Impact of time of harvest and drying method on antimicrobial activity of Saccharina latissima against two Staphylococcus aureus strains

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ABSTRACT
Antibiotic resistance is one of the greatest public health threats of our time, and the bacterium Staphylococcus aureus, of which there are numerous drug-resistant and drug-sensitive strains, is a pathogen of worldwide concern. Scientists are turning their focus to underexplored marine ecosystems to identify novel antibacterial agents effective against S. aureus. Here, we report inhibition of S. aureus strains Newman and USA300 by extracts from Saccharina latissima (sugar kelp), grown and harvested in the Western Gulf of Maine, USA. We examined how time of harvest throughout the growing season as well as the drying method pre-extraction affected the antimicrobial activity of the kelp extracts. Optimal antimicrobial activity was observed at the beginning of April (203 days since sporing), when increased water pH and higher salinity levels were also observed. Oven-dried crude extracts showed greater inhibition against S. aureus Newman, whereas freeze-dried crude extracts demonstrated greater inhibition against S. aureus USA300. Overall, our data indicate that cultivated S. latissima from the Western Gulf of Maine possesses significant value-added antimicrobial activity and identify early spring as an optimal harvest time to harness antimicrobial activity.

Introduction

Marine macroalgae are a potential source of beneficial therapeutic compounds (Haefner, 2003). Extracts from numerous species of macroalgae have been shown to exhibit antimicrobial activity against human bacterial, fungal, and protozoal pathogens (Cox, Abu-Ghannam, & Gupta, 2010; Deveau et al., 2016; Perez, Falque, & Dominguez, 2016; Shannon & Abu-Ghannam, 2016). Given the worldwide rise in antimicrobial-resistant pathogens and the urgent need to discover new antimicrobials (CDC, 2018; World Health Organization [WHO], 2018), seaweed-derived compounds may have utility as important anti-infective agents.

Studies have shown that extracts from a variety of macroalgal species are inhibitory to human pathogens. In our previous study, crude extracts from the green macroalga Ulva fenestrata (as Ulva lactuca) inhibited numerous strains of the bacterial pathogen Staphylococcus aureus (Deveau et al., 2016). Other studies have shown that extracts from the red macroalga Callophyllus serratus, Sphaerococcus coronopifolius, Laurencia obtusa and Pterocladia capillacea (as Pterocladia capillacea) have antimicrobial effects against bacterial and fungal pathogens including Escherichia coli, Pseudomonas aeruginosa, S. aureus, Candida albicans, Klebsiella pneumoniae, Bacillus cereus and Bacillus subtilis (Shannon & Abu-Ghannam, 2016). Similarly, extracts from brown algae, Himanthalia elongata, Laminaria digitata, Saccharina latissima (as Laminaria saccharina), Ascophyllum nodosum and Laminaria hyperborea have been shown to inhibit S. aureus, Listeria monocytogenes, E. coli and Salmonella typhimurium (Cox et al., 2010; Kadam et al., 2015; Shannon & Abu-Ghannam, 2016).

Algal antimicrobial activity is attributed to the production of secondary metabolites that contain bioactive properties (Val et al., 2001). In particular, brown macroalgae contain several types of saturated fatty acids, polyunsaturated fatty acids and phenolic compounds (Abou Zeid, Aboutabl, Sleem, & El-Rafie, 2014; Beaulieu, Bondu, Doiron, Rioux, & Turgeon, 2015; Cox et al., 2010; Deyab & Abou-Dobara, 2013; Kadam et al., 2015; Perez et al., 2016; Rodrigues et al., 2015; Sappati, Nayak, VanWalsum, & Mulrey, 2019; Shannon & Abu-Ghannam, 2016). These secondary metabolites have been shown to possess antimicrobial activity, and...
therefore, are of high interest as potential anti-infective compounds (Abou Zeid et al., 2014; Beaulieu et al., 2015; Cox et al., 2010; Deyab & Abou-Dobara, 2013; Kadam et al., 2015; Perez et al., 2016; Rodrigues et al., 2015; Shannon & Abu-Ghannam, 2016).

The production, composition and activity of algal secondary metabolites can be influenced by exogenous factors, such as geography, growing environment, time of harvest and post-harvest processing conditions (Ehrig & Alban, 2015; Liu et al., 2018; Milledge, Smith, Dyer, & Harvey, 2014; Overland, Mydland, & Skrede, 2018; Robles-Centeno, Ballantine, & Gerwick, 1996; Schiener, Black, & Stanley, 2015; Vidyavathi & Sridhar, 1991). For example, lipid and fatty acid content in brown macroalgae is highest in the winter and spring, and lower in the summer (El Maghraby & Fakhry, 2015; Nomura et al., 2012; Schiener et al., 2015). Concentration of phenolic compounds, such as chlorogenic acid, benzoic acid and gallic acid, increases with the rise in water temperature and light intensity (Pavia et al. 1997; Sappati et al., 2019). Environmental factors such as algal life cycle, season, water temperature, salinity, pH and availability of light have been shown to contribute to the variation of lipid and fatty acid content of crude algal extracts (Ehrig & Alban, 2015; Olofsson et al., 2012; Sappati et al., 2019; Zubia, Payri, & Deslandes, 2008). Such exogenous factors might therefore also impact the antimicrobial activity of algal extracts. Indeed, reports have shown that antimicrobial activity of algal extracts varies throughout growing season, probably due to variation in algal chemical composition at different growth stages, as well as the post-harvest drying method used prior to extraction (Ehrig & Alban, 2015; Liu et al., 2018; Milledge et al., 2014; Overland et al., 2018; Sappati et al., 2019; Schiener et al., 2015; Vidyavathi & Sridhar, 1991; Zubia et al., 2008).

The cultivation and harvesting of the edible brown macroalga, *S. latissima*, commonly known as sugar kelp, is a rapidly growing sector of the New England aquaculture and food industries (Grebe, Byron, Gelais, Kotowicz, & Olson, 2019; Piconi, Veidenheimer, & Chase, 2020). Identification and optimization of any potential antimicrobial properties would add value to this important commodity. Little is known of potential antimicrobial properties of *S. latissima* harvested from coastal New England, or whether exogenous factors or post-harvesting processing conditions might influence its antimicrobial activity. Therefore, our objectives were to examine the effect of time of harvest and post-harvest drying method on antimicrobial activity of *S. latissima* harvested from the southern coast of Maine, USA. Specifically, we harvested on eight dates during the kelp growing season (March, April and May 2019) and subjected the kelp to either oven-drying or freeze-drying prior to chemical extraction. Our results provide insight into the optimal time to harvest farmed sugar kelp and the optimal drying method prior to extraction to ensure and preserve the highest degree of antimicrobial activity.

**Materials and methods**

**Saccharina latissima cultivation**

*S. latissima* “seed” was produced using methods described by Redmond, Green, Yarish, Kim, and Neefus (2014). In short, wild reproductive *S. latissima* was collected and stressed via desiccation in the laboratory to induce zoospore release on 11 September 2019 (termed “sporing”). The meioospores were allowed to settle on thin, nylon line for 24 hours. Then the line was transferred to aquaria maintained at optimal growth conditions and the gametophyte stages produced juvenile sporophytes. On the 5th of December, the kelp sporophytes (1–2 mm in length) were outplanted on a 60 m longline located near Wood Island, Saco Bay, ME, USA (Figure 1). Spacer buoys were used to maintain the longline at 2 m below the water surface.

**Saccharina latissima sampling and drying**

*S. latissima* was harvested eight times between March and May 2019 (176–259 days since sporing). Whole thalli were cut from the longline, placed into plastic bags, transported in a cooler at 8°C, and refrigerated until time of processing (no longer than 12 h). To prepare them for drying, the fronds were gently cleaned with tap water to remove epiphytes and then randomly sorted into one of two drying groups with equal mass. The first group was oven-dried in a 60°C in a Thermo Scientific™ Heratherm™ Advanced Protocol Oven for 5 days. The second group was frozen overnight at –20°C, then placed in a LABCONCO™ FreeZone freeze dryer at –58°C for 48 h. Each group was kept in the respective drying unit until 90% water loss was achieved for both groups. Water loss was determined by calculating the change in mass of the algae before and after drying. The dried algae were then ground to flakes using a mortar and pestle. Individual 4 g portions of dried, ground algae were immediately stored in glass scintillation vials at –80°C until further use. All samples were stored under argon with parafilm seal and protected from light with aluminium foil until extraction.
**Measurement of water temperature, salinity and pH in situ**

Water temperature at the farm site was recorded using Hobo Pendant Temperature/Light 8 K Data Loggers (Part 210 #: UA-002-08) suspended from the longline. At each kelp sampling event, water samples were also collected for salinity and pH measurements. Salinity was quantified using a Cole-Parmer RSA-BR90A Refractometer (0–90%). A HACH benchtop metre (model #: PW172KB0703F01) calibrated to certified standards was used to measure pH.

**Generation of crude Saccharina latissima extracts**

Dried, ground algae (4 g) was transferred to glass test tubes and 20 ml of dichloromethane was added, adapting procedures of Deveau et al. (2016). Three replicates of the extraction were run simultaneously. The triplicate algae-dichloromethane samples were incubated in a 40–50°C water bath for 5 min and then individually agitated with a vortex mixer for 20 s to facilitate compound extraction. After repeating the heating and mixing cycle twice, the samples were placed in an ice bath for 3 min followed by a 3 min centrifugation at 400 rpm and 25°C to remove particulates. Supernatants were transferred to individual clean round bottom flasks. Dichloromethane (20 ml) was added twice as the procedure was repeated for three cycles in total. The dichloromethane was evaporated from each flask using a Büchi rotary evaporator at 45°C under vacuum. The round bottom flasks were placed on a vacuum pump for 24 h. The resulting extract concentrates were weighed and percentage recovery calculated, before being resuspended in methanol, a solvent with less volatility than dichloromethane that is compatible with antimicrobial assay experiments. Methanolic extracts were brought to a final concentration of 10 mg ml⁻¹ for use in disc diffusion assays. Extract solutions were stored at −80°C until use.

**Bacterial strains and growth conditions**

The methicillin-sensitive *Staphylococcus aureus* (MSSA) strain Newman was sourced from the American Type Culture Collection (ATCC 25904). The methicillin-resistant *S. aureus* (MRSA) USA300 strain was obtained from the Network on Antimicrobial Resistance in *Staphylococcus aureus* (NARSA NR-46070). All bacterial strains were sub-cultured from ~80°C stocks in Mueller Hinton (MH) broth at 37°C in a shaking incubator (Deveau et al., 2016). Prior to performing disc diffusion assays, bacterial colonies were isolated on MH agar plates and cultures were evaluated for purity.

**Disc diffusion antimicrobial activity assays**

Disc diffusion assays were performed using the guidelines of the Clinical Laboratory Standards Institute (CLSI) and as previously described (Deveau et al., 2016). Filter paper discs (7 mm) were infused with individual methanolic algal extracts (15 µl of 10 mg ml⁻¹ extract to achieve 150 µg extract per disc),
vancomycin (30 μg per disc), ampicillin (10 μg per disc), chloramphenicol (5 μg per disc) and methanol (15 μl per disc, vehicle control). Discs were applied to the surface of MH agar plates after the plates were inoculated with 100 μl of each bacterial culture adjusted to a 0.5 McFarland standard (approximately 10^8 CFU ml^-1). Plates were incubated at 37°C for 24 h and then assessed for zones of growth inhibition around treated discs. When zones of inhibition were present, zone diameters were measured and corrected for disc diameter (7 mm). For all studies reported, disc diffusion zones of inhibition are the average of triplicate experiments.

**Statistical analysis**

Differences in the zone of inhibition were assessed across independent variables (time points and drying method) using linear mixed-effects models. A suite of all models incorporating all possible parameter combinations was ranked using Akaike’s Information Criterion (AIC). Pairwise comparisons were then conducted for the top model (ΔAIC > 2). All error bars represent standard error. Effects of environmental factors (water salinity and water pH) on zone of inhibition were assessed across independent variables (time-points and drying methods) using linear regression models. We set α at 0.05 throughout. All statistical analyses were conducted in R v2.1 (Rstudio Team, 2016).

**Results**

**Effect of harvest date on antimicrobial activity of crude Saccharina latissima extracts**

An average calculated percentage recovery of 0.5–3.9% (Supplementary table S1) was achieved for each triplicate extraction, across harvest dates. There was minimal difference in the recovery values for individual harvest dates, but the date of *S. latissima* harvest had a significant impact on antimicrobial activity of the crude methanolic kelp extracts (p < 0.05). When observing the zones of inhibition of the crude *S. latissima* extracts for the first two harvest dates of the 6th of March 2019 (176 days post sporing) and the 13th of March 2019 (183 days post sporing) against both strains, *S. aureus* Newman and USA300, there was no bacterial inhibition and therefore no antimicrobial activity (Figure 2a, b; Supplementary figure S1 and table S2). On the harvest date of the 25th of March 2019 (195 days post sporing), regardless of drying method, there was an increase in antimicrobial activity. However, the crude methanolic kelp extracts exhibited the largest zones of inhibition and reached their maximum antimicrobial activity on the harvest date of the 2nd of April 2019 (203 days post sporing).

Both water salinity and pH were greatest (31 psu; pH 8) on the harvest date of the 2nd of April 2019 (Figure 3). We observed a significant relationship between salinity and antimicrobial activity against both *S. aureus* Newman (y = 0.071x + 0.140, p < 0.05; Supplementary figure S2) and USA300 (y = 0.116x - 1.26, p < 0.05; Supplementary figure S3). The maximum antimicrobial activity of the crude methanolic kelp extracts for the season occurred in April when salinity was high (Figure 3). The decrease in antimicrobial activity between the 17th and 29th of April against both strains of *S. aureus* (Figure 2a, b) correlate with the drop in water salinity and pH (Figure 3). We also observed a significant relationship between water pH and antimicrobial activity of algal extracts against both *S. aureus* Newman (y = 5.273x-39.19, p < 0.05; Supplementary figure S4) and USA300 (y = 5.852x - 44.0, p < 0.05; Supplementary figure S5). On the harvest date of the 17th of April, when a decrease in salinity was observed, there was also a decrease in water pH, which correlated with the decrease in antimicrobial activity (Figures 2, 3). The salinity of the seawater increased as the growing season continued, whereas the pH continued to decrease. However, on the last harvest date of the season (28th of May) increased antimicrobial activity was observed but the pH of the seawater was comparable to the pH observed on the 2nd of April harvest date, and water salinity was markedly higher on 28th of May in comparison to the harvest dates between 17th and 29th of April. The increase in both pH and salinity on the last harvest date corresponds to the increase in antimicrobial activity on the 28th of May 2019 (259 days post sporing). Water temperature was measured as 2.3, 3.1, 3.9, 4.3, 5.0, 6.3, 6.4 and 9.9°C for the eight sequential harvest dates. No significant relationship between the water temperature and antimicrobial activity was observed (p > 0.05).

**Effect of drying method on antimicrobial activity of crude Saccharina Latissima extracts**

Crude methanolic extracts from kelp collected on the first two harvest dates (6 March, 2019–176 days post sporing, and 13 March, 2019–183 days post sporing) exhibited no zones of bacterial inhibition and therefore no antimicrobial activity against either strain of *S. aureus*, regardless of drying method (Figure 2; Supplementary table S1 and figure S1). However, for both drying methods, an increase in antimicrobial activity was observed on the 25th of March 2019 (195 days post sporing) against both
Figure 2. Effect of date of harvest and drying method on antimicrobial activity of crude *Saccharina latissima* extracts against *Staphylococcus aureus* Newman (a) and USA300 (b). A disc diffusion assay was used to test the antimicrobial activity of crude extracts prepared from *S. latissima* harvested on different dates of the growing season and dried via freeze drying (−58°C for 48 hours) or oven drying (60°C for 5 days). Filter paper discs were saturated with extracts (150 μg/disc) or methanol (vehicle control) and applied to MH agar plates immediately after inoculation with *S. aureus* USA300. Data are presented as a diameter of the zone of inhibition (mm) surrounding extract-saturated discs, which is indicative of bacterial growth inhibition. Zone sizes are corrected for diameter of disc as well as the vehicle control (methanol, always less than 1 mm/disc). Different letters (a, b, c, d, e, f) represent significant differences using pairwise comparisons (p < 0.05). NZ represents no zone of inhibition measured. Error bars indicate standard error.

*S. aureus* strains. Importantly, both oven and freeze-dried kelp extracts showed the largest zones of bacterial inhibition (against both *S. aureus* Newman and USA300) and reached the maximum activity for 2019 growing season on the harvest date of the 2nd of April, 2019 (203 days post sporing). On the 2nd of April, the oven-dried extracts possessed 1.2-times more antimicrobial activity than the freeze-dried extracts against *S. aureus* Newman (Figure 2a), whereas the freeze-dried extracts possessed 1.3-times more antimicrobial activity than the oven-dried extracts against *S. aureus* USA300 (Figure 2b). There was a decrease in activity for both drying methods for the remainder of the harvest dates, save the 28th of May (259 days post sporing) when a significant increase in antimicrobial activity against *S. aureus* was seen in both drying methods (p < 0.05). Antimicrobial activity against *S. aureus* USA300 in oven-dried extracts had two times greater antimicrobial activity than freeze-dried extracts (p < 0.05).
Discussion

In an effort to determine an optimal time of harvest and drying method for preserving and extracting *S. latissima* antimicrobial compounds, we tested the antimicrobial activity of crude methanolic *S. latissima* extracts harvested at eight different dates throughout the growing season and dried the algae either in an oven (60°C) or freeze drier (–58°C). Other studies have shown that differences in the chemical composition and antimicrobial activity of algal extracts can be seen depending on when the algae are harvested during their growing season (Ehrig & Alban, 2015; Liu et al., 2018; Overland et al., 2018; Schiener et al., 2015). Previous reports have also shown that the method by which the algae is dried can impact algal chemical composition (Ehrig & Alban, 2015; Liu et al., 2018; Milledge et al., 2014; Overland et al., 2019; Patarra, Paiva, Neto, Lima, & Baptista, 2011; Schiener et al., 2015). Even though lipid and phenolic content were not directly measured in this study, secondary metabolites are common in macroalgae and not only possess antimicrobial activity, but also to be affected by various exogenous factors (Abou Zeid et al., 2014; Beaulieu et al., 2015; Cox et al., 2010; Deyab & Abou-Dobara, 2013; Kadam et al., 2015; Perez et al., 2016; Rodrigues et al., 2015; Shannon & Abu-Ghannam, 2016).

**Effect of date of harvest**

In this study, data from Figure 2 (and Supplementary figure S1 and table S2) indicate that crude methanolic *S. latissima* extracts possessed the lowest antimicrobial activity in early March and late April, the highest activity in early April, and moderate antimicrobial activity at the end of May. Other research indicates that lipid and fatty acid content in algae is highest in the winter and spring when the algae are relatively young, and the water is relatively cold (El Maghraby & Fakhry, 2015; Nomura et al., 2012; Sappati et al., 2019; Schiener et al., 2015) while lower lipid and fatty acid contents are observed in the summer when the algae are more mature, and the water is relatively warmer (El Maghraby & Fakhry, 2015; Nomura et al., 2012; Sappati et al., 2019; Schiener et al., 2015). With the water temperatures in Saco Bay averaging 3.3°C in March, 5.2°C in April, and 8.2°C in May, our data suggest that a change in the chemical composition of polar extracts in *S. latissima* also occurs during March, April and May when water is colder and individuals are younger. These trends could help explain the increase in antimicrobial activity in early April, suggesting that the young algae in colder water (4.3°C ± 0.2) potentially contain biologically active compounds with greater antimicrobial activity in comparison to the older algae (259 days post sporing) in warmer water (9.9°C ± 0.4). However, our study shows no significant relationship between water temperature and antimicrobial activity of crude methanolic sugar kelp extracts (p > 0.05).

Salinity, as well as temperature, within Saco Bay fluctuates from season to season, especially in the spring (April) due to snow melt. Ehrig & Alban (2015) showed that *S. latissima* growing in higher salinity environments produced biologically active compounds with

Figure 3. Salinity and pH measurements at 2 metres below sea level at same depth as longline. At each harvest date, salinity was measured using a Cole-Parmer RSA-BR90A Refractometer (0–90%), and pH was measured using a HACH benchtop metre (model #: PW172KB0703F01) calibrated to certified standards.
increased activity. Furthermore, Floreto, Hirata, Ando, & Yamasaki (1993) found that algae contain higher concentrations of lipids and fatty acids when exposed to higher salinity environments. Water pH is related to salinity, such that when seawater drops in salinity, pH usually decreases as well. These observations suggest that water salinity and pH may impact the types of compounds produced by *S. latissima* from season to season. These data and our experimental results suggest that when the salinity is high in Saco Bay, *S. latissima* contains higher amounts of bioactive compounds that are potent against *S. aureus* Newman and USA300. Therefore, the types of biologically active compounds that can be extracted from Maine sugar kelp may also vary by growth season.

### Effect of drying method

In our study, we observed greater inhibition of *S. aureus* Newman and USA300 by crude methanolic *S. latissima* extracts from marine algae harvested in the middle of our growing season, regardless of the drying method used. Our data suggest that the biologically active compounds present in *S. latissima* extracts when oven dried (60°C) have more of an effect against *S. aureus* Newman (1.2 times more activity than the freeze-dried extracts in best collection, 2nd of April). Conversely, the biologically active compounds present in *S. latissima* extracts when freeze-dried can have more of an effect against *S. aureus* USA300 (1.3 times more activity than the oven dried extracts, 2nd of April). The collections from the 2nd of April possessed significantly more antimicrobial activity against both strains of *S. aureus* for both drying methods than any other time point. These data suggest that regardless of the drying method on this harvest date, bioactive compounds have significant antimicrobial activity against each bacterial strain. Other research by Sappati et al. (2019) found that depending on whether *S. latissima* was freeze-dried, sun-dried, or dried at varying temperatures with varying humidity, different chemicals, bioactive compounds, and components of the kelp were preserved. These data together further suggest that drying method post-harvest has an overall effect on the chemical composition of *S. latissima* resulting in varying levels of biologically active compounds.

Since drying methods have been shown to have differing effects on the chemical composition of *S. latissima*, this could therefore help us explain the differences seen in antimicrobial activity between oven dried algae and freeze-dried algae against different strains of *S. aureus* (Zubia et al., 2008; Olofsson et al., 2012; Sappati et al., 2019; this study). For the algal extracts tested against *S. aureus* Newman, the oven-dried methanolic extract possessed significantly more antimicrobial activity than the freeze-dried methanolic extracts, suggesting the biologically active compounds preserved during oven-drying effectively inhibit this bacterium (Cadieux, Vijayakumaran, Bernards, McGavin, & Heinrichs, 2014; Olofsson et al., 2012; Sappati et al., 2019; Zubia et al., 2008). Furthermore, for the algal extracts tested against *S. aureus* USA300, the freeze-dried methanolic extracts showed significantly more antimicrobial activity at the early April harvest date, suggesting that the compounds preserved from freeze-drying are more potent against this bacterium. While not explored in our work, others have found that enhanced antimicrobial activity of extracts may be attributed to synergistic antimicrobial effects achieved from interacting bioactive compounds (Cadieux et al., 2014). This increase in bioactivity observed at the end of May could ultimately be a result of higher concentrations of biologically active compounds in the crude extract during that time of year, and/or less masking of activity by other compounds during the transition period from spring to summer, as suggested by Zubia et al. (2008). However, the significant difference between the antimicrobial activity in both drying methods in early April compared to late May against both bacterial strains suggests that early spring is still the best collection time regardless of the drying method used (Cox et al., 2010; Shannon & Abu-Ghannam, 2016).

In conclusion, our results indicate that crude methanolic extracts from sugar kelp cultivated in southern coastal Maine possess greater antimicrobial activity in early spring (203 days post sporing) when water pH and salinity are high. The data do not indicate a correlation between antimicrobial activity and water temperature, but show that pH, salinity, and kelp age each contribute to the observed bacterial inhibition (Figures 2, 3). *S. latissima* extracts possess the greatest antimicrobial activity in early spring regardless of drying method. However, because extracts from the freeze-dried and oven-dried sugar kelp optimally inhibited different bacterial strains, we posit that these two drying methods may each preserve unique compounds and/or different quantities of biologically active compounds. Overall, this study suggests that antimicrobial activity of *S. latissima* extracts may be enhanced through careful selection of harvest windows and drying methods. Additional studies of bioactive properties of southern Maine *S. latissima* constituents will lead to a broader understanding of the medicinal value of a crop that is important to an evolving aquaculture industry (Cole et al., 2017) and promote the discovery of novel bioactives that inhibit pathogenic Staphylococci as well as other targets.
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References

Abou Zeid, A. H., Aboutabl, E. A., Sleem, A. A., & El-Rafie, H. M. (2014). Water soluble polysaccharides extracted from Pterocladia capillacea and Dictyopteris membranacea and their biological activities. Carbohydrate Polymers, 113, 62–66. doi: 10.1016/j.carbpol.2014.06.004
Beaulieu, L., Bondu, S., Doiron, K., Rioux, L. E., & Turgeon, S. L. (2015). Characterization of antibacterial activity from protein hydrolysates of the macroalga Saccharina longicuris and identification of peptides implied in bioactivity. Journal of Functional Foods, 17, 685–697. doi:10.1016/j.jff.2015.06.026
Cadieux, B., Vijayakumaran, V., Bernards, M. A., McGavin, M. J., & Heinrichs, D. E. (2014). Role of lipase from community-associated methicillin-resistant Staphylococcus aureus Strain USA300 in hydrolyzing triglycerides into growth-inhibitory free fatty acids. Journal of Bacteriology, 196(23), 4044–4056. doi:10.1128/JB.02044-14
Center for Disease Control and Prevention (2018). About Antimicrobial Resistance. Centers for Disease Control and Prevention. https://www.cdc.gov/drugresistance/about.html
Cole, A., Langston, A., Davis, C., Belle, S., McConnon, J., & Gabe, T. (2017). Maine aquaculture economic impact report. The University of Maine Aquaculture Research Institute.
Cox, S., Abu-Ghannam, N., & Gupta, S. (2010). An assessment of the antioxidant and antimicrobial activity of six species of edible Irish seaweeds. The International Food Research Journal, 17, 205–220. doi:10.21427/D7HC92
Deveau, A. M., Miller-Hope, Z., Lloyd, E., Williams, B. S., Bolduc, C., Meader, J. M., Burkholder, K. M. (2016). Antimicrobial activity of extracts from macroalgae Ulva lactuca against clinically important staphylococci is impacted by lunar phase of macroalgal harvest. Letters in Applied Microbiology, 62, 363–371. doi:10.1111/lam.12563
Deyab, M. A., & Abou-Dobara, M. I. (2013). Antibacterial activity of some marine algal extracts against most nosocomial bacterial infections. The Egyptian Journal of Experimental Biology, 9, 281–286.
Ehrig, K., & Alban, S. (2015). Sulfated galactofucan from the brown alga Saccharina latissima —variability of yield, structural composition and bioactivity. Marine Drugs, 13, 76–101. doi: 10.3390/md13010076
El Maghraby, D. M., & Fakhry, E. M. (2015). Lipid content and fatty acid composition of Mediterranean macro-algae as dynamic factors for biodiesel production. Oceanologia, 57, 86–92. doi:10.1016/j.ocean.2014.08.001
Floreto, E. A. T., Hirata, H., Ando, S., & Yamasaki, S. (1993). Effects of temperature, light intensity, salinity and source of nitrogen on the growth, total lipid and fatty acid composition of Ulva pertusa Kjellman (Chlorophyta). Botanica Marina, 36, 149–158. doi:10.1515/bottom.1993.36.2.149.
Grebe, G. S., Byron, C. J., Gelais, A. S., Kotowicz, D. M., & Olson, T. K. (2019) An ecosystem approach to kelp aquaculture in the 713 Americas and Europe. Aquaculture Reports 15:100215
Haefner, B. (2003). Drugs from the deep: Marine natural products as drug candidates. Drug Discovery Today, 8, 536–544. doi:10.1016/S1359-6446(03)02713-2
Kadam, S. U., O’Donnell, C. P., Rai, D. K., Hossain, M. B., Burgess, C. M., Walsh, D., & Tiwari, B. K. (2015). Laminarin from Irish brown seaweeds Ascosiphum nodosum and Laminaria hyperborea: Ultrasound assisted extraction, characterization and bioactivity. Marine Drugs, 13, 4270–4280. doi:10.3390/md13074270
Liu, N., Wu, X., Fu, X., Duan, D., Xu, J., & Gao, X. (2018). Characterization of polysaccharides extracted from a cultivated brown alga Costaria costata during the harvest period. The Journal of Ocean University of China, 17, 1209–1217. doi:10.1007/s11802-018-3621-8
Milledge, J. J., Smith, B., Dyer, P. W., & Harvey, P. (2014). Macroalgae-derived biofuel: A review of methods of energy extraction from seaweed biomass. Energies, 7, 7194–7222. doi:10.3390/energies71803621-8
Nomura, M., Kamogawa, H., Susanto, E., Kawagoe, C., Yasui, H., Saga, N., Miyashita, K. (2012). Seasonal variations of total lipids, fatty acid composition, and fucoidan contents of Sargassum horneri (Turner) and Cystoseira hakodatensis (Yendo) from the northern seas-eshore of Japan. Journal of Applied Phycology, 25, 1159–1169. doi:10.1007/s10811-012-9934-x
Olofsson, M., Lamela, T., Nilsson, E., Berge, J. P., del Pino, V., Uronen, P., & Legrand, C. (2012). Seasonal variation of lipids and fatty acids of the macroalgae Nannochloropsis oculata grown in outdoor large-scale photobioreactors. Energies, 5, 1577–1592. doi:10.3390/en5051577
Overland, M., Mydland, L. T., & Skrede, A. (2018). Marine macroalgae as sources of protein and bioactive compounds in feed for monogastric animals. Journal of the Science of Food and Agriculture, 99, 13–24. doi:10.1002/jsfa.9143
Patarra, R. F., Paiva, L., Neto, A. I., Lima, E., & Baptista, J. (2011). Nutritional value of selected macroalgae. *Journal of Applied Phycology*, 23, 205–208. doi:10.1007/s10811-010-9556-0

Pavia, H., Cervin, G., Lindgren, A., & Åberg, P. (1997). Effects of UV-B radiation and simulated herbivory on phlorotannins in the brown alga *Asphodeline nodosum*. *Marine Ecology Progress Series*, 157, 139–146.

Perez, M. J., Falque, E., & Dominguez, H. (2016). Antimicrobial action of compounds from Marine Seaweed. *Marine Drugs*, 14, 1–38. doi:10.3390/md14030052

Piconi, P., Veidenheimer, R., & Chase, B. (2020) Edible Seaweed Market Analysis. Island Institute. Retrieved from http://www.islandinstitute.org/edible-seaweed-market-analysis–2020

Redmond, S., Green, L., Yarish, C., Kim, J., & Neefus, C. (2014) New England seaweed culture handbook. Retrieved from https://opencommons.uconn.edu/seagrant_weedcult/1

Robles-Centeno, P. O., Ballantine, D. L., & Gerwick, W H. (1996). Dynamics of nitribacterial activity in three species of Caribbean marine algae as a function of habitat and life history. *Hydrobiologia*, 326, 457–462. doi:10.1007/BF00047846

Rodrigues, D., Alves, C., Horta, A., Pinteaus, S., Silva, J., Culio, G., Thomas OP, & Pedrosa, R. (2015). Antitumor and antimicrobial potential of bromoderterpenes isolated from the red alga, *Sphaerococcus Coronopifolius*. *Marine Drugs*, 13, 713–726. doi:10.3390/md13020713

RStudio Team. (2016). RStudio: Integrated Development for R. RStudio. Inc., Boston, MA URL. Retrieved from http://www.rstudio.com/;Boston.

Sappati, P. K., Nayak, B., VanWalsum, G. P., & Mulrey, O. T. (2019). Combined effects of seasonal variation and drying methods on physicochemical properties and antioxidant activity of sugar kelp (*Saccharina latissima*). *Journal of Applied Phycology*, 31, 1311–1332. doi:10.1007/s10811-018-1596-x

Schiener, P., Black, K. D., & Stanley, M. S. (2015). The seasonal variation in the chemical composition of the kelp species *Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima* and *Alaria esculenta*. *Journal of Applied Phycology*, 27, 363–373. doi:10.1007/s10811-014-0327-1

Shannon, E., & Abu-Ghannam, N. (2016). Antibacterial derivatives of marine algae: An overview of pharmacological mechanisms and applications. *Marine Drugs*, 14, 1–23. doi:10.3390/md1404081

Val, A., Platas, G., Basilio, A., Cabello, A., Gorrochategui, J., Suay, I., Vicente, F., Rio, P., & Pelaye, G. (2001). Screening of antimicrobial activities in red, green, and brown macroalgae from Gran Canaria (Canary Islands, Spain). *International Microbiology*, 4, 35–40.

Vidyavathi, N., & Sridhar, K. R. (1991). Seasonal and geographical variations in the antimicrobial activity of seaweeds from the Mangalore coast of India. *Botanica Marina*, 34, 279–284. doi:10.1515/botm.1991.34.4.279

World Health Organization. (2018). Antibiotic resistance. Retrieved from https://www.who.int/en/news-room/fact-sheets/detail/antibiotic-resistance

Zubia, M., Payri, C., & Deslandes, E. (2008). Alginate, mannitol, phenolic compounds and biological activity of two range-extending brown algae, *Sargassum Mangarevense* and *Turbinaria Ornatia* (Phaeophyta: Fucales) from Tahiti (French Polynesia). *Journal of Applied Phycology*, 20, 1033–1043. doi:10.1007/s10811-007-9303-3