

Structural Features and Antioxidant Activity of Polysaccharides from *Colpomenia sinuosa* (Phaeophyceae)

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Abstract

Polysaccharides from brown algae are valuable bioactive compounds with diverse structures and antioxidant potential. Environmental factors strongly influence their properties. However, studies on how ecological conditions shape the biochemical characteristics of algal polysaccharides are limited. This study aimed to examine the structural and antioxidant properties of polysaccharides from the brown alga *Colpomenia sinuosa* collected from Izmir (Aegean Sea, Türkiye) and Canakkale (Canakkale Strait, Türkiye). FTIR, ¹H NMR, XRD, and HPLC analyses showed clear structural differences between the samples. The Izmir extract (PSI) had a branched, amorphous structure, with higher levels of D-glucose and L-fucose contents ($p < 0.05$). The Canakkale extract (PSC) was crystalline and chain-condensed. DPPH scavenging activities were similar ($20.40 \pm 0.12\%$ in PSI and $20.10 \pm 0.31\%$ in PSC; $p > 0.05$). PCA and correlation heatmap analyses showed that salinity correlated positively with glucose ($r = 0.9988$) and antioxidant activity. These results demonstrate that environmental conditions, salinity, affect the biochemical properties of *C. sinuosa*. Our results showed that the amorphous PSI extract may be suitable for antioxidant or pharmaceutical use, while the crystalline PSC extract can be used for structural applications. Future studies should investigate the effects of seasonal and environmental conditions on the polysaccharide composition of this species.

Introduction

Marine polysaccharides from seaweeds are valuable natural products used in various industries, including the pharmaceutical, cosmetic, biomedical, and functional food industries (Li et al., 2021; Hurtado et al., 2022). Their structural and functional features vary with environmental conditions such as salinity, temperature, light, and nutrients, as well as genetic differences among species (Qu et al., 2019; Benslima et al., 2021; Miguel et al., 2023; Kammler et al., 2024; Saeed & Wang, 2025; Zhou et al., 2025). Such variations can affect the reproducibility and quality of bio-products (Ptak et al., 2021).

Brown algae (Phaeophyceae) are economically significant because their cell walls are rich in polysaccharides, mainly alginate, laminaran, and

fucoidan (Li et al., 2021; Al Monla et al., 2022; Zhou et al., 2024). Alginate is composed of α -L-guluronic acid and β -D-mannuronic acid blocks, and it provides gel strength and structure (Hurtado et al., 2022; Wang et al., 2024). Laminaran is a storage polysaccharide, and fucoidan has sulfate content with unique biological activity (Atya et al., 2021; Chen et al., 2021; Al Monla et al., 2022). In recent years, sulfated polysaccharides, particularly fucoidan, have been studied for their anti-inflammatory, antitumoral, antioxidant and antiviral activities (Atya et al., 2021; Al Monla et al., 2022; Zhou et al., 2024; Alfinaiikh et al., 2025). The bioactivity of fucoidan and other sulfated compounds is strongly linked to their molecular structure, especially the degree of sulfation and the types of monosaccharides and linkages involved (Qu et al., 2019; Ponce et al., 2020). In addition, unsulfated polysaccharides such as alginates

have been used as matrix materials for pharmaceutical applications (Hurtado et al., 2022; Wang et al., 2024). Among these compounds, sulfated polysaccharides can differ in their structure and activity with changes in geographic location and salinity (Ptak et al., 2021; Li et al., 2023).

Colpomenia is a genus of brown algae in the family Scytosiphonaceae (Guiry & Guiry, 2022). Its thalli are usually spherical or bladder-like and can grow as epiphytic on other algae, on seagrass leaves, or as epilithic on rocks. The surface cells are irregularly arranged, each with a single chloroplast, and the thalli are covered with phaeophycean hairs (Taşkın & Öztürk, 2012). The genus has 13 accepted species in tropical and temperate seas, mainly in intertidal zones (Guiry & Guiry, 2022). Members of *Colpomenia* produce polysaccharides and other bioactive compounds that have been studied for potential applications in food, pharmaceutical, and biotechnological fields (Ponce et al., 2020; Al Monla et al., 2022; Kammler et al., 2024). Among them, *Colpomenia sinuosa* (Mertens ex Roth) Derbès and Solier in Castagne, 1851 is the most widespread and cosmopolitan species, and it occurs widely in tropical and temperate coastal waters, especially in the intertidal zone (Rostami et al., 2017; Rostami et al., 2018; Martins et al., 2022; Song et al., 2025). *C. sinuosa* is an annual brown macroalga that usually develops macroscopic gametophytic thalli from late spring to early summer along the Turkish coast (Türker et al., 2024). This species can grow in seawater temperatures from 9 to 29 °C and salinity levels between 32 and 38‰, according to several studies (Ohno et al., 1990; Choi et al., 2002; Freitas et al., 2003; Poza et al., 2018; Song et al., 2025). Growth and thallus formation are mostly seen at moderate temperatures between 15 and 22 °C (Choi et al., 2002; Ohno et al., 1990). Freitas et al. (2003) reported that some reproductive structures appear only at low temperatures. There are a limited number of studies on the structural properties of sulfated polysaccharides extracted from *C. sinuosa* (Ponce et al., 2020; Parvathy et al., 2021; Salem et al., 2022), whereas several studies have examined the chemical structure and biological activity of this brown alga (Cirik et al., 2012; Türker et al., 2024). These studies characterized the functional groups and sugar composition using analytical techniques such as FTIR, NMR, GC-MS, and TLC (Ponce et al., 2020; Parvathy et al., 2021; Salem et al., 2022). However, there is no comprehensive structural analysis available for comparing the polysaccharide composition of *C. sinuosa* from different environments.

This study aims to isolate and analyze the structural properties of sulfated polysaccharide fractions from *C. sinuosa* collected in Izmir and Canakkale (Türkiye), using FTIR, ¹H NMR, XRD, and HPLC. The antioxidant capacity of the extracts was also quantified through DPPH radical-scavenging assays to identify possible functional differences associated with regional environmental factors.

Materials and Methods

Sampling

The samples of *C. sinuosa* were manually collected in July 2019 from two coastal stations in Türkiye: Izmir (38°22'48.6"N 26°54'24.7" E) and Canakkale (40°23'49.8"N 26°53'11.6" E) (Figure 1). Samples were collected in triplicate at each site at 0–1 m depth, transported on ice within four h, and processed separately throughout all analytical steps.

In situ environmental parameters

Sea-surface temperature, salinity and pH were measured in triplicate at each site using a multi-parameter probe (Hanna Instruments HI9829).

Pretreatment

The samples were first cleaned of epiphytic organisms and washed several times with pure water (Milli-Q). Samples were cleaned and dried at 40 °C for 48 h. The dried material was ground with a blender and sieved through a 500 µm mesh to obtain a homogeneous powder. Ten grams of powder were extracted using Soxhlet with dichloromethane, acetone and ethanol (10 mL g⁻¹, 6 h each; ~10 cycles h⁻¹) to remove pigments, lipids and phenolics. The residues were air-dried and stored in a desiccator (Türker et al., 2022).

Isolation of Sulfated Polysaccharides

The extraction was performed according to the protocol described by Türker et al. (2022), using sodium phosphate buffer (0.05 M, pH 7.4, 0.10 M NaCl) and cold ethanol precipitation (1:5, v/v). The flowchart in Figure 2 presents the analytical workflow of the study.

Fourier Transform Infrared (FTIR) Spectroscopy Analysis

One milligram of polysaccharide was homogenized with 100 mg dry spectroscopic-grade KBr and ground to a fine powder. Infrared spectra were obtained using a spectrometer (Perkin–Elmer Spectrum One-B) operated over 4000–650 cm⁻¹ at room temperature. Each sample was analyzed in triplicate to ensure reproducibility and accuracy of the FTIR spectra.

¹H-NMR Spectroscopy

Polysaccharides (20 mg) from each station were dissolved in D₂O (1 mL) and maintained at room temperature for 24 h before analysis. ¹H NMR spectra were acquired at 400 MHz at room temperature, covering the δ 0–6 ppm range. Assignments considered anomeric protons (4.5–5.5 ppm), methyl protons (~1.2–

1.6 ppm) and ring proton regions (3.2–4.5 ppm) (Türker et al., 2022).

X-Ray Diffraction

Dried sulfated polysaccharide powders were used for direct analysis, and no pretreatment was applied. XRD measurements were performed using an X-ray diffractometer with a Cu-K α radiation ($\lambda = 1.5406 \text{ \AA}$) source. Scans were performed in the range of $2\theta = 5^\circ$ – 60° , with a step width of $0.02^\circ/\text{s}$ and at 40 kV – 30 mA operating conditions. Crystallinity Index (CI%) was calculated according to the method described by Segal et al. (1959).

HLPC Monosaccharide Composition

Monosaccharide composition of the samples was determined according to Türker et al. (2022). Chromatographic separation was carried out on an HPLC system (Shimadzu SCL-10A controller, LC-10AT pump)

equipped with a RID-10A refractive index detector and a Shodex sugar column ($300 \times 7.8 \text{ mm}$). The operating conditions were: column oven at 30°C , detector cell at 35°C , ultrapure water as the mobile phase, a flow rate of 0.20 mL min^{-1} , injection volume of $20 \mu\text{L}$, and a total run time of 30 min. Reference standards included L-galacturonic acid, L-fructose, L-rhamnose, L-arabinose, L-galactose, L-mannose, D-glucose, and L-fucose. Peaks were identified by comparing retention times with standards and quantified by external calibration (five-point curves, $R^2 \geq 0.995$ for each monosaccharide).

Antioxidant Activity (DPPH assay)

The free-radical scavenging capacity was determined using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) method described by Brand-Williams et al. (1995). Absorbance was measured at 517 nm using a Shimadzu UV-1800 spectrophotometer against a reagent blank. Percent inhibition was calculated as

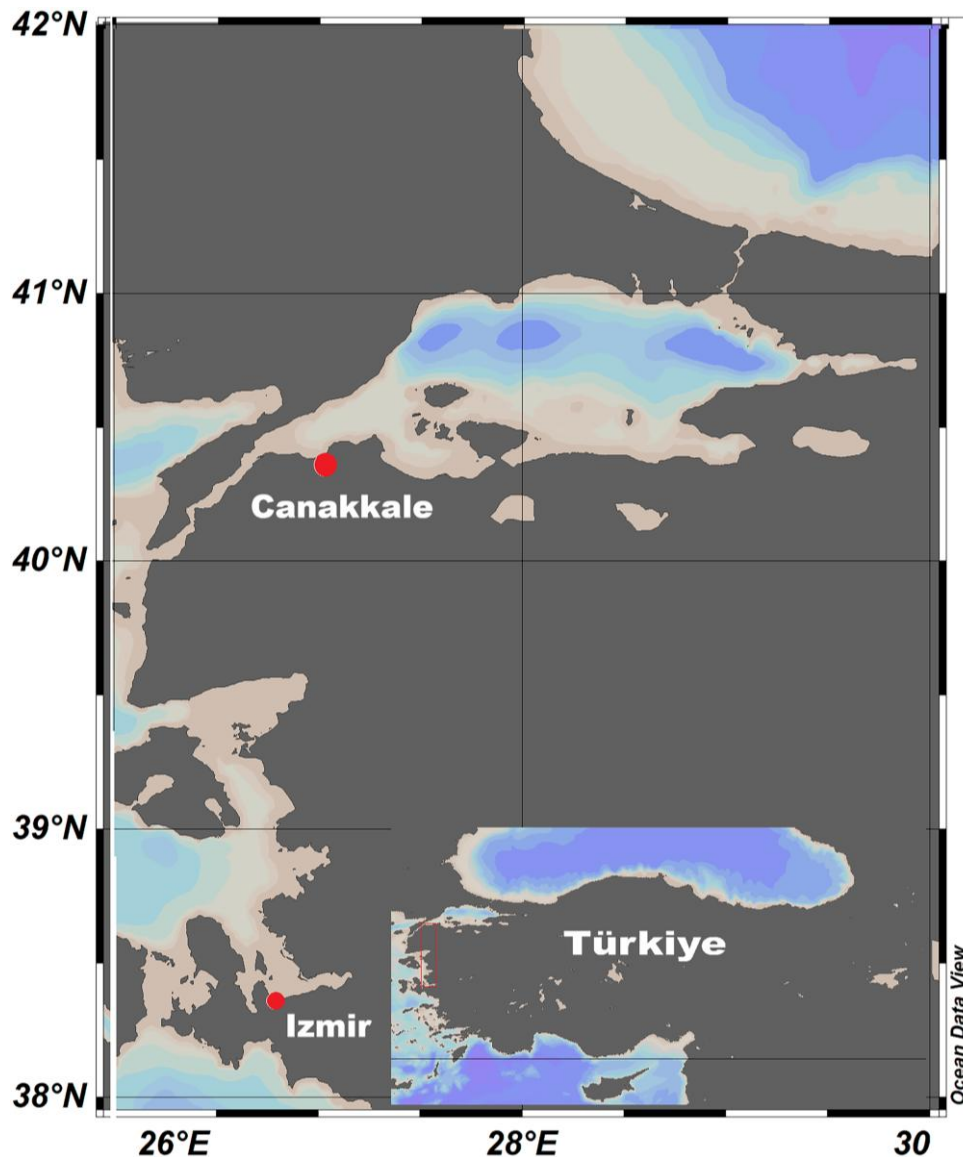


Figure 1. Sampling locations of *C. sinuosa*. Red dots represent sampling sites in Izmir and Canakkale.

$$\text{Inhibition (\%)} = \frac{A_0 - A_1}{A_0} \times 100$$

A_0 is the absorbance of the control, and A_1 is the absorbance of the sample mixture. Inhibition (%) versus concentration (mg mL^{-1}) was plotted, and the concentration providing 50 % inhibition (IC_{50}) was obtained by non-linear regression. BHT (butylated hydroxytoluene) was used as the reference antioxidant standard.

Statistical Analysis

The extraction yield, monosaccharide composition, and DPPH IC_{50} (mg mL^{-1}) were obtained from three replicates ($n=3$), and the data are given as mean \pm standard deviation. Normality (Shapiro–Wilk) and variance homogeneity (Levene) were tested at an α level of 0.05. Unpaired two-tailed t-tests evaluated site-wise differences. Statistical analyses were performed using Minitab 16 (trial version, Minitab Inc., USA). Principal

Component Analysis (PCA) was conducted to explore the relationships between polysaccharide composition, antioxidant activity, and environmental variables. Before analysis, all variables were standardized to eliminate the effect of scale. PCA was conducted based on the correlation matrix using the covariance structure of the data. Eigenvalues and eigenvectors were calculated to derive the principal components, and the percentage of variance explained by each component was recorded. Two principal components were selected for graphical representation, as they collectively explained the majority of the total variance (Abdi & Williams, 2010; Jolliffe & Cadima, 2016).

Pairwise relationships among monosaccharide composition, antioxidant properties, and environmental parameters were examined through Pearson correlation-based heatmap analysis. Correlation coefficients were computed using MATLAB R2024a (The MathWorks Inc., Natick, MA, USA), and the heatmap visualization was generated according to Gu et al. (2016) and Kumar & Banerjee (2020).

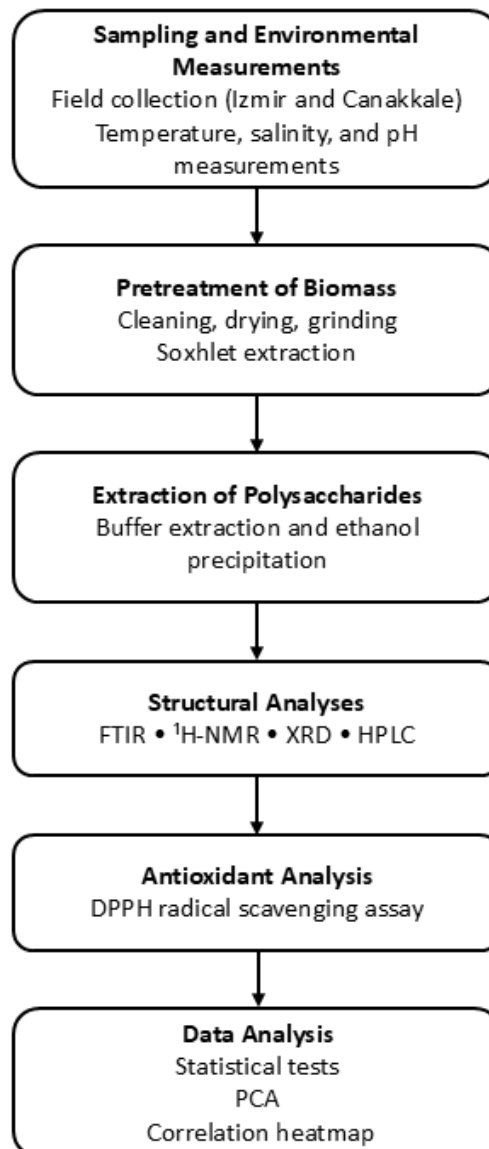


Figure 2. The main experimental steps of extraction, structural, and functional analyses.

Results and Discussion

FTIR-Based Structural Characterization

Sulfated polysaccharides were identified in both *C. sinuosa* samples based on characteristic FTIR absorption bands (Figure 2). In both PSI and PSC spectra, strong absorptions at 1044 cm^{-1} and 894 cm^{-1} correspond to C–O–C glycosidic stretching and β -D-galactose/ β -anomeric ring vibrations. A more intense band at 1177 cm^{-1} in the PSC sample shows a higher degree of sulfation. This band corresponds to the O=S=O asymmetric stretching of sulfate esters. Low-frequency bands between 657 and 735 cm^{-1} , detected only in PSC, indicate the presence of sulfate-rich and highly ordered complexes (Figure 3).

These spectral patterns are typical of brown-algal polysaccharides (Gómez-Ordóñez & Rupérez, 2011; Rostami et al., 2017; Atya et al., 2021; Al Monla et al., 2022). The presence of sulfate ester peaks together with glycosidic and anomeric proton bands agrees with earlier reports for brown algae (Gómez-Ordóñez & Rupérez, 2011; Benslimma et al., 2021; Pacheco et al., 2021). Salem et al. (2022) also observed similar C–O–C vibrations in the 1055 – 1066 cm^{-1} region in cellulose and nanofiber fractions of *C. sinuosa*, indicating that glycosidic features are consistently preserved across structural derivatives.

$^1\text{H-NMR}$ -Based Structural Characterization

$^1\text{H-NMR}$ spectra showed the complex structures of polysaccharides obtained from *C. sinuosa* that varied with the stations (Figure 4). PSI showed widespread and overlapping signals in the 3.2 – 5.5 ppm range. This distribution indicates the presence of multiple monosaccharides and a branched, nonuniform chain structure. The mild resonances observed in the 1.3 – 1.6 ppm region can be assigned to the C6 methyl protons of α -L-fucose or potential pyruvyl substitutions. In PSI, signals of laminarin (4.70 ppm) and mannitol (3.5 – 3.7 ppm) indicate the presence of soluble glucans and sugar alcohols. In addition to major fucoidan-related signals,

other resonances at 5.07 , 4.67 , and 4.46 ppm were detected in PSI. In contrast, the spectral characteristics of PSC were narrower and more distinct. Grouped anomeric proton signals observed between 4.8 and 4.9 ppm indicate a regular chain structure.

The spectral features match the ranges of 5.0 – 5.5 ppm and 0.8 – 1.4 ppm reported by Al Monla et al. (2022). The results are also consistent with the results of Parvathy et al. (2021) for the same species. A diffuse and intense anomeric region, similar to the one in PSC, was also more diffuse and intense in summer- and autumn-collected samples of the brown alga *Cystoseira schiffneri* (Benslimma et al., 2021). This spectrum type was associated with more complex, highly sulfated structures. Hoang et al. (2024) also reported resonances in fractions of the red alga *Nemalion cari-cariense*, including the β -anomeric glucose (5.4 – 5.5 ppm) sugar and the α -D-glucopyranose (5.1 – 5.2 ppm). These signals are similar to those observed mainly in the PSI in our study. Except for the fucoidan-related signals, the additional resonances detected in PSI resemble those reported for alginate fractions in the brown algae *Fucus guiryi* and *Cystoseira crinita* (Belattmania et al., 1980; Kokova et al., 2003). This similarity may suggest that traces of co-extracted alginate are responsible for part of the amorphous, heterogeneous structure observed in the PSI.

XRD-Based Structural Characterization

XRD analysis revealed variations in the molecular arrangement and crystallinity of polysaccharides extracted from *C. sinuosa* (Figure 5). PSI showed a low-intensity, broad-based diffraction profile over $2\theta = 19$ – 25° . The Crystallinity Index of PSI was 14.7% , consistent with loosely packed chains. PSC showed a different pattern. Sharp and high-intensity peaks appeared at $2\theta = 31^\circ$, 34° , 36° , 38° , and 44° . These peaks indicate more ordered chain stacks. The crystallinity index of PSC was 28.9% . Minor and repeated peaks were also observed in the PSC diffraction pattern.

The diffraction profile of PSI corresponds to an amorphous structure comprising short-chain, branched,

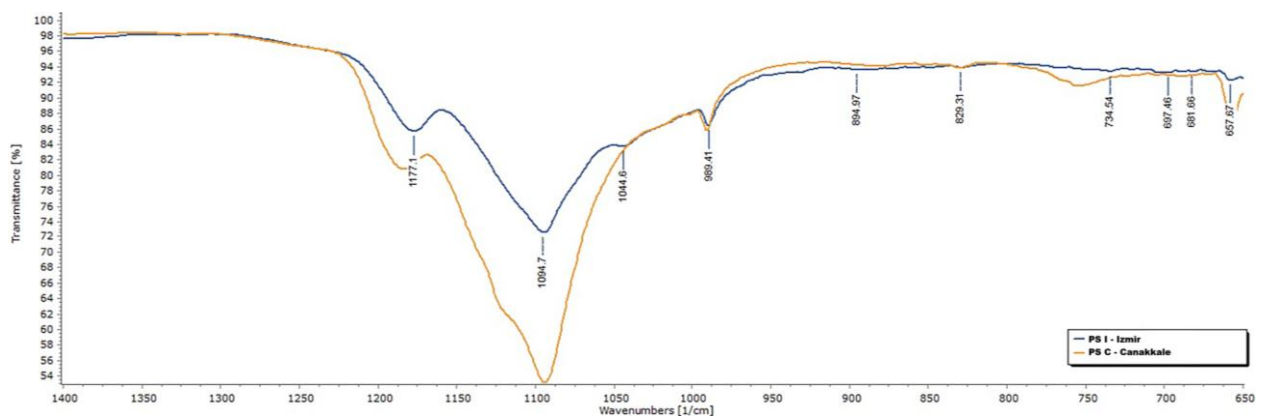


Figure 3. FTIR profiles of polysaccharide fractions extracted from *C. sinuosa* collected from Izmir (PSI, blue line) and Canakkale (PSC, orange line).

and randomly extended polymers, as described by Udaipuria and Bhattacharya (2025). The structural interpretation of PSI is also supported by the broadened glycosidic bands observed in FTIR and the wide resonance distribution in ¹H-NMR (Figures 3-4). PSC shows features consistent with a more ordered polymer organization, which agrees with the structural profiles reported for well-organized polysaccharide regions in previous studies (Anisah et al., 2024; Ghazy et al., 2024). Semi-crystalline materials commonly exhibit both amorphous and crystalline regions (Lotz, 2023). Crystallinity may sometimes be attributed to repeating monomer sequences or to ion bonds between chains (Alfinaikh et al., 2025). The minor and repeated peaks present in PSC resemble the semi-crystalline patterns reported by Parvathy et al. (2021). Inácio et al. (2022) also observed that sulfated polysaccharides could form a semi-crystalline structure of the brown algal type due to their repeating structure and functional group

interactions. The crystalline order seen in PSC in this study may reflect a less erratic distribution of sulphate groups or the presence of alginate-like sequences, which have been linked to structural organization in brown algae (Belattmania et al., 2020; Kokova et al., 2023).

Monosaccharide Composition

HPLC indicated that the monosaccharide composition of the purified sulfated polysaccharide fractions of *C. sinuosa* varied significantly (Table 1). Early-eluting anionic sugars, including L-galacturonic acid, were present in approximately equal amounts in PSC and PSI. However, the late-eluting sugars, including glucose and fructose, were relatively more concentrated in the PSI. The central peak observed at 13.71 min, with overlapped L-fructose, L-rhamnose, and L-arabinose signals, was also the most intense in both raw materials

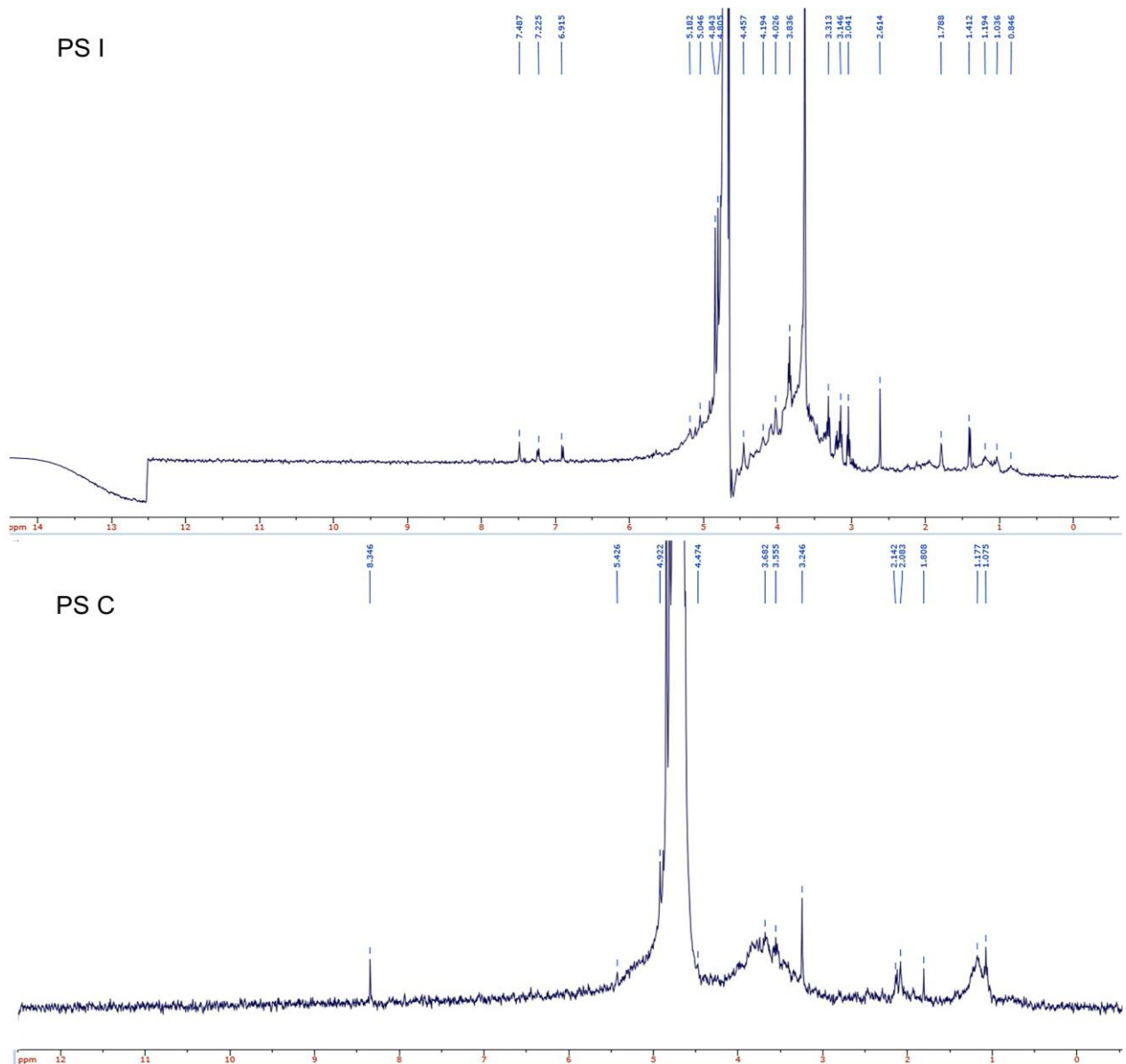


Figure 4. ¹H-NMR spectra of sulfated polysaccharide fractions from *C. sinuosa* collected in Izmir (PSI) and Canakkale (PSC).

and contributed statistically similar proportions (41.57±0.88 mol% in PSI; 43.97±0.55 mol% in PSC). The peak at 14.75 min, assigned to L-galactose and L-mannose, showed somewhat higher values in PSI (21.73±2.09 mol%) than in PSC (18.72±2.13 mol%). The contents of D-glucose and L-fucose were significantly higher in PSI samples (p<0.05). L-galacturonic acid content was not significantly different between the two regions, averaging 7.3 mol%.

Higher levels of glucose and fructose in PSI are consistent with a more branched and disordered structure, as described for amorphous polysaccharide regions in earlier studies (Ponce et al., 2020). Rostami et al. (2017) reported that fucose, galactose, and glucuronic acid are the major sugars in fucoidan from *C. sinuosa*, which aligns with their presence in both fractions. Pacheco et al. (2021) emphasized the structural role of fucose, galacturonic acid, and xylose in *C. peregrina*. In addition, the mannan-enriched preparations proposed by Benslimam et al. (2021) in *C. schiffneri* and other brown algae may exhibit remarkable differences in sugar dominance.

Antioxidant Activity (DPPH) and IC₅₀ Values

The antioxidant capacity of *C. sinuosa* extracts was assessed by DPPH radical scavenging assay (Table 2). The

PSI and PSC exhibited scavenging activities of 20.40±0.12% and 20.10±0.31%, respectively (p>0.05). Their IC₅₀ values were calculated as 14.78±0.51 mg/mL for PSI and 13.25±0.49 mg/mL for PSC (p>0.05).

Although antioxidant responses were similar, they revealed distinct differences in structural properties (Figures 2-4). These structural variations can be linked to environmental factors (Rostami et al., 2018). It has also been shown in other studies that the structural and functional properties of brown algae polysaccharides are influenced by the extraction method as well as other variables (Ak et al., 2018; Hoang et al., 2024). Although sulfated polysaccharides are well-established as being excellent radical scavengers (Figueroa et al., 2022), the antioxidant potential of these may also be driven by monosaccharide composition, bond types and the position of sulfate groups (Ehrig & Alban, 2015; Benslimam et al., 2021). Al Monla et al. (2022) reported up to 89% inhibition and an IC₅₀ of 46.2 µg/mL in purified fucoidan from *C. sinuosa*.

Water Quality Data and Relationship with Structural Differences

The temperature, salinity, and pH values during the sampling stations are presented in Table 3. The values obtained are within the range of annual variation

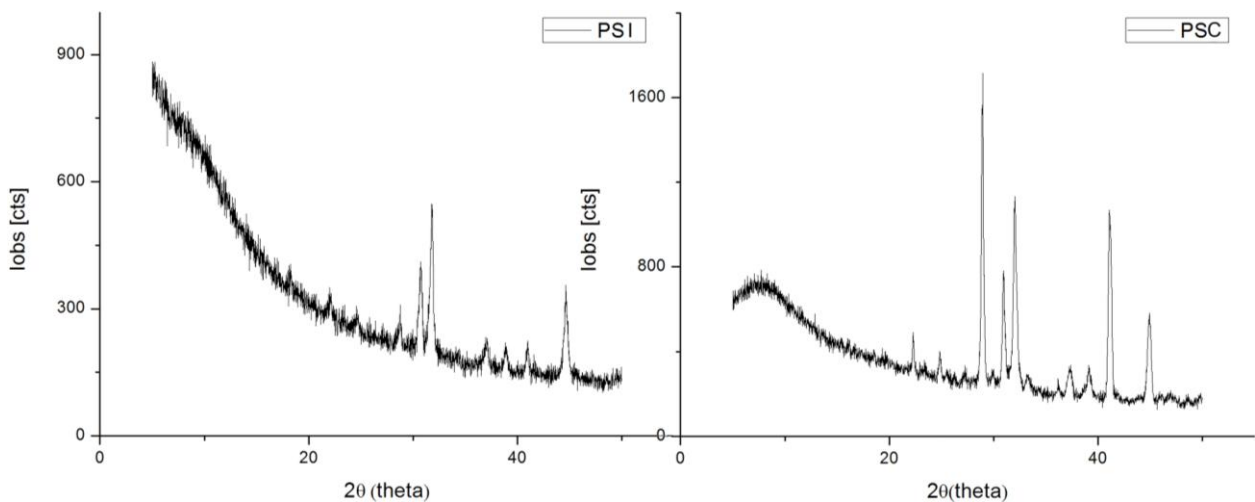


Figure 5. X-ray diffraction (XRD) patterns of sulfated polysaccharide fractions from *C. sinuosa* collected in Izmir (PSI) and Canakkale (PSC).

Table 1. Monosaccharide compositions of sulfated polysaccharide fractions of *C. sinuosa* obtained from Izmir and Canakkale (n=3)

Monosaccharide	RT (min)	PSI (% mol±SD)	PSC (% mol±SD)
L-Galacturonic acid	10.90	7.37±1.20 ^a	7.38±1.17 ^a
L-Fructose			
L-Rhamnose	13.71	41.57±0.88 ^b	43.97±0.55 ^a
L-Arabinose			
L-Galactose	14.75	21.73±2.09 ^a	18.72±2.13 ^a
L-Mannose			
D-Glucose	15.50	9.05±0.05 ^a	7.03±0.44 ^b
L-Fucose	15.10	4.02±0.83 ^a	3.35±0.46 ^b

There is a statistically significant difference between the values indicated with different letters (a-b) in the same row (p<0.05).

reported in both regions (Artüz, 2018; Mutlu, 2021; Daban et al., 2024). The PCA and heat map analyses were used to verify the relationship between these and environmental variables (Figures 6 and 7). The first and second components of the PCA described 91.5% of the variance in the data. In the PCA biplot, the samples were clustered well by stations. The samples at the Izmir station were noted to be particularly related to high salinity, high glucose concentration, and potent antioxidant activity. The effects indicate that the heat and salt in Izmir Bay place pressure on *C. sinuosa*, leading to the accumulation of glucose-rich, amorphous and branched polysaccharides. In the correlation heat

map analysis, there was also a strong positive correlation ($r=0.9988$) with salinity and glucose; negative correlations ($r=-0.8881$, -0.8001) were determined for IC_{50} and both salinity and glucose. Positive associations were also identified between L-fructose, L-rhamnose and L-arabinose groups and pH.

Our results show that PSI and PSC of *C. sinuosa* present different structural characteristics and antioxidant abilities. PSI was more branched, amorphous, and water-soluble, whereas PSC was more crystalline and exhibited a higher density chain profile of polysaccharides. These structural differences probably correspond to the biochemical responses of the alga *C.*

Table 2. DPPH radical scavenging activities and IC_{50} values of *C. sinuosa* samples (n=3)

Samples	DPPH Scavenging Activity (%)	IC_{50} (mg/mL)
PSI	20.40±0.12 ^b	14.78±0.51 ^b
PSC	20.10±0.31 ^b	13.25±0.49 ^b
BHT	99.00±0.10 ^a	1.30±0.03 ^a

There is a statistically significant difference between the values indicated with different letters (a-b) in the same row ($P<0.05$).

Table 3. *In situ* water parameters of Izmir and Canakkale stations (n=3)

Parameters	PSI	PSC
Water Temp. °C	24.50±0.19 ^a	20.15±0.07 ^b
Salinity ‰	40.35±0.52 ^a	28.29±0.40 ^b
pH	8.10±0.05 ^a	8.33±0.04 ^b

There is a statistically significant difference between the values indicated with different letters (a-b) in the same row ($p<0.05$).

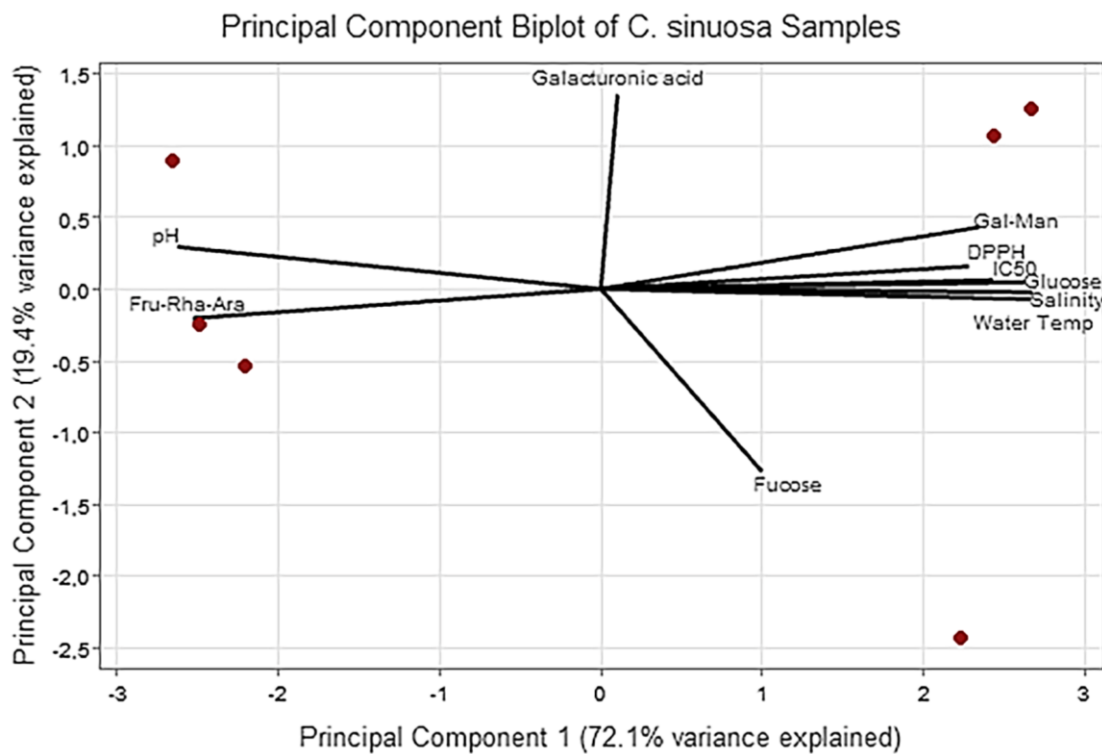


Figure 6. Principal component analysis (PCA) biplot of sulfated polysaccharide samples from *C. sinuosa* collected in Izmir (PSI) and Canakkale (PSC), showing the distribution of samples based on environmental parameters (salinity, temperature, pH), antioxidant activity (DPPH, IC_{50}), and monosaccharide composition.

sinuosa to environmental conditions (Rostami et al., 2018). Miguel et al. (2023) reported that polysaccharides from the green alga *Codium* sp. and the red alga *Osmundea* sp. species were collected in summer with an amorphous structure, high sulfate and good antioxidant activity. Additionally, Qu et al. (2019) found increased fucoidan and sulfate contents in the brown alga *Saccharina sculpera* from early spring to summer. Bruhn et al. (2017) reported that fucoidan concentrations of *Saccharina latissima* and *Laminaria digitata* increased at moderate (15–25‰) but decreased at high (30‰) salinity. They also suggested that high salinity is more of an inhibitor than a stimulant in the biosynthesis of sulfated polysaccharides. Kravchenko et al. (2018) reported that the polysaccharide content in the red alga *Ahnfeltiopsis flabelliformis* deposit feeders decreased with higher temperature and salinity, and deposit regularity was higher in colder months due to lower environmental stress. Similarly, polysaccharides were reported to increase in the brown alga *Sargassum wightii* at low salinity and temperature, and reductions in carbohydrate and protein content were significant in the summer (Kumar et al., 2015). The higher crystallinity

of PSC is likely due to the relatively low salinity and temperature conditions, which are reported to encourage a regular arrangement of polymer in brown algae (Bruhn et al., 2017; Kumar et al., 2015). Likewise, more branched and amorphous polysaccharides in the PSI were produced than in the PSC, suggesting an increase in its solubility and flexibility (Ehrig & Alban, 2015; Bruhn et al., 2017). Salinity, temperature, and pH have been linked to changes in polysaccharide composition and antioxidant activity in both red and brown macroalgae. Miguel et al. (2023) found that temperature and salinity affected the monosaccharide profile and antioxidant capacity of the brown alga *Sargassum muticum*. Bruhn et al. (2017) reported increased fucoidan levels in *S. latissima* at moderate salinities (15–25‰). In the brown alga *Saccharina sculpera*, fucoidan and sulfate contents were higher during reproductive stages, with increased antioxidant activity (Qu et al., 2019). A decline in polysaccharide content with increasing temperature was also observed in *A. flabelliformis* (Kravchenko et al., 2018). In the present study, similar associations were observed between salinity, pH, glucose levels, and antioxidant capacity in *C. sinuosa*.

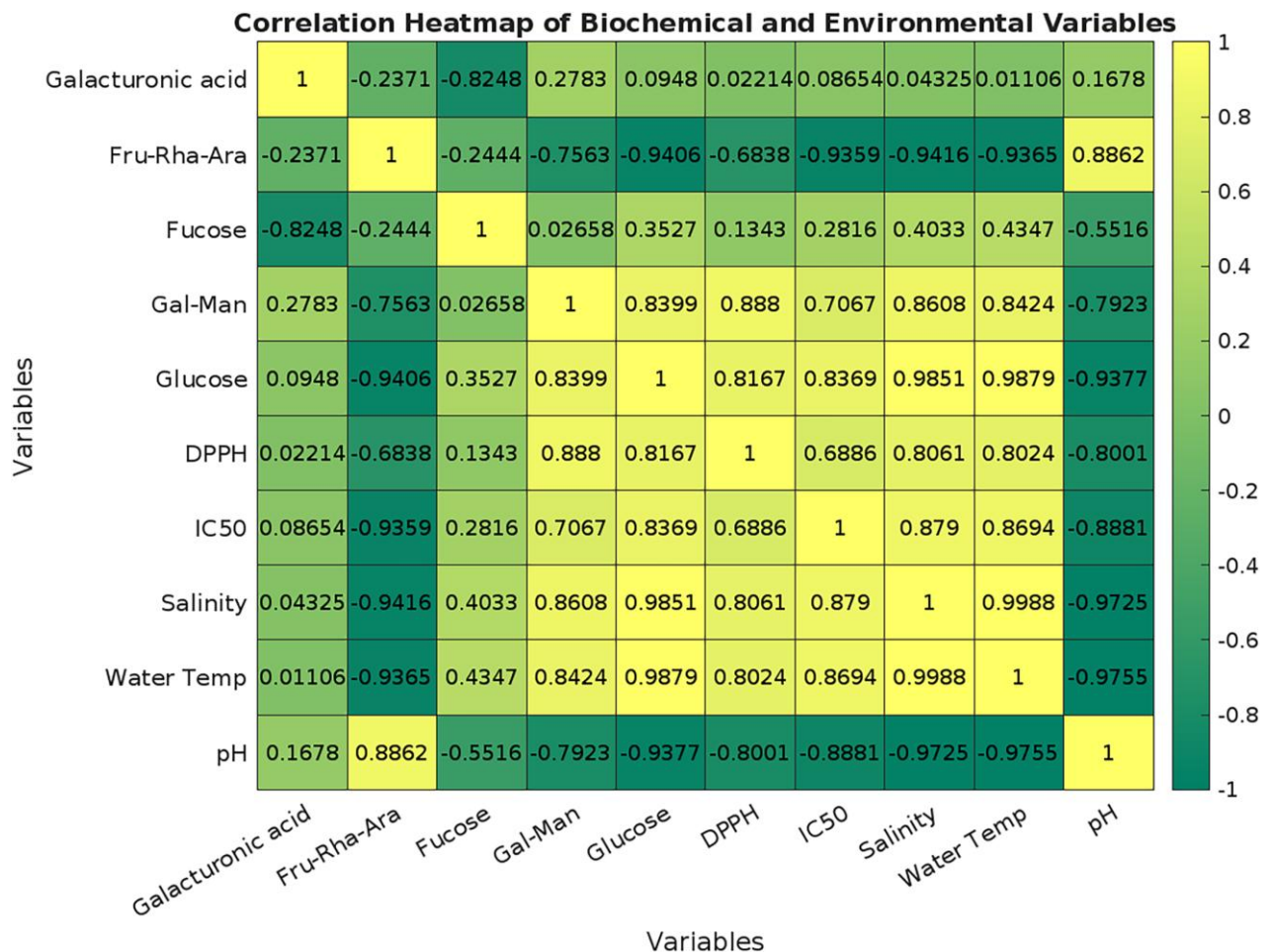


Figure 7. Heatmap of pairwise correlations between biochemical and environmental variables for PSI and PSC. The color intensity corresponds to the direction and strength of the Pearson correlation coefficient. Strong positive correlations ($r \approx +1$) are displayed in yellow, while strong negative correlations ($r \approx -1$) are displayed in dark green.

Conclusion

This study demonstrates that the structural and functional properties of sulfated polysaccharides obtained from *C. sinuosa* are influenced by environmental conditions. These findings may support the production of targeted biocompounds under controlled conditions. *C. sinuosa* is a brown alga with an annual life cycle and typically occurs along the Turkish coast between late April and early June. Therefore, sampling opportunities are temporally limited. Structural analyses revealed that PSI possessed a branched, amorphous, and water-soluble polysaccharide structure, whereas PSC exhibited a crystalline and chain-dense structure. These results indicate that *C. sinuosa* has evolved a biochemically adaptive polymer level in response to region-specific osmotic stress, temperature, and salinity profiles. A strong positive correlation was observed between salinity and glucose content, while a significant negative correlation was found between salinity and IC₅₀ values. Accordingly, high-osmotic conditions in Izmir (Aegean Sea) might have stimulated the production of branched glucose-rich polysaccharides. In contrast, more ordered/crystalline polysaccharide fractions were identified in the cooler and less saline conditions in Canakkale (Canakkale Strait). Equal antioxidant activities were observed, although the structural characteristics of both extracts suggest different application potentials. The amorphous and water-soluble nature of the PSI extract, rich in glucose and with branching characteristics, may be more suitable for pharmaceutical formulations, antioxidant delivery systems, or nutraceutical applications. In contrast, the highly sulfated and crystalline PSC extract, with its dense polymeric structure, may be used for structural or encapsulating applications, such as biomaterials, hydrogel scaffolds, or slow-release matrices. This highlights the relevance of site-specific collection and characterization when evaluating the industrial potential of macroalgal polysaccharides. While our results provide a robust comparison between these two distinct coastal environments, the reported structural variations may reflect the specific meteorological and hydrological conditions of the sampling window. Future studies investigating the impact of short-term weather fluctuations would further clarify how dynamic environmental shifts influence the polysaccharide biosynthesis of *C. sinuosa*. These results demonstrate the effect of environmental variation on the biochemical properties of *C. cinuosa* and support the potential exploitation of its sulfated polysaccharides in food, pharmaceutical, and cosmetic industries.

Ethical Statement

This study did not involve any vertebrates or cephalopods. Therefore, ethical approval was not required, as per national and institutional regulations.

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Author Contribution

Conceptualization, Writing - Original draft, Writing-Review and Editing: GT, İA, methodology: GT, Sampling and Survey: İA.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal interests that could have influenced the work reported in this paper.

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