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Distribution Patterns of Benthic Microalgae Across Differently Exposed Rocky Shore Habitats

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Abstract: In other words, the importance of the benthic microalgae as components of rock shore ecosystems functioning, nutrient cycles, photosynthesis, and food webs can hardly be overestimated. On the other hand, there are great differences in the distribution patterns of these species in the rocky shore environments subjected to different degrees of wave exposure, tides, desiccation, and other factors. The importance of the investigation of these processes for the understanding of coastal ecosystem health and ecological changes caused by environmental factors cannot be underestimated. The necessity of the research appears because of the lack of knowledge about the effect of contrasting exposure conditions on the abundance, diversity, and structure of benthic microalgal communities. The originality of this study is connected with the comprehensive investigation of habitat exposure, physicochemical properties, and microalgal community distribution in the ecological comparison. The suggested research method implies the selection of the rocky shore habitats characterized by high, moderate, and low exposure. Statistical techniques, such as diversity indices, correlation studies, and multivariate analyses, will be employed to explore possible connections between environmental factors and the distribution of microalgae. The study is anticipated to show variations between exposure groups in terms of microalgal density, richness, and communities. This discussion will consider the impact of waves, moisture, substratum stability, and nutrient availability from an ecological perspective. This research is going to serve as a baseline for further ecological exploration of microalgae on rocky shores.

Keywords: Benthic Microalgae; Rocky Shore Ecosystems; Wave Exposure; Microalgal Diversity; Habitat Distribution; Chlorophyll-a; Intertidal Ecology; Environmental Gradients.

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I. Introduction

The rocky shore environments are the examples of coastal ecosystems featuring the dynamics of tides, waves, fluctuations of water content, as well as varying substrate properties (Belleza et al., 2023). They comprise numerous biological communities, including the benthic microalgae, which play an important role in primary production and biogeochemical cycles. Such photosynthetic microorganisms as benthic microalgae, diatoms, and cyanobacteria colonize rock surfaces and create biofilms, supplying food for the grazing organisms (Pires-Teixeira et al., 2024; Somma et al., 2023). The presence of microorganisms depends on the environmental gradients related to the exposure to waves, tidal elevation, light availability, surface temperature, and nutrients content. The highly exposed rocky shores feature greater hydrodynamic forces, whereas the sheltered environments represent rather stable environmental conditions. The differences in the conditions might influence the attachment, survival, growth, and composition of the communities. The research of the habitat-related features is crucial for investigating the ecology of intertidal ecosystems (Leite et al., 2021; Sbrocca et al., 2021; Veiga et al., 2022). The microalgal communities are good indicators of the environmental changes due to their dependence on the conditions. Furthermore, the distribution of the benthic microalgal communities depends on the frequency and duration of tidal immersion and exposure. Low tides cause the exposure of rock surfaces, causing higher levels of dehydration, temperature changes, and solar exposure. On the other hand, immersed surfaces offer more stable moisture conditions and chances for nutrient exchanges. Roughness of the surfaces, type of rock and availability of microhabitats all play a role in the capacity of the microalgae to attach and thrive in stable communities. Some species of microalgae produce extracellular polymeric substances that make them better adherent to the surfaces and resistant to physical disruptions. Finally, the differences in nutrient availability such as nitrogen and phosphorous affect the biomass of microalgae, their productivity and

composition of species (Spector et al., 2020). Seasonal changes in rainfall, temperature and wave action may add another factor into this equation. The study of these interactions of environmental variables contributes to the understanding of the distribution and functioning of the benthic microalgae in rocky shores. Such studies are useful as the base of the assessment of the coastal ecosystems, environmental disturbances and response of biological communities in the intertidal zone to climate change.

Problem Statement

However, there is not enough information concerning the differences in distribution of benthic microalgae on rocky shores differing by their exposure features. Various physical and chemical exposure factors, such as the intensity of waves action, desiccation, stability of substrates, and nutrient supply can affect microalgal abundance and diversity; however, there is no information about their relative role. Hence, due to the lack of comparative data, there is a limited ability to assess the effects of exposure conditions on the ecological responses of benthic microalgae and the application of this organism group for the coastal monitoring. Therefore, the current research is aimed at examining the relationship between exposure conditions and benthic microalgae distribution on rocky shores.

Research Significance

It is expected that this research will give an integrated view on the ecology of benthic microalgae in terms of their exposure to various physical factors. Comparison of exposed, moderately exposed, and sheltered sites can increase the knowledge about biodiversity, adaptations, and functioning of the ecosystems of rocky shores.

Organization of the Paper

The article describes the ecological significance of benthic microalgae and reviews the available information about rocky shore habitat distribution. Then, the research gap is identified and the methodology is presented in terms of how sampling and data analysis would be carried out. The results of the habitat survey are analyzed using ecological comparisons and graphs. Finally, the paper concludes on the research issues and future recommendations related to habitat and microalgae distribution.

II. Literature Review

Benthic microalgae are important parts of intertidal rocky shore ecosystems because of their role in primary production, biofilm formation, nutrient cycling, and energy flow. The communities of these microalgae usually consist of diatoms, cyanobacteria, and other photosynthesizing microorganisms that settle on rock surfaces and substrate crevices. The presence of these microalgae in the environment depends on the physical and environmental factors.

Wave action can be considered as one of the key factors controlling the organization of benthic communities. High wave action causes the hydrodynamic stress in the habitat, which may remove the weakly adherent microalgae and affect the biofilm formation. Nevertheless, there are the species with special physiological and morphological adaptations to withstand this factor. Sheltered habitats are characterized by low mechanical stress and suitable conditions for biofilm formation. Tidal height also affects the distribution of microalgae by regulating the period of their exposure to air and seawater. Organisms living at high levels of the intertidal zone have more chances to dry out and suffer from changes in temperature. These differences in the environment may affect photosynthesis and the composition and productivity of the community. Substrate properties play another role in determining the patterns of colonization. Substrate roughness, inclination, porosity, and accumulation of sediments may influence attachment and water retention. Availability of nutrients, lighting, salinity, and temperature can contribute to the differences in abundance of microalgae (Fegley et al., 2020; Pavlova et al., 2023).

Past studies of ecology have shown the significance of environmental gradients in creating intertidal biological communities. However, the joint effect of hydrodynamic regime, substrate properties, and

physicochemical environment still needs to be studied in comparative ways, especially taking into account the seasonality and biodiversity of microalgae. In addition, changes in the density of microalgae could have an effect on food resources available to grazers, which includes snails and other intertidal invertebrates (Scrosati & Ellrich, 2024). Additionally, differences in the thickness of biofilms and the species making up the community could have an effect on the stabilization of sediments and nutrient exchange at the rock-water boundary. Regular monitoring of these communities will provide information about how environmental changes can affect their stability. Comparison studies on exposed and sheltered rocky shores are crucial to determine which environmental factors are dominant and how different species respond.

Unresolved Research Gap

There is existing knowledge on some individual factors that affect benthic microalgal communities; however, there are notable deficiencies in the knowledge of how these factors work together in different rocky shore habitats. Integration of wave exposure, tidal height, substrate, and physiochemical variables is commonly necessary in comparative studies. Seasonal changes in the abundance and community structure of microalgae must be systematically studied. In addition, the link between the environmental gradient and the species diversity is not always considered within a single conceptual framework. This research tries to fill these gaps by conducting comparative habitat sampling, microscopic enumeration, biomass calculation, and multivariate statistics.

III. Methodology and Research Framework

Proposed System Architecture

The proposed research design is guided by an integrated ecological assessment framework, which links together habitat selection, field sampling, environmental characterization, laboratory identification, and statistical analysis. Three habitat types will be chosen, namely highly exposed, moderately exposed, and sheltered rocky shores. Replicate samples will be collected at similar tidal heights and in similar seasons. The environmental data and microalgae data will be combined in one database. Then diversity indices, biomass estimates, and multivariate statistics will reveal the relationship between habitat exposure and microalgae community distribution.

Research Workflow Diagram

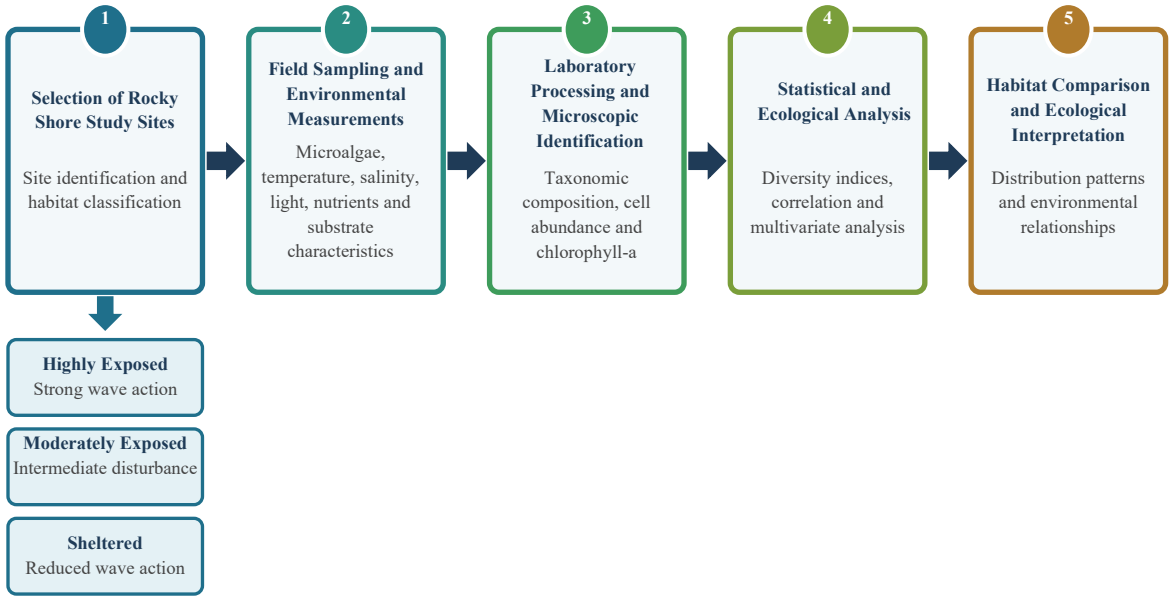


Figure 1: Methodological Workflow for Rocky Shore Microalgal Distribution Assessment

The total methodology used in the determination of the distribution of benthic microalgae in rocky shores is depicted in figure 1 starting from the classification of sites on the basis of wave exposure to analysis.

Study Area Classification and Sampling Design

The study will concentrate on rocky shore habitats that can be distinguished based on the level of wave movement that they experience. It is important to classify the habitats since physical disturbance might affect the attachment, growth, and survival of microalgae growing at the bottom. There are three habitat categories that will be taken into account for creating an ecological comparative model. Highly exposed habitats are associated with powerful wave action, high water circulation, and significant mechanical disturbance. The last aspect might affect the stability of the biofilm and favor the species that are good at attaching to the surface. Powerful wave movements can promote nutrient exchange and decrease the amount of sediment deposited on rocks. Moderately exposed habitats have intermediate hydrodynamic conditions. The environmental conditions of such an area may allow the development of favorable conditions for different groups of functionally oriented benthic microorganisms. In sheltered areas, the influence of waves is usually weak, while the water conditions are relatively stable. In these areas, it may be more biofilms accumulated, due to the low intensity of mechanical action, which makes it possible for the microalgae to stay attached to the rocks for longer periods. On the other hand, there may be some local changes in sedimentation, nutrients availability, and water movement in sheltered areas. The sampling will take place through standard quadrats located at equal tidal levels within the habitat type. Rock-surface samples will be taken during different seasons of the year. Thus, this method will decrease sampling bias and increase comparability of exposure types. At the same time, various environmental factors, such as seawater temperature, salinity, pH, dissolved oxygen, nutrients, light intensity, and substratum features, will be recorded.

Microalgal Identification and Ecological Assessment

Samples of benthic microalgaes shall be collected from standardized areas on rocks by scraping with sterile equipment. Preserving or processing of collected material shall be done depending on the needs of the procedure of identification and analyses. Laboratory work shall include microscopic studies for identification of the main taxonomic groups such as diatoms, cyanobacteria, and other benthic microalgae. Number of cells shall be counted using adequate counting chambers or microscopic techniques. Concentration of chlorophyll-a shall be analyzed as the indicator of biomass of photosynthetic organisms. Where needed, standardized extraction and spectrophotometric analysis shall be performed. Diversity of species shall be assessed using ecological indices. Shannon index shall give an estimation of community diversity whereas Simpson index shall evaluate dominance patterns.

The following mathematical expressions will support ecological analysis in equation 1.

Shannon Diversity Index

$$H' = -\sum_{i=1}^{S} p_i \ln(p_i) \qquad (1)$$

Here, $p_i$represents the proportion of individuals belonging to species i, and Srepresents the total number of identified species in equation 2.

Species Evenness

$$J' = \frac{H'}{\ln(S)} \qquad (2)$$

Microalgal Density

$$D = \frac{N}{A} \qquad (3)$$

With N denoting the cell number and A denoting the sampled surface area in equation 3.

The comparative statistics will involve analysis of variance or relevant non-parametric tests as dictated by the distribution of the data and assumptions of the experiment. The correlation analysis will consider relationships between the environmental variables and the microalgal abundance. Principal component analysis and/or non-metric multidimensional scaling could be used in order to determine patterns in the community composition. The seasonal and habitat differences will be analyzed through appropriate statistical analyses taking into consideration the replication in sampling and variation at the site level.

Comparative Habitat Assessment

Table 1 contrasts the significant features of the ecology of three exposure groups in rocky shore environments and possible impacts of these environments on the benthic microalgae populations. This is used to build a conceptual basis for analyzing biological responses under particular habitats. Microalgal density and variety are specified to be factors that need to be measured empirically and not to be predetermined results.

Table 1: Ecological Characteristics and Expected Benthic Microalgal Distribution Across Rocky Shore Habitats

Ecological parameter	Highly exposed	Moderately exposed	Sheltered
Wave intensity	High	Intermediate	Low
Mechanical disturbance	Strong	Moderate	Weak
Water circulation	High	Moderate	Relatively low
Biofilm stability	Potentially low	Intermediate	Potentially high
Desiccation influence	Variable	Variable	Variable
Substrate disturbance	High	Moderate	Low
Microalgal abundance	Site-dependent	Site-dependent	Site-dependent
Community diversity	To be evaluated	To be evaluated	To be evaluated

Graphical Representation of Expected Distribution

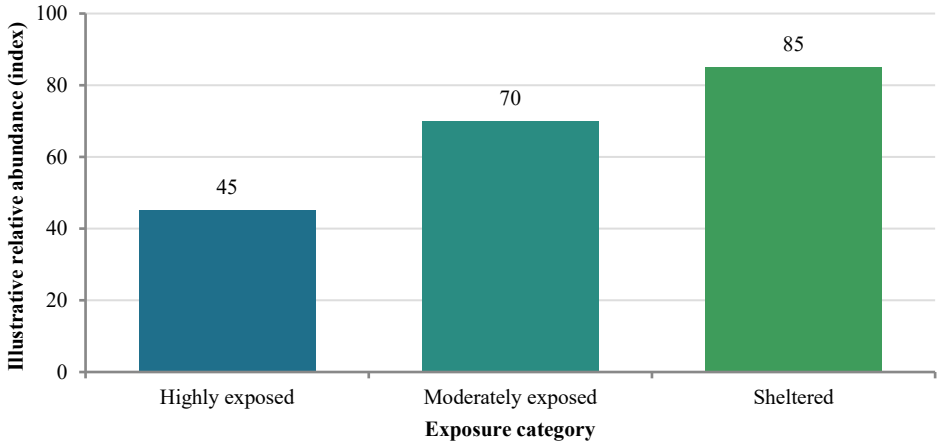


Figure 2: Conceptual Comparison of Relative Benthic Microalgal Abundance Across Exposure Categories

Figure 2 is a hypothetical example of the bar chart showing the relative abundance of benthic microalgae between highly, moderately, and sheltered rocky coast environments. Hypothetical index values of 45, 70, and 85 are just one example of how reduced hydrodynamic influence increases the ability of biofilm accumulation. It is important to mention that it is not a general rule, as other factors, like nutrients, adaptation, etc., can affect the amount.

IV. Ecological Interpretation of Habitat-Dependent Distribution

Influence of Wave Exposure on Microalgal Communities

The exposure to waves is one of the critical environmental factors that affect the settlement and distribution of benthic microalgae in the intertidal zone. The force of wave action is directly related to the intensity of mechanical disturbance that the sessile organisms experience. In highly exposed environments, mechanical forces can dislodge loosely attached cells and damage forming biofilms. As a result, such environments will be suitable for microalgal species that have efficient anchoring systems and physical resistance properties. In moderately exposed environments, the microalgae can settle at intermediate levels of physical stress. Lack of mechanical disturbance and water movement will facilitate the growth of complex microbial communities. Nutrient transfer caused by the movement of water will affect the physiological processes within the microbial populations. Nevertheless, the relation between the level of exposure and diversity is not always linear.

Sheltered rocky shores are usually exposed to less mechanical disturbance and thus allow the growth of microbial films in fairly stable conditions. Increased substrate stability could enhance the build-up of benthic microalgae; however, increased sedimentation, grazing effects, and reduced water movement could alter these trends. Tidal height further affects the impact of wave action. The higher the tide height, the more is the aerial exposure and desiccation experienced by the microalgae. On the other hand, lower tidal heights allow the microalgae to be submerged for a longer duration. Wave exposure can also affect the stability and recovery processes of benthic microalgal communities throughout the year. The constant action of waves results in the formation of empty spaces on rocks, thus enabling newly arrived microorganisms to settle there. The potential of microalga recovery from physical disturbances is linked to their reproductive abilities, attachment power, and resistance to environmental changes. In addition, water movement contributes to nutrient and organic matter transport, providing necessary conditions for microbial functioning and development. The difference in wave energy levels can lead to different dynamics of biomass formation and species predominance.

Environmental Relationships and Community Structure

The distribution of microalgae will depend on the relationship between biological traits and environmental factors. Temperature affects metabolic activity, photosynthesis efficiency, and seasonal growth. Variations in salinity might have an impact on water balance in cells and performance of different species. Availability of nutrients such as nitrogen and phosphorus is responsible for microalgal growth and biomass formation. Rough substrate and rock surface are factors affecting the process of microbial colonization. Irregular substrates provide protection from physical stress and maintain moisture levels. Availability of light will determine the ability of microorganisms to perform photosynthesis. Grazing organisms will control biofilm formation through eating. Assessment of species richness, abundance, concentrations of chlorophyll-a, and diversity indices will enable distinguishing ecological responses to the environment. Multivariate statistical methods will be helpful in identifying relationships between environmental variables and composition of microalgal communities. Integrated assessment is necessary as a single factor cannot explain all the distribution patterns. The interactions between these environmental factors also affect the functioning of ecosystems on rocky shores. Since various microalgal species react differently to any change in the environment, differences in the composition and dominance will be observed. By conducting seasonal sampling, one may acquire knowledge about temporal variations in terms of abundance of species, biomass production, and diversity. Observing the environment along with

biological studies can contribute to better understanding of ecological trends. Furthermore, statistical analysis of various habitats and microalgal species can reveal important links between the habitat and its microalgal content.

V. Discussion

The suggested study offers a comparative approach for assessing the effect of wave exposure on the benthic microalgae communities in rocky shores. Hydrodynamic disturbance can play an important role in controlling the attachment of bacteria, stability of biofilms and their formation. High-exposure areas may facilitate the proliferation of stress-resistant and well-adherent microalgal taxa, while sheltered areas may be characterized by a high density of biofilms in proper environmental conditions. Moderate exposure may represent an intermediate ecological niche which affects the community structure. The factors such as water temperature, salinity, nutrient supply, light and substrate type are expected to cause variation in the number and composition of microalgae. The use of microscopic determination, chlorophyll-a content analysis, and ecological indices of diversity is expected to result in a full understanding of these relationships. It should be noted, however, that these assumptions need to be confirmed via field studies and statistical analyses.

Future Research Directions

Further studies should take into account the inclusion of seasonal measurements in order to reveal temporal changes in benthic microalgae under different exposures. Molecular techniques and environmental DNA analyses might enhance the taxonomic precision of microorganism identification, especially in case of closely related microorganisms. Remote sensing and digital image analysis techniques might help to obtain more data on the spatial distribution and cover of the biofilm. It is necessary to study the effect of warming, pollution, acidification, and altered wave climate on benthic microalgae communities. Comparative studies on different rocky shore environments would increase knowledge on ecological variations and the applicability of benthic microalgae as environmental indicators.

Research Challenges

Studying the distribution of benthic microalgae is not without its problems and difficulties. Variability in the environment seasonally can have an effect on community composition and confound any analysis of comparisons in sampling intervals. Identification under the microscope might prove difficult if there is similarity in the morphology of the algae or if algae exist in a mixed biofilm. Variations in the surface roughness of the rock and variations in the sampling process itself can also add to the variance in the measurements. In addition, strong waves can prevent sampling because of difficulty in gaining access to the area.

VI. Conclusion

This study aims to explore the distribution pattern of benthic microalgae within rocky shore communities under varying degrees of environmental exposure. The importance of the knowledge about such distribution pattern is associated with the need to reveal the ecology of microalgal communities under certain hydrodynamic regimes and habitat conditions. The novelty of the proposed study is the use of an integrated approach that combines classification of wave exposure, physicochemical properties of the environment, microalgal species identification, and evaluation of their ecological diversity. In contrast to studies exploring single factors of environmental conditions, the proposed study takes into account multiple interacting factors. The methodological process will include the choice of highly, moderately, and minimally exposed rocky shore environments; followed by the conducting of a field sampling and laboratory analysis procedure. Microalgal community identification, chlorophyll-a quantification, cell densities calculations, and the application of diversity indices will be used as a part of a characterization process. The statistical methods will be applied in order to create the relations between environmental parameters and the biological distribution of microalgae. Expected outcomes will include a better understanding of habitat-related differences in microalgal population numbers, diversity, composition and

biomass. Moreover, it will be possible to determine the possible influence of wave action, substrate stability, moisture availability and nutrients on community development. All of this will result in an improved understanding of the functioning of rocky shores as well as environmental variability. Therefore, the research project creates a basis for further studies concerning benthic microalgae. Possible validation of the results through field measurements will make it useful in biodiversity assessment of coastal areas.

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