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Assessment of Macroalgae Phytocenoses within the Black Sea Coastal Marine Area near Sochi, Russia

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Abstract The paper presents changes in the structure of macroalgae phytocenoses, as well as variations in morphometric parameters of dominant macrophyte species, in the Black Sea coastal area, within the influence zone of Sochi River in southern Russia. The center of the city's agglomeration with the same name surrounds its valley, and the resort's maritime port is also located near the studied area. Complex anthropogenic impacts from several different sources and specific natural properties of water in the Sochi River create conditions for the transformation of macrophyte phytocenoses, when perennial indigenous species such as *Ericaria crinita* Duby (1830) are gradually replaced by pollution-tolerant annual or seasonal species. The species composition of brown (*Fucophyceae*), red (*Rhodophyceae*), and green (*Chlorophyceae*) algae, which are considered to be bioindicators of water pollution at different levels, was described during this study. The abundance and biomass of these species in the phytocenoses were studied. The morphometric characteristics, such as the average thallus length and weight of the dominant species, were measured. A strong negative correlation has been identified between the percentage share of *E. crinita* within the total abundance of macrophytes in the investigated phytocenoses and both the suspended solid content and BODult values. Additionally, it was found that as the values of these physico-chemical parameters increase, the abundance of *E. crinita* in the phytocenosis significantly decreases, as well as the length of its thallus. At the same time, the correlations between the average algal biomass and both suspended solids and BOD parameters were weaker. The abundance and average weight of the *E. crinita* thallus generally decrease from areas with minimal river inflow impact to those that are significantly affected, reaching minimum values at the station closest to the river mouth. The results of these studies have significant implications for environmental management and public health policies. The bioindication approach represents a significant advance in the assessment and management of marine environment quality in coastal areas. It provides comprehensive information about areas significantly impacted by technogenic activities in their catchment basins.

Keywords Macrophytes, Abundance, Biomass, Marine Coastal Phytocenoses, Bioindication, Biotesting, Biochemical Oxygen Demand (BOD), Suspended Solids

1. Introduction

Marine biological resources and their natural regulatory systems are subject to stress caused by a variety of factors, including both natural and anthropogenic ones. At the same time, alterations in the structural and functional characteristics of coastal marine biotic communities serve as an indicator of the susceptibility of marine ecosystems to the effects of human activities [1], [2], [3].

Among the most significant sources of pollutants and nutrients released into the coastal marine environment are: river inflows, sewage and storm drains, predominantly from urbanized and recreational areas [4], [5].

Considering the intensification of development in the Black Sea coastal areas and, consequently, the increased anthropogenic pressure on their ecosystems [1], significant attention is being given to the development of marine environmental state biomarkers that belong to various taxonomic and trophic groups, in line with international best practices [6], [7].

However, relatively few studies have focused on the examination and implementation of biological monitoring of marine coastal ecosystem indicators based on macroalgae phytocenoses, despite these organisms being producers and therefore able to not only reflect the effects of environmental impacts on the marine environment but also provide an opportunity to forecast bioproduction in coastal areas and the potential successions and developments of subsequent trophic levels [8], [9], [10], [11]. The algae comprising marine coastal phytoceonsis are essential components of the nutrient circulation and natural recovery processes occurring in the hydroecosystem, preventing secondary sedimentation and providing nutrition and habitat for a variety of associated hydrobionts [12], [13].

Algae, as autotrophic organisms, are more sensitive than other organisms occupying subsequent trophic levels in this ecosystem to the physical and chemical characteristics of seawater and bottom sediment, such as nutrient concentration, pH and light intensity in the water column, which depends on water clarity [14]. In addition, changes in specific electrical conductivity, alkalinity, and concentrations of magnesium, calcium, and sodium can regulate the development of aquatic phyto-communities, while algae provide the basis of the food chain and perform ecosystem-forming functions [10], [15], [16], [17]. Therefore, the parameters of the satisfactory state of macrophytes communities reflect the overall health of the coastal ecosystem [18].

Currently, in the study area, an increase in anthropogenic pressure on the coastal zone of the Black Sea has been observed, due to demographic, economic and anthropogenic factors. Therefore, it is essential to develop and test in specific conditions, economically viable and reliable biomarker systems that are suitable for various types of pollution, reflecting both the current state and long-term changes in the aquatic environment [19], [20]. Also, an assessment of the transformation of multicellular algal communities allows determining the further decline in the abundance of long-lived aboriginal *Fucophycea*, which are oligosaprobic organisms sensitive to pollution, and the succession of cosmopolitan opportunistic genera such as Rhodophyceae and *Chlorophycea* genuses, which are mostly monocyclic, relatively low productive and do not perform a habitat-forming function.

This paper aims to investigate the properties of coastal seawater in one of the most ecologically stressed areas of Sochi, specifically at the point where the Sochi River discharges into the Black Sea. In order to evaluate the general ecological status of the studied area, the macrophyte community bioindication data were compared and analyzed in order to potentially apply this approach as part of biological monitoring and assessment of anthropogenic pollution in the coastal marine environment of the Black Sea within resort and recreational areas in Russia.

2. Materials and Methods

2.1. Sampling Location and Procedure

Sampling was carried out in the plume zone of the Sochi River in October 2024, along the northern pier of the Sochi Maritime Port. Transportation along the pier was conducted by a small vessel, and sampling operations were carried out by divers. The sampling locations and their descriptions are presented in the scheme (Fig. 1).

In order to assess the condition of the macroalgae growing on the benches of the northern pier, 6 observation stations were established at distances of 10, 50, 100, 300, and 700 meters from the coastal zone. Their coordinates are provided in Table 1.

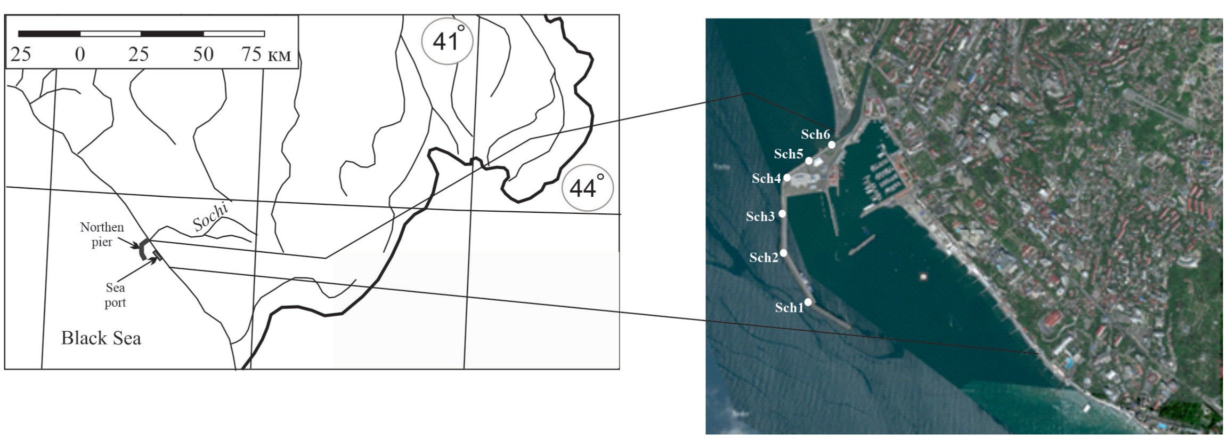


Figure 1. Sampling stations along the northern pier of the Sochi Maritime Port

Table 1. Results of measurements with standard error

Sampling stations	Latitude	Longitude
Sch 1	43.57311127305886	39.71121291889943
Sch 2	43.57618458701369	39.70891694798268
Sch 3	43.57864936435878	39.708895490310574
Sch 4	43.5805056800999	39.709152982376
Sch 5	43.581940775583604	39.711856649063
Sch 6	43.58267390882409	39.71357326283255

Algae were collected from concrete structures of the pier at a depth of 0.2-1.0 meters from the water surface using a scraper. At each station, macrophytes were collected and placed in polythene bags along with seawater samples from the site of their growth. The biological samples were subsequently transported to a laboratory, where taxonomic identification of the macrophyte species was performed, and the morphological dimensions of the macroalgal species thallus were measured.

2.2. Physical and Chemical Methods

The seawater was analyzed using classical methods of analytical chemistry: the hydrogen index was determined by potentiometry, suspended solids and mineralization by gravimetry, and biochemical oxygen consumption by iodometry.

Biochemical oxygen demand (BOD) is a parameter of water contamination caused by organic substances that are susceptible to biochemical decomposition.

In order to ensure that the oxidation process has been completed for all organic material present in the sample, BOD analysis was conducted according to the method of measuring residual dissolved oxygen on days 5, 10, 15 and 20, as well as at the experiment completion, when the nitrification process commenced. The oxygen flask incubation was performed under standard conditions at 20°C without access to light or air [21].

2.3. Bioassay Methods

Macrophyte species were identified using the determinant in [22]. Algae nomenclature changes have been taken into account [23], [24], [25], [26]. The indicative significance of the selected algae species has been determined based on prior research [27].

Abundance and biomass of each algal taxonomic group were counted, and the size and condition of the thalluses were recorded. Quantitative indicators were calculated based on the obtained data: the number of thalluses and their biomass per square meter, and the dominant species were identified by their percentage proportion to the total abundance and biomass of macrophytes in the sample [28].

The Black Sea flora comprises 292 species of macrophytes algae, the majority of which are found along the Turkish coastline [29]. The macroflora of the Russian part of the Black Sea includes 152 different species, comprising 37 species of green algae, 36 species of brown algae, 77 species of red algae, and two flowering plants species. At the same time, the Sochi coast has relatively low species diversity with only 39 species of macrophytes represented by 16 phytocenoses at depths ranging from 0.1 to 25 m [19].

The bioindicative characteristics of algae macrophytes are primarily determined by their sensitivity to nutrient availability, which influences the process of eutrophication in aquatic systems. Consequently, the dynamics of macrophytes' growth can play a significant role in long-term assessments of environmental change caused by prolonged human activities. For instance, the species composition of macrophytes is changing, their biomass is decreasing, and the replacement of dominant perennial species with short-lived algae is occurring in polluted coastal marine areas [24], [30].

In this context, macrophyte communities dominated by species that are tolerant to eutrophication are formed near discharges of wastewater that contain excessive concentrations of nutrients, indicating anthropogenic pollution [31], [32]. An indicator of pure oligosaprobic waters is the phytocenosis of *Ericaria sp*., which usually forms the foundation of uncontaminated coastal biocenoses and is legally protected in several European countries [33].

The statistical calculations and graphs for this work were carried out using Excel 2010.

3. Results

3.1. Physical and Chemical Characteristics

Studies of hydrochemical macroparameters have allowed for an assessment of the impact of the Sochi River and the maritime port's entrance on the marine water quality within the study area.

Despite the fact that station Sch 1 is the farthest from the Sochi River estuary and the influence of river water on the chemical composition of seawater is minimal there, a deterioration in water quality has been observed at this station compared to stations Sch 2 and Sch 3 with regard to parameters such as suspended solids content and BODult level. The proximity of station Sch 1 to the maritime port may explain this. Station Sch 2, located 100 meters from Station Sch 1, has been found to be the least polluted with the highest mineralization and pH readings of all the samples analyzed, and is accepted as the reference sample. Subsequently, as the sampling approaches the confluence of the Sochi River and the sea, the concentration of suspended solids increases, while the pH and salinity decrease. The influence of the river becomes more pronounced and reaches its maximum in samples from station Sch 6. At this location, the concentration of suspended solids increases 24 times, while BODult increases 5 times and mineralization decreases by 4.5 times, relative to reference values (Table 2).

Table 2. Results of measurements with standard error

Stations	pH, val. pH	Mineralization, mg/l	Suspended solids, mg/l	BOD_5, mgO_2/l	BODult, mgO_2/l
Sch 1	8.05±0.08	21.3±0.5	2.5±0.5	0.27	0.98±0.14
Sch 2	8.10±0.08	22.7±0.6	1.0±0.2	0.23	0.44±0.06
Sch 3	8.10±0.08	20.8±0.5	1.7±0.3	0.18	0.52±0.07
Sch 4	8.09±0.08	20.2±0.5	4.1±0.7	0.15	0.66±0.09
Sch 5	8.05±0.08	15.3±0.4	11.2±1.3	0.48	1.74±0.24
Sch 6	7.98±0.08	5.0±0.1	23.9±2.9	0.61	2.21±0.31

Based on the results of the measurements, the BOD_5 values were significantly lower than the BODult values, indicating a relatively low rate of biochemical degradation of pollutants. Using BOD_5 as an indicator of water quality may lead to an inaccurate assessment if pollutants are resistant to biological degradation and require a longer period of time for oxidation by microorganisms [34].

Thus, the BODult values provide a more comprehensive picture of pollution than BOD_5 and allow for a correct assessment of water quality.

3.2. Bioassay Results

During this study, algal biodiversity was detected to be relatively low in the macrophyte samples. In total, six species of macroalgae were identified throughout the sampling region. These included six stations located at different distances from the coast and the confluence of the Sochi River and the Black Sea. The macrophyte species, identified during the research, include brown (*Fucophyceae*), red (*Rhodophyceae*) and green (*Chlorophyceae*). However, the distribution of detected algal taxa in study areas was not consistent, as shown in Table 3.

The productive perennial brown algae (*Ericaria crinita* D.), which is an indicator of clean water, was the dominant and edifying species at stations Sch 1-5, where other species were present only as epiphytes on *E. crinita*, and their abundance and biomass were insignificant. Additionally, the green alga *Codium fragile* H., which can only be found in open, unpolluted areas of the sea and its presence was occasional at stations Sch 4 and Sch 5.

The species composition of the phytocenosis at Station 6, located at the confluence of the Sochi River and the Black Sea, represents a qualitatively different association of macrophytes. In contrast to stations Sch 1-5, the predominant algae identified at this site were the green algae species *Cladophora albida* and *Ulva compressa*. Perennial brown algae were not found in this sample (Table 2).

The dominant species in this association at the time of the study was C. albida, which formed the basis of the phytocenosis. The species *U. compressa* was not abundant. The low abundance of these species is probably explained by the fact that the samples for this study were taken outside the seasonal vegetation period and in the summer low-water period. When the river is in its low-flow regime, eutrophication levels increase and water temperatures rise; while hydrodynamic condition decreases, these algae populations may increase [35], [36].

The analysis of the abundance and biomass of macrophytes in the study area demonstrated the highest density of algal thalli per 1 m² of substrate surface at station Sch 6. The dominant species there was C. albida, a green macroalgae, which is an indicator of contaminated water. The biocenoses of *E. crinita* were found to have the highest abundance at Station 3 (with 115 thalli per square meter). In contrast, the abundance of algae in samples collected at Stations 1 and 2 was rather lower.

At the same time, an analysis of algal biomass indicated that values were lower at Station Sch 1 compared to those at Stations Sch 2 and Sch 3. However, the algae biomass at station Sch 4 demonstrated a significant decrease. The biomass of macrophytes was minimal at station Sch 5. In addition, at Station 6, which is most affected by the river's inflow, the overall biomass of macroalgae has increased, although the dominant species has changed (Table 4).

E. crinita phytocenoses were observed at the sites of stations Sch 1 – Sch 5. It has been determined that the total abundance and biomass of algae in these areas are primarily formed from this dominant species, with an insignificant contribution from epiphytic algae. The site of station Sch 6 is characterized by a different phytocenosis dominated by an association of green algae. The graph (Fig. 2) illustrates the density of the dominant species in abundance and biomass per square meter at all the investigated sites.

It was observed that the proportion of *E. crinita* within the biocenoses differed between stations, with the highest levels of this parameter recorded at station Sch 3. At station Sch 5, there is evidence of a decrease in the abundance of *E. crinita* and an increase in the proportions of epiphytic green (*C. laetevirens*) and red (*C. virgatum*) algae, which are indicators of water contamination.

Additionally, it was observed that the samples collected from station Sch 2 exhibited the highest average values for algae thallus length and biomass within the study area.

Table 3. Distribution of macrophyte algal taxa within the study area

Macrophytes species	Sampling stations					
	Sch 1	Sch 2	Sch 3	Sch 4	Sch 5	Sch 6
Fucophyceae						
Ericariaa crinita Duby (1830)	+++	+++	+++	++	++	
Codium frigile (Suringar) Hariot (1889)	++	++	++	+	+	
Rhodophyceae						
Ceramium virgatum Roth (1797)	++	++	++	++	++	
Chlorophyceae						
Cladophora laenteverens Dillwyn (1805)	++	+	+	++	++	+
Cladophora albida Nees (1820)						+++
Ulva compressa Linnaeus (1753)						++

Note: +++ - abundant species; ++ - average occurrence; + - occurs occasionally;

Table 4. Bioassay parameters determined within the study area

Station	Sch 1	Sch 2	Sch 3	Sch 4	Sch 5	Sch 6
Total macrophyte abundance per 1 m^2	107±2.20	60±7.91	115±11.78	74±7.42	13.3±2.69	1430±17.88
Proportion of dominating species in the total algae abundance, %	67.3	66.7	78.3	56.8	25	91
Total biomass, raw weight, g/m^2	772±0.97	946±11.11	984±5.04	572±9.59	78.67±3.69	485±0.14
Proportion of dominating species in the total algae biomass, %	99.7	99.8	99.8	99.6	95.9	90.1
Average thallus length of dominating species, cm.	19.93±1.01	30.22±2.32	20.58±1.07	22.42±1.77	23.64±1.55	1.35±0.05
Average thallus weight of dominating species, g.	10.69±1.21	23.61±2.65	10.91±1.11	13.57±1.80	5.68±1.78	2.98±0.05

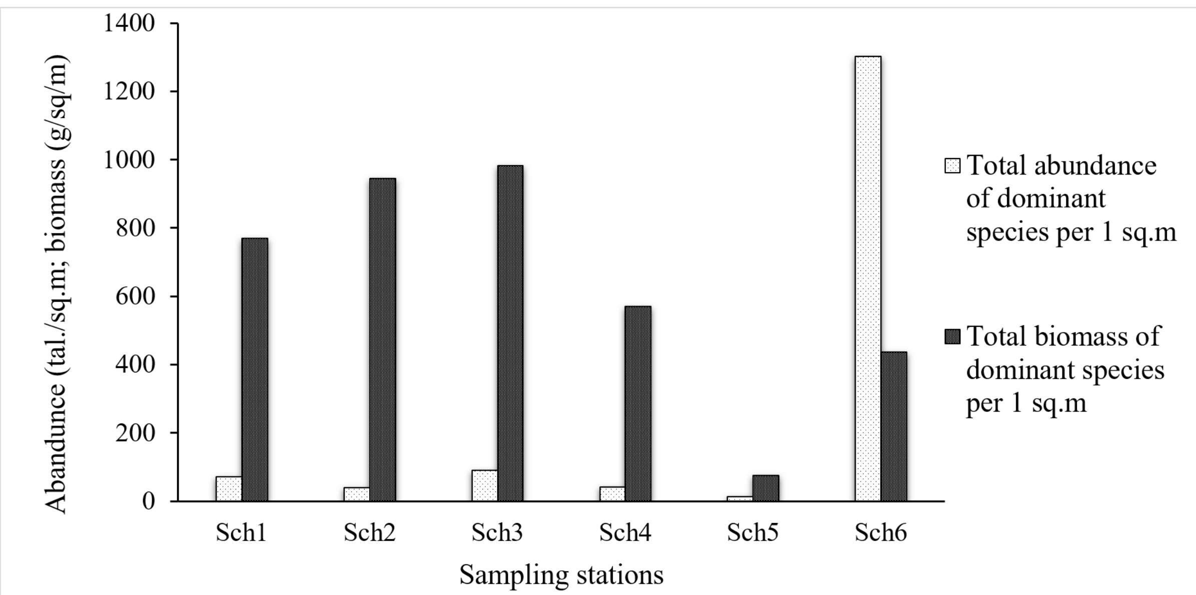


Figure 2. Abundance and biomass of the dominant macrophytes within the study area

At the same time, the average length of the *E. crinita* thallus was significantly lower both at the location of station Sch 1, which is closest to the maritime port, and at stations Sch 3-6. However, the value increases slightly from Sch 3 to Sch 5. Meanwhile, the values of average weight of algae thallus generally decrease from station Sch 2 to station Sch 5, with minimum values recorded at station Sch 5.

4. Discussion

4.1. Pollution Characteristics

The study revealed the negative impact of maritime port operations on the seawater quality in the section furthest away from the confluence of the Sochi River and the Black Sea. At this station, there was detected not only an increase in the BODult and suspended solids concentration compared to the nearest station, but also a decline in the biological parameters that characterize the macrophyte algae community. This effect is presumably caused by the proximity of this site to the Sochi Maritime Port exit, where excursion boats, yachts, and other vessels are actively operating.

At the same time, the site located off the coast of the aforementioned station demonstrated the most favorable hydrochemical and biological parameters. As sampling progressed towards the confluence of the Sochi River and the sea, the values of biochemical oxygen consumption (BODult) and suspended solid concentration increased, while the pH and salinity values decreased. This leads to the assumption that the qualitative characteristics of the coastal marine environment are altered under the influence of river discharge, resulting in the suppression of *E. crinita* phytocenoses and their subsequent replacement by a different type of macroalgae community consisting of species that are tolerant to pollution and pH variations (Table 3).

As mentioned previously (Table 1), the concentrations of BOD_5 are significantly lower than those of BODult in the studied marine waters, suggesting a low rate of biochemical decomposition of pollutants. Low BOD_5 levels create an appearance of ecological health and stability in aquatic environments, but do not account for negative changes in hydrobiocenoses in adjacent waters. Research has established that the biochemical oxidation of organic substances varies in rate and is influenced by several factors, including their chemical composition, initial concentration, and adaptation of microbial flora.

Based on the rate of decomposition, organic substances are classified into three categories: biologically soft, intermediate, and hard [21], [34]. It is assumed that the seawater studied was contaminated with hard biological pollutants, which required more than five days for microorganisms to oxidize them [21]. The river carries a significant amount of fine clay particles and organic matter, while oil products and nitrogen-based pollutants are discharged from the maritime port. Therefore, the concentration of suspended solids transported by the river increases starting from station Sch 3; however, the BOD_5 values, on the other hand, begin to change from station Sch 4, and increase significantly in samples collected from stations Sch 5 and Sch 6, which is where the impact of river discharge on marine waters is greatest.

4.2. Analysis of Macrophytes Phytocenoses

Analyzing the responses of macrophyte communities to various factors within the study area, a negative impact from the maritime port was revealed in a sample located farthest from the river's mouth (Sch 1), which is evident both in the condition of *E. crinita* phytoceenoses and in the values of morphometric parameters of its thalli (Fig. 3).

Additionally, a significant impact of river drainage is observed, while extending from station Sch 4 towards the coastline. In this area, the abundance and biomass of *E. crinita* in the phytoceonosis, which is an indicator of unpolluted water, begin to decrease, while the proportion of annual green and red algae that grow as epiphytes on *E. crinita*, in contrast, increases. Scientific research and international experience demonstrate that this phenomenon indicates eutrophication and pollution of the aquatic environment [37], [38], [39].

At the location of Sch 6, which is situated in the immediate vicinity of the confluence of the Sochi River and the Black Sea, a complete replacement of the *E. crinita* phytocenosis by an association of green algae, a phenomenon typical of desalinated and eutrophic water in the pseudo-littoral area subject to river runoff [35].

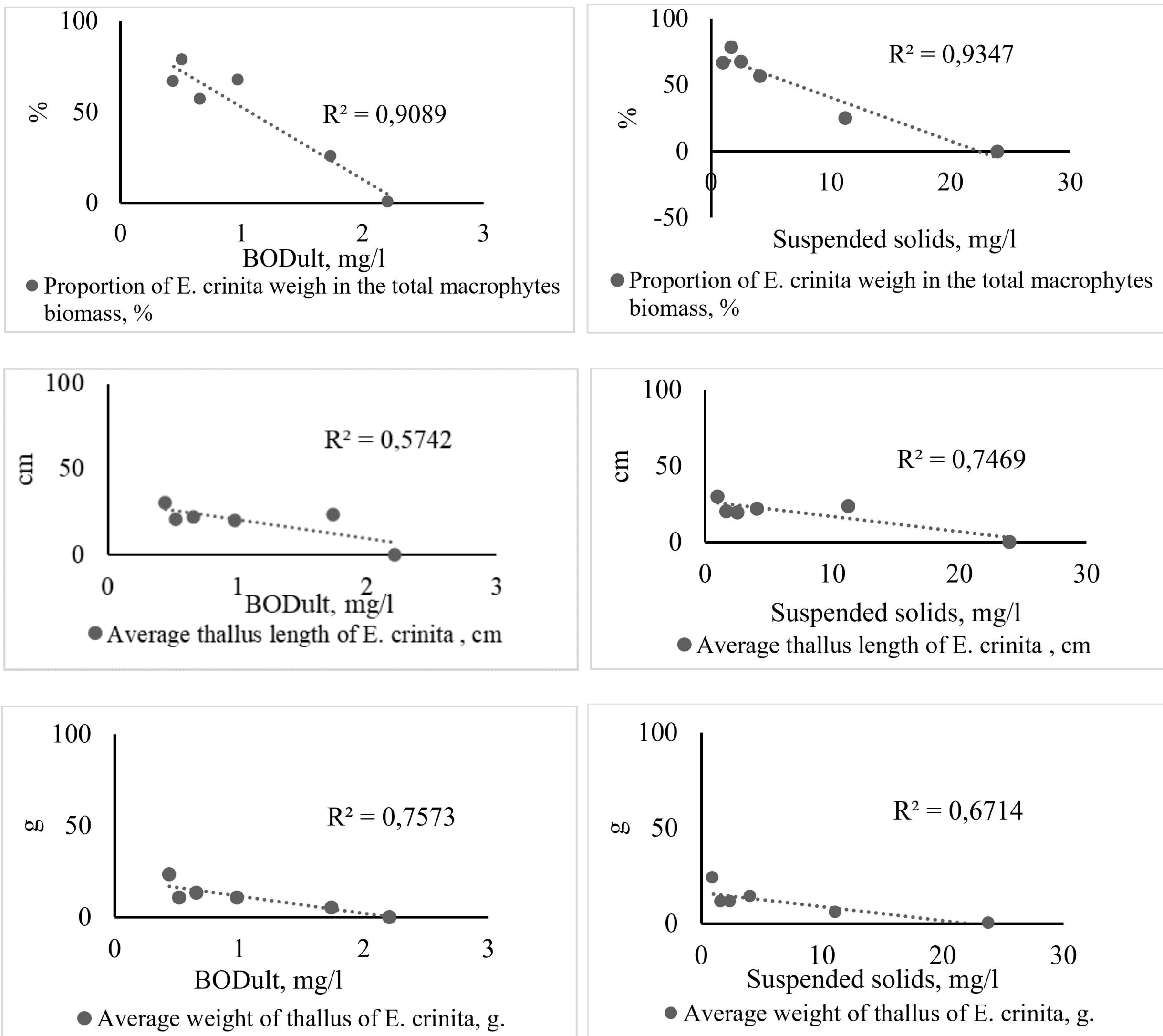
In order to understand the characteristics and dynamics of the development of this phytoceonosis, it is necessary to continue research covering all seasons of macrophyte vegetation. According to the results of our short-term survey, it is possible to consider the site of station Sch 6, represented by the phytocenosis where the main abundance and biomass of algae are determined by the dominant species, *C. albida*, as a distinct independent association that has different ecological requirements compared to the *E. crinita* biocenosis located further towards the open sea [34].

4.3. Correlations between Studied Indices

In the study, a strong correlation was found between the proportion of dominant species in the overall abundance and biomass of macrophytes and both the level of suspended solid concentration (R^2=0.93; R^2=0.91 correspondingly) and the BODult concentration (R^2=0.79; R^2=0.93 correspondingly). At the time, it was generally demonstrated that total macrophyte abundance and biomass had weaker correlations with these physical - chemical parameters (Table 5).

The correlations between the average length and biomass of *E. crinita* thalli and the values of suspended solids content (R^2= 0.75 and R^2= 61, respectively), and biochemical oxygen consumption (R^2=0.61 and 0.57 respectively) were also weaker. However, all studied biological parameters demonstrated significant correlations with the physical and chemical characteristics. It was observed that as these physical and chemical parameters increased, the abundance of *E. crinita* within the phytocenosis significantly decreased, as did the average length of its thalli. The correlations between the average algal thallus biomass and suspended solids and BODult concentrations were substantially lower compared to other dependencies between biological and physical - chemical parameters (Fig. 4).

As an indicator species of oligosaprobic water, *E. crinita* is unable to tolerate eutrophic pollution associated with contaminated river's drain.



A B

Figure 3. Correlation between growth parameters of E. crinita (proportion in overall macrophyte abundance, average thallus length, and average biomass) and physical-chemical values: (A) BODult and (B) suspended solids concentrations

Table 5. Pearson's correlation between the biological parameters and general physical-chemical characteristics of water quality

Correlating parameters	Suspended solids concentration, mg/l (R^2)	BODult, mgO_2/l (R^2)
Total macrophytes abundance, thallus /1 m^2	0.78	0.53
Total macrophytes biomass, raw weight, g/m^2	0.74	0.56
Proportion of dominating species in overall macrophytes abundance, %	0.93	0.79
Proportion of dominating species in overall macrophytes biomass, %	0.91	0.93
Average thallus length, cm	0.75	0.76
Average biomass of *E. crinita* thallus, cm	0.61	0.57

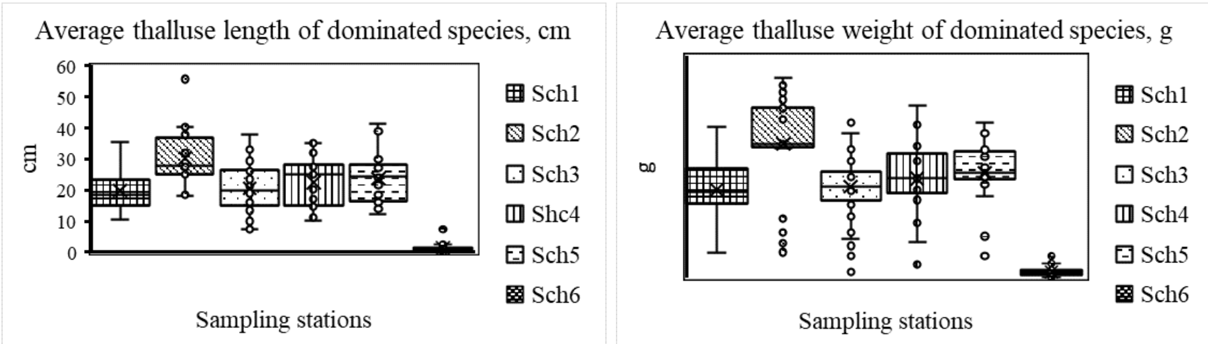


Figure 4. Variation in average length and weight of *E. crinita* thallus

On the other hand, the decreased transparency of coastal marine waters, due to increased suspended solid matter, inhibits photosynthesis and results in the suppression of algae. It was determined that the strongest correlations were observed between the physical and chemical characteristics of coastal seawater and the abundance and biomass of dominant species within the overall macrophyte community. Significant correlations were identified between the physical-chemical parameters and the average length of the *E. crinita* thallus.

Furthermore, a significant correlation was identified between the concentrations of suspended matter and the overall abundance and biomass of macrophytes collected from the research site. We consider these characteristics of macroalgal phytocenoses to be the most reliable indicators of coastal marine ecosystem health (Table 5).

It should be noted that the assessment of the condition of macroalgal biocenoses is relevant as a biomarker for long-term, persistent, or recurrent impacts. Therefore, bioindication based on the analysis of phytocenoses can be used as the basis for continuous monitoring of the condition of the marine environment.

Furthermore, it is essential to emphasize the significance of considering BODult values when assessing the quality of natural water bodies and the anthropogenic impacts on them, as underestimating these values can distort the picture of the ecological status of a water body. According to the Maximum Permissible Concentrations of Pollutants in Waters of Fishery Significance (MPC) [40], the BOD_5 level should not exceed 2.1 mg/l and the BODult value should not exceed 3 mg/l. The seawater sampled during this study did not exceed the Maximum Permissible Concentration (MPC) for the BOD parameter at any of the studied stations. However, bioindication parameters based on vital characteristics and the functioning of autotrophic organisms demonstrate sufficient sensitivity to changes in their environment.

5. Conclusions

Studies of the responses of photosynthetic organisms that form the basis of coastal ecosystems and their trophic chains to the complex influence of various environmental factors have led to the following conclusions.

An application of data on ultimate biochemical oxygen demand (BODult) to assess the quality of natural water is justified, as oxidation processes occur at varying rates depending on the type of pollutant present and the characteristics of organisms involved in biological transformations. BOD_5 values do not always accurately reflect the true dynamics of biochemical processes in natural aquatic environments, considering the complexity and variety of influencing factors.

Macrophytes serve as an indicator of the chronic, long-term effects of pollution, primarily due to eutrophication; therefore, it is essential to monitor changes in the quantitative and qualitative composition of macrophyte phytocenoses over multiple years in order to assess these effects.

The research identified two distinct types of macrophyte associations: estuarine communities dominated by green algae, which indicate a polluted and desalinated water environment, and marine communities dominated by brown algae that are sensitive to pollution.

An analysis of the *E. crinita* phytocenosis revealed that partial containment of the dominant algae species was noted at the location adjacent to the exit of the Sochi Maritime Port. The impact of polluted river discharges is reflected in a consistent reduction in the biomass and population density of *E. crinita*. Such dynamics of seawater pollution at the study stations was confirmed by data from general physical and chemical analysis.

Changes in the coastal marine environment have facilitated the succession of native aquatic phytocenoses to algal communities, with an increased proportion of cosmopolitan species that are tolerant to physical and chemical pollution factors.

The findings from these studies provide a basis for further in-depth research on hydrobiocenoses during different vegetation periods and in various locations. The results of the expanded research on macroalgae respond to the environmental changes caused by both natural and anthropogenic impacts at other Black Sea coastal regions with similar characteristics, such as influence of river discharge and continuing affects from the maritime port activity.

The bioindication method represents a significant advancement in the assessment and management of marine water quality in coastal areas, providing integrated information for regions significantly affected by anthropogenic activity within their catchment basins.

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REFERENCES

[1] Barabanshchikov D.A., Serdyukova A.F., “The specificities of the Black Sea ecology,” Young Scientist, vol. 25, no. 159, pp. 98–101, 2017. Available from: https://moluch.ru/archive/159/44713/

[2] Landi P., Minoarivelo H.O., Brännström Å., Hui C., Dieckmann U., “Complexity and stability of ecological networks: a review of the theory,” Popular Ecology, no. 60, pp. 319–345, 2018. DOI: 10.1007/s10144-018-0628-3W.

[3] Campagne C.S., Roy L.A., Langridge J., et al., “Existing evidence on the impact of changes in marine ecosystem structure and functioning on ecosystem service delivery: a systematic map,” Environmental Evidence, vol. 12, no. 13, 2023. DOI: 10.1186/s13750-023-00306-1A.

[4] Orekhova N.A., Varenik A.V., “Current Hydrochemical Regime of the Sevastopol Bay,” Physical Oceanography, vol. 25, pp. 124–35, 2018. DOI: 10.22449/1573-160X-2018-2-124-1353

[5] Bakiu R., Roncarati A., Kamberi E., “Inorganic and organic pollutants in marine and coastal environments,” Frontiers in Marine Science, vol. 10, p. 1245833, 2023. DOI: 10.3389/fmars.2023.124583.

[6] Wijeyaratne D.N., Bellanthudawa B.K.A., “Assessment of suitability of macrobenthic mollusc diversity to monitor water quality and shallow sediment quality in a tropical rehabilitated and non – rehabilitated wetland system,” International Journal of Aquatic Biology, vol. 5, no. 2, pp. 95–107, 2017. DOI: 10.22034/ijab.v5i2.288.

[7] Stelmakh L.V., Gorbunova T.L., “Carbon-to-chlorophyl-a ratio in the phytoplankton of the Black Sea surface layer: variability and regulatory factors,” Ecologica Montenegriana, vol. 17, pp. 60–73, 2018. DOI: 10.37828/em.2018.17.8.

[8] Schaumburg J., Schranz C., Hofmann G., Stelzer D., Schneider S., Schmedtje U., “Macrophytes and phytobenthos as indicators of ecological status in German lakes – a contribution to the implementation of the Water Framework Directive,” Limnologica, vol. 34, pp. 302–314, 2004. DOI: 10.1016/S0075-9511(04)80003-3.

[9] Birk S., Bonne W., Borja A., Brucet S., Courrat A., Poikane S., “Three hundred ways to assess Europe’s surface waters: an almost complete overview of biological methods to implement the Water Framework Directive,” Ecological Indicators, vol. 18, pp. 31–41, 2012. DOI: 10.1016/j.ecolind.2011.10.009.

[10] Lyche S.A., Feld, C., Birk S., Phillips G., Carvalho L., Morabito G., “Comparison of common metrics for phytoplankton, macrophytes, macro-invertebrates and fish for ecological status assessment of European lakes: a synthesis from the WISER project Module 3,” Hydrobiologia, vol. 704, pp. 57–74, 2013. DOI: 10.1007/s10750-012-1436-y.

[11] Stepanyan O.V., “Macrophytobenthos of the Black and Azov Seas: floristic and ecological aspects (review),” Science of Russian South, vol. 16, no. 4, pp. 26–38, 2020. DOI: 10.7868/S25000640200404.

[12] Kunii H., “Aquatic macrophyte composition in relation to environmental factors of irrigation ponds around Lake Shinji, Shimane, Japan,” Vegetatio, vol. 97, pp. 137–148, 1991.

[13] Wijeyaratne D., Bellanthudawa A., “Macrophytes as indicators of the ecological status of a tropical rehabilitated wetland ecosystem: Application of multivariate statistics and Ecological State Macrophyte Index (ESMI),” International Journal of Aquatic Biology, vol. 8, no. 6, pp. 434–446, 2020. DOI: 10.22034/ijab.v0i0.675.

[14] Henry-Silva G.G., Camargo A.F.M., Pezzato M.M., “Growth of free-floating aquatic macrophytes in different concentrations of nutrients,” Hydrobiologia, vol. 610, pp. 153–160 2008. DOI: 10.1007/s10750-008-9430-0.

[15] Lee P.F., McNaughton K.A., “Macrophyte induced microchemical changes in the water column of a northern Boreal Lake,” Hydrobiologia, vol. 522, pp. 207–220, 2004. DOI: 10.1023/B:HYDR.0000029987.64557.36.

[16] Fu H., Zhong J., Yuan G., Ni L., Xie P., Cao T., “Functional traits composition predicts macrophytes community productivity along a water depth gradient in a freshwater lake,” Ecology and Evolution, vol. 4, pp. 1516–1523, 2014. DOI: 10.1002/adma.201104714.

[17] Stelmakh L., Kovrigina N., Gorbunova T., “Response of marine microalgae Phaeoductilum tricornutum, Prorocentrum cordatum and Gyrodinium fissum to complex pollution of Sevastopol Bay (Black Sea),” Ecologica Montenegrina, vol. 48, pp. 109–116, 2021. DOI: 10.3389/fmars.2019.00488.

[18] Mandal S., Mukherjee S., “Floristic Analysis of Macrophytes in Bheur Canal of North Dinajpur District, West Bengal,” International Journal of All Research Education and Scientific Methods, vol. 11, pp. 2455–6211, 2023.

[19] Teyubova V. F., Milchakova N. A., Floristic diversity of macrophytes of the Russian Black Sea shelf (from Panagia to Vidny), Condition of ecosystems of the shelf zone of the Black and Azov Seas under anthropogenic impact: a collection of articles dedicated to the 90th anniversary of the Novorossiysk Marine Biological Station named after Professor V.M. Arnoldi. Krasnodar: Kuban State University, 2011, pp. 152–165.

[20] Glibert P.M., “Phytoplankton in the aqueous ecological theater: Changing conditions, biodiversity, and evolving ecological concepts,” Journal of Marine Research, vol. 77,

no. 2, pp. 83–137, 2019. DOI: 10.1357/002224019828474304.

[21] Gotovtsev A.V., Danilov-Danilyan V.I., Nikanorov A.M., “Perspectives of BOD measurement and application,” Water Chemistry and Ecology, vol. 5, no. 47, pp. 24–27, 2012b.

[22] Zinova A.D. Identifier of green, brown and red algae of the southern seas of the USSR, USSR: Nauka,1967, 386 p.

[23] McNeill J., Turland N.J., “Major changes to the Code of Nomenclature,” Melbourne: Taxon, vol. 60, no. 4, pp. 1495–1497, 2011. DOI: 10.1002/tax.60503.

[24] Milchakova N. A., Marine plants of the Black Sea. An illustrated field Guide, Sevastopol: Digit Print Press, 2011a, p. 144, ISBN 978-966-02-5801-3

[25] Milchakova N.A., Mironova N.V., Ryabogina V.G. Marine plant resources, Fisheries bioresources of the Black and Azov Seas, Sevastopol: ECOSI-Hydrophysics, 2011b, pp. 117–139.

[26] Guiry M.D., Guiry G.M., “AlgaeBase. World-wide electronic publication,” National University of Ireland, Galway, 2025, Online available at http://www.algaebase.org

[27] Kalugina-Gutnik A.A. Phytobenthos of the Black Sea, Kiev: Naukova Dumka, 1975, p. 248.

[28] Pavshenko D.A., “Application of geobotanical methods for studying the bottom vegetation of the Black Sea,” Ecosystems, vol. 36, pp. 18–29, 2023. DOI: 10.5281/zenodo.10370568.

[29] Aysel V., Dural B., Şenkardeşler A., Erduğan H., Aysel F., “Marine algae and seagrasses of Samsun (Black Sea, Turkey),” Journal of Black Sea/Mediterranean Environment, vol. 14, no. 1, pp. 53–67, 2008.

[30] Afanasyev D.F., Abdullin S.R., “Experience of analysing of benthic vegetation organization of the Russian Black Sea shelf using indirect ordination,” Ecology, vol. 1, pp. 74–76, 2014. DOI: 10.7868/S0367059714010028.

[31] Stepanyan O.V., “How is phytobenthos of the southern seas of Russia changing?,” Nature, vol. 2, pp. 32–42, 2016.

[32] Teyubova V.F., Efimova O.V., “Macrophytobenthos of the coastal zone of the Novorossiyskaya Bay (Black Sea) under anthropogenic impact,” Marine Ecology, vol. 64, pp. 67–71, 2003.

[33] Habitats Directive, 42/93/EEC, 1992, Natura, 2000.

[34] Gotovtsev A.V., Danilov-Danilyan V.I., Nikanorov A.M., “Problems of BOD monitoring,” Water Resources, vol. 5, pp. 510–520, 2012a.

[35] Afanasyev D.F., Abdullin S.R., “About a new vegetation association of the pseudolittoral zone of the Black Sea,” Vegetation of Russia, vol. 23, pp. 3–8, 2013.

[36] Minicheva G.G., Bolshakov V.N., Kalashnik E.S., Zotov A.B. Marinets A.V., “Assessment of the reactions of algal communities to influence of climatic factors in the North Western Black Sea ecosystem,” International Journal on Algae, vol. 20, no. 2, pp. 121–134, 2018. DOI: 10.1615/InterJAlgae.v20.i2.20.

[37] Mancuso F.P., Strain E.M.A., Piccioni E., De Clerck O., Sarà G., “Status of vulnerable Cystoseira populations along the Italian infralittoral fringe, and relationships with environmental and anthropogenic variables,” Marine Pollution Bulletin, vol. 129, no. 2, pp. 762–771, 2018. DOI: 10.1016/j.marpolbul.2017.10.068.

[38] Catra M., Along G., Leonardi R., Negri M., Sanfilippo R., Sciuto F., Serio D., Viola A., Rosso A., “Degradation of a photophilic algal community and its associated fauna from eastern Sicily (Mediterranean Sea),” Mediterranean Marine Science, vol. 20, no. 1, pp. 74–89, 2019.

[39] Baeva Y.I., Chernykh N.A., “Assessment of the ecological state of the Black Sea coastal waters using the bioindication methods,” Water and Ecology: Problems and Solutions, vol. 3, no. 83, pp. 22–33, 2020. DOI: 10.23968/2305-3488.2020.25.3.22-31.

[40] Water Quality Standards for Fishery Water Bodies, Including Standards for Maximum Permissible Concentrations of Harmful Substancesin the Waters of Fishery Water Bodies. Federal Agency for Fisheries of the Russian Federation: Moscow, Russia, 2010, p. 406.