2	–	0.63 ± 0.34	1.38 ± 0.20	–	1.35 ± 0.01
C20:5 ω3	8.83 ± 0.60	1.45 ± 0.39	1.14 ± 0.25	0.42 ± 0.21	2.84 ± 0.33
C21:4 ω9	–	–	–	–	–
C22:6 ω3	2.91 ± 0.50	3.14 ± 0.67	2.37 ± 0.89	0.30 ± 0.06	1.85 ± 0.21
∑PUFA	**71.97 ± 3.48**	**27.62 ± 4.42**	**12.63 ± 2.51**	**38.86 ± 3.43**	**16.54 ± 1.24**
∑PUFA/ ∑SAFA	**3.02 ± 1.60**	**0.58 ± 0.13**	**0.24 ± 0.11**	**0.95 ± 0.59**	**0.25 ± 0.04**

from the obtained results some interesting issues can be inferred:

- On average, the examined species had a lipid content between 30.20 ± 3.20 and 1.70 ± 0.05 mg/g dry weight (dw) with *G. barbata* showing the highest value followed by *G. turuturu* and then by *G. dura* and *R. rupestris*. It is well known that lipids are essential for human health being energy sources. At the same time, they ensure the maintenance of cell membrane integrity and an adequate hormone production. Moreover, lipids are necessary for the transport and absorption of fat-soluble vitamins (i.e., A, D, E, and K). In the species *G. barbata* and *G. turutuu*, in addition to a high lipid content, the highest concentration of phospholipids was also observed. Phospholipids are among the major polar lipids of marine macrophytes and perform protective barrier and intracellular transport functions. In humans, they are essential components of cell membranes and play a crucial role in maintaining their structure and functionality and are also involved in transport and metabolism (Lordan et al., 2017). Triglycerides, on the other hand, prevailed in *G. gracilis, G. dura* and *G. longissima*. Triglycerides are the main form of lipid storage in most plant species, as well as in macroalgae (Benning et al., 1998) and in humans they are fundamental as a source of energy (Barbosa & Siniossoglou, 2024).
- The interest on seaweeds comes also from their content in unsaturated fatty acids, ω3 and ω6 polyunsaturated fatty acids and monounsaturated fatty acids (El-Beltagi et al., 2022; Lomartire & Gonçalves, 2022; Galloway et al., 2012; Rocha et al., 2021). Among the examined species, PUFAs prevailed in *C. linum* followed by *G. gracilis, G. turuturu, U. pinnatifida* and *G. barbata* while the lowest value of PUFAs was recorded in *G. dura*. Regarding the difference in PUFAs content between *C. linum* and *G. dura*, it is known that the chemical composition of seaweeds can vary depending on their species, habitat, maturity, and environmental conditions, as pointed out by various authors (Cassani et al., 2022; Vlaisavljević et al., 2021). Different percentages of PUFAs were found in Chlorophyta and Rhodophyta in different marine zones, explained with a different adaptation to stress conditions (dos Santos et al., 2021). In the warm waters of the Arabian Gulf, Chlorophyta showed considerably higher percentages in comparison with Rhodophyta (Al-Adilah et al., 2021). The increase in temperature, measured in recent years in the waters of the Northern Ionian Sea (Gulf of Taranto), related to climate change (Calabrese et al., 2025), could have favoured the significant differences in the percentages of PUFAs detected in the two examined species. The high content of PUFAs in *C. linum* suggest this algal species as a source of these fatty acids as already indicated by Stabili et al. (2019a) also taking into account the presence of fatty acids of ω3 and ω6 series such as linoleic acid (C18:2 ω6) and ɣ-linolenic acid (C18:3 ω6), which are involved in several human processes. Linoleic

Table 5

Fatty acid profiles of total lipids extracted from the algal species examined, in particular the species*: Grateloupia turuturu, Hypnea corona, Gongolaria barbata* and *Undaria pinnatifida*. Forty fatty acids were identified, ranging in the C8:0 - C22:6 ω3 range, and exceeding a minimum of 0.01 % of total fatty acids (FA). Sum of Saturated fatty acids (∑SAFA), Monounsaturated fatty acids (∑MUFA), Polyunsaturated fatty acids (∑PUFA), Saturated fatty acids Polyunsaturated fatty acids ratios (∑PUFA/∑SAFA).

	G. turuturu	***H. corona***	***G. barbata***	***U. pinnatifida*** (Tabakaeva et al., 2017)
C8:0	–	–	–	–
C10:0	–	–	–	–
C11:0	–	–	–	–
C12:0	0.84 ± 0.08	0.54 ± 0.16	0.66 ± 0.17	–
C13:0	–	0.36 ± 0.12	1.02 ± 0.17	–
C14:0	3.24 ± 0.32	10.04 ± 0.70	6.92 ± 0.13	9.90 ± 0.30
C15:0	–	–	–	2.40 ± 0.10
C16:0	30.55 ± 1.10	33.00 ± 0.69	36.58 ± 0.65	28.90 ± 1.10
C17:0	–	0.09 ± 0.16	1.05 ± 0.30	–
C18:0	3.12 ± 0.14	11.18 ± 0.85	4.18 ± 0.29	4.00 ± 0.10
C20:0	–	–	1.28 ± 0.44	1.10± 0.03
C21:0	–	–	–	–
C22:0	–	–	–	–
C23:0	–	0.27 ± 0.09	0.13 ± 0.01	–
C24:0	–	–	–	–
∑SAFA	**37.76 ± 1.64**	**55.49 ± 2.68**	**51.82 ± 2.15**	**46.30 ± 1.90**
C14:1	1.35 ± 0.12	4.78 ± 1.05	3.04 ± 0.22	–
C16:1	2.79 ± 0.18	12.51 ± 0.38	3.47 ± 0.60	–
C16:1 ω7	–	–	–	1.90 ± 0.07
C17:1	–	0.54 ± 0.04	0.93 ± 0.06	–
C18:1ω9t	11.02 ± 0.73	3.90 ± 0.15	7.48 ± 0.48	16.70 ± 0.70
C18:1ω9c	8.29 ± 0.38	6.82 ± 0.88	7.12 ± 0.47	–
C18:1ω7	–	–	–	–
C20:1ω9	0.32 ± 0.15	0.15 ± 0.02	–	–
C24:1ω9	0.47 ± 0.10	0.38 ± 0.15	–	–
∑MUFA	**24.24 ± 1.66**	**29.08 ± 2.67**	**22.04 ± 1.85**	**18.60 ± 0.70**
C18:2ω6t	1.88 ± 0.11	0.77 ± 0.28	6.22 ± 0.63	4.80 ± 0.10
C18:2ω6c	2.39 ± 0.14	0.10 ± 0.17	–	–
C18:3ω3	0.73 ± 0.05	1.82 ± 0.18	0.22 ± 0.05	1.30 ± 0.05
C18:3ω6	1.42 ± 0.07	1.11 ± 0.14	7.19 ± 0.33	10.70 ± 0.40
C18:4ω3	–	–	–	2.50 ± 0.10
C20:2	0.97 ± 0.05	1.04 ± 0.18	1.31 ± 0.24	–
C22:0 + 20:3ω6	1.06 ± 0.07	0.98 ± 0.25	–	–
C20:3ω3 + C22:1	0.24 ± 0.21	1.46 ± 0.27	–	–
C20:4ω6	9.30 ± 0.45	2.33 ± 0.29	4.86 ± 0.22	5.80 ± 0.20
C22:2	0.96 ± 0.08	–	0.30 ± 0.11	–
C20:5ω3	16.98 ± 0.65	3.79 ± 0.21	4.46 ± 0.20	8.60 ± 0.20
C21:4ω9	–	–	–	0.10 ± 0.04
C22:6ω3	2.05 ± 0.11	2.04 ± 0.07	1.58 ± 0.36	–
∑PUFA	**38.00 ± 1.54**	**15.44 ± 2.03**	**26.14 ± 2.14**	**33.80 ± 1.40**
∑PUFA/ ∑SAFA	**1.01 ± 0.04**	**0.28 ± 0.08**	**0.50 ± 0.27**	**± 0.33**

acid helps in keeping the skin impermeable to water, in reducing cholesterol levels, and in controlling the glucose homeostasis (Hamilton & Klett, 2021). Scientific data show that linolenic acid improves insulin resistance and glucose tolerance in obese diabetic and non-diabetic subjects and that ɣ-linolenic acid has a positive impact on diabetic nephropathy by reducing inflammation and fibrosis (Kim et al., 2012; Sneddon et al., 2008). On account of these features the potentiality of *C. linum* in the production of fortified food was already proposed (Stabili et al., 2019a). Furthermore, the presence of arachidonic acid (AA, C20:4 ω6) and eicosapentaenoic acid (EPA, C20:5 ω3) in *G. turuturu is* also noteworthy. These results are in agreement with the studies of da Costa et al. on *G. turuturu* (da Costa et al., 2021). Specimens of this species collected in Brittany and Portugal showed the highest content of PUFAs among the lipids, in particular eicosapentaenoic acid (EPA), commonly derived from fish, and arachidonic acid (Denis et al., 2010; Kendel et al, 2012, 2013; Munier et al., 2013). EPA has been well documented for its health benefits, triggering the production of anti-inflammatory mediators, such as cytokines and eicosanoids (Calder, 2006). In addition, this fatty acid showed antimicrobial (Simopoulos, 1999) and antioxidant activities (Bowen et al., 2016) resulting effective in avoiding cardiovascular infections and recurrent illnesses (de Roos et al., 2009; Lee et al., 2013). Furthermore, da Costa et al. (2021) reported a total lipid content of *G. turuturu* for specimens from Portugal accounting for 0.88 ± 0.25 g/100 g of biomass in dry weight (dw). Therefore, our results indicating a value of 0.600 ± 0.081 g/100 g dw are consistent with data from the literature (ca. 0.7 %, up to 4.0 % dw), also for other species of the same genus (Floreto & Teshima, 1998; Kendel et al., 2015; Hotimchenko, 2002; Perfeto, 1998) and in line for that of other red seaweeds (da Costa et al., 2017; Fleurence et al., 1994; Kumari et al., 2010; Lopes et al., 2019). Moreover, da Costa et al. (2021) determined a ω6/ω3 corresponding to a value of 0.87 ± 0.01, similar to the one recorded in the present study accounting for 0.80 ± 0.02. The interesting nutritional value of *G. turuturu* extracts was corroborated by the ∑PUFA/∑SAFA ratio calculated in the present work and corresponding to 1.01 ± 0.04 as it was greater than the recommended threshold 0.45, as well as by its ω6/ω3 ratio (< 1). These data are consistent with those previously observed in *Grateloupia* spp. (Rodrigues et al., 2015) and other red seaweeds (Lopes et al., 2019) and have been associated with human health benefits, such as the prevention of noncommunicable and cardiovascular diseases (Calder, 2017; Calder et al., 2009). Actually, all the examined seaweeds proved to be an excellent wellspring of PUFAs with a ω6 FA: ω3 FA ratio less than 10 which is largely recommended by the WHO to avoid inflammatory, cardiovascular and neuro-chronic sickness (Kumari, 2010; Santos et al., 2020; Shanab et al., 2018). The World Health Organization (WHO) suggests that a balanced ω6 to ω3 fatty acid ratio in the diet is beneficial for health and many experts recommend a range between 1:1 and 4:1 (ω6 to ω3). This ratio can be achieved through the consumption of foods rich in both ω3 and ω6 fatty acids. A balanced intake of these essential fats is important for overall health and well-being. Thus, the ω6/ω3 ratio of all seaweed species addressed in the present work suggests that their introduction in diets may be beneficial from a nutraceutical perspective (Oktanella et al., 2024). The ω6/ω3 fatty acid ratio is a critical metric for assessing the benefits of PUFAs. Previous studies showed that a 3/1 to 5/1 ω6/ω3 fatty acid ratio lowers the risk of breast, prostate, colon, and renal cancers (Simopulos, 2002; Zárate et al., 2017). In other cases, the ω6/ω3 fatty acid ratio of 2/1 to 3/1 was found to minimize inflammation in rheumatoid arthritis patients. A 5/1 ratio, for example, was shown to be effective in asthma patients (Zárate et al., 2017). In the present paper a 1/1 ω6/ω3 fatty acid ratio was recorded for *G. turuturu*, a ratio of 3/1 for *C. linum* and a ratio of approximately 2/1 for *U. pinnatifida*. In the case of *C. linum* and *U. pinnatifida* the PUFA/SAFA ratio was to 3.02 ± 0.20 and 0.73 ± 0.01 respectively. Therefore, in terms of the most suitable seaweeds among the studied ones that would be suitable in the industry of fortified food and in nutraceuticals it is important to consider the potential cumulative benefits that would arise from low overall ω6/ω3 ratios in combination with low SAFA contents (higher ∑PUFA/∑SAFA ratios). Therefore, we judge *G. turuturu* and *C. linum* could be the species among the studied seaweeds gathering the mentioned characteristics, followed by *U. pinnatifida* (Rocha et al., 2021; Tabakaeva & Tabakaeva, 2017).

- Another interesting application of fatty acids from algae could be related to their employment as antibacterial means (El Amrani

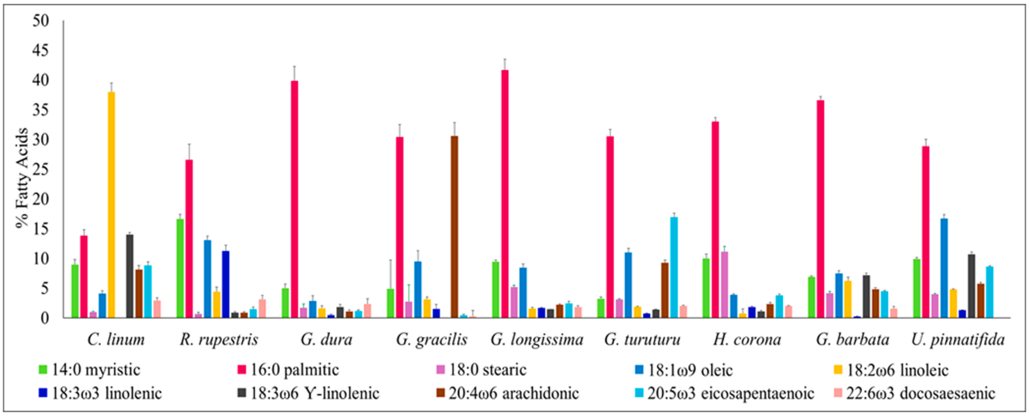

Fig. 2. Profiles of the main fatty acids are present in the examined algal species. Each column represents the mean value ± standard deviation (n=3).

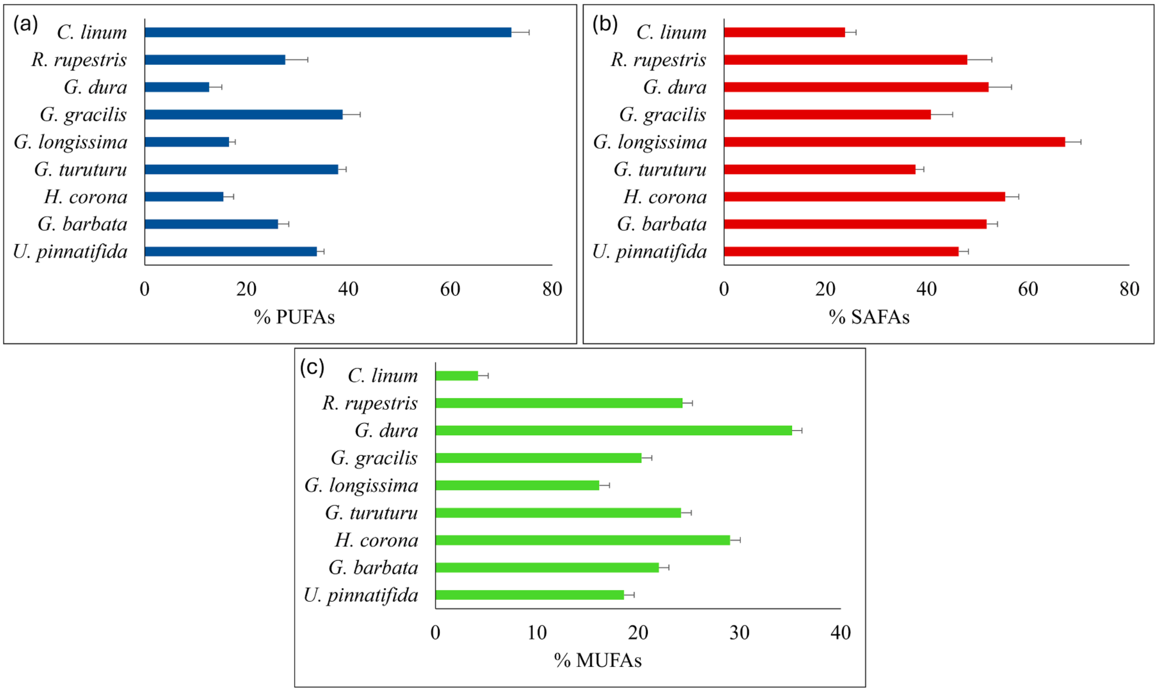

Fig. 3. Percentages of (a) polyunsaturated (% PUFAs), (b) monounsaturated (% MUFAs) and (c) saturated (% SAFAs) fatty acids in the examined algal species.

Table 6
Percentage of ω3 (%), ω6 (%), ω6/ω3 and ω3/ω6 ratio in the investigated seaweeds.

Algae Species	ω3 (%)	ω6 (%)	ω6/ω3	ω3/ω6
Chaetomorpha linum	25.74	60.14	2.34	0.43
Rama rupestris	15.84	11.26	0.71	1.41
Gracilaria dura	4.75	5.55	1.17	0.86
Gracilaria gracilis	4.80	36.07	7.51	0.13
Gracilariopsis longissima	7.53	7.12	0.95	1.06
Grateloupia turuturu	20.01	16.06	0.80	1.25
Hypnea corona	9.11	5.29	0.58	1.72
Gongolaria barbata	6.26	18.27	2.92	0.34
Undaria pinnatifida	12.40	21.30	1.72	0.58

Zerrifi et al., 2018; Stabili et al., 2012, 2014). Previous studies on the here examined species were conducted by using different extracts. In particular, crude extract as in the case of *R. rupestris* from India showed an antibacterial activity against *Escherichia coli* and *Pseudomonas aeruginosa* (Krish & Das, 2014); aqueous and ethanolic extracts, as in the case of *G. gracilis* were capable of inhibiting several *Aeromonas* species, *Fotobatterio damselae, Yersinia ruckeri, Edwarsiella piscicida* and *Bacillus subtilis* (Afonso et al., 2021, Capillo et al., 2018); ethanolic and polysaccharidic extracts as in the case of *G. turuturu* from Portuguese coasts showed antibacterial activity against *Staphylococcus aureus, E. coli* and *Candida albicans* (Cardoso et al., 2019; Félix et al., 2021; Zengin et al., 2024). Moreover, methanolic, ethyl acetate and hexane extracts of *H. corona* from the Red Sea (Egypt) were capable to act against *Staphylococcus aureus, Salmonella* spp., *Aeromonas hydrophila, Pseudomonas aeruginosa, E. coli* and *Edwarsiella tarda.* Antibacterial activity *of H. corona* crude extract from the Italian coasts was evidenced against *P. aeruginosa* and *S. aureus* (Zamurro et al., 2022). *Gongolaria barbata* from the Red Sea was active against *S. aureus* and *B. subtilis, P. aeruginosa, Candida albicans* and *Serratia marcescens* (Abdel-Raouf et al., 2017). Finally, methanolic extract form *U. pinnatifida* collected in Asian regions showed antibacterial activity against *S. aureus* and *Salmonella typhimurium* (Patra et al., 2017). By contrast the here examined species of the Mediterranean Sea were never examined for the antibacterial activity of the methanolic lipidic extract, therefore the present paper represents a first insight on this topic. In seaweeds, oleic, linoleic, linolenic and eicosapentaenoic acids represent the major component of UFAs, exerting antibacterial activity capable to inhibit pathogenic bacterial growth (Cardoso et al., 2017; Ismail et al., 2018; Stabili et al., 2014). These properties seem to be due to the capacity of the above mentioned long chain PUFAs to interfere in the bacterial FAs synthesis, and are associated with incubation time, concentration and FAs unsaturation degree (Ismail et al., 2018). In this study, we analyzed a wide range of microbial strains taking into account the potential implication in the seaweed exploitation for the research of antimicrobials active against humans and marine organisms. Obviously, having considered 30 different microbial strains and nine seaweed species, we arrived at 270 tests and 14 % of them gave us positive results. As regards the antibacterial activity, all the algal lipidic extracts were able to inhibit the growth of at least one *Vibrio* species, including some aquaculture pathogens. In particular, *C. linum* lipidic extract exerted an antibacterial activity against *Vibrio ordalii* and *V. vulnificus*. The antibacterial activity seems to be related to the presence of linoleic acid present at high density (about 38.00 % recovered by gas chromatography analysis), as already reported by Stabili et al. (2019a). The growth of *V. ordalii* and *V. vulnificus*, by in vitro assay, was in fact inhibited by pure α-linoleic acid. In particular, 0.009, 0.018, 0.035, 0.051, 0.067, 0.082 mg/mL of α-linoleic acid in ethanol were used and *Vibrio* growth inhibition was recorded starting from 0.018 mg/mL. (Stabili et al., 2014, 2019a). As regard the antibacterial activity against vibrios exerted by *R. rupestris, G. dura, G. gracilis, G. longissima, G. turuturu, G. barbata, H. corona,* and *U. pinnatifida,* since the analysis of fatty acid methyl esters by gas chromatography showed that palmitic acid methyl ester (C16:0) was the predominant saturated fatty acid in all the above-mentioned seaweeds, it is therefore reasonable to hypothesize its involvement in the observed antibacterial activity. Palmitic acid is indeed another SFA example showing antibacterial activity towards Gram-positive and Gram-negative bacteria (Elgendy et al., 2024; Ismail et al., 2018). Recently, it has also been highlighted that antibacterial activity related to fatty acids and palmitic acid represents a promising option for developing the next generation of antibacterial agents to treat a broad spectrum of bacterial infections (Casillas-Vargas et al., 2021). For example, palmitic acid has been encapsulated in liposomal vectors that show bactericidal activity against multidrug-resistant *Staphylococcus epidermidis* and vancomycin-resistant *Enterococcus faecalis* (Cheung et al., 2016). In a previous study conducted by Stabili et al. (2014) it was already demonstrated that palmitic acid is responsible for the antibacterial activity observed in *Cladophora rupestris*, thus supporting its involvement in the inhibition of *Vibrio* growth also observed in the present study. The aquaculture industry is one of the fastest growing industries globally worldwide (Ibrahim et al., 2020; Kumar et al., 2021a; Kumar et al., 2021b; Sarkar et al., 2022). Animals reared in aquaculture facilities can often be infected by several vibrios responsible for the most common animal and human diseases known as vibriosis (Beleneva et al., 2004; de Souza Valente & Wan, 2021; Marques et al., 2022) responsible for heavy economic losses. In particular, *Vibrio ordalii* is responsible for worldwide severe haemorrhagic septicaemia leading to mortality in fish including cultured Atlantic salmon, Pacific salmon, rainbow trout, rockfish and gilthead sea bream (Colquhoun et al., 2024). *Vibrio vulnificus* is an opportunistic bacterium causing human diseases (Jones & Oliver, 2009; Kim & Kim, 2002) and is associated with a wide variety of seafood. This microorganism is a particularly difficult problem for the shellfish industry, as the disease caused by ingestion of this pathogen is frequently highly lethal, being responsible for several seafood-related deaths (Kim & Kim, 2002; Kim et al., 2007). *Vibrio aestuarinus* has been isolated, for the first time, from estuarine waters and shellfish from the Oregon coast (Tison & Seidler, 1983). In several European countries, the cause of mortality outbreaks in Pacific oysters, *Crassostrea gigas*, was ascribed to this pathogen (Lupo et al., 2019). *Vibrio furnissii, Vibrio diazotrophicus, V. mediterraneii* and *V. metschnikovii* are other pathogen bacteria commonly present in marine waters and organisms (Hansen, 1993; Jensen & Jellinge, 2014; Konechnyi et al., 2021; Linde et al., 2004; Pariente Martín et al., 2008). In particular, the consumption of either fresh or undercooked *Vibrio furnissii* infected bivalve molluscs, as well as the contact with warm and high bacterial loaded marine waters, can cause acute gastroenteritis in humans (Ahmed, 1991; Ballal et al., 2017). *Vibrio diazotrophicus*, lives both in water and sediments, as well as in the digestive tract of some marine animal, firstly isolated from gastrointestinal tract of sea urchins (Fleming et al., 2021; Guerinot et al., 1982; Joublin-Delavat et al., 2022). As an opportunistic pathogen, in infected larvae of the sea urchin *Strongylocentrotus purpuratus,* it can seriously undermine their survival with potential ecological relapses (Stabili et al., 2023a). The species *V. mediterranei,* has been considered responsible for mass mortality in larvae and juveniles of bivalves in hatcheries (Fan et al., 2023). Furthermore, within the Mediterranean basin, this bacterial species is also recognized as a pathogen for the noble pen shell *Pinna nobilis* (Andree et al., 2021) as well as the causative agent of the yellow spot disease of seaweeds of the genus *Pyropia* (Yang et al., 2020). V*ibrio metschnikovii,* is able to colonize shellfish and produce infections in fish. Finally, *Vibrio fischeri*, isolated from pond water of shrimp farms in southern India during some mass mortality events due to shell disease, showed a moderate pathogenicity (Manilal et al., 2010). Traditionally, to avoid *Vibrio* infections, a massive prophylactic use of antibiotics has been implemented in aquaculture facilities. To reduce the consequences on human health and ecosystems related to the excessive use of antibiotics, the exploration of innovative and sustainable additives is essential. Indeed, antibiotic residues remain in aquaculture products causing health problems to consumers and, last but not least, huge amounts of these chemicals are released into the environment (Sanches-Fernandes et al., 2022). This is particularly important, since providing food for humans and guarding the planet from decline are two important goals to be achieved according to the 2030 United Nations (UN) Agenda of Sustainable Development Goals (SDGs) (Stabili et al., 2024; UN, 2018). In this scenario, seaweed represents a sustainable bioresource (Pérez et al., 2016; Stabili et al., 2024), and the above-mentioned seaweed species could be good candidates for use in this field.

- Among human pathogens antibacterial activity was recorded only in the case of few lipidic extracts and in particular for *R. rupestris* against *Enterococcus* sp., and *Streptococcus agalactiae*, for *H. corona* against *Enterococcus* sp., for *G. barbata* towards *Pseudomonas aeruginosa* and for *U. pinnatifida* towards *Staphylococcus* sp. The antibacterial activity recorded against *Streptococcus agalactiae* is noteworthy since *S. agalactiae* (Group B Streptococcus [GBS]) is a Gram-positive opportunistic human pathogen and the worst evidence of disease occurs mainly in neonates and women in the postpartum period (Gergova et al., 2024; Silva et al., 2020). It is indeed a major cause of neonatal mortality. When populating the lower genital tract of pregnant women, GBS can generate premature labor and stillbirths. However, it can influence life-threatening diseases, including sepsis, meningitis and pneumonia, especially if transmitted to the newborn. Due to the increasing resistance of GBS to generally used macrolides (Betriu et al., 2004), the algal species *R. rupestris* could be used in human care as a tool for pharmaceutical preparations useful for GBS control as already suggested by Stabili et al. (2014).
- The problem of antibiotic resistance is also related to several bacterial pathogens, including *Enterococcus faecium, Staphylococcus aureus*, and *Pseudomonas aeruginosa*, commonly associated with antimicrobial resistance and denoted by their acronym ESKAPE (Boccella et al., 2021). Antimicrobial resistance is increasing at a rate that is difficult to manage and has become the major public health threat of the 21st century. Over 40 countries have shared their AMR surveillance reports with the World Health Organization (WHO),

highlighting its criticality (Global Antimicrobial Resistance Surveillance System (GLASS) report, 2018). Consequently, rapid and effective alternatives to conventional antibiotics are needed to circumvent this problem (Bhowmick et al., 2020). In particular, seaweeds are abundant reserves of bioactive compounds whose immense potential can no longer be overlooked. In this scenario we performed our tests also on this kind of bacteria. Interestingly the algal extract of *Cystoseira barbata*, isolated from the coastal waters of the Red Sea (Safaga, Egypt), demonstrated potent activity against *Bacillus subtilis, Staphylococcus aureus, Serratia marcescens, Pseudomonas aeruginosa* and *Candida albicans* (Neveen et al., 2017). Tested algal extracts of *H. corona*, collected from the Red Sea (Hurghada, Egypt), also showed antibacterial potential against human and fish pathogenic bacteria, such as *Staphylococcus aureus, Salmonella* spp., *Vibrio anguillarum, Aeromonas hydrophila, Pseudomonas aeruginosa, E. coli* and *Edwarsiella bagna*. (Aboul-Ela et al., 2021). In contrast, no data are available on these algal species in the Mediterranean; furthermore, apart from our investigations, no studies are available on *R. rupestris*. Therefore, the antibacterial activity exerted by *R. rupestris, G. barbata* and *H. corona* against the above-mentioned antibiotic-resistant bacteria is new a promising challenge on this topic. Noteworthy, the here evidenced antibacterial activity exerted by the lipidic extract of *U. pinnatifida* against *Staphylococcus* sp. is in agreement with other studies reporting an activity of the *U. pinnatifida* extract against *Staphylococcus aureus* ATCC 6538 (González-Ballesteros et al., 2023).

- None of the yeasts (e.g. *C. albicans, C. famata* and *C. glabrata*) tested with the lipid extract of the selected seaweed species showed sensitivity. This could be due to the composition of their cell wall, different from that of bacteria and in particular *Vibrio* (Pepper et al., 2011). Another explanation could be the polarity of the extraction, since in the present study we investigated the antibacterial activity of the lipid extract, but further explorations will be needed to evaluate whether the crude extract or the aqueous extract of these algal species could prove effective on other microorganisms, including yeasts, or capable of other interesting biological activities. As an explanation, Barletta et al. (2024) evidenced an antibacterial activity of the hydroalcoholic *C. linum* extract against *Enterococcus faecalis* not here recorded for the lipidic extract of the same algal species.
- Another interesting result transpired from the analysis of the lipid extract of the selected seaweeds was the presence of an in vitro antioxidant activity. TEAC and ORAC assays were jointly used to assess this antioxidant capacity because the use of a single method for the detection of antioxidants could underestimate or even overlook their content (Huang et al., 2005; Prior et al., 2005). TEAC and ORAC assays are two popularly used tests based on two different reaction mechanisms, electron transfer and hydrogen atom transfer, respectively. In the present work the higher ORAC values compared to TEAC reported in Table 2 are in agreement with literature reports. Zulueta et al. (2009) suggested that ORAC test shows higher specificity than TEAC and measures antioxidant activity of several compounds in addition to phenolic molecules. Previous studies have demonstrated that compounds with potent antioxidant activity have been found in brown, red and green algae. Seaweeds are a source of natural antioxidant molecules: polysaccharides, polyphenols, carotenoids (β-carotene and astaxanthin) phycocyanin, and phycoerythrin. Moreover, a contribution of chlorophylls can be invoked on the in vitro tested antioxidant capacity as already demonstrated in the case of plant extract, virgin olive oils, green tea and some algae (Michalak et al., 2022). As reported by Tenorio-Rodriguez et al. (2017), the total phenolic content of brown seaweeds was significantly higher than red and green seaweeds suggesting that higher total phenolic content can result in higher antioxidant capacity. Our antioxidant activity assays on different seaweeds species from the Ionian Sea population confirm the above reported studies as the highest value has been measured for *G. barbata* species belonging to Heterokontophyta phylum. Therefore, the results obtained suggested that the antioxidant activity might be due to the presence of polar phenolic compounds in this macroalgal extract. Moreover, results here reported demonstrated a positive correlation between antioxidant activity and total lipid content in the seaweeds extracts higher for *G. barbata* in comparison to the other analysed species. This positive correlation is supported by literature data. In particular, studies on *Codium fragile, Ulva lactuca* and *Eisenia arborea* investigated the antioxidant activity and lipid profile, demonstrating that methanolic extracts showed a potent antioxidant activity (Raja et al., 2016). Furthermore, Santos et al. (2020) reported a correlation between lipid content and antioxidant activity of the seaweeds *Bifurcaria bifurcata* and *Sargassum muticum* collected along the Portuguese coast. As reported by Jakobek (2015) lipids interact with polyphenols and have a protective effect. Moreover, Cerón et al. (2007) demonstrated that the fatty acid profile contributes to the antioxidant capacity of algal lipid extract. The antioxidant capacity of carotenoids that have been esterified with oleic acid is higher than that of free carotenoids. Oleic acid was here identified by CG analysis in the algal lipid extracts, and thus it could be involved in the evidenced activity. The antioxidant activities highlighted here suggest the use of the studied seaweeds as a source of natural antioxidants, also considering the safety concerns of synthetic antioxidants. Algal lipid extracts could be used in the formulation of drugs useful in the treatment of numerous diseases, since oxidative stress is involved in the pathogenesis of atherosclerosis, alcoholic liver cirrhosis, cancer, etc. and it is triggered by free radicals, especially reactive oxygen species (ROS) against which antioxidant compounds act. It is presumable that in the examined seaweeds this activity could be related to the carotenoid and phenolic molecules.

Due to the increasing demand for seaweeds, more frequent and widespread harvests could affect the sustainability of these practices. Therefore, the development of species-specific cultivation strategies in Integrated Multitrophic Aquaculture (IMTA) systems has the potential to contribute to environmental sustainability (Choudhary et al., 2025; Hala et al., 2024; Rusco et al., 2024; Yang et al., 2025). In this context, we have already achieved the cultivation of *C. linum* at pre-industrial scale in an IMTA system set up in a mariculture farm in the Gulf of Taranto (Southern Italy, Ionian Sea, Mediterranean Sea), where bioremediator organisms such as macroalgae, polychaetes, sponges and mussels were farmed in proximity to the fish cages. The estimated algal biomass production in this IMTA system is about 0.84 t per annual cycle (Borghese et al., 2025; Giangrande et al., 2020; Stabili et al., 2019b, 2023b, 2024) and represents a bioremediation co-product with potential applications in different fields. In particular, 1400 Kg of algal biomass were able to degrade nitrogen and phosphorus salts that derive from fish excretions and every 100 ha it is possible to obtain a removal of 80 % of the nitrogen load produced. If this same strategy was applied to several of the seaweeds examined in this work and spread along the Mediterranean coasts, it could lead to two interesting issues related to the dual contextual use of cultivated macroalgal species as i) bioremediators in an aquaculture scenario and ii) sources of bioactive compounds useful for animal and human nutrition, as well as in the nutraceutical and pharmaceutical sectors (Tahir et al., 2021). IMTA is indeed an eco-friendly practice that aims to mitigate overharvesting and reduce the risk of invasive species by integrating different aquatic organisms in a way that mimics natural ecosystems (Khan et al., 2024). It is well known that overharvesting can deplete targeted populations affecting the balance of ecosystems, but, obviously, the management of the IMTA system must avoid the exploitation and overexploitation of bioremediating organisms. In particular, the cultivation/rearing of bioremediators in the IMTA system must allow to reach a high biomass starting from a sustainable harvesting strategy that includes the introduction of catch limits, size restrictions and seasonal closures. As regard invasive species these can outcompete native species, alter habitats and potentially introduce diseases. Therefore, the IMTA system must carefully choose the species to introduce into a farm, avoiding, for example, the cultivation of invasive species for the Mediterranean such as *Undaria pinnatifida*, and must implement monitoring plans to minimize the risk of invasive introductions.

5. Conclusion

In the present study, for the first time, nine algal species collected in the Mediterranean Sea (Italy) were compared by investigating their antibacterial and antioxidant activities and total lipid and fatty acid profiles. The results obtained are very interesting and represent a perspective for their potential exploitation. Noteworthy, all the algal lipid extracts exerted antibacterial activity against different *Vibrio* species, including aquaculture pathogens, suggesting their potential exploitation to control vibriosis and to reduce public health risks related to antibiotic use in aquaculture. Furthermore, the lipidic extracts of *H. corona, G. barbata, R. rupestris* and *U. pinnatifida* were effective against some emerging human pathogens exerting antibiotic resistance such as *Enterococcus* sp., *Staphylococcus* sp., *Streptococcus agalactiae* and *Pseudomonas aeurginosa*. suggesting their potential employment in the pharmaceutical field as a promising challenge. Antibiotic resistance, in fact, currently represents the most serious global threat to the effective treatment of bacterial infections and therefore from the above-mentioned algae it is possible to obtain safer alternative antibacterial drugs which therefore represent an innovative solution in the light of the "Blue Growth". The seaweeds investigated also show an interesting antioxidant activity with the highest value recorded for *G. barbata*. This activity was significantly correlated to the total algal lipid content leading to hypothesize the employment of the algal lipid extract in the field of nutraceuticals and cosmetics, since natural antioxidants play an important role against various pathologies and the aging process, protecting cells from oxidative damage. Finally, all the examined seaweeds exerted an optimal ω6/ω3 ratio and in particular *C. linum, G. turuturu* and *U. pinnatifida*, on account of their high-quality fatty acid profiles, with also noteworthy $\sum$PUFA/$\sum$SFA ratios, resulted in the most suitable seaweeds that would be exploitable in the fortified food sector in accordance with international health recommendations. In the near future, we will aim to optimize the extraction of bioactive substances from the examined seaweeds, performing integrated analytical approaches (e.g. HPLC, GC–MS and LC-MS techniques) in order to consider their possible biotechnological uses. Furthermore, based on a previous positive experience on the cultivation of *C. linum* in an IMTA system implemented in the Mediterranean area, we suggest the cultivation of the selected promising seaweeds in a sustainable aquaculture scenario, in order to avoid the overharvesting of marine resources. Therefore, this study represents a contribution to the expected progress in Europe of new production chains related to the use and valorization of algal resources.

CRediT authorship contribution statement

Loredana Stabili: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Maria Immacolata Acquaviva:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Ester Cecere:** Methodology, Investigation, Data curation. **Carmela Gerardi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation. **Antonella Petrocelli:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis. **Elisa Quarta:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study was mainly supported by the "National Biodiversity Future Center (NBFC)", funded by European Union Next Generation EU (PNRR), Spoke 2 Activity 3 Task 3.2 CUP B83C22002930006, by the Project "REmediation of Marine Environment and Development of Innovative Aquaculture": exploitation of edible/not edible biomass "REMEDIA Life" under Grant Agreement No. Life 16 ENVIT/000343 and partly funded by EU-Next Generation EU, IR0000035, Project EMBRC-UP.

Data availability

Data will be made available on request.

References

Abdel-Raouf, N., Mohamed, H. M., Samah, M. S. S., & Ibraheem, B. M. I (2017). Controlling microbial growth by using *Cystoseira barbata* extract. *Egyptian Journal of Botany, 57*(3), 469–477. https://doi.org/10.21608/ejbo.2017.911.1071

Aboul-Ela, H. M., Elkomy, R. G., Saleh, H., & Hafez, S. M. M. A. L. (2021). Phylogenetic characterization based on mitochondrial cox 1 gene analysis, antibacterial and antioxidant potential of the red algae *Hypnea cornuta* extracts. *International Journal of Pharmaceutical Research, 13*(1). https://doi.org/10.31838/ijpr/2021.13.01.420. ISSN 0975-2366.

Afonso, C., Correia, A. P., Freitas, M. V., Mouga, T., & Baptista, T. (2021). In vitro evaluation of the antibacterial and antioxidant activities of extracts of *Gracilaria gracilis* with a view into its potential use as an additive in fish feed. *Applied Sciences, 11*(14), 6642. https://doi.org/10.3390/app11146642

Ahmed, F. E. (1991). Microbiological and parasitic exposure and health effects. In F. E. Ahmed (Ed.), *Seafood safety* (pp. 30–84). Washington: National Academy Press. https://www.ncbi.nlm.nih.gov/books/NBK235727/.

Al-Adilah, H., Al-Sharrah, T. K., Al-Bader, D., Ebel, R., Küpper, F. C., & Kumari, P. (2021). Assessment of arabian gulf seaweeds from kuwait as sources of nutritionally important polyunsaturated fatty acids (PUFAs). *Foods, 10*(10), 2442 (Basel, Switzerland).

Álvarez-Martínez, F. J., Barrajón-Catalán, E., & Micol, V. (2020). Tackling antibiotic resistance with compounds of natural origin: A comprehensive review. *Biomedicines, 8*(10), 405. https://doi.org/10.3390/biomedicines8100405

Andree, K. B., Carrasco, N., Carella, F., Furones, D., & Prado, P. (2021). *Vibrio mediterranei*, a potential emerging pathogen of marine fauna: Investigation of pathogenicity using a bacterial challenge in *Pinna nobilis* and development of a species-specific PCR. *Journal of Applied Microbiology, 130*(2), 617–631. https://doi.org/10.1111/jam.14756

Ballal, M., Shetty, V., Bangera, S. R., Prabhu, M., & Umakanth, S. (2017). *Vibrio furnissii,* an emerging pathogen causing acute gastroenteritis: A case report. *JMM Case Reports, 4*(9), Article e005111. https://doi.org/10.1099/jmmcr.0.005111

Barbosa, A. D., & Siniossoglou, S. (2024). Membranes that make fat: Roles of membrane lipids as acyl donors for triglyceride synthesis and organelle function. *FEBS Letters, 598*(10), 1226–1234. https://doi.org/10.1002/1873-3468.14793

Barletta, R., Trezza, A., Geminiani, M., Frusciante, L., Olmastroni, T., Sannio, F., Docquier, J. D., & Santucci, A. (2024). *Chaetomorpha linum* extract as a source of antimicrobial compounds: A circular bioeconomy approach. *Marine Drugs, 22*(11), 511. https://doi.org/10.3390/md22110511

Basir, A. P., Rejeki, S., Purwanti, F., & Purnomo, P. W. (2024). Implementation of integrated multi-trophic Aquaculture in the cultivation of giant trevally (*Caranx ignobilis*), seaweed (*Kappaphycus alvarezii*) and sea cucumber (*Holothuria atra*) in the Aquaculture Sub-Zone of the Banda Marine Conservation Area. *International Journal of Agriculture and Biosciences, 13*(4), 610–616. https://doi.org/10.47278/journal.ijab/2024.166

Bauer, A. W., Kirby, W. M., Sherris, J. C., & Turck, M. (1966). Antibiotic susceptibility testing by a standardized single disk method. *American Journal of Clinical Pathology, 45*(4), 493–496.

Beleneva, I. A., Maslennikova, E. F., & Magarlamov, T. Y. (2004). Physiological and biochemical characteristics of the halophilic bacteria *vibrio parahaemolyticus* and *V. alginolyticus* isolated from marine invertebrates of peter the great Bay, sea of Japan. *Russian Journal of Marine Biology, 30*, 96–100. https://doi.org/10.1023/B:RUMB.0000025985.38429.11

Benning, C. (1998). Membrane lipids in anoxygenic photosynthetic bacteria. *Lipids in photosynthesis: Structure, function and genetics 6* (pp. 83–101). Dordrecht: Springer Netherlands. https://doi.org/10.1007/0-306-48087-5_5

Betriu, C., Culebras, E., Rodríguez-Avial, I., Gómez, M., Sánchez, B. A., & Picazo, J. J. (2004). In vitro activities of tigecycline against erythromycin-resistant *Streptococcus* *pyogenes* and *Streptococcus agalactiae*: Mechanisms of macrolide and tetracycline resistance. *Antimicrobial Agents and Chemotherapy, 48*(1), 323–325. https://doi.org/10.1128/AAC.48.1.323-325.2004

Bhowmick, S., Mazumdar, A., Moulick, A., & Adam, V. (2020). Algal metabolites: An inevitable substitute for antibiotics. *Biotechnology Advances, 43*, Article 107571. https://doi.org/10.1016/j.biotechadv.2020.107571

Boccella, M., Santella, B., Pagliano, P., De Filippis, A., Casolaro, V., Galdiero, M., Borrelli, A., Capunzo, M., Boccia, G., & Franci, G. (2021). Prevalence and antimicrobial resistance of enterococcus species: A retrospective cohort study in Italy. *Antibiotics, 10*(12), 1552. https://doi.org/10.3390/antibiotics10121552 (Basel, Switzerland).

Borghese, J., Giangrande, A., Arduini, D., Trani, R., Doria, L., Anglano, M., Rizzo, L., & Rossi, S. (2025). Influence of an innovative IMTA system (Mediterranean Sea, Italy) on environmental and biological parameters: Seasonal analysis. *Aquaculture, 596*(1), Article 741726. https://doi.org/10.1016/j.aquaculture.2024.741726 (Amsterdam, Netherlands)ISSN 0044-8486.

Bowen, K. J., Harris, W. S., & Kris-Etherton, P. M. (2016). Omega-3 fatty acids and cardiovascular disease: Are there benefits? *Current Treatment Options in Cardiovascular Medicine, 18*(11), 69. https://doi.org/10.1007/s11936-016-0487-1

Budge, S. M., & Parrish, C. C. (2003). FA determination in cold water marine samples. *Lipids, 38*(7), 781–791. https://doi.org/10.1007/s11745-003-1127-4

Calabrese, C., Arduini, D., Portacci, G., Quarta, E., Giangrande, A., Acquaviva, M. I., Biandolino, F., Giandomenico, S., Prato, E., & Stabili, L. (2025). Farming strategy under climate change: Growth performances and quality of *Mytilus galloprovincialis* in an Integrated Multi-Trophic Aquaculture system (North-West Mediterranean Sea). *Marine Pollution Bulletin, 220*, Article 118377. https://doi.org/10.1016/j.marpolbul.2025.118377. ISSN 0025-326X.

Calder, P. C. (2006). n-3 polyunsaturated fatty acids, inflammation, and inflammatory diseases. *The American Journal of Clinical Nutrition, 83*(6 Suppl), 1505S–1519S. https://doi.org/10.1093/ajcn/83.6.1505S

Calder, P. C., Albers, R., Antoine, J. M., Blum, S., Bourdet-Sicard, R., Ferns, G. A., Folkerts, G., Friedmann, P. S., Frost, G. S., Guarner, F., Løvik, M., Macfarlane, S., Meyer, P. D., M'Rabet, L., Serafini, M., van Eden, W., van Loo, J., Vas Dias, W., Vidry, S., Winklhofer-Roob, B. M., & Zhao, J. (2009). Inflammatory disease processes and interactions with nutrition. *The British Journal of Nutrition, 101*(Suppl 1), S1–S45. https://doi.org/10.1017/S0007114509377867

Calder, P. C. (2017). Omega-3 fatty acids and inflammatory processes: From molecules to man. *Biochemical Society Transactions, 45*(5), 1105–1115. https://doi.org/10.1042/BST20160474

Caneschi, A., Bardhi, A., Barbarossa, A., & Zaghini, A. (2023). The use of antibiotics and antimicrobial resistance in veterinary medicine, a complex phenomenon: A narrative review. *Antibiotics, 12*(3), 487. https://doi.org/10.3390/antibiotics12030487

Capillo, G., Savoca, S., Costa, R., Sanfilippo, M., Rizzo, C., Lo Giudice, A., Albergamo, A., Rando, R., Bartolomeo, G., Spanò, N., & Faggio, C. (2018). New insights into the culture method and antibacterial potential of *Gracilaria gracilis*. *Marine Drugs, 16*(12), 492. https://doi.org/10.3390/md16120492

Cardoso, C., Ripol, A., Afonso, C., Freire, M., Varela, J., Quental-Ferreira, H., Pousão-Ferreira, P., & Bandarra, N. (2017). Fatty acid profiles of the main lipid classes of green seaweeds from fish pond aquaculture. *Food Science & Nutrition, 5*(6), 1186–1194. https://doi.org/10.1002/fsn3.511

Cardoso, I., Cotas, J., Rodrigues, A., Ferreira, D., Osório, N., & Pereira, L. (2019). Extraction and analysis of compounds with antibacterial potential from the red alga *Grateloupia turuturu*. *Journal of Marine Science and Engineering, 7*(7), 220. https://doi.org/10.3390/jmse7070220

Cassani, L., Lourenço-Lopes, C., Barral-Martinez, M., Chamorro, F., Garcia-Perez, P., Simal-Gandara, J., & Prieto, M. A. (2022). Thermochemical characterization of eight seaweed species and evaluation of their potential use as an alternative for biofuel production and source of bioactive compounds. *International Journal of Molecular Sciences, 23*(4), 2355.

Casillas-Vargas, G., Ocasio-Malavé, C., Medina, S., Morales-Guzmán, C., Del Valle, R. G., Carballeira, N. M., & Sanabria-Ríos, D. J. (2021). Antibacterial fatty acids: An update of possible mechanisms of action and implications in the development of the next-generation of antibacterial agents. *Progress in Lipid Research, 82*, Article 101093. https://doi.org/10.1016/j.plipres.2021.101093

Cavallo, R. A., & Stabili, L. (2002). Presence of vibrios in seawater and *mytilus galloprovincialis* (Lam.) from the Mar Piccolo of Taranto (Ionian Sea). *Water Research, 36*(15), 3719–3726. https://doi.org/10.1016/s0043-1354(02)00107-0

Cavallo, R. A., Acquaviva, M., Stabili, L., Cecere, E., Petrocelli, A., & Narracci, M. (2013). Antibacterial activity of marine macroalgae against fish pathogenic Vibrio species. *Central European Journal of Biology, 8*, 646–653. https://doi.org/10.2478/s11535-013-0181-6

Cecere, E., Petrocelli, A., & Saracino, O. D. (2000). *Undaria pinnatifida* (Fucophyceae, Laminariales) spread in the central Mediterranean: Its occurrence in the Mar Piccolo of Taranto (Ionian Sea, southern Italy). *Cryptogamie Algologie, 21*(3), 305–309. https://doi.org/10.1016/S0181-1568(00)00113-6

Cecere, E., & Petrocelli, A. (2009). The Mar Piccolo of Taranto. In E. Cecere, A. Petrocelli, G. Izzo, & A. Sfriso (Eds.), *Flora and vegetation of the Italian transitional water systems* (pp. 195–227). Spinea (VE): CoRiLa, Stampa Multigraph.

Cerón, M. C., García-Malea, M. C., Rivas, J., Acien, F. G., Fernandez, J. M., Del Río, E., Guerrero, M. G., & Molina, E. (2007). Antioxidant activity of *Haematococcus pluvialis* cells grown in continuous culture as a function of their carotenoid and fatty acid content. *Applied Microbiology and Biotechnology, 74*(5), 1112–1119. https://doi.org/10.1007/s00253-006-0743-5

Cheung Lam, A. H., Sandoval, N., Wadhwa, R., Gilkes, J., Do, T. Q., Ernst, W., Chiang, S. M., Kosina, S., Howard Xu, H., Fujii, G., & Porter, E. (2016). Assessment of free fatty acids and cholesteryl esters delivered in liposomes as novel class of antibiotic. *BMC Research Notes, 9*, 337. https://doi.org/10.1186/s13104-016-2138-8

Choudhary, B., Deb, S., Chouhan, N., Sangeetha, A., & Choudhary, V. (2025). Integrated multi-trophic aquaculture (IMTA) for wastewater treatment and resource recovery: A sustainable approach. *Nature-Based Technologies for Wastewater Treatment and Bioenergy Production. IWA Publishing*, 77–96. https://doi.org/10.2166/9781789064100

Colquhoun, D., Aase, I. L., Wallace, C., Baklien, Å., & Gravningen, K. (2024). First description of *Vibrio ordalii* from Chile. *Bulletin of the European Association of Fish Pathologists, 24*(4), 185–188.

Cook, M. A., & Wright, G. D. (2022). The past, present, and future of antibiotics. *Science Translational Medicine, 14*, 657. https://doi.org/10.1126/scitranslmed.abo7793

Cormaci, M., Furnari, G., Catra, M., Alongi, G., & Giaccone, G. (2012). Flora marina bentonica del mediterraneo: Phaeophyceae. *Bollettino dell'Accademia Gioenia di Scienze Naturali di Catania, 45*, FP1–FP508.

Cormaci, M., Furnari, G., & Alongi, G. (2014). Flora marina bentonica del Mediterraneo: Chlorophyta. *Bollettino dell'Accademia Gioenia di Scienze Naturali di Catania, 47*, 11–436.

Cormaci, M., Furnari, G., & Alongi, G. (2020). Flora marina bentonica del mediterraneo: Rhodophyta – Rhodymeniophycidae I. Acrosymphytales, bonnemaisoniales, gelidiales, gigartinales, gracilariales. *Bullettin of the Gioenia Academy of Catania, 53*(383), FP11–FP436. https://doi.org/10.35352/gioenia.v53i383.87

Cormaci, M., Furnari, G., & Alongi, G. (2021). Flora marina bentonica del mediterraneo: Rhodophyta – Rhodymeniophycidae II. Halymeniales, nemastomatales, peyssonneliales, plocamiales, rhodymeniales, sebdeniales. *Bullettin of the Gioenia Academy of Natural Sciences of Catania, 54*(384), FP9–FP342. https://doi.org/10.35352/gioenia.v54i384.94

Cotas, J., Gomes, L., Pacheco, D., & Pereira, L. (2023). Ecosystem services provided by seaweeds. *Hydrobiology, 2*, 75–96. https://doi.org/10.3390/hydrobiology2010006

Couturier, L. I. E., Michel, L. N., Amaro, T., Budge, S. M., Da Costa, E., De Troch, M., Di Dato, V., Fink, P., Giraldo, C., Le Grand, F., Loaiza, I., Mathieu-Resuge, M., Nichols, P. D., Parrish, C. C., Sardenne, F., Vagner, M., Pernet, F., & Soudant, P. (2020). State of art and best practices for fatty acid analysis in aquatic sciences. *ICES Journal of Marine Science, 77*, 2375–2395. https://doi.org/10.1093/icesjms/fsaa121

da Costa, E., Melo, T., Moreira, A. S., Bernardo, C., Helguero, L., Ferreira, I., Cruz, M. T., Rego, A. M., Domingues, P., Calado, R., Abreu, M. H., & Domingues, M. R. (2017). Valorization of lipids from *Gracilaria* sp. through lipidomics and decoding of antiproliferative and anti-inflammatory activity. *Marine Drugs, 15*(3), 62. https://doi.org/10.3390/md15030062

da Costa, E., Melo, T., Reis, M., Domingues, P., Calado, R., Abreu, M. H., & Domingues, M. R. (2021). Polar lipids composition, antioxidant and anti-inflammatory activities of the Atlantic Red Seaweed *Grateloupia turuturu*. *Marine Drugs, 19*(8), 414. https://doi.org/10.3390/md19080414

Dávalos, A., Gómez-Cordovés, C., & Bartolomé, B. (2004). Extending applicability of the oxygen radical absorbance capacity (ORAC – fluorescein) assay. *Journal of Agricultural and Food Chemistry, 52*, 48–54. https://doi.org/10.1021/jf0305231

Denis, C. M., Morançais, M., Li, M., Deniaud, E., Gaudin, P., Wielgosz-Collin, G., Barnathan, G., Jaouen, P., & Fleurence, J. (2010). Study of the chemical composition of edible red macroalgae *grateloupia turuturu* from Brittany (France). *Food Chemistry, 119*(3), 913–917. https://doi.org/10.1016/j.foodchem.2009.07.047

Denti, G., Ricci, P., Cecere, E., & Petrocelli, A. (2024). Long term monitoring activities to investigate the colonization dynamics of non-indigenous seaweeds in transitional waters. In *Proceedings of the IEEE international workshop on metrology for the sea*, 2024 14-16 October.

de Roos, B., Mavrommatis, Y., & Brouwer, I. A. (2009). Long-chain n-3 polyunsaturated fatty acids: New insights into mechanisms relating to inflammation and coronary heart disease. *British Journal of Pharmacology, 158*(2), 413–428. https://doi.org/10.1111/j.1476-5381.2009.00189.x

de Souza Valente, C., & Wan, A. H. L. (2021). Vibrio and major commercially important vibriosis diseases in decapod crustaceans. *Journal of Invertebrate Pathology, 181*, Article 107527. https://doi.org/10.1016/j.jip.2020.107527

dos Santos, M. A. Z., Berneira, L. M., Goulart, N. L., Mansilla, A., Astorga-España, M. S., & de Pereira, C. M. P. (2021). Rhodophyta, ochrophyta and chlorophyta macroalgae from different sub-antarctic regions (Chile) and their potential for polyunsaturated fatty acids. *Brazilian Journal of Botany, 44*, 429–438.

El-Beltagi, H. S., Mohamed, A. A., Mohamed, H. I., Ramadan, K. M. A., Barqawi, A. A., & Mansour, A. T. (2022). Phytochemical and potential properties of seaweeds and their recent applications: A review. *Marine Drugs, 20*(6), 342. https://doi.org/10.3390/md20060342

Elgendy, M. Y., Ali, S. E., Dayem, A. A., Khalil, R. H., Moustafa, M. M., & Abdelsalam, M. (2024). Alternative therapies recently applied in controlling farmed fish diseases: Mechanisms, challenges, and prospects. *Aquaculture International, 32*, 9017–9078. https://doi.org/10.1007/s10499-024-01603-3

Ely, R., Supriya, T., & Naik, C. G. (2004). Antimicrobial activity of marine organisms collected off the coast of South East India. *Journal of Experimental Marine Biology and Ecology, 309*, 121–127. https://doi.org/10.1016/j.jembe.2004.03.010

Falace, A., Manfrin, C., Furnari, G., D'Ambros Burchio, S., Pallavicini, A., Descourvieres, E., Kaleb, S., Lokovšek, A., Grech, D., & Alongi, G. (2024). Contribution to the knowledge of *Gongolaria barbata* (Sargassaceae, Fucales) from the Mediterranean: Insights into infraspecific diversity. *Phytotaxa, 635*, 191–205. https://doi.org/10.11646/phytotaxa.635.3.1

Félix, C., Félix, R., Carmona, A. M., Januário, A. P., Dias, P. D. M., Vicente, T. F. L., Silva, J., Alves, C., Pedrosa, R., Novais, S. C., & Lemos, M. F. L. (2021). Cosmeceutical potential of *Grateloupia turuturu*: Using low-cost extraction methodologies to obtain added-value extracts. *Applied Sciences, 11*(4), 1650. https://doi.org/10.3390/app11041650

Fan, C., Liu, S., Dai, W., He, L., Xu, H., Zhang, H., & Xue, Q. (2023). Characterization of *Vibrio mediterranei* isolates as causative agents of Vibriosis in marine bivalves. *Microbiology Spectrum, 11*(2), Article e0492322. https://doi.org/10.1128/spectrum.04923-22. Advance online publication.

Fleming, T. J., Schrankel, C. S., Vyas, H., Rosenblatt, H. D., & Hamdoun, A. (2021). CRISPR/Cas9 mutagenesis reveals a role for ABCB1 in gut immune responses to *Vibrio diazotrophicus* in sea urchin larvae. *Ecophysiology: Responses to Environmental Stressors and Change, 224*, Article jeb232272. https://doi.org/10.1242/jeb.232272

Fleurence, J., Gutbier, G., & Mabeau, S. (1994). Leray, C. Fatty acids from 11 marine macroalgae of the French Brittany coast. *Journal of Applied Phycology, 6*(5), 527–532. https://doi.org/10.1007/BF02182406

Floreto, E. A. T., & Teshima, S. (1998). The fatty acid composition of seaweed exposed to different levels of light intensity and salinity. *Botanica Marina, 41*, 467–481. https://doi.org/10.1515/botm.1998.41.1-6.467

Folch, J., Lees, M., & Sloane Stanley, G. H. (1957). A simple method for the isolation and purification of total lipides from animal tissues. *The Journal of Biological Chemistry, 226*(1), 497–509.

Francavilla, M., Manara, P., Kamaterou, P., Monteleone, M., & Zabaniotou, A. (2015). Cascade approach of red macroalgae *Gracilaria gracilis* sustainable valorization by extraction of phycobiliproteins and pyrolysis of residue. *Bioresource Technology, 184*, 305–313. https://doi.org/10.1016/j.biortech.2014.10.147

Galloway, A. W., Britton-Simmons, K. H., Duggins, D. O., Gabrielson, P. W., & Brett, M. T. (2012). Fatty acid signatures differentiate marine macrophytes at ordinal and family ranks (1). *Journal of Phycology, 48*(4), 956–965. https://doi.org/10.1111/j.1529-8817.2012.01173.x

Gerardi, C., Pinto, L., Baruzzi, F., & Giovinazzo, G. (2021). Comparison of antibacterial and antioxidant properties of red (cv. Negramaro) and white (cv. Fiano) skin pomace extracts. *Molecules, 26*, 5918. https://doi.org/10.3390/molecules26195918 (Basel, Switzerland).

Gergova, R., Boyanov, V., Muhtarova, A., & Alexandrova, A. (2024). A review of the impact of streptococcal infections and antimicrobial resistance on human health. *Antibiotics, 13*(4), 360. https://doi.org/10.3390/antibiotics13040360 (Basel, Switzerland).

Giangrande, A., Pierri, C., Arduini, D., Borghese, J., Licciano, M., Trani, R., Corriero, G., Basile, G., Cecere, E., Petrocelli, A., Stabili, L., & Longo, C. (2020). An Innovative IMTA System: Polychaetes, sponges and macroalgae co-cultured in a Southern Italian in-shore mariculture plant (Ionian Sea). *Journal of Marine Science and Engineering, 8* (10), 733. https://doi.org/10.3390/jmse8100733

Global Antimicrobial Resistance Surveillance System (GLASS), (2018), Editors world health organization p. 268, ISBN: 9789241515061. https://www.who.int/publications/i/item/9789241515061.

González-Ballesteros, N., Fernandes, M., Machado, R., Sampaio, P., Gomes, A. C., Cavazza, A., Bigi, F., & Rodríguez-Argüelles, M. C. (2023). Valorisation of the invasive macroalgae *undaria pinnatifida* (Harvey) suringar for the green synthesis of gold and silver nanoparticles with antimicrobial and antioxidant potential. *Marine Drugs, 21*(7), 397. https://doi.org/10.3390/md21070397

Guedes, B. N., Krambeck, K., Durazzo, A., Lucarini, M., Santini, A., Oliveira, M. B. P. P., Fathi, F., & Souto, E. B. (2024). Natural antibiotics against antimicrobial resistance: Sources and bioinspired delivery systems. *Brazilian Journal of Microbiology: [Publication of the Brazilian Society for Microbiology], 55*(3), 2753–2766. https://doi.org/10.1007/s42770-024-01410-1

Guerinot, M. L., West, P. A., Lee, J. V., & Colwell, R. R. (1982). *Vibrio diazotrophicus* sp. nov., a marine nitrogen-fixing bacterium. *International Journal of Systematic and Evolutionary Microbiology, 32*(3), 350–357. https://doi.org/10.1099/00207713-32-3-350

Guo, J., Qi, M., Chen, H., Zhou, C., Ruan, R., Yan, X., & Cheng, P. (2022). Macroalgae-derived multifunctional bioactive substances: The potential applications for food and pharmaceuticals. *Foods, 11*, 3455. https://doi.org/10.3390/foods11213455 (Basel, Switzerland).

Hala, A. F., Chougule, K., Cunha, M. E., Caria Mendes, M., Oliveira, I., Bradley, T., Forbes, J., & Speranza, L. G (2024). Life cycle assessment of integrated multi-trophic aquaculture: A review on methodology and challenges for its sustainability evaluation. *Aquaculture, 590*, Article 741035. https://doi.org/10.1016/j.aquaculture.2024.741035 (Amsterdam, Netherlands)ISSN 0044-8486.

Halliwell, B. (2024). Understanding mechanisms of antioxidant action in health and disease. *Nature Reviews Molecular Cell Biology, 25*, 13–33. https://doi.org/10.1038/s41580-023-00645-4

Hamilton, J. S., & Klett, E. L. (2021). Linoleic acid and the regulation of glucose homeostasis: A review of the evidence. *Prostaglandins, Leukotrienes, and Essential Fatty Acids, 175*, Article 102366. https://doi.org/10.1016/j.plefa.2021.102366

Hansen, W., Freney, J., Benyagoub, H., Letouzey, M. N., Gigi, J., & Wauters, G. (1993). Severe human infections caused by *Vibrio metschnikovii*. *Journal of Clinical Microbiology, 31*(9), 2529–2530. https://doi.org/10.1128/jcm.31.9.2529-2530.1993

Hotimchenko, S. V. (2002). Fatty acid composition of algae from habitats with varying amounts of illumination. *Russian Journal of Marine Biology, 28*(3), 218–220. https://doi.org/10.1023/A:1016861807103

Huang, D., Ou, B., & Prior, R. L. (2005). The chemistry behind antioxidant capacity assays. *Journal of Agricultural and Food Chemistry, 53*(6), 1841–1856. https://doi.org/10.1021/jf030723c

Huisman, J. M., & Petrocelli, A. (2021). Cryptic cryptogam revealed: *Hypnea corona* (Gigartinales: Cystocloniaceae), a new red algal species described from the *Hypnea cornuta* complex. *Pacific Science, 75*(2), 263–268. https://doi.org/10.2984/75.2.8

Jakobek, L. (2015). Interactions of polyphenols with carbohydrates, lipids and proteins. *Food Chemistry, 175*, 556–567. https://doi.org/10.1016/j.foodchem.2014.12.013

Jensen, J., & Jellinge, M. E. (2014). Severe septic shock and cardiac arrest in a patient with *Vibrio metschnikovii:* A case report. *Journal of Medical Case Reports, 8*, 348. https://doi.org/10.1186/1752-1947-8-348

Jones, M. K., & Oliver, J. D. (2009). *Vibrio vulnificus:* Disease and pathogenesis. *Infection and Immunity, 77*, 1723–1733. https://doi.org/10.1128/IAI.01046-08

Joublin-Delavat, A., Touahri, K., Crétin, P., Morot, A., Rodrigues, S., Jesus, B., Trigodet, F., & Delavat, F. (2022). Genetic and physiological insights into the diazotrophic activity of a non-cyanobacterial marine diazotroph. *Environmental Microbiology, 24*(12), 6510–6523. https://doi.org/10.1111/1462-2920.16261

Katiyar, R., Banerjee, S., & Arora, A. (2021). Recent advances in the integrated biorefinery concept for the valorization of algal biomass through sustainable routes. *Biofuels, Bioproducts and Biorefining, 15*(3), 879–898. https://doi.org/10.1002/bbb.2187

Kendel, M., Couzinet-Mission, A., Viau, M., Fleurence, J., Barnathan, G., & Wielgosz-Collin, G. (2012). Seasonal composition of lipids, fatty acids, and sterols in the edible red alga *Grateloupia turuturu*. *Journal of Applied Phycology, 25*, 425–432. https://doi.org/10.1007/s10811-012-9876-3

Kendel, M., Barnathan, G., Fleurence, J., Rabesaotra, V., & Wielgosz-Collin, G. (2013). Non-methylene interrupted and hydroxy fatty acids in polar lipids of the alga *Grateloupia turuturu* over the four seasons. *Lipids, 48*(5), 535–545. https://doi.org/10.1007/s11745-013-3783-5

Kendel, M., Wielgosz-Collin, G., Bertrand, S., Roussakis, C., Bourgougnon, N., & Bedoux, G. (2015). Lipid composition, fatty acids and sterols in the seaweeds *Ulva armoricana,* and *Solieria chordalis* from Brittany (France): An analysis from nutritional, chemotaxonomic, and antiproliferative activity perspectives. *Marine Drugs, 13*(9), 5606–5628. https://doi.org/10.3390/md13095606

Khan, N., Sudhakar, K., & Mamat, R. (2024). Macroalgae farming for sustainable future: Navigating opportunities and driving innovation. *Heliyon, 10*(7), Article e28208. https://doi.org/10.1016/j.heliyon.2024.e28208

Kientz, B., Thabard, M., Cragg, S., Pope, J., & Hellio, C. (2011). A new method for removing microflora from macroalgal surfaces: An important step for natural product discovery. *Botanica Marina, 54*(5), 457–469. https://doi.org/10.1515/BOT.2011.053

Kim, B. S., & Kim, J. S. (2002). Cholesterol induces oligomerization of *vibrio vulnificus* cytolysin specifically. *Experimental & Molecular Medicine, 34*, 239–242. https://doi.org/10.1038/emm.2002.33

Kim, C. M., Park, Y. J., & Shin, S. H. (2007). A widespread deferoxamine-mediated iron-uptake system in *Vibrio vulnificus*. *The Journal of Infectious Diseases, 196*(10), 1537–1545. https://doi.org/10.1086/523108

Kim, D. H., Yoo, T. H., Lee, S. H., Kang, H. Y., Nam, B. Y., Kwak, S. J., Kim, J. K., Park, J. T., Han, S. H., & Kang, S. W. (2012). Gamma linolenic acid exerts anti-inflammatory and anti-fibrotic effects in diabetic nephropathy. *Yonsei Medical Journal, 53*(6), 1165–1175. https://doi.org/10.3349/ymj.2012.53.6.1165

Konechnyi, Y., Khorkavyi, Y., Ivanchuk, K., Kobza, I., Sękowska, A., & Korniychuk, O. (2021). *Vibrio metschnikovii:* Current state of knowledge and discussion of recently identified clinical case. *Clinical Case Reports, 9*(4), 2236–2244. https://doi.org/10.1002/ccr3.3999

Krish, S., & Das, A. (2014). In-vitro bioactivity of marine seaweed, *Cladophora rupestris*. *International Journal of Pharma and Bio Sciences, 5*, 898–908.

Kumar, Y., Tarafdar, A., & Badgujar, P. C. (2021a). Seaweed as a source of natural antioxidants: Therapeutic activity and food applications. *Journal of Food Quality, 1*, Article 5753391. https://doi.org/10.1155/2021/5753391

Kumar, V., Roy, S., Behera, B. K., Bossier, P., & Das, B. K. (2021b). Acute hepatopancreatic necrosis disease (AHPND): Virulence, pathogenesis and mitigation strategies in shrimp aquaculture. *Toxins, 13*(8), 524. https://doi.org/10.3390/toxins13080524

Kumari, P., Kumar, M., Gupta, V., Reddy, C. R. K., & Jha, B. (2010). Tropical marine macroalgae as potential sources of nutritionally important PUFAs. *Food Chemistry, 120*(3), 749–757. https://doi.org/10.1016/j.foodchem.2009.11.006

Ibrahim, M., Ahmad, F., Yaqub, B., Ramzan, A., Imran, A., Afzaal, M., Mirza, S. A., Mazhar, I., Younus, M., Akram, Q., Ali Taseer, M. S., Ahmad, A., & Ahmed, S. (2020). Current trends of antimicrobials used in food animals and aquaculture. In M. Z. Hashmi (Ed.), *Antibiotics and antimicrobial resistance genes in the environment* (pp. 39–69). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-818882-8.00004-8, 1.

Ismail, A., Ktari, L., Ben Redjem Romdhane, Y., Aoun, B., Sadok, S., Boudabous, A., & El Bour, M. (2018). Antimicrobial fatty acids from green alga *ulva rigida* (Chlorophyta). *BioMed Research International, 2018*, Article 3069595. https://doi.org/10.1155/2018/3069595

Larsson, D. G. J., & Flach, C. F. (2022). Antibiotic resistance in the environment. *Nature Reviews Microbiology, 20*, 257–269. https://doi.org/10.1038/s41579-021-00649-x

Lee, J. C., Hou, M. F., Huang, H. W., Chang, F. R., Yeh, C. C., Tang, J. Y., & Chang, H. W. (2013). Marine algal natural products with anti-oxidative, anti-inflammatory, and anti-cancer properties. *Cancer Cell International, 13*(1), 55. https://doi.org/10.1186/1475-2867-13-55

Linde, H. J., Kobuch, R., Jayasinghe, S., Reischl, U., Lehn, N., Kaulfuss, S., & Beutin, L. (2004). *Vibrio metschnikovii,* a rare cause of wound infection. *Journal of Clinical Microbiology, 42*(10), 4909–4911. https://doi.org/10.1128/JCM.42.10.4909-4911.2004

Lomartire, S., & Gonçalves, A. M. M. (2022). An overview of potential seaweed-derived bioactive compounds for pharmaceutical applications. *Marine Drugs, 20*(2), 141. https://doi.org/10.3390/md20020141

Lopes, D., Melo, T., Meneses, J., Abreu, M. H., Pereira, R., Domingues, P., Lillebø, A. I., Calado, R., & Domingues, R. M. (2019). A new look for the red macroalga *palmaria palmata*: A seafood with polar lipids rich in EPA and with antioxidant properties. *Marine Drugs, 17*(9), 533. https://doi.org/10.3390/md17090533

Lopes, D., Rey, F., Leal, M. C., Lillebø, A. I., Calado, R., & Domingues, M. R. (2021). Bioactivities of lipid extracts and complex lipids from seaweed: Current knowledge and future prospects. *Marine Drugs, 19*(12), 686. https://doi.org/10.3390/md19120686

Lordan, R., Tsoupras, A., & Zabetakis, I. (2017). Phospholipids of animal and marine origin: Structure, function, and anti-inflammatory properties. *Molecules, 22*(11), 1964. https://doi.org/10.3390/molecules22111964 (Basel, Switzerland).

Lupo, C., Travers, M. A., Tourbiez, D., Barthélémy, C. F., Beaunée, G., & Ezanno, P. (2019). Modeling the transmission of *vibrio aestuarianus* in Pacific oysters using experimental infection data. *Frontiers in Veterinary Science, 6*, 142. https://doi.org/10.3389/fvets.2019.00142

Manchanayake, T., Salleh, A., Amal, M. N. A., Yasin, I. S. M., & Zamri-Saad, M. (2023). Pathology and pathogenesis of Vibrio infection in fish: A review. *Aquaculture Reports, 28*, Article 101459. https://doi.org/10.1016/j.aqrep.2022.101459. ISSN 2352-5134.

Manilal, A., Sugathan, S., Selvin, J., Shakir, C., Gandhimathi, R., & Kiran, S. (2010). Virulence of vibrios isolated from diseased black tiger shrimp, Penaeus monodon, Fabricius. *Journal of the World Aquaculture Society, 41*, 332–343. https://doi.org/10.1111/j.1749-7345.2010.00375.x

Marques, F., Lopes, D., da Costa, E., Conde, T., Rego, A., Ribeiro, A. I., Abreu, M. H., & Domingues, M. R. (2021). Seaweed blends as a valuable source of polyunsaturated and healthy fats for nutritional and food applications. *Marine Drugs, 19*(12), 684. https://doi.org/10.3390/md19120684

Marques, P. H., Prado, L. C.d. S., Felice, A. G., Rodrigues, T. C. V., Pereira, U. D. P., Jaiswal, A. K., Azevedo, V., Oliveira, C. J. F., & Soares, S. (2022). Insights into the *Vibrio* genus: A one health perspective from host adaptability and antibiotic resistance to in silico identification of drug targets. *Antibiotics, 11*(10), 1399. https://doi.org/10.3390/antibiotics11101399

Masarin, F., Cedeno, F. R. P., Chavez, E. G. S., de Oliveira, L. E., Gelli, V. C., & Monti, R. (2016). Chemical analysis and biorefinery of red algae *kappaphycus alvarezii* for efficient production of glucose from residue of carrageenan extraction process. *Biotechnology for Biofuels, 9*, 122. https://doi.org/10.1186/s13068-016-0535-9

Michalak, I., Tiwari, R., Dhawan, M., Alagawany, M., Farag, M. R., Sharun, K., Emran, T. B., & Dhama, K. (2022). Antioxidant effects of seaweeds and their active compounds on animal health and production - a review. *The Veterinary Quarterly, 42*(1), 48–67. https://doi.org/10.1080/01652176.2022.2061744

Munier, M., Dumay, J., Morançais, M., Jaouen, P., & Fleurence, J. (2013). Variation in the biochemical composition of the edible seaweed *Grateloupia turuturu* Yamada harvested from two sampling sites on the Brittany coast (France): The influence of storage method on the extraction of the seaweed pigment r-phycoerythrin. *Journal of Chemistry, 2013*(1), Article 568548. https://doi.org/10.1155/2013/568548

Murai, U., Yamagishi, K., Kishida, R., & Iso, H. (2021). Impact of seaweed intake on health. *European Journal of Clinical Nutrition, 75*, 877–889. https://doi.org/10.1038/s41430-020-00739-8

Noorjahan, A., Mahesh, S., Anantharaman, P., & Aiyamperumal, B. (2022). Antimicrobial potential of seaweeds: Critical review. In A. Ranga Rao, & G. A. Ravishankar (Eds.), *Sustainable global resources of seaweeds volume 1*. Cham: Springer. https://doi.org/10.1007/978-3-030-91955-9_21.

Oktanella, Y., Hendrawan, V. F., Firmawati, A., Agustina, G. C., & Yuliana, R. (2024). Optimizing reproductive outcomes of peranakan Etawa goat with microalgae diet by determining ovarian activity, estradiol 17β levels, and serum malondialdehyde. *International Journal of Veterinary Science, 13*(6), 935–940. https://doi.org/10.47278/journal.ijvs/2024.176

Pacheco, D., Araújo, G. S., Cotas, J., Gaspar, R., Neto, J. M., & Pereira, L. (2020). Invasive seaweeds in the Iberian Peninsula: A contribution for food supply. *Marine Drugs, 18*(11), 560. https://doi.org/10.3390/md18110560

Pancu, D. F., Scurtu, A., Macasoi, I. G., Marti, D., Mioc, M., Soica, C., Coricovac, D., Horhat, D., Poenaru, M., & Dehelean, C. (2021). Antibiotics: Conventional therapy and natural compounds with antibacterial activity-a pharmaco-toxicological screening. *Antibiotics, 10*(4), 401. https://doi.org/10.3390/antibiotics10040401 (Basel, Switzerland).

Pariente Martín, M., Escribano Garaizábal, E., Liria Sánchez, P. J., & Crespo Sánchez, M. D. (2008). *Vibrio metschnikovii* from a human infected leg ulcer. *Revista do Instituto de Medicina Tropical de Sao Paulo, 50*(5), 311–312. https://doi.org/10.1590/s0036-46652008000500012

Patra, J. K., Lee, S. W., Park, J. G., & Baek, K. H. (2017). Antioxidant and antibacterial properties of essential oil extracted from an edible seaweed *Undaria Pinnatifida*. *Journal of Food Biochemistry, 41*, Article e12278. https://doi.org/10.1111/jfbc.12278

Peñalver, R., Lorenzo, J. M., Ros, G., Amarowicz, R., Pateiro, M., & Nieto, G. (2020). Seaweeds as a functional ingredient for a healthy diet. *Marine Drugs, 18*(6), 301. https://doi.org/10.3390/md18060301

Pepper, I., Gerba, C. P., Gentry, T., & Maier, R. M. (2011). *Environmental microbiology* (2nd ed.). Hardback: Academic Press. October 13, Imprint:ISBN: 9780123705198. eBook ISBN: 9780080919409.

Pérez, M. J., Falqué, E., & Domínguez, H. (2016). Antimicrobial action of compounds from marine seaweed. *Marine Drugs, 14*(3), 52. https://doi.org/10.3390/md14030052

Pérez-Lloréns, J. L., Critchley, A. T., Cornish, M. L., & Mouritsen, O. G. (2023). Saved by seaweeds (II): Traditional knowledge, home remedies, medicine, surgery, and pharmacopoeia. *Journal of Applied Phycology, 35*, 2049–2068. https://doi.org/10.1007/s10811-023-02965-6

Perfeto, P. N. M. (1998). Relation between chemical composition of *Grateloupia doryphora* (Montagne) Howe, *Gymnogongrus griffithsiae* (Turner) Martius, and abiotic parameters. *Acta Botanica Brasilica, 12*, 77–88. https://doi.org/10.1590/S0102-33061998000100006

Petrocelli, A., & Cecere, E. (2019). A 20-year update on the state of seaweed resources in Italy. *Botanica Marina, 62*, 249–264.

Petrocelli, A., Cecere, E., & Rubino, F. (2019). Successions of phytobenthos species in a Mediterranean transitional water system: The importance of long-term observations. *Nature Conservation, 34*, 217–246. https://doi.org/10.3897/natureconservation.34.30055

Petrocelli, A., Alabiso, G., Cecere, E., Ricci, P., & Carlucci, R. (2020). Invasive or not? The case of *Grateloupia turuturu* (Rhodophyta, Halymeniales) in the Northern Ionian Sea (Mediterranean Sea). *Marine Pollution Bulletin, 161*, Article 111748. https://doi.org/10.1016/j.marpolbul.2020.111748

Prior, R. L., Wu, X., & Schaich, K. (2005). Standardized methods for the determination of antioxidant capacity and phenolics in foods and dietary supplements. *Journal of Agricultural and Food Chemistry, 53*(10), 4290–4302. https://doi.org/10.1021/jf0502698

Ramola, B., Kumar, V., Nanda, M., Mishra, Y., Tyagi, T., Gupta, A., & Sharma, N. (2019). Evaluation, comparison of different solvent extraction, cell disruption methods and hydrothermal liquefaction of oedogonium macroalgae for biofuel production. *Biotechnology Reports, 22*, Article e00340. https://doi.org/10.1016/j.btre.2019.e00340 (Amsterdam, Netherlands).

Raja, R., Hemaiswarya, S., Arunkumar, K., & Carvalho, I. S. (2016). Antioxidant activity and lipid profile of three seaweeds of Faro, Portugal. *Brazilian Journal of Botany, 39*, 9–17. https://doi.org/10.1007/s40415-015-0200-8

Re, R., Pellegrini, N., Proteggente, A., Pannala, A., Yang, M., & Rice-Evans, C. (1999). Antioxidant activity applying an improved ABTS radical cation decolorization assay. *Free Radical Biology & Medicine, 26*(9-10), 1231–1237. https://doi.org/10.1016/s0891-5849(98)00315-3

Rengasamy, K. R., Mahomoodally, M. F., Aumeeruddy, M. Z., Zengin, G., Xiao, J., & Kim, D. H. (2020). Bioactive compounds in seaweeds: An overview of their biological properties and safety. *Food and Chemical Toxicology: An International Journal Published for the British Industrial Biological Research Association, 135*, Article 111013. https://doi.org/10.1016/j.fct.2019.111013

Rocha, C. P., Pacheco, D., Cotas, J., Marques, J. C., Pereira, L., & Gonçalves, A. M. M. (2021). Seaweeds as valuable sources of essential fatty acids for human nutrition. *International Journal of Environmental Research and Public Health, 18*(9), 4968. https://doi.org/10.3390/ijerph18094968

Rodrigues, D., Freitas, A. C., Pereira, L., Rocha-Santos, T. A., Vasconcelos, M. W., Roriz, M., Rodríguez-Alcalá, L. M., Gomes, A. M., & Duarte, A. C. (2015). Chemical composition of red, brown and green macroalgae from Buarcos bay in Central West Coast of Portugal. *Food Chemistry, 183*, 197–207. https://doi.org/10.1016/j.foodchem.2015.03.057

Rusco, G., Roncarati, A., Di Iorio, M., Cariglia, M., Longo, C., & Iaffaldano, N. (2024). Can IMTA system improve the productivity and quality traits of aquatic organisms produced at different trophic levels? The benefits of IMTA — Not only for the ecosystem. *Biology, 13*(11), 946. https://doi.org/10.3390/biology13110946

Sanches-Fernandes, G. M. M., Sá-Correia, I., & Costa, R. (2022). Vibriosis outbreaks in aquaculture: Addressing environmental and public health concerns and preventive therapies using gilthead seabream farming as a model system. *Frontiers in Microbiology, 13*, Article 904815. https://doi.org/10.3389/fmicb.2022.904815

Santos, F., Monteiro, J. P., Duarte, D., Melo, T., Lopes, D., da Costa, E., & Domingues, M. R. (2020). Unraveling the lipidome and antioxidant activity of native *bifurcaria bifurcata* and invasive *sargassum muticum* seaweeds: A lipid perspective on how systemic intrusion may present an opportunity. *Antioxidants, 9*(7), 642. https://doi.org/10.3390/antiox9070642 (Basel, Switzerland).

Sarkar, B., Mahanty, A., Gupta, S. K., Choudhury, A. R., Daware, A., & Bhattacharjee, S. (2022). Nanotechnology: A next-generation tool for sustainable aquaculture. *Aquaculture, 546*, Article 737330. https://doi.org/10.1007/978-3-031-31104-8_10 (Amsterdam, Netherlands).

Sfriso A. (2011). Ochrophyta (Phaeophyceae e Xanthophyceae). Ambienti di transizione italiani e litorali adiacenti. I Quaderni di ARPA. ARPA Emilia-Romagna, Bologna, Odoya srl, pp. 234. ISBN 978-88-87854-28-2.

Shanab, S. M. M., Hafez, R. M., & Fouad, A. S. (2018). A review on algae and plants as potential source of arachidonic acid. *Journal of Advanced Research, 11*, 3–13. https://doi.org/10.1016/j.jare.2018.03.004

Siddik, M. A. B., Francis, P., Rohani, M. F., Azam, M. S., Mock, T. S., & Francis, D. S. (2023). Seaweed and seaweed-based functional metabolites as potential modulators of growth, immune and antioxidant responses, and gut microbiota in fish. *Antioxidants, 12*(12), 2066. https://doi.org/10.3390/antiox12122066

Silva, A., Silva, S. A., Carpena, M., Garcia-Oliveira, P., Gullón, P., Barroso, M. F., Prieto, M. A., & Simal-Gandara, J. (2020). Macroalgae as a source of valuable antimicrobial compounds: Extraction and applications. *Antibiotics, 9*(10), 642. https://doi.org/10.3390/antibiotics9100642

Simopoulos, A. P. (1999). Essential fatty acids in health and chronic disease. *The American Journal of Clinical Nutrition, 70*(3 Suppl), 560S–569S. https://doi.org/10.1093/ajcn/70.3.560s

Simopoulos, A. P. (2002). The importance of the ratio of omega-6/omega-3 essential fatty acids. *Biomedicine & Pharmacotherapy, 56*(8), 365–379. https://doi.org/10.1016/s0753-3322(02)00253-6

Sneddon, A. A., Tsofliou, F., Fyfe, C. L., Matheson, I., Jackson, D. M., Horgan, G., Winzell, M. S., Wahle, K. W., Ahren, B., & Williams, L. M. (2008). Effect of a conjugated linoleic acid and omega-3 fatty acid mixture on body composition and adiponectin. *Obesity, 16*(5), 1019–1024. https://doi.org/10.1038/oby.2008.41 (Silver Spring, Md.).

Stabili, L., Acquaviva, M. I., & Cavallo, R. A. (2005). *Mytilus galloprovincialis* filter feeding on the bacterial community in a Mediterranean coastal area (Northern Ionian Sea, Italy). *Water Research, 39*(2-3), 469–477. https://doi.org/10.1016/j.watres.2004.10.010

Stabili, L., Acquaviva, M. I., Biandolino, F., Cavallo, R. A., De Pascali, S. A., Fanizzi, F. P., Narracci, M., Petrocelli, A., & Cecere, E. (2012). The lipidic extract of the seaweed *gracilariopsis longissima* (Rhodophyta, Gracilariales): A potential resource for biotechnological purposes? *New Biotechnology, 29*(3), 443–450. https://doi.org/10.1016/j.nbt.2011.11.003

Stabili, L., Acquaviva, M. I., Biandolino, F., Cavallo, R. A., De Pascali, S. A., Fanizzi, F. P., Narracci, M., Cecere, E., & Petrocelli, A. (2014). Biotechnological potential of the seaweed *Cladophora rupestris* (Chlorophyta, Cladophorales) lipidic extract. *New Biotechnology, 31*, 436–444. https://doi.org/10.1016/j.nbt.2014.05.002

Stabili, L., Acquaviva, M. I., Angilè, F., Cavallo, R. A., Cecere, E., Del Coco, L., Fanizzi, F. P., Gerardi, C., Narracci, M., & Petrocelli, A. (2019a). Screening of *chaetomorpha linum* lipidic extract as a new potential source of bioactive compounds. *Marine Drugs, 17*(6), 313. https://doi.org/10.3390/md17060313

Stabili, L., Cecere, E., Licciano, M., Petrocelli, A., Sicuro, B., & Giangrande, A. (2019b). Integrated Multitrophic Aquaculture by-products with added value: The polychaete *sabella spallanzanii* and the seaweed *chaetomorpha linum* as potential dietary ingredients. *Marine Drugs, 17*(12), 677. https://doi.org/10.3390/md17120677

Stabili, L., Acquaviva, M. I., Cecere, E., Gerardi, C., Petrocelli, A., Fanizzi, F. P., Angilè, F., & Rizzo, L. (2023a). Screening of *undaria pinnatifida* (Laminariales, Phaeophyceae) lipidic extract as a new potential source of antibacterial and antioxidant compounds. *Journal of Marine Science and Engineering, 11*(11), 2072. https://doi.org/10.3390/jmse11112072

Stabili, L., Giangrande, A., Arduini, D., Borghese, J., Petrocelli, A., Alabiso, G., Ricci, P., Cavallo, R. A., Acquaviva, M. I., Narracci, M., Pierri, C., Trani, R., & Longo, C. (2023b). Environmental quality improvement of a mariculture plant after its conversion into a multi-trophic system. *The Science of the Total Environment, 884*, Article 163846. https://doi.org/10.1016/j.scitotenv.2023.163846

Stabili, L., Quarta, E., & Giotta, L. (2024). The seaweed *chaetomorpha linum* cultivated in an integrated multitrophic aquaculture system: A new tool for microplastic bioremediation? *The Science of the Total Environment, 954*, Article 176262. https://doi.org/10.1016/j.scitotenv.2024.176262

Susanto, E., Fahmi, A. S., Hosokawa, M., & Miyashita, K. (2019). Variation in lipid components from 15 species of tropical and temperate seaweeds. *Marine Drugs, 17* (11), 630. https://doi.org/10.3390/md17110630

Tabakaeva, O., & Tabakaev, A. (2017). Compositions of lipids and fatty acids from various parts of the brown alga *Undaria pinnatifida*. *Chemistry of Natural Compounds, 53*, 843–848. https://doi.org/10.1007/s10600-017-2137-6, 2017.

Tahir, F., Fatima, F., Fatima, R., & Ali, E. (2021). Fruit peel extracted polyphenols through ultrasonic assisted extraction: A review. *Agrobiological Records, 15*, 1–12. ISSN: 2708-7182 (Print), ISSN: 2708-7190 (Online).

Tenorio-Rodriguez, P. A., Murillo-Álvarez, J. I., Campa-Cordova, Á. I., & Angulo, C. (2017). Antioxidant screening and phenolic content of ethanol extracts of selected Baja California Peninsula macroalgae. *Journal of Food Science and Technology, 54*(2), 422–429. https://doi.org/10.1007/s13197-016-2478-3

Theobald, E. J., Irving, A. D., Capper, A., Costa, J. F., Diaz-Pulido, G., Andrews, E. L., Kelly, J., & Jackson, E. L. (2024). Selection of marine macroalgae for nutrient biofilter and bioproduct trials in the coastal waters of Queensland, Australia. *Aquaculture International, 32*, 9631–9669. https://doi.org/10.1007/s10499-024-01632-y

Tison, D., & Seidler, R. (1983). *Vibrio aestuarianus*: A new species from estuarine waters and shellfish. *International Journal of Systematic and Evolutionary Microbiology, 33*, 699–702. https://doi.org/10.1099/00207713-33-4-699

Trivedi, N., Baghel, R. S., Bothwell, J., Gupta, V., Reddy, C. R. K., Lali, A. M., & Jha, B. (2016). An integrated process for the extraction of fuel and chemicals from marine macroalgal biomass. *Scientific Reports, 6*, Article 30728. https://doi.org/10.1038/srep30728

UN. The Sustainable Development Goals Report; United Nations: New York, NY, USA, (2018). United Nations publication issued by the department of economic and social affairs. ISBN: 978-92-1-101390-0.

Vlaisavljević, S., Rašeta, M., Berežni, S., Passamonti, S., & Tramer, F. (2021). Four selected commercial seaweeds: Biologically active compounds, antioxidant and cytotoxic properties. *International Journal of Food Sciences and Nutrition, 72*(6), 757–766.

Wali, J. A., Jarzebska, N., Raubenheimer, D., Simpson, S. J., Rodionov, R. N., & O'Sullivan, J. F. (2020). cardio-metabolic effects of high-fat diets and their underlying mechanisms — A narrative review. *Nutrients, 12*(5), 1505. https://doi.org/10.3390/nu12051505

Yang, R., Liu, Q., He, Y., Tao, Z., Xu, M., Luo, Q., Chen, J., & Chen, H. (2020). Isolation and identification of *Vibrio mediterranei* 117-T6 as a pathogen associated with yellow spot disease of Pyropia (Bangiales, Rhodophyta). *Aquaculture, 526*, Article 735372. https://doi.org/10.1016/j.aquaculture.2020.735372 (Amsterdam, Netherlands).

Yang, H., Tang, B., Zhou, H., Zhong, P., & Zhao, L. (2025). Research on the construction of an integrated multi-trophic aquaculture (IMTA) model in seawater ponds and its impact on the aquatic environment. *Water, 17*(6), 887. https://doi.org/10.3390/w17060887

Zárate, R., El Jaber-Vazdekis, N., Tejera, N., Pérez, J. A., & Rodríguez, C. (2017). Significance of long chain polyunsaturated fatty acids in human health. *Clinical and Translational Medicine, 6*(1), 25. https://doi.org/10.1186/s40169-017-0153-6

Zerrifi, S. E. A., El Khalloufi, F., Oudra, B., & Vasconcelos, V. (2018). Seaweed bioactive compounds against pathogens and microalgae: Potential uses on pharmacology and harmful algae bloom control. *Marine Drugs, 16*(2), 55. https://doi.org/10.3390/md16020055

Zengin, B., Toraman, G.Ö. A., & Yanikoğlu, R. S. (2024). Chemical contents and bioactivities of green algae *ulva rigida* C. Agardh red algae *grateloupia turuturu* yamada extracts. *Bezmialem Science, 12*(3), 317–326. https://doi.org/10.14235/bas.galenos.2024.21347

Zulueta, A., Esteve, M. J., & Frígola, A. (2009). ORAC and TEAC assays comparison to measure the antioxidant capacity of food products. *Food Chemistry, 114*(1), 310–316. https://doi.org/10.1016/j.foodchem.2008.09.033