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VITOR RICARDO DE SOUZA

EFEITOS DA URBANIZAÇÃO SOBRE ASSEMBLEIAS DE MACROALGAS MARINHAS BENTÔNICAS EM RECIFES DO LITORAL DE PERNAMBUCO

Recife
2023

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Dissertação apresentada ao Programa de Pós-graduação em Oceanografia da Universidade Federal de Pernambuco, como requisito parcial para a obtenção do título de Mestre em Oceanografia.

Área de concentração: Oceanografia Biológica.

Orientador: Prof. Dr. José Souto Rosa Filho.

Coorientador: Prof. Dr. Edson Régis Tavares Pessoa Pinho de Vasconcelos.

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RESUMO

A densa ocupação humana em regiões costeiras tem provocado uma série de modificações na paisagem natural e biodiversidade marinha. Dessa forma, a realização de estudos de monitoramento é uma alternativa viável para compreender a intensidade dos distúrbios ambientais. A presente dissertação tem como objetivo descrever os impactos da urbanização sobre comunidades de macroalgas de recifes tropicais, considerando as variações sazonais e anuais, e os efeitos da descarga de esgotos domésticos. Amostragens não destrutivas foram realizadas durante as estações seca e chuvosa de 2014, 2021 e 2022 em recifes com diferentes níveis de urbanização. A abundância das macroalgas diferiu entre os níveis de urbanização, entre as estações seca e chuvosa, e entre os anos 2014, 2021 e 2022. Declínios significativos da riqueza, equabilidade e diversidade de espécies foram verificados entre 2014 e 2022, e entre 2021 e 2022. Regiões de urbanização consolidada exibiram elevada dominância das algas oportunistas *Gelidium*, *Ulva lactuca* e *Chondracanthus acicularis*, enquanto as áreas em processo de urbanização e não urbanizadas foram compostas principalmente por espécies indicadoras de ambientes estáveis, como *Gelidiella acerosa* e *Palisada perforata*. Ainda, foram realizadas amostragens biológicas e da água do mar em áreas inseridas em um gradiente de poluição por esgotos. A descarga de efluentes causou mudanças na estrutura das comunidades, provocando reduções da riqueza, equabilidade e diversidade de espécies. *Gelidium* spp. e *Ulva lactuca* foram as algas mais representativas em áreas próximas ao emissário de esgotos, enquanto *Corallina officinalis* na área de referência. Diferenças significativas foram verificadas para amônia e fosfato, os quais exibiram maiores concentrações na área sob a descarga direta de esgotos, e menores na área de referência. As comunidades de algas mostraram forte correlação com os nutrientes dissolvidos, especialmente com teores de fosfato. Em conclusão, as macroalgas foram capazes de fornecer respostas qualitativas e quantitativas aos impactos causados pela urbanização e pelo despejo de esgotos, reforçando, a importância da realização de estudos de monitoramento para identificar os efeitos da degradação de ecossistemas de regiões tropicais.

Palavras-chave: bioindicadores; espécies oportunistas; monitoramento ecológico; urbanização costeira.

ABSTRACT

Dense human occupation in coastal regions has caused a series of changes in the natural landscape and marine biodiversity. Thus, carrying out monitoring studies is a viable alternative to understand the intensity of environmental disturbances. This dissertation aims to describe the impacts of urbanization on macroalgal communities of tropical reefs, considering seasonal and annual variations, and the effects of domestic sewage discharge. Non-destructive samplings were carried out during dry and rainy seasons of 2014, 2021 and 2022 in reefs with different levels of urbanization. Macroalgae abundance differed between urbanization levels, between dry and rainy seasons, and between 2014, 2021 and 2022. Significant declines in species richness, evenness and diversity were verified between 2014 and 2022, and between 2021 and 2022. Consolidated urbanization regions exhibited a high dominance of the opportunistic algae *Gelidium*, *Ulva lactuca* and *Chondracanthus acicularis*, while areas in the process of urbanization and non-urbanized were mainly composed of species that indicate stable environments, such as *Gelidiella acerosa* and *Palisada perforata*. Also, biological and seawater samplings were carried out in areas inserted in a sewage pollution gradient. The discharge of effluents caused changes in the structure of communities, causing reductions in richness, evenness, and diversity of species. *Gelidium* spp. and *Ulva lactuca* were the most representative algae in areas close to the sewage outfall, while *Corallina officinalis* in the reference area. Significant differences were verified for ammonia and phosphate, which exhibited higher concentrations in the area under direct sewage discharge, and lower in the reference area. Algal communities showed strong correlation with dissolved nutrients, especially with phosphate contents. In conclusion, macroalgae were able to provide qualitative and quantitative responses to the impacts caused by urbanization and sewage disposal, reinforcing the importance of carrying out monitoring studies to identify the effects of degradation of ecosystems in tropical regions.

Keywords: bioindicators; opportunistic species; ecological monitoring; coastal urbanization.

SUMÁRIO

1 INTRODUÇÃO

O rápido crescimento de centros urbanos tem provocado mudanças na biodiversidade marinha e terrestre (Burt, 2014; Burt et al., 2019). As zonas costeiras são áreas dinâmicas e altamente produtivas, capazes de ofertar uma ampla variedade de recursos naturais importantes para o comércio local e mundial (Neumann et al., 2015). Apesar dos benefícios ofertados, a intensa ação humana tem causado impactos de curto a longo prazo na estrutura dos habitats (Burt, 2014). Diferentes atividades são responsáveis por distúrbios nos ecossistemas, dentre estas o uso da terra para construção de residências domésticas, estabelecimento de indústrias, turismo e comércio portuário (Andrés et al., 2017). Mesmo que as grandes cidades tenham se tornado cada vez mais populosas ao longo das últimas décadas, um aumento populacional é esperado durante os próximos anos, incluindo regiões da costa do Brasil (Neumann et al., 2015).

A exploração excessiva de recursos naturais, o despejo de esgotos e a construção de estruturas artificiais estão entre os principais impulsionadores de mudanças em ambientes marinhos (Todd et al., 2019; Alter et al., 2021). A captura demasiada de animais de interesse comercial (tais como peixes, mariscos e moluscos, p.e.) provoca reduções na abundância e riqueza das comunidades, atrelado a isso, o desaparecimento de espécies de vários grupos pertencentes a fauna marinha foi constatado em diversas regiões do planeta (Todd et al., 2019). A construção de estruturas artificiais, como pontes, paredões, edifícios e estabelecimentos domésticos próximos ao mar, podem reduzir a conectividade entre ecossistemas e alterar o fluxo gênico de espécies que vivem em substratos inconsolidados (Alter et al., 2021). Ainda, a entrada de águas de esgotos, seja de origem doméstica ou industrial, contribui significativamente com o enriquecimento de nutrientes, facilitando a ocorrência de florações de microalgas nocivas e o crescimento em larga escala de macroalgas oportunistas (Le Moal et al., 2019).

Diante dos problemas ecológicos provocados pela ação humana, a realização de estudos de monitoramento da saúde dos habitats costeiros tem fornecido importantes feedbacks acerca do nível e intensidade dos distúrbios ambientais (Gall et al., 2016; D’Archino & Piazzi, 2021). Dessa forma, o uso de comunidades naturais como descritores biológicos tem se mostrado confiável, uma vez que fornecem respostas precisas sobre o status de conservação de ecossistemas de fundo duro (Leite et al., 2020).

As macroalgas são organismos fotossintetizantes que oferecem serviços essenciais para manutenção da vida marinha (Koch et al., 2013; Bonano & Orlando-Bonnaca, 2018; Manca et al., 2022). Em habitats costeiros rasos, provêm estruturas tridimensionais que atuam como refúgio e berçário para o desenvolvimento de animais vertebrados e invertebrados (Manca et al., 2022), produzem oxigênio e carbonato de cálcio (Koch et al., 2013). Além disso, respondem quali-quantitativamente a estressores ambientais de diferentes origens, seja natural ou antrópica (Areco et al., 2021). Considerando o caráter bioindicador das macroalgas, D'Archino & Piazzi (2021) propõem diferentes métodos diretos e indiretos de coleta e mapeamento das comunidades algais, os quais envolvem, por exemplo, o uso de sensoriamento remoto, fotografias, dispositivos acústicos e observações feitas ao longo de transectos. Ainda, Orfanidis et al. (2003) e Caldeira & Reis (2019) indicam amostragens de espécies de algas pertencentes a vários grupos taxonômicos e funcionais, com diferentes ciclos de vida e crescimento, para avaliar os ecossistemas.

Estudos de monitoramento com macroalgas produzem respostas qualitativas e quantitativas sobre a saúde ambiental (Areco et al., 2021; D'Archino & Piazzi, 2021), identificando impactos de diferentes origens como, por exemplo, contaminação por nutrientes (Alquézar et al., 2013; Barr et al., 2020) e metais pesados (Chakraborty et al., 2014). Diversas características são indispensáveis para o uso das algas como indicadoras de impactos ambientais, entre essas: serem capazes de acumular poluentes sem apresentar danos que comprometam a vida e o desenvolvimento, serem sésseis e com ampla distribuição (Areco, 2021). Além disso, as espécies devem ser abundantes durante todo o ano e dispor de alta tolerância a concentrações elevadas de componentes tóxicos (como elementos traço, p.e.) (Bonano & Orlando-Bonnaca, 2018).

No Brasil, o monitoramento de habitats costeiros tem permitido a compreensão dos problemas originados pela urbanização em regiões de costões rochosos (Martins et al., 2012; Scherner et al., 2013; Portugal et al., 2017) e recifais (Portugal et al., 2016; Vasconcelos et al., 2019). O aumento da urbanização, por exemplo, causa reduções na riqueza e diversidade de espécies de macroalgas (Martins et al., 2012; Scherner et al., 2013), onde muitas dessas são capazes de impregnar cálcio em suas estruturas internas, como *Halimeda* (Scherner et al., 2013), que são indispensáveis para formação de recifes e produção de carbonato de cálcio biogênico (Koch et al., 2013). Regiões urbanizadas, caracterizadas pelo alto nível de impacto antrópico, tendem a exibir alta cobertura de algas oportunistas como *Ulva*, *Chondracanthus* e *Bryopsis* (Vasconcelos et al., 2019), resultando em declínios na riqueza e diversidade de espécies (Martins et al., 2012).

As macroalgas respondem ao enriquecimento de nutrientes (Teichberg et al., 2010), sendo uma boa ferramenta para detectar e mitigar a eutrofização (Areco et al., 2021; Manca et al., 2022). Em regiões costeiras, a descarga de esgotos é uma das principais fontes de nitrogênio e fosforo dissolvido (Willis et al., 2022). Consequentemente, o despejo de efluentes provoca mudanças nas comunidades bentônicas, causando uma substituição de espécies sensíveis, e importantes para construção de habitats, por algas oportunistas de rápido crescimento (Bellgrove et al., 2017). A comunidade fitobentônica exibe variações significativas na cobertura e composição taxonômica quando expostas a um gradiente de poluição (Dhargalkar & Komarpant, 2003; Arévalo et al., 2007). Dessa forma, alterações na estrutura das comunidades são detectadas conforme se aproxima de uma fonte de lançamento de efluentes, sendo possível verificar menor número de espécies e alta dominância de algas oportunistas em áreas mais próximas a saídas de esgotos (Arévalo et al., 2007). Além disso, a presença de nutrientes em elevadas concentrações na água do mar estimula o desempenho fotossintético e respiração, sendo possível notar uma coloração mais escurecida do talo das algas em razão ao acúmulo de pigmentos acessórios (Dailer et al., 2012).

1.1 OBJETIVOS

O presente trabalho tem como objetivo geral avaliar os impactos da urbanização sobre comunidades de macroalgas bentônicas de recifes da costa de Pernambuco. Diante disto, foram estabelecidos os seguintes objetivos específicos:

a) Caracterizar as comunidades de macroalgas, considerando os descritores composição taxonômica, riqueza, abundância e diversidade em recifes costeiros de praias com distintos níveis de ocupação na costa de Pernambuco;
b) Descrever variações temporais (períodos seco e chuvoso) e anuais da abundância e composição taxonômica de macroalgas de recifes tropicais;

c) Comparar as comunidades de macroalgas de recifes inseridos em diferentes níveis de urbanização;
d) Avaliar os efeitos do despejo contínuo de esgotos sobre a abundância e diversidade de macroalgas;
e) Caracterizar os teores de nutrientes dissolvidos (nitrito, nitrato, amônia e fosfato) em recifes urbanizados;
f) Correlacionar as concentrações de nutrientes com a abundância das comunidades de macroalgas.

1.2 ESTRUTURA DA DISSERTAÇÃO

A dissertação está estruturada em dois artigos que abordam diferentes respostas das comunidades de macroalgas aos efeitos da urbanização costeira. O primeiro artigo, intitulado “MONITORING IMPACTS OF URBANIZATION ON MACROALGAE COMMUNITIES IN TROPICAL COASTAL REEFS: SEASONAL AND ANNUAL CHANGES”, descreve os impactos da urbanização sobre a abundância e biodiversidade de macroalgas, considerando variações sazonais (seco e chuvoso) e anuais. O segundo artigo tem por título “EFFECTS OF SEWAGE ON THE STRUCTURE AND DIVERSITY OF MACROALGAE FROM URBANIZED TROPICAL REEFS”, o qual caracteriza os efeitos da descarga de esgotos sobre a estrutura e composição taxonômica de comunidades de macroalgas de recifes tropicais urbanizados inseridos em um gradiente de poluição orgânica.

2 ÁREA DE ESTUDO

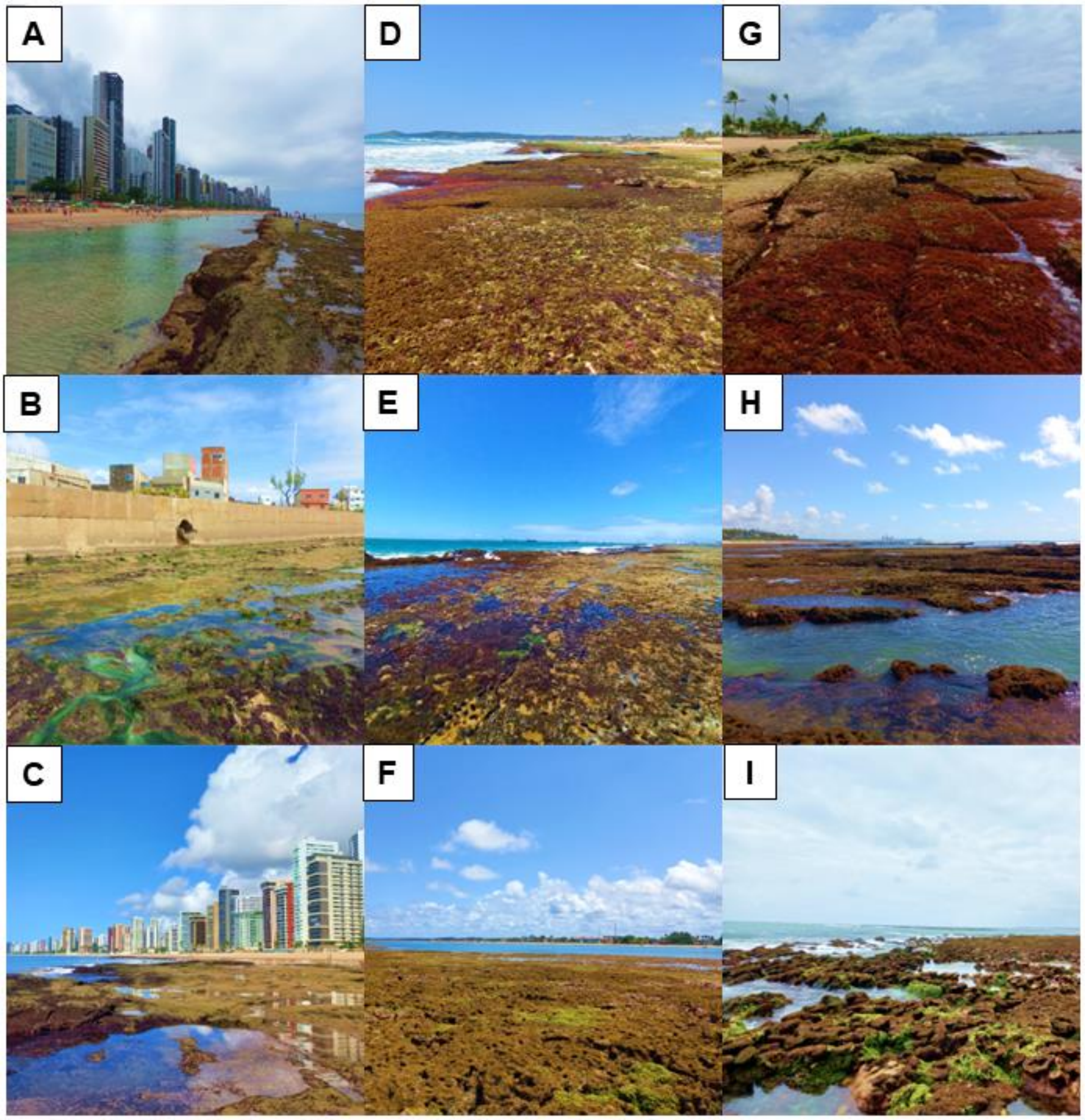
O estado de Pernambuco está localizado na província biogeográfica do Atlântico Sudoeste Tropical (Spalding et al., 2007) e apresenta uma plataforma continental com aproximadamente 155 km de extensão e 35 km de largura (Barcellos et al., 2020). A zona costeira é caracterizada pela presença de bancos de arenito e recifes de corais descontínuos, dispostos paralelamente à costa, que afloram durante períodos de marés baixas (Dominguez et al., 1990). Tais sistemas contam com alta cobertura de organismos sésseis, como algas vermelhas, verdes e pardas, e corais (Horta et al., 2001). As estruturas recifais são formadas principalmente por grãos de quartzo e carbonato de cálcio de origem biogênica (Dominguez et al., 1990). As praias estão sob regimes de mesomarés semi-diúrnas (Amaral et al., 2016), com duas preamares e duas baixa-mares, e altura média de marés de 1,67m, podendo alcançar uma altura média de 2,07m em marés de sizígia e 0,97m em marés de quadratura (Manso et al., 2018).

O clima da região costeira é quente e úmido com elevadas taxas de precipitação (Bezerra et al., 2021), apresentando uma umidade média anual acima de 80%, evaporação média anual de 170mm, e dois períodos climáticos bem definidos: seco (setembro a fevereiro) e chuvoso (março a agosto) (Bontempo-Filho et al., 2022). A pluviosidade exibe um forte ciclo sazonal, com maiores taxas de precipitação observadas em junho (média: 390,5mm) e julho (média: 314,8mm), e menores em outubro (média: 52,8mm) e novembro (média: 39,0mm) (INMET, 2022). Entretanto, fenômenos climáticos como La Niña e El Niño são capazes de alterar positivamente ou negativamente o regime de chuvas na região (Bezerra et al., 2021). A temperatura média anual do ar varia entre 21,9°C e 29,1°C, com maiores temperaturas verificadas entre dezembro a março e menores entre junho a setembro (Manso et al., 2018). Ainda, durante a estação seca, a região litorânea é fortemente influenciada por ventos de Nordeste, enquanto na estação chuvosa predomina-se ventos de Sul/Sudeste (Lira et al., 2010). A salinidade das águas costeiras difere sazonalmente, exibindo valores máximos (37,16) na estação seca e mínimos (28,8) na estação chuvosa (Manso et al., 2018). Um padrão sazonal semelhante pode ser observado para temperatura da superfície da água, com máximo (média 27,9°C) no verão e mínimo (média 26,7°C) no inverno (Domingues et al., 2017).

A presente dissertação foi desenvolvida em nove praias distribuídas ao longo do litoral pernambucano que possuem diferentes níveis de urbanização (classificadas segundo Vasconcelos et al., 2019). Diante disso, amostragens foram realizadas em recifes de praias em Urbanização consolidada - Boa Viagem (08° 7'29.60"S; 034°53'45.36"W), Brasília Teimosa (08° 5'18.33"S; 034°52'44.16"W) e Piedade (08°10'42.05"S; 034°54'54.66"W), em Processo de Urbanização - Enseada dos Corais (08°19'8.81"S; 034°56'53.68"W), Suape (08°22'20.02"S; 034°57'1.07"W) e Campas (08°45'5.30"S; 035°5'12.90"W), e Não Urbanizadas - Toquinho (08°34'10.11"S; 035°1'53.12"W); Paiva (08°16'48.53"S; 034°56'43.74"W) e Mamucabas (08°47'7.82"S; 035°5'48.08"W) (Figura 1).

As praias de Boa Viagem, Brasília Teimosa e Piedade são caracterizadas pela presença de construções artificiais dos mais variados tipos e funções (Araújo et al., 2007). Dentre essas, longos cordões de enrocamento, edifícios residenciais e comerciais, quiosques, avenidas, sistemas de esgotamento sanitário e muros de contenção (Costa et al., 2008). Por outro lado, as áreas localizadas ao Sul de Pernambuco (Enseada dos Corais, Suape, Campas, Paiva, Mamucabas e Toquinho), apresentam menores níveis de urbanização e densidade humana (Araújo et al., 2007; Vasconcelos et al., 2019), sendo ocupadas principalmente por edifícios domésticos de veraneio (Araújo et al., 2007). Em 2019/2020, as praias de Boa Viagem, Piedade, Enseada dos Corais, Suape, Paiva e Mamucabas foram significativamente impactadas pelo derrame de óleo bruto, o qual provocou danos consideráveis na economia local e biodiversidade marinha (IBAMA, 2020; Câmara et al., 2021; Campelo et al., 2021; Lira et al., 2021).

Figura 1 - Áreas de estudo distribuídas ao longo da costa de Pernambuco



A: Boa Viagem; B: Brasília Teimosa; C: Piedade; D: Enseada dos Corais; E: Suape; F: Campas; G: Toquinho; H: Paiva e I: Mamucabas.

Fonte: O Autor (2023).

3 MONITORING IMPACTS OF URBANIZATION ON MACROALGAE COMMUNITIES IN TROPICAL COASTAL REEFS: SEASONAL AND ANNUAL CHANGES

ARTIGO SUBMETIDO À REVISTA MARINE POLLUTION BULLETIN

ABSTRACT

Changes in natural communities have been observed after the development of urban centers in coastal areas, indicating the need monitoring studies to understand the intensity and magnitude of human impacts. Non-destructive samples were performed during the dry and rainy seasons of 2014, 2021 and 2022 in reefs of the coast of Pernambuco, Northeastern Brazil. The areas were classified as consolidated urbanization (UC), process of urbanization (UP) and non-urbanized (NU). Macroalgae abundance differed between UC and UP, UP and NU, and NU and NU during the dry and rainy seasons of 2014, 2021, and 2022. However, richness, diversity and evenness differ only between UC and UP over the years. *Ulva lactuca* and *Chondracanthus acicularis* were dominant in UC areas, while *Gelidiella acerosa* and *Palisada perforata* in NU and UP. Overall, macroalgae communities provided important responses on the impacts of urbanization on tropical reefs, reflecting effects of seasonality and annual variations.

Keywords: anthropic impacts; benthic communities; ecological indicators; seasonality.

1. Introduction

The growth of urban centers in coastal areas has caused a series of cumulative modifications in local geomorphology, water quality and marine biodiversity (Burt et al., 2019). Habitat degradation through artificial constructions, sewage discharge and overfishing are problems caused by increasing urbanization in regions near the sea, which cause changes in dispersion, gene flow and reproduction of aquatic organisms (Alter et al., 2021). In addition, cases of harmful algae blooms, destruction or fragmentation of seagrass meadows and coral reefs are also impacts associated with the urbanization of coastal marine ecosystems (Burt, 2014). One of the alternatives to understand the intensity and extension of impacts of anthropic origin on local biodiversity, is through monitoring studies using biological communities (phytoplankton, macroalgae, marine phanerogams, invertebrate animals) (WFD, 2000/60ec; E.C., 2000; Clarke et al., 2014).

Human action through overexploitation of living and non-living natural resources, construction of artificial structures, and discharge of industrial and domestic pollutants, for example, is reflected in biodiversity, contributing to changes in communities of primary producers and declines of populations of mammals, fish and shellfish (Todd et al., 2019). Hard bottom benthic organisms, which are generally sessile or of low mobility, respond to physicochemical changes in the water column and sediments, providing accurate quantitative feedbacks about spatiotemporal changes in water quality (Desrosiers et al., 2013; Aréco et al., 2021). Assessments for richness, presence, and absence of sensitive species, and macroalgal cover is a way to identify the nature and magnitude of environmental disturbances (Desrosiers et al., 2014).

Macroalgae are photosynthetic organisms with different origins and evolutionary divergences (Cortona et al., 2020). In hard-bottom coastal ecosystems, they play essential roles in the production of oxygen and biogenic calcium carbonate (Koch et al., 2013), and provide habitats for several species of vertebrates and invertebrates (Manca et al., 2022). Some species have morphological and physiological characteristics (type of growth, cell wall thickness and contact area surface) that facilitate interaction with chemical components available in seawater and sediments, being able to capture and accumulate heavy metals (Bonanno & Orlando-Bonaca, 2018; Areco et al., 2021), and respond to variations in nutrient levels (Barr et al., 2020), showing as an important tool for recovering water quality in degraded habitats.

Biological indicators are organisms (plants or animals) that provide qualitative and quantitative information about the ecological health of environments (Desrosiers et al., 2013). To be a reliable indicator, species need to have characteristics that facilitate survival in contrasting scenarios, such as being sessile, tolerating high pollutant loads and having a wide distribution (García-Seoane et al., 2018; Areco et al., 2021). The implementation of macroalgae bioindicators collection and analysis protocols has been promising (Gall et al., 2016; D'Archino & Piazzi, 2021). In Brazil, the National Environment Council (CONAMA), through Resolution 357/2005, indicates the use of aquatic bioindicators as an alternative tool to evaluate water quality (CONAMA, 2005). Since are sessile and sensitive to pollutants, macroalgae are considered excellent indicators of environmental impacts, providing accurate responses about ecological health (Areco et al., 2021). In addition, monitoring studies along the brazilian coast indicate that the increase in urbanization is one of the drivers responsible for reducing diversity (Martins et al., 2012) and losses of non-articulated calcareous algae (Scherner et al., 2013).

Algal communities are driven by several biotic and abiotic factors such as salinity, temperature, hydrodynamics, herbivory, substrate type and nutrient availability (Zaneveld, 1969; Lalegerie et al., 2020). In tropical reefs, macroalgae can respond to seasonal environmental changes, with modification in biomass (Akrong et al., 2021) and concentration of chemical compounds (proteins, carbohydrates, chlorophyll, and carotenoids) between the dry and rainy seasons (Melo et al., 2021). Additionally, the increased urbanization facilitates the input of nutrients into water bodies, especially through the flow of untreated sewage (Todd et al., 2019; Alter et al., 2021). The presence of forms of nitrogen and phosphorus in high concentrations in the water column favors the development of opportunistic algae (Arévalo et al., 2007; Areco et al., 2021) with fast growth and short life history (Orfanidis et al., 2003), causing changes in the structure of natural communities (Bellgrove et al., 2017).

Despite the efforts to describe the impacts of human action on natural communities (Scherner et al., 2013; Portugal et al., 2016; Vasconcelos et al., 2019; Häder et al., 2020), monitoring studies are still necessary to expand knowledge about the ecological condition of tropical and subtropical regions, especially considering the influence of seasonal and annual variations. Understanding the mechanisms behind the processes that cause changes in the structure of macroalgae communities is important to propose strategies for the management and conservation of ecosystems, as well as indicating possible future scenarios. The present study aims (1) evaluate the effects of urbanization on the structure and taxonomic composition of macroalgae communities, and (2) identify seasonal and annual changes in the structure of macroalgal communities of coastal tropical coastal reefs.

2. Material and methods

2.1. Study area

The Pernambuco State occupies an area of 98.067.877 km² of the Brazilian territory (IBGE, 2021), presenting a continental shelf 187km long and 35 km wide (Domingues et al., 2017). It is located in the Brazil's Northeastern Ecoregion under the Tropical Southwestern Atlantic Province (Spalding et al., 2007). The total population is estimated at 9.674.793 inhabitants (IBGE, 2021), however, only 45% of homes are served with any type of sewage, where approximately 61% of the material collected is properly treated (ANA, 2017). The climate of the coastal zone is hot and wet with high precipitation rates (Bezerra et al., 2021), average temperatures above 25°C (Domingues et al., 2017) and two annual climate periods: rainy (march to august – rainfall above 100mm) and dry (september to february– rainfall less than 100mm) (Santos et al., 2020). The beaches are relatively narrow and have semidiurnal meso-tidal regimes (Amaral et al., 2016). Along the coast can be observed the presence of sandstone reefs with high diversity of calcareous algae and coral (Horta et al., 2001).

2.2. Sampling design of macroalgae communities

Nine sampling areas distributed along the coast of Pernambuco were selected (figure 1). Vasconcelos et al. (2019) classified the locations in different degrees of urbanization through data on population density and occupancy rate of residences (table 1). Thus, areas with more than 500 inhabitants km² were classified as Consolidated Urbanization (UC), while areas with demographic density ranging between 20 and 500 inhabitants km² and 5 and 250 inhabitants km² were respectively classified as under in the Urbanization Process (UP) and Non-Urbanized (NU) (table 1; Vasconcelos et al., 2019). Samplings were carried out took place at low tide during the dry (September to February) and rainy (March to August) seasons in the years 2014, 2021 and 2022, with a collection cycle per season. Macroalgae qualitative and quantitative data were collected using *Line point* methodology (Murray, 2002; with adaptations). At each beach, transects with 10m long, arranged perpendicularly to the coast, were placed in the lower compartments of the reefs, followed by the insertion of 25 x 25 cm quadrats with 25 contact points. Individuals were identified in the field to the lowest possible taxonomic level, with collection of specimens, when necessary, for identification in the laboratory through microscopic views of the external and internal characters of the thallus.

Table 1: Study areas classified as consolidated urbanization (UC), in the process of urbanization (UP) and non-urbanized (NU) and their population densities (km²).

Study area	Urbanization level[a]	Population density (inhab by km²)[b]	Coordinates
Boa Viagem	UC	> 500	8° 7'29.60"S; 34°53'45.36"W
Brasília Teimosa	UC	> 500	8° 5'18.33"S; 34°52'44.16"W
Piedade	UC	> 500	8°10'42.05"S; 34°54'54.66"W
Enseada dos Corais	UP	250.1 to 500	8°19'8.81"S; 34°56'53.68"W
Suape	UP	100.1 to 500	8°22'20.02"S; 34°57'1.07"W
Campas	UP	100.1 to 500	8°45'5.30"S; 35° 5'12.90"W
Mamucabas	NU	5.1 to 10	8°47'7.82"S; 35° 5'48.08"W
Paiva	NU	10.1 to 15	8°16'48.53"S; 34°56'43.74"W
Toquinho	NU	100.1 to 250	8°34'10.11"S; 35° 1'53.12"W

[a]: classification proposed by Vasconcelos et al. (2019); [b]: Data provided by the Brazilian Institute of Geography and Statistics (IBGE, 2010).

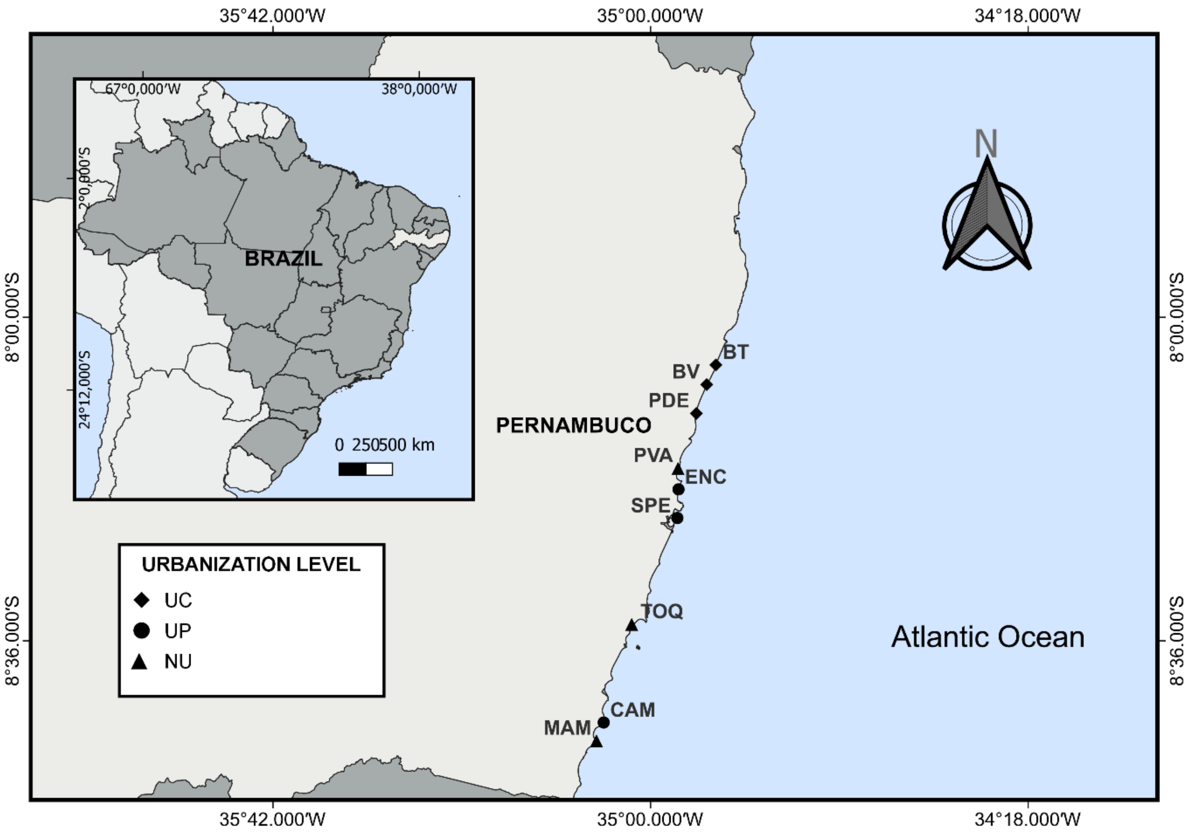


Figure 1: Map of beaches on the coast of Pernambuco inserted in areas with different levels of urbanization. UC: consolidated urbanization; UP: urbanization process; NU: non-urbanized. BT: Brasilia Teimosa; BV: Boa Viagem; PDE: Piedade; PVA: Paiva; ENC: Enseada dos Corais; SPE: Suape; TOQ: Toquinho; CAM: Campas; MAM: Mamucabas.

2.3. Data analysis

The quadrats were considered as sampling units. Thus, 1.636 samples were taken with a total of 40.900 points. Relative abundance data were calculated to estimate the macroalgal total coverage. For each sample, richness (total number of taxa), evenness (Pielou index - J), diversity (Simpson index – 1- 'Lambda') were calculated. These data were transformed into a fourth root and tested for normality and homoscedasticity using the Kolmogorov-Smirnov and Bartlet tests, respectively. Since data were not normally distributed, Kruskal-Wallis test was performed to compare samples considering urbanization level, year and season as fixed levels. These analyzes were performed using STATISTICA v10 (Statsoft, 2011).

The interactions of algal communities with levels of urbanization were graphically illustrated using Principal Coordinate Analysis (PCO) (Pearson's correlation > 0.4). A Permutational analysis of variance (PERMANOVA) was performed to compare macroalgae communities among beaches considering urbanization level, year and season as fixed factors. For this analysis, frequency of occurrence data was transformed by fourth root and a matrix of resemblance was calculated using the Bray-Curtis similarity index. When PERMANOVA results were significant, a posteriori Pair-wise tests were performed. A PERMDISP was employed to characterize the multivariate dispersion of the data. In addition, a SIMPER analysis was used to identify the taxa with the highest contributions in areas with different levels of urbanization, between the dry and rainy seasons, and between the years 2014, 2021 and 2022. All multivariate analyses were performed using the PRIMER + Permanova (Clark & Warwick, 2005; Anderson et al., 2008). For all analyses a level of significance of 5% was considered.

3. Results

A total of 73 macroalgae taxa were recorded, belonging to Chlorophyta (Ulvophyceae), Rhodophyta and Ochrophyta (Phaeophyceae) (table 2). Rhodophyta were dominant (45 taxa), followed by Chlorophyta (19) and Ochrophyta (Phaeophyceae) (9). A similar pattern was found for algal coverage. Rhodophyta had the highest coverage at all levels of urbanization, followed by Chlorophyta and Ochrophyta. Ochrophyta had minimum coverage values in UC areas and were more common in UP and NU areas (table 2). The highest values of total macroalgae coverage were observed in UC areas, while lowest in UP and NU areas, respectively (table 2). Total coverage varied significantly between UC and UP areas ($p < 0.0001$), between UP and NU ($p < 0.005$), and between UC and NU areas ($p < 0.0001$) (figure 2A, 2E, 2I). Furthermore, differences for coverage were found between the dry and rainy seasons ($p = 0.0002$), with higher coverage values during the dry season. There were no statistical differences ($p > 0.05$) for total coverage between the years 2014, 2021 and 2022.

Total species varied between levels of urbanization, with the lowest number (22) during the 2014 dry season in UC areas, and the highest (43) during the 2021 rainy season in UP areas (table 2). Statistical differences were verified for diversity descriptors in relation to urbanization levels. Richness (S), Pielou’s evenness (J') and Simpson’s diversity varied significantly between UC areas and UP areas (S: $p < 0.0002$; J': $p < 0.02$; 1-Lambda': $p < 0.05$), however, no differences were observed between UP and NU, and between NU and UC ($p > 0.05$) for all descriptors (figure 2B-D). There were significant temporal variations on short to long term. Richness, diversity, and evenness reduced over the years, showing significant differences between 2014 and 2022 (S: $p < 0.0001$; J’: $p < 0.\ 0001$; 1-Lambda’: $p < 0.\ 0001$), and between 2021 and 2022 (S: $p < 0.\ 0001$; J’: $p < 0.02$; 1-Lambda: $p < 0.0001$) (figure 2F-H). No significant differences were found between 2014 and 2021 for all descriptors. Seasonality had no significant effects on species richness, diversity, and evenness, with no statistical differences being identified between the dry and rainy seasons ($p > 0.05$) (figure 2J-L).

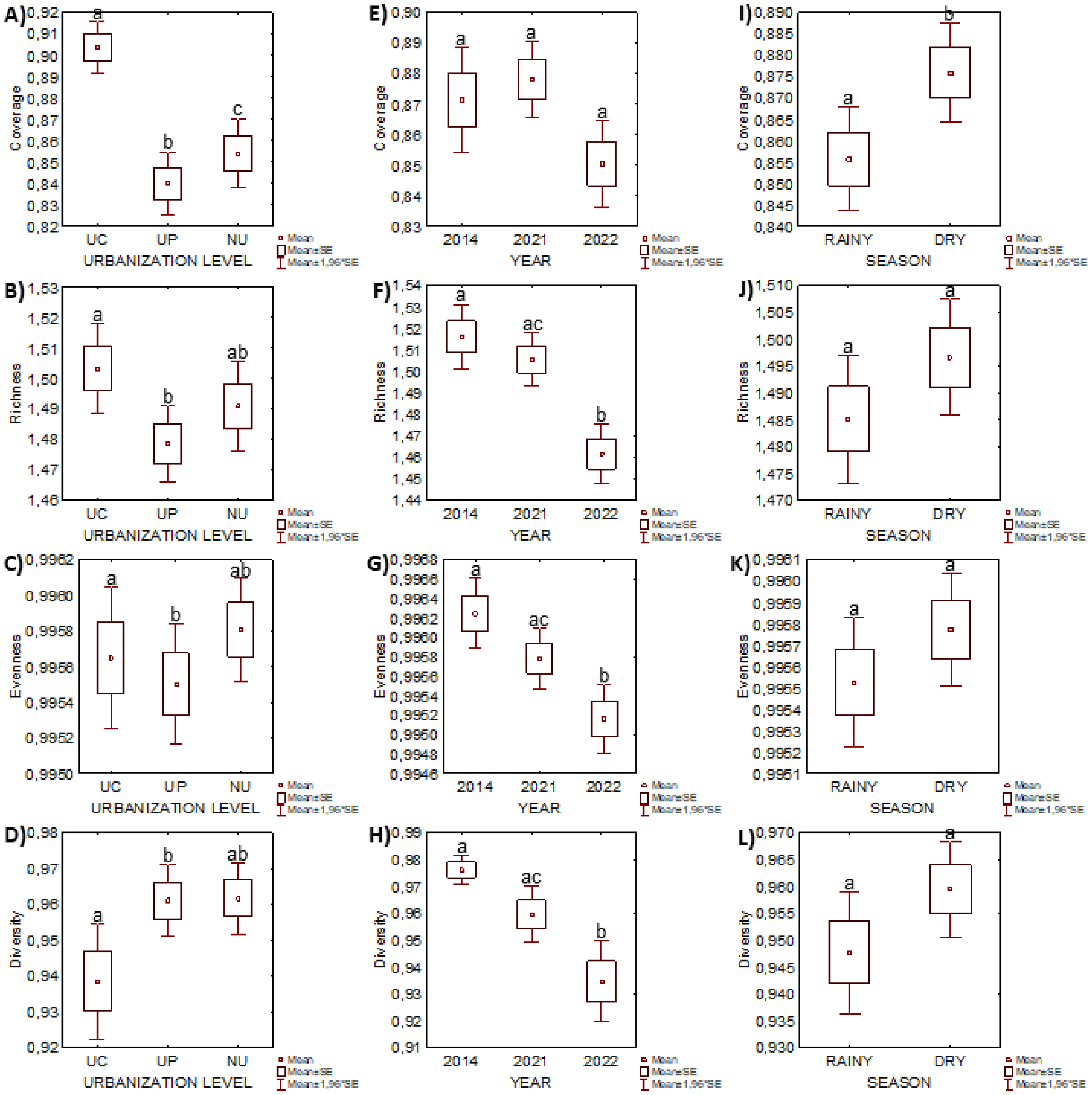


Figure 2: Boxplot for the total coverage of macroalgae and the descriptors species richness, diversity and equitability indicated by the Kruskal-Wallis analysis.

Table 2: List of macroalgae species and their respective relative abundances (%) distributed between the dry and rainy seasons of 2014, 2021 and 2022 in areas of consolidated urbanization (UC), in the process of urbanization (UP) and non-urbanized (NU).

	Year 2014						Year 2021						Year 2022					
	DRY			RAINY			DRY			RAINY			DRY			RAINY		
Species composition	**UC**	**UP**	**NU**	**UC**	**UP**	**NU**	**UC**	**UP**	**NU**	**UC**	**UP**	**NU**	**UC**	**UP**	**NU**	**UC**	**UP**	**NU**
Chlorophyta																		
Anadyomene sp.	-	0.29	0.07	-	0.10	0.17	-	0.19	0.26	-	0.33	0.70	-	0.43	0.67	-	0.30	0.61
Bryopsis spp.	14.25	0.59	1.87	8.47	3.10	3.72	6.70	5.30	6.74	12.45	2.78	7.11	5.73	3.64	4.49	6.41	7.93	5.43
Caulerpa sp.	-	-	-	-	-	-	-	-	-	0.04	0.04	-	-	-	-	-	0.22	-
Caulerpa cupressoides (Vahl) C.Agardh	3.69	-	-	0.13	0.10	-	2.41	-	-	2.54	0.11	-	1.65	-	-	0.89	0.04	-
Caulerpa fastigiata Montagne	0.44	-	-	0.07	-	-	-	-	-	-	-	-	-	-	-	0.04	-	-
Caulerpa mexicana Sonder ex Kützing	-	-	-	1.13	-	-	0.78	-	-	0.75	-	-	0.88	-	-	0.37	-	-
Caulerpa prolifera (Forsskål) J.V.Lamouroux	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04	-	-
Caulerpa racemosa (Forsskål) J.Agardh	-	2.88	9.40	0.60	3.00	10.1	-	4.00	8.37	-	8.81	4.74	-	4.32	7.03	-	7.26	4.00
Caulerpa sertularioides (S.G.Gmelin) M.Howe	-	-	-	0.53	0.10	-	0.44	-	-	0.07	-	-	0.08	0.04	-	-	-	-
Caulerpa taxifolia (M.Vahl) C.Agardh	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.48	-	-

Chaetomorpha antennina (Bory) Kützing	-	0.18	0.47	2.60	1.20	3.61	0.15	0.04	-	0.60	0.22	0.33	-	0.11	0.22	0.52	-	0.96
Cladophora sp.	-	-	0.07	0.13	-	0.11	1.15	0.30	0.04	0.56	0.04	-	0.85	0.07	-	1.00	0.15	0.04
Dictyosphaeria sp.	-	1.76	1.47	-	3.10	1.28	-	1.48	0.22	-	0.67	0.19	-	0.82	0.45	0.04	1.04	0.22
Halimeda opuntia (Linnaeus) J.V.Lamouroux	-	0.94	0.73	-	0.20	2.00	-	0.15	1.22	-	0.70	1.44	-	0.43	0.15	-	1.19	1.17
Phyllodictyon sp.	-	-	-	-	-	-	-	0.04	-	-	-	-	-	-	-	-	-	-
Rhizoclonium sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.07	-	-
Struvea sp.	-	-	-	-	-	-	-	-	-	0.04	-	-	-	-	-	0.56	-	-
Ulva lactuca Linnaeus	25.38	1.65	0.40	19.67	1.90	0.33	8.96	0.63	0.07	7.78	1.04	0.07	18.88	2.54	-	7.26	0.26	-
Ulva flexuosa Wulfen	-	-	-	-	-	-	0.15	-	1.26	0.49	-	-	0.04	-	-	0.48	-	0.17
Phyllum coverage	**43.8**	**8.3**	**14.5**	**33.3**	**12.8**	**21.3**	**20.7**	**12.1**	**18.2**	**25.3**	**14.7**	**14.6**	**28.1**	**12.4**	**13.0**	**20.2**	**18.4**	**12.6**
Rhodophyta																		
Acanthophora muscoides (Linnaeus) Bory	-	-	-	-	-	-	-	-	0.11	-	-	-	-	-	0.07	-	-	-
Acanthophora spicifera (M.Vahl) Børgesen	0.81	2.88	2.93	0.20	0.90	1.50	0.37	1.85	0.37	-	2.33	0.70	0.08	2.21	0.60	0.07	3.33	0.17
Alsidium seaforthii (Turner) J.Agardh	-	0.18	0.33	0.07	0.10	-	0.78	-	0.63	1.05	0.04	0.48	0.85	-	0.07	0.74	0.11	0.48
Alsidium triquetrum (S.G.Gmelin) Trevisan	0.06	-	2.47	-	0.10	0.28	-	0.19	1.33	0.49	0.04	0.78	0.46	0.04	0.79	-	-	2.48
Amansia multifida J.V.Lamouroux	0.50	1.00	4.13	0.07	0.90	2.72	0.22	0.07	1.22	0.30	0.41	1.33	0.50	1.43	3.33	0.19	-	1.00
Bostrychia sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04
Botryocladia sp.	-	-	-	-	-	0.06	-	-	-	-	-	-	-	-	-	-	-	-

Botryocladia occidentalis (Børgesen) Kylin	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.07	-	-	-
Centroceras clavulatum (C.Agardh) Montagne	-	-	-	-	-	-	-	0.11	0.07	0.04	0.37	-	0.08	0.25	0.07	-	0.63	-
Ceramiaceae	1.38	1.71	0.07	1.27	-	1.44	0.74	1.37	0.33	0.04	0.74	0.59	-	0.36	0.19	-	0.11	0.30
Ceramium sp.	-	-	-	-	-	-	-	-	0.11	-	-	-	-	0.61	0.04	-	-	-
Ceratodictyon planicaule (W.R.Taylor) M.J.Wynne	0.38	-	-	1.07	0.20	0.22	-	-	-	-	-	-	-	-	-	-	-	-
Ceratodictyon variabile (J.Agardh) R.E.Norris	-	-	-	-	-	-	2.85	0.04	0.15	4.07	0.30	0.37	4.73	0.29	0.19	4.19	0.04	0.52
Chondracanthus acicularis (Roth) Fredericq	13.31	-	0.27	-	0.10	0.28	27.4	-	0.52	13.35	0.04	0.48	19.2	0.07	0.97	12.9	0.11	2.65
Corallina officinalis Linnaeus	1.56	-	-	3.60	-	0.06	5.48	-	-	7.81	-	0.07	3.31	-	0.15	7.52	-	0.22
Corallinaceae	-	0.41	-	-	-	-	-	-	-	-	-	-	0.23	-	-	-	-	-
Corynomorpha sp.	-	-	-	-	-	-	-	-	-	-	-	0.04	-	-	0.04	-	-	-
Crassiphycus corneus (J.Agardh) Gurgel. J.N.Norris & Fredericq	-	-	-	-	-	-	-	-	-	-	0.11	-	-	0.04	-	-	-	-
Cryptonemia spp.	0.06	0.18	0.33	0.07	-	0.06	0.52	-	0.19	0.52	0.07	0.19	0.42	-	0.11	2.04	-	0.26
Digenea simplex (Wulfen) C.Agardh	-	1.06	-	-	1.20	-	-	0.52	0.11	-	0.59	-	-	0.89	-	-	-	-
Galaxaura sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.07	-	-	-
Gelidiella acerosa (Forsskål) Feldmann & Hamel	2.13	7.00	12.07	6.47	13.2	20.7	1.78	11.1	13.7	2.99	10.15	17.4	1.92	5.89	16.93	3.96	10.96	21.8
Gelidium spp.	3.50	1.47	1.73	4.27	3.20	2.67	13.3	2.67	4.59	14.95	2.48	7.11	10.9	3.96	4.64	21.4	4.15	4.39

Gelidium lineare Iha & Freshwater	-	-	-	-	-	-	-	0.04	-	-	-	-	0.08	-	-	-	-	-
Gracilaria spp.	11.25	0.82	1.47	11.3	0.80	3.22	8.11	0.48	1.70	7.36	2.04	2.04	8.42	0.93	2.58	5.48	0.44	1.96
Gracilaria caudata J.Agardh	-	-	-	-	-	-	0.30	-	-	0.22	-	-	0.08	0.04	-	-	-	-
Gracilaria cervicornis (Turner) J.Agardh	-	-	-	-	-	-	-	-	-	-	-	-	-	0.14	-	-	-	-
Gracilaria domingensis (Kützing) Sonder ex Dickie	-	-	-	-	-	-	-	-	-	0.11	0.04	0.30	-	-	-	-	-	-
Grateloupia sp.	-	-	-	-	-	-	0.04	-	-	0.19	-	0.04	0.08	-	0.19	0.04	-	-
Griffithsia sp.	-	-	-	-	-	-	-	-	0.04	-	-	-	-	-	-	-	-	0.04
Hypnea spp.	3.75	2.94	4.40	2.60	3.80	3.28	5.04	1.37	2.78	2.95	1.67	1.37	5.46	0.86	3.33	3.44	1.22	0.48
Jania spp.	-	1.35	1.40	0.27	0.80	0.94	0.30	1.07	4.44	0.45	1.70	1.67	0.08	0.50	3.36	0.78	0.04	1.74
Laurencia sp.	-	-	-	-	-	-	-	1.04	0.78	-	0.19	0.15	-	-	-	-	1.11	0.04
Laurencia dendroidea J.Agardh	0.50	4.35	2.27	0.53	3.00	2.44	0.37	4.00	0.89	0.34	1.96	1.04	0.42	4.21	0.56	0.37	0.52	1.48
Laurencia flagellifera J.Agardh	-	-	-	-	0.20	-	-	0.15	0.04	-	0.26	0.07	-	0.11	-	-	-	0.17
Laurencia translucida Fujii & Cordeiro-Marino	-	0.59	-	-	0.10	-	-	0.30	0.26	-	0.11	0.30	-	0.43	-	0.41	-	0.17
Palisada furcata (Cordeiro-Marino & Fujii) Cassano & Fujii	0.06	1.00	0.33	-	1.00	1.06	-	0.22	0.78	0.04	0.59	0.33	-	2.14	-	0.67	-	0.70
Palisada perforata (Bory) K.W.Nam	4.38	23.71	22.40	5.00	24.2	13.06	3.48	24.9	16.78	3.03	22.5	10.70	1.12	18.93	13.76	1.78	23.19	9.39
Porphyra sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.09
Rhodymenia sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.15	-

Vidalia obtusiloba (Mertens ex C.Agardh) J.Agardh	-	-	-	-	-	-	-	-	1.93	0.19	0.19	2.78	0.23	-	0.19	0.11	-	3.09
Wrangelia sp.	-	-	0.07	0.13	4.20	0.06	-	0.85	0.04	-	0.15	0.11	-	0.64	0.79	-	0.11	0.13
Wrangeliaceae	-	-	-	-	-	-	-	-	-	-	0.04	-	-	-	-	-	-	-
Non-articulated calcareous algae	-	-	-	-	-	-	-	-	-	3.36	5.41	4.59	2.23	7.11	2.65	-	2.41	5.04
Red filamentous algae	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.22	0.09
Phyllum coverage	**43.6**	**50.7**	**56.7**	**36.9**	**58.0**	**54.1**	**71.1**	**52.3**	**53.9**	**63.9**	**54.5**	**55.0**	**60.9**	**52.1**	**55.7**	**66.1**	**48.9**	**58.9**
Ochrophyta																		
Asteronema sp.	-		-	-	-	-	-	-	-	-	-	-	0.04	0.07	0.34	-	-	0.09
Chnoospora minima (Hering) Papenfuss	-	0.82	-	-	0.70	-	-	0.04	-	-	0.22	-	-	0.57	-	-	-	-
Dictyopteris spp.	2.81	0.12	1.07	0.47	0.80	1.50	1.22	0.89	2.04	0.93	1.63	5.63	0.69	2.64	6.13	0.52	0.78	3.30
Dictyota spp.	0.06	0.29	0.60	-	0.30	1.78	-	0.26	3.15	0.04	0.19	2.70	-	1.00	3.51	-	0.15	0.57
Lobophora variegata (J.V.Lamouroux) Womersley	-	-	-	-	-	-	-	-	0.04	-	-	-	-	-	-	-	-	-
Padina sp.	-	4.94	1.33	-	3.60	0.33	0.11	1.93	0.89	-	0.85	0.07	0.04	1.18	1.23	0.04	0.89	0.43
Sargassum spp.	0.19	18.76	9.53	0.07	11.4	8.06	-	12.4	5.37	-	14.1	5.22	-	12.75	4.93	-	9.85	6.00
Spatoglossum schroederi (C.Agardh) Kützing	-	-	-	-	-	-	-	0.07	-	0.04	-	-	-	0.04	-	-	-	-
Ectocarpales	-	-	1.00	-	0.20	0.17	-	-	0.52	-	0.11	-	-	0.04	0.60	-	0.04	0.30
Phyllum coverage	**3.1**	**24.9**	**13.5**	**0.5**	**17.0**	**11.8**	**1.3**	**15.6**	**12.0**	**1.0**	**17.1**	**13.6**	**0.8**	**18.3**	**16.8**	**0.6**	**11.7**	**10.7**
Macroalgae total coverage	**90.5**	**83.9**	**84.7**	**70.7**	**87.8**	**87.2**	**93.1**	**80.0**	**84.1**	**90.2**	**86.3**	**83.2**	**89.8**	**82.8**	**85.5**	**86.9**	**79.0**	**82.2**

The structure of macroalgae communities responded significantly to the level of urbanization and to seasonal and annual variations (table 3). Significant differences were found between the UC and UP areas (p = 0.001), UP and NU (p = 0.001), and between UC and NU (p = 0.001) (table 4). The communities exhibited seasonal and temporal variations in regions with different degrees of urbanization, with interaction between level of urbanization and seasonality (p = 0.001), level of urbanization and year sampling (p = 0.001), and between the combination of all factors (p = 0.001) (table 3). During the rainy and dry seasons of 2014, 2021 and 2022 there were significant differences between UC and UP, UP and NU, and UC and NU (Table 4).

SIMPER analysis revealed that *Ulva lactuca*, *Chondracanthus acicularis*, *Gelidium* spp. were the species with the highest contributions in UC areas. On the other hand, *Palisada perforata*, *Gelidiella acerosa*, *Sargassum* spp. were more representative in UP areas, while *G. acerosa*, *P. perforata* in NU areas. During the dry and rainy seasons of 2014, *P. perforata*, *G. acerosa* and *Caulerpa racemosa* were the species with the highest contributions to similarity in NU areas, while *P. perforata*, *G. acerosa* and *Sargassum* spp. mostly contributed to UP areas, and *U. lactuca* and *C. acicularis* to UC areas. In 2021, *P. perforata* and *G. acerosa* were more abundant taxa in NU and UP areas in both the dry and rainy seasons. In UC areas, *C. acicularis* and *Gelidium* spp. had high contribution during the dry season, while *Gelidium* spp. and *Bryopsis* spp. in the rainy season. In 2022, *G. acerosa* and *P. perforata* were dominant in NU areas during the dry and rainy seasons, and in UP areas during the rainy season, while *P. perforata*, *Sargassum* spp. and non-articulated calcareous algae were abundant in the UP area during the dry season. In the UC regions the same year, *C. acicularis* and *Gelidium* spp. were dominant in the rainy season, while *U. lactuca* and *C. acicularis* in the dry season.

Table 3: Summary of Permanova results for the comparisons among urbanization level (UR), year (YE) and season (SE) factors.

Source	df	SS	MS	Pseudo-F	P(perm)
UR	2	8.16E+05	4,08E+05	169.24	**0.001**
YE	2	1.01E+05	50275	20.849	**0.001**
SE	1	18403	18403	7.6317	**0.001**
URxYE	4	39592	9898	4.1047	**0.001**
URxSE	2	21121	10560	4.3793	**0.001**
YExSE	2	18400	9200	3.8152	**0.001**
URxYExSE	4	23354	5838,4	2.4212	**0.001**
Total	1635	5.03E+06			

DF: Dregree of freedom; SS: Sun of square:; MS: Mean of square.

The PCO presented the formation of two groups with the axes explaining about 40.5% of the total variation of the samples, with axis 1 and axis 2 explaining respectively 23.7% and 16.8% of the total variation of the data (figure 3). Group 1 was mainly composed of samples from the UC areas, being better correlated with axis 1, while group 2 by samples from the UP and NU areas, showing a strong interaction with axis 2 (figure 3). Pearson's correlation (r<0.4) indicated that *Chondracanthus acicularis* and *Gelidium* spp. were related to samples from UC areas, while *Laurencia dendroidea*, *Palisada perforata*, *Gelidiella acerosa* and *Sargassum* spp. were related to samples from the NU and UP areas (Figure 3). Additionally, PERMDISP showed significant differences in data dispersion (p = 0.001), indicating that NU and UP areas are similar to each other, but differ from UC areas (Table 5).

Table 4: Pairwise test results for the urbanization level (UR), season (SE) and year (YE).

PAIR-WISE TESTS					
Term 'UR'			**Term 'YE'**		
Groups	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**
UC, UP	16.316	**0.001**	2021, 2022	1.7123	**0.006**
UC, NU	14.895	**0.001**	2021, 2014	5.8105	**0.001**
UP, NU	5.7276	**0.001**	2022, 2014	5.6768	**0.001**
Term 'URxSE'					
Within level 'RAINY'			**Within level 'DRY'**		
Groups	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**
UC, UP	10.257	**0.001**	UC, UP	13.144	**0.001**
UC, NU	9.3721	**0.001**	UC, NU	11.828	**0.001**
UP, NU	3.8951	**0.001**	UP, NU	4.6063	**0.001**
Term 'YExSE'					
Within level 'RAINY'			**Within level 'DRY'**		
Groups	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**
2021, 2022	1.9627	**0.001**	2021, 2022	1.8654	**0.004**
2021, 2014	4.705	**0.001**	2021, 2014	3.838	**0.001**
2022, 2014	4.1489	**0.001**	2022, 2014	4.2671	**0.001**

Term 'URxYE'								
Within level '2014'			**Within level '2021'**			**Within level '2022'**		
Groups	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**
UC, UP	8.6359	**0.001**	UC, UP	11.551	**0.001**	UC, UP	10.073	**0.001**
UC, NU	8.4386	**0.001**	UC, NU	9.7749	**0.001**	UC, NU	8.7855	**0.001**
UP, NU	2.5845	**0.001**	UP, NU	4.2465	**0.001**	UP, NU	4.4154	**0.001**

Within level '2014'			Within level '2021'			Within level '2022'		
Within level 'RAINY'			**Within level 'RAINY'**			**Within level 'RAINY'**		
Groups	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**
UC, UP	4.9389	**0.001**	UC, UP	7.6498	**0.001**	UC, UP	7.1441	**0.001**
UC, NU	5.4101	**0.001**	UC, NU	6.3169	**0.001**	UC, NU	5.4899	**0.001**
UP, NU	1.9598	**0.004**	UP, NU	3.1427	**0.001**	UP, NU	3.3369	**0.001**
Within level '2014'			**Within level '2021'**			**Within level '2022'**		
Within level 'DRY'			**Within level 'DRY'**			**Within level 'DRY'**		
Groups	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**
UC, UP	7.7636	**0.001**	UC, UP	8.8421	**0.001**	UC, UP	7.4645	**0.001**
UC, NU	6.6583	**0.001**	UC, NU	7.5982	**0.001**	UC, NU	7.391	**0.001**
UP, NU	1.9459	**0.004**	UP, NU	3.2171	**0.001**	UP, NU	3.6535	**0.001**

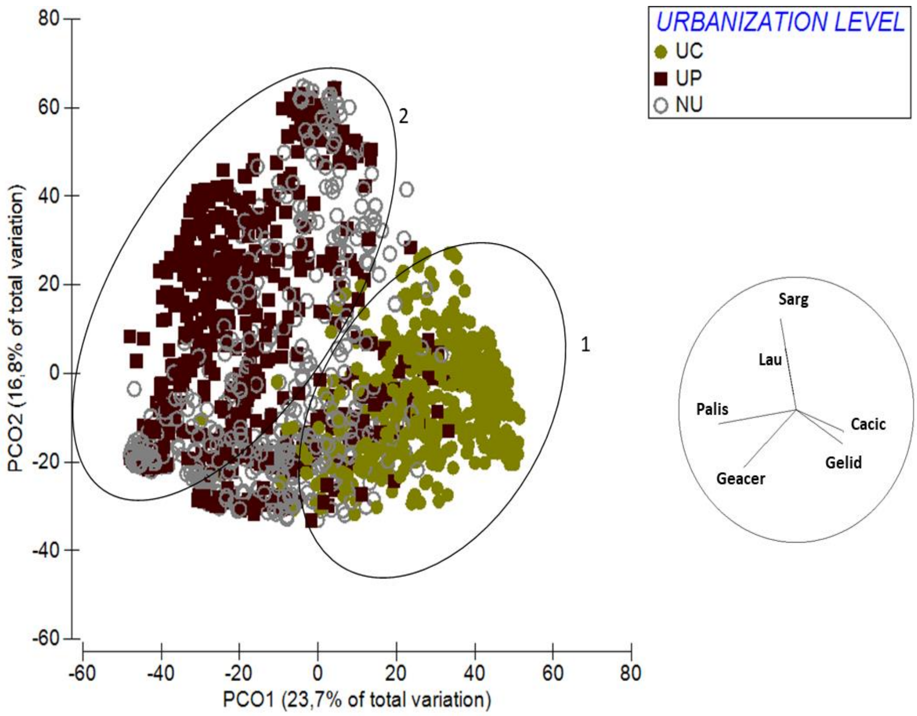


Figure 3: Graphical illustration of Principal coordinates for the "level of urbanization" factor. Circle 1 groups samples from areas of consolidated urbanization (UC), while circle 2 groups samples from areas in the process of urbanization (UP) and non-urbanized (NU). The vectors indicate multiple Pearson correlations (r <0.4) of the most representative taxa of macroalgae. Sarg: *Sargassum* spp.; Lau: *Laurencia dendroidea*; Palis: *Palisada Perforata*; Geacer: *Gelidiella acerosa*; Gelid: *Gelidium* spp.; Cacic: *Chondracanthus acicularis*.

Table 5: PERMADISP results for the level of urbanization. UC: Consolidated urbanization; UP: Under the process of urbanization; NU: Non-urbanized.

PAIRWISE COMPARISONS			**MEANS AND STANDARD ERRORS**			
Groups	**t**	**P(perm)**	**Group**	**Size**	**Average**	**SE**
(UC,UP)	7.2141	**0.001**	UC	548	45.289	0.54747
(UC,NU)	6.674	**0.001**	UP	544	50.31	0.42863
(UP,NU)	0.34293	0.771	NU	544	50.554	0.56802

4. Discussion

Our results showed Rhodophyta was dominant in richness and coverage, followed by Chlorophyta and Ochrophyta. This pattern is common in the Pernambuco continental shelf (Horta et al., 2001; Pereira et al., 2002). The low occurrence of Ochrophyta compared to other groups of algae may be related to the group's low affinity for tropical waters (Santos et al., 2006; Simões et al., 2009; Guimaraens et al., 2014). Our data revealed that urbanized regions (UC) had lower coverage (less than 3%) and number of species of Ochrophyta compared to other phyla of macroalgae. Santos et al. (2006), Simões et al. (2009) and Santos et al. (2020) reported a low number of species of brown algae in reefs of urbanized areas of Pernambuco characterized by a high level of anthropic impact. Some species of brown algae are highly sensitive to pollutants, not being able to tolerate wide variations in water quality (Dhargalkar & Komarpant, 2003).

Macroalgae communities significantly changed among areas with different levels of urbanization, with differences in the abundance, coverage, and community's descriptors (richness, diversity, and evenness). Similar variations were found when comparing urbanized and non-urbanized areas on the coast of Brazil (Martins et al., 2012; Scherner et al., 2013; Vasconcelos et al., 2019; Santos et al., 2020). Martins et al. (2012) indicated differences in species richness and diversity between urbanized and pristine areas in the south of Brazil. Schernet et al. (2013) described changes in macroalgae community coverage according to the level of urbanization, with a reduction in Rhodophyta and Ochrophyta coverage followed by an increase in Chlorophyta coverage in urbanized areas. Vasconcelos et al. (2019) observed changes in the abundance and composition of algal communities between UC, UP and NU areas, with an increase in the abundance of foliose and turf-forming algae, as well as opportunistic species such as *Ulva* spp. and *C. acicularis*, in UC areas. The PERMDISP analysis showed that there are differences between the dispersions (UC, UP and NU), however, it showed that this did not occur between the NU and UP levels, indicating that these groups have differences in position but similar dispersion. Dispersal can lead to ecological inferences, especially regarding stress in marine communities (Warwick and Clarke 1993, Chapman et al.,1995).

Areas of consolidated urbanization (UC) showed high interactions and dominance of *Gelidium* spp., *Ulva lactuca* and *Chondracanthus acicularis*. High human activity in coastal marine areas can lead to processes, such as eutrophication, which cause reductions in water quality (Le Moal et al., 2019). The fertilization of habitats caused by the discharge of sewage is one of the factors that stimulate the development of opportunistic algae, which can tolerate high loads of pollutants and can replace species sensitive to anthropogenic stressors (Bellgrove et al., 2017). The opportunistic algae *U. lactuca* has a high rate of growth and photosynthesis in environments with high concentrations of nitrogen and phosphorus, favored by its large surface area that contributes to the absorption of nutrients (Areco et al., 2021). Martins et al. (2012) and Vasconcelos et al. (2019) also observed high coverage of *Ulva* spp. in urbanized areas. The red algae *C. acicularis* has a short life history and rapid growth (Orfanidis et al., 2003), which favors dense populations in impacted environments. Scherner et al. (2013) and Vasconcelos et al. (2019), verified that *C. acicularis* exhibits high coverage in urban areas under high sewage discharges. Similarly, *Gelidium* has a fast growth and short life history (Orfanidis et al., 2003), having morphophysiological mechanisms that facilitate the assimilation of nutrients, ensuring success in impacted areas (Bellgrove et al., 2017).

Palisada perforata and *Gelidiella acerosa* were the most representatives in UP and NU areas in all years (2014, 2021 and 2022) and seasons. Studies indicate *P. perforata* and *G. acerosa* are common species in areas with low urbanization, which are not subject to intense disturbances of anthropic origin (Scherner et al., 2013; Vasconcelos et al., 2019; Santos et al., 2020). *P. perforata* is a species with a wide vertical distribution, being able to occupy different reef microhabitats, such as exposed and protected regions, plateaus, and reef pools (Vasconcelos et al., 2021), while *G. acerosa* is a perennial (Costa et al., 2002) and slow-growing species with strict tolerance to variations in salinity and pH (Rao & Mehta, 1973), showing high affinity for pristine environments (Vasconcelos et al., 2019).

The structure of macroalgae communities at all levels of urbanization varied among years (2014, 2021 and 2022), showing reductions in species richness, diversity, and evenness. Contrasting findings were verified by Lin et al. (2018), where a gradual increase in species richness was found from 2007 to 2015 in different coastal ecosystems of Taiwan, China. Changes in environmental conditions may be responsible for shifts in macroalgae communities over the years, where these changes can favor the growth of opportunistic species, causing a homogenization of communities (Lanari & Copertino, 2016). Gorman et al. (2020) reported losses of canopy-forming algae over the last 50 years in coastal regions of Brazil due to the interaction between climatic processes and urban expansion, resulting in a replacement by turf-forming species. Additionally, in 2019/2020, around 53 areas of the coast of Pernambuco were significantly affected by crude oil, (Câmara et al., 2021), among these, the beaches of Boa Viagem, Piedade, Paiva, Enseada dos Corais, Suape and Mamucabas, areas present in our study (IBAMA, 2020; Câmara et al., 2021; Campelo et al., 2021). The crude oil spill on the Brazilian coast caused significant impacts on the local economy and marine biodiversity (IBAMA, 2020), including benthic organisms such as polychaetes and sponges (Lira et al., 2021). It is possible that the oil spill contributed to reductions in macroalgae richness and diversity between 2014 (before the impact) and 2022 (after the impact). Stepaniyan (2008) observed that increasing crude oil concentrations causes reductions in the photosynthetic activity and changes in growth rate of red and brown algae species.

The total coverage of macroalgae and species abundance showed seasonal influence, with differences between the dry and rainy seasons. Costa et al. (2002) observed differences in the structure and composition of algal communities between the dry and rainy seasons in reefs in southern Bahia, Brazil. On the Pernambuco's coast, the dry season is characterized by low rainfall and high salinity (Grego et al., 2009) and temperatures (Bastos et al., 2011) and strong northeast winds that contribute to increased water transparency (Lira et al., 2010), while the rainy season exhibits low temperatures, high precipitation, and river discharge (Bastos et al., 2011), and more turbid waters (Lira et al., 2010). Seasonal variations in oceanographic conditions (salinity, nutrients, and temperature, e.g.) can cause shifts in algal communities (Guimaraens & Coutinho, 1996). Although abundance and coverage showed clear seasonal variation in our data, few differences were identified in terms of dominant species composition, with *P. perforata* and *G. acerosa* with the highest contributions in NU and UP, while *U. lactuca*, *C. acicularis* and *Gelidium* spp. in UC areas. These results agree with findings for reefs off the coast of Pernambuco by Santos et al. (2020), where few changes were found in the composition and coverage of dominant species, with *C. acicularis*, *Gracilaria* sp. and *Bryopsis pennata* J. V.

Lamouroux the species with the highest coverage in urbanized areas during the dry and rainy seasons, while *C. racemosa*, *P. perforata* and *G. acerosa* in non-urbanized areas during both seasons.

5. Conclusion

Our study identified changes in the structure and composition of macroalgal communities of tropical reefs caused by urbanization, with these changes also occurring between the dry and rainy seasons and among the years 2014, 2021 and 2022. It was observed that the species richness, diversity, and evenness descriptors varied between areas of consolidated urbanization and areas in the process of urbanization, while the abundance of algae differed between all levels of urbanization, showing that communities respond differently to anthropic impacts. In urban areas, high abundance of opportunistic algae such as *U. lactuca, Chondracanthus acicularis* and *Gelidium* spp. were found during the dry and rainy seasons in the years 2014, 2021 and 2022. The areas less urbanized had higher abundance of *P. perforata* and *G. acerosa*, species considered indicators of pristine environments. Finally, we emphasize the importance of carrying out long-term monitoring studies on tropical reefs to characterize the extent and consequences of anthropic impacts on benthic communities.

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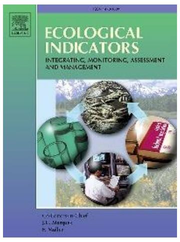
4 EFFECTS OF SEWAGE ON THE STRUCTURE AND DIVERSITY OF MACROALGAE FROM URBANIZED TROPICAL REEFS



ARTIGO A SER SUBMETIDO À REVISTA ECOLOGICAL INDICATORS

ABSTRACT

The discharge of sewage is one of the main problems for the health of coastal ecosystems. One of the alternatives to understand the impacts of wastewater on biodiversity is through biological indicators. During the dry and rainy seasons, two non-destructive sampling cycles were carried out in urban environments (1) under direct sewage discharge, (2) <100m from the outfall and (3) an area located 4 km from the outfall. Physical-chemical parameters of the water surface were collected to characterize the environments and understand the interaction of environmental variables with algal abundance. The data revealed that sewage discharge caused different responses in algal abundance, richness, diversity and evenness. *Gelidium* spp. was the most abundant taxon in areas subject to direct discharge of effluents, while *Corallina officinalis* in less impacted areas. The concentrations of NH_4^+ and PO_4^{3-} nutrients varied between the sampling sites, showing higher values in environments under the impact of sewage. Strong interactions were observed between algal abundance and environmental parameters, with PO_4^{3-} being the variable with the best explanatory power. Macroalgae responded to impacts caused by direct sewage discharge, proving to be a useful tool for analysis of reefs inserted in urbanized regions.

Keywords: wastewater; pollution indicators; vertical zonation; urbanized coastal areas; water quality

1. Introduction

The expansion of urban centers close to the sea has intensified in recent decades (Todd et al., 2019) and currently most of the world's population inhabits the coastal zone, taking food, income and services from beaches, coral reefs, and estuaries (Longhust & Pauly, 2007; Neumann et al., 2015). The increasingly use of coastal zones has led these areas to be among the most easily impacted on the planet (Morecroft et al., 2012; Burt et al., 2019). Among the numerous problems caused by urbanization, disordered occupation and irregular discharge of domestic effluents have a strong effect on water quality (Todd et al., 2019), with consequent alteration in the structure of biological communities (Arévalo et al. 2007; Alter et al., 2020; Harder et al., 2020).

Sewage is among the main sources of contaminants to coastal systems (Amin et al., 2017; Häder et al., 2020). Untreated sewage is generally rich in heavy metals, nitrogen, and phosphorus compounds (Aréco et al., 2021). The continuous input of nutrients results in the eutrophication of water bodies (Menésguen & Lacroix, 2018), supports the occurrence of harmful algal blooms and green tides, hypoxia and anoxia events and significant biodiversity losses (Le Moal et al., 2019). Coral reef ecosystems subject to effluent discharge may exhibit a replacement of the native community by macroalgae-dominated communities (Harder et al., 2020). Additionally, nitrogen flow through inland waters is especially regulated by local climate and freshwater discharge, thus regions with many coastal rivers and high rainfall tend to have higher concentrations of nitrogen compounds (Howarth, 2008).

The management and treatment of domestic effluents is a challenge in emerging countries (Wear & Turber, 2015). Although Brazil is the richest country in Latin America, sewage collection and treatment is still difficult (Vitor, 2021). It is estimated that only half of sewage is properly treated in Brazil, while the other half is discarded directly into the environment without proper treatment (IBGE, 2017). In Pernambuco (Northeastern Brazil), about 45% of the population is served with sewage collection, however, only 27% of households have adequate treatment of these waters (ANA, 2017). To encourage the provision of services that improve the Brazilian population's access to a quality sewage system, some goals were established to supply 99% of the population with drinking water and 90% with sewage collection and treatment by 2033 (Brasil, 2020).

Marine macroalgae are important components of coastal benthos, particularly in shallow areas with consolidated bottoms, where they play important roles such as oxygen production (Jung et al., 2013), food web base (Burt, 2014), calcium carbonate synthesis (Koch et al., 2013) and habitats for vertebrates and invertebrates (Tano et al., 2016; Craveiro et al., 2019). Monitoring studies using benthic organisms in hard-bottom coastal habitats have been carried out to assess extension and magnitude of anthropogenic impacts (Scherner et al., 2013; Vasconcelos et al. 2019; Leite et al., 2020). Because of their sessile character, tolerance of contrasting environmental variations, and wide distribution (García-Seoane et al., 2018; Areco et al., 2021), macroalgae have been considered excellent indicators of organic pollution, providing several qualitative and quantitative responses to environmental disturbances (Bellgrove et al., 2017; Archino & Piazzi, 2021).

Enrichment of nutrients in water can have different effects on macroalgae (Arévalo et al., 2007; Barr et al., 2020), such an increase in the growth rates (Teichberg et al., 2010), changes in coverage and intracellular contents of chlorophyll, free-amino acids, and nitrogen (Barr et al., 2020), and increased production of photosynthetic pigments (Dailer et al., 2012). At the community level, the discharge of untreated wastewater can cause changes on benthic macroalgal abundance, promoting the replacement of ecosystem-building species by opportunistic algae (Bellgrove et al., 2017), and reductions in species richness (Arévalo et al., 2007).

Most efforts to understand the effects of sewage discharge on algae focus on rocky shores in temperate regions (Arévalo et al., 2007; O'Connor, 2013; García-Seoane et al. 2019), leaving important gaps in the responses of reef communities in tropical regions to eutrophication. Thus, this study aims to describe the effects of domestic sewage discharge on the abundance and diversity of benthic macroalgae in urbanized intertidal reefs, considering short-term seasonal variations and the concentration of dissolved nutrients in the water column.

2. Materials and methods

2.1. Study area

The beaches of Boa Viagem (08°06’59.91’’S, 034°53’39.17”W) and Brasília Teimosa (8°05’09.28”S, 34°52’42.12”W) are located in the metropolitan area of Recife (Pernambuco, Brazil) (Figure 1). The area belongs to Tropical Phycogeographic Region (Horta et al., 2001), and has humid tropical climate (As) with dry summers and rainy winters (Köppen, 1936). Large sandstone reefs, composed mainly of quartz grains, occur perpendicular to the coast (Vasconcelos et al., 2019). The tidal regime is mesotidal with semidiurnal tides with amplitude ranging from 2 to 4m (Amaral et al., 2016). Vasconcelos et al. (2019), when studying the effects of urbanization on macroalgae communities along Pernambuco coast, classified Boa Viagem and Brasília Teimosa (like Pina beach) as with consolidated urbanization areas (demographic density greater than 500 inhab. Km^2).

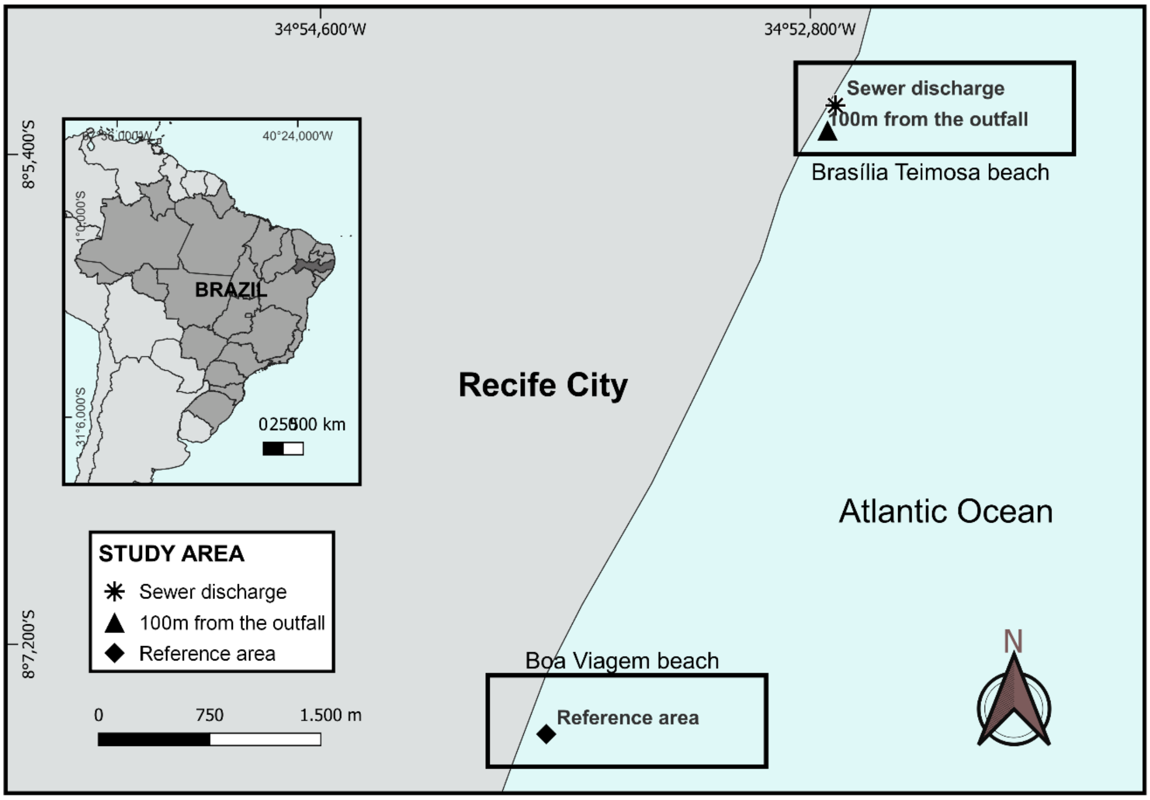


Figure 1: Map of sampling points of macroalgae communities of urbanized sandstone reefs inserted in Northeast Brazil. Site 1: Region under direct sewage discharge; Site 2: <100m from the outfall and Site 3: Reference area.

Boa Viagem is an 8 km long ocean beach located in the south of Recife (Costa et al., 2008). It is inserted in the neighborhood of the same name, which is considered one of the noblest and oldest in the municipality, with the beginning of occupation dating back to 1707 (Silva, 2016). Since the 1950s this area has undergone an intense urbanization process that has caused significant changes in the local landscape (Silva, 2016). Along the beach there are commercial and residential buildings of varying sizes, hotels, kiosks, lanes, sidewalks, walls, and public restrooms (Costa et al., 2008). In a total of 42.272 households, about 33.756 has semi-adequate sewage treatment, while 8.455 has inadequate treatment (Miranda, 2014).

Brasília Teimosa beach, where is located the discharge point (Figure 2), is mostly inhabited by low-income population (Mendes & Rubio, 2020). Until the 2000's this area was mainly occupied by unhealthy clandestine residences built on stilts close to the coast and with precarious basic sanitation (Ferreira et al., 2013; Mendes & Rubio, 2020). About 82.65% of households have access to potable water, while only 63.63% have access to the sewage system (Pereira-Filho et al., 2021). In addition, the region is subject to discharges of industrial and domestic effluents from the Port of Recife and the Pina Basin (Ferreira et al., 2010). Currently, after urban revitalization projects, Brasilia Teimosa has undergone improvements in infrastructure, with a better drainage system (Mendes & Rubio, 2020) consisting of stormwater galleries that receive the discharge of domestic sewage (figure 2).

Figure 2: Sewage output over reef systems at Brasília Teimosa beach.

2.2. Sampling design of macroalgae communities

Non-destructive sampling was carried out during the dry (December/21 and February/22) and rainy (June and July/22) seasons. Samples were taken at crescent distances from the discharge point: (1) under sewage discharge; (2) < 100m from the discharge point; (3) > 4 km from the discharge point (reference area) (figure 1). Data were obtained using the *Line Point* approach (Murray, 2002; with adaptations) along five transects placed perpendicular to the coast at each sampling site. Quadrats (25 x 25 cm - 25 contact points) were placed every three meters (1m, 3m, 6m and 9m) along the transect, covering the middle and upper-lower intertidal zones of the reef. Macroalgae were identified to the lowest possible taxonomic level.

2.3. Sampling design and analysis of environmental variables

Water samples (three per site) were taken at the same sites of macroalgae sampling, 15 and 7 days before and on the day of algae sampling. In laboratory water samples were filtered using vacuum pumps and glass microfiber filters (GF/C) with 47 mm in diameter. To avoid photodegradation of the pigments, the filters were placed in 14 mL Falcon tubes and wrapped in aluminum foil, then frozen until future chlorophyll analysis. From the filtered water 300 mL aliquots were taken to measure the concentrations of nitrite, nitrate, ammonia, and phosphate. The contents of dissolved inorganic nutrients and chlorophyll were estimated using spectrophotometric methods. Nitrite and nitrate were measured according to García-Robledo et al. (2014), ammonia according to Bower and Holm-Hansen (1980) and phosphate by Grasshof et al. (1983). Chlorophyll data was obtained through methods proposed by UNESCO (1966) with values expressed in mg/m^3. Rainfall data were collected for the sampling day from reports provided by Agência Pernambucana de Águas e Clima (APAC, 2022).

2.4. Data analysis

For each sample, the descriptors of communities richness (total number of taxa), evenness (Pielou index – J), diversity (Simpson index – 1- λ) and macroalgae total coverage calculated. These data were fourth root transformed and tested for normality and homoscedasticity using the Kolmogorov-Smirnov and Bartlett tests, respectively. Since data were not normally distributed, Kruskal-Wallis test was performed for comparisons considering as fixed factors discharge point and season. These analyses were performed using STATISTICA v10 (Statsoft, 2011).

Environmental data (log x+1) and resemblance matrices were calculated using Bray-Curtis similarity index (biological data) and Euclidian distance (abiotic data). To compare the structure of macroalgae communities and environmental characteristics, Permutational Multivariate Analysis of Variance (PERMANOVA) was employed considering sewage distance (0, <100m and >4 Km from the discharge point) and season (dry x rainy) as fixed factor. Pair-Wise tests were applied when PERMANOVA results were significant. To assess the spatial patterns of communities and environmental characteristics Canonical Analysis of Principal Coordinates (CAP) were performed. For PERMANOVA and CAP data were transformed (frequency of occurrence of each macroalgae) on fourth root. The contribution of each taxon to the similarity of samples from sewage, season and combination of sewage x season groups was assessed using SIMPER (Anderson et al., 2008). Distance-based Linear Model (DistLM) analysis was used to fit models that best explained the relationship between macroalgae and environmental characteristics. After fitting DistLM models, a dbRDA analysis was employed to illustrate the interactions between environmental parameters and macroalgae communities. All multivariate analyses were performed using the PRIMER 6 + Permanova (Clark & Warwick, 2005; Anderson et al., 2008). For all analyses a level of significance of 5% was considered.

3. Results

3.1. Environmental variables

The highest mean NH_4^+ values were recorded in the area under direct sewage discharge during the rainy season (4.26±9.07 µmol/L^{-1}) and the lowest value in the reference area in the same season (0.2±0.15 µmol/L^{-1}) (table 1). NO_2 average concentrations ranged from 0.94±0.55 µmol/L^{1} in the direct sewage discharge area during the dry season to 0.34±0.18 µmol/L^{-1} in the reference area during the rainy season (table 1). A similar pattern was observed for NO_3^-, with a maximum value in the area under direct sewage discharge during the dry season (7.4±2.85 µmol/L^{-1}) and a minimum value in the reference area during the rainy season (3.72±2µmol/L^{-1}) (table 1). The PO_4^{3-} maximums were recorded in the rainy season in the area under direct sewage discharge (3.98±8.08 µmol/L^{-1}) and the minimums in the reference area during the dry season (0.19±0.1 µmol/L^{-1}) (table 1). Chlorophyll ranging between 4.45±6.11 and 1.15±0.53 mg/m^{-3}, with higher values in the dry season and lower values in the rainy season in the reference areas (table 1). The temperatures ranging from 29.4 to 29.5°C during the dry season, and 27.8 to 27.9°C during the rainy season (table 1; table 2). Rainfall was higher in the rainy season (8.96 mm) than in the dry season (3.81

mm) (table 1; table 2). Salinity ranged from 34.4 to 31.2, being higher in the dry season than in the rainy (table 1; table 2).

Kruskal-Wallis tests indicated seasonal differences for NO_2 ($p < 0.0001$), chlorophyll ($p < 0.002$), rainfall ($p < 0.02$), temperature ($p < 0.0001$), and salinity ($p < 0.0001$) (table 1). The presence of the sewage outfall caused significant changes in NH_4^+ and PO_4^{3-} concentrations. NH_4^+ varied between under sewage discharge area and reference area ($p < 0.05$) but did not differ between sites under sewage discharge and <100m from the outfall ($p > 0.05$), and between < 100m from the outfall and reference area (figure 3a). The PO_4^{3-} contents varied between under sewage discharge area and reference area ($p < 0.0001$), and between <100m from the outfall and reference site ($p < 0.01$) (figure 3d). Temperature, salinity, rainfall, NO_2, NO_3^- and chlorophyll a did not statistically vary between study areas ($p > 0.05$; figure 3). PERMANOVA showed that the environmental parameters varied between the dry and rainy seasons, however, no differences were verified between the sampling areas (table 3).

Table 1: Mean values of environmental variables at the site under direct sewage discharge (Sewer), < 100m to sewer and reference area throughout the dry and rainy seasons. NH_4^+: ammonia; NO_2: nitrite; NO_3^-: nitrate; PO_4^{3-}: phosphate. (Mean ± SD).

	Dry			**Rainy**		
	Sewer	**<100m**	**Reference**	**Sewer**	**<100m**	**Reference**
NH_4^+ (µmol/L^{-1})	0.89±0.42	0.34±0.27	0.29±0.23	4.26±9.07	0.34±0.2	0.2±0.15
NO_2 (µmol/L^{-1})*	0.94±0.55	0.78±0.28	0.62±0.32	0.72±0.79	0.35±0.15	0.34±0.18
NO_3^- (µmol/L^{-1})	7.4±2.85	7.12±2.72	4.48±2.8	5.31±2.82	3.88±2.99	3.72±2
PO_4^{3-} (µmol/L^{-1})	0.76±0.37	0.55±0.2	0.19±0.1	3.98±8.08	0.36±0.13	0.28±0.12
Chlorophyll a (mg/m^3)*	2.06±1.04	2.06±0.96	4.45±6.11	1.27±0.53	1.38±0.4	1.15±0.53
Temperature (°)*	29.35±0.24	29.36±0.29	29.53±0.34	27.91±0.72	27.85±0.84	27.81±0.86
Salinity (%)*	34.2±0.19	34.4±0.17	34.3±0.19	31.2±0.15	31.2±0.14	31.6±0.12
Rainfall (mm)*	3.81±5.52	3.81±5.52	3.81±5.52	8.96±8.25	8.96±8.25	8.96±8.25

*Indicates significant differences from the Kruskal-Wallis test for the season factor (p < 0.05).

Table 2: Results of environmental parameters of areas under sewage discharge, <100m from outfall and reference.

	Dry season																	
	December/21									**February/22**								
	Sewer			**100m**			**Reference area**			**Sewer**			**100m**			**Reference area**		
Variable	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**
NH_4^+ (µmol/L^{-1})	1.37	0.16	0.91	0.22	0.04	0.28	0.09	0.15	0.01	1.13	0.96	0.86	0.90	0.32	0.30	0.66	0.47	0.37
NO_2 (µmol/L^{-1})	2.00	0.49	0.57	1.19	0.37	0.66	1.23	0.54	0.30	0.81	0.86	0.92	0.71	0.79	0.97	0.68	0.48	0.51
NO_3^- (µmol/L^{-1})	10.61	2.84	5.32	7.02	2.92	5.04	8.82	1.73	1.94	8.78	8.30	8.60	8.79	8.05	10.91	6.61	3.72	4.08
PO_4^{3-} (µmol/L^{-1})	0.33	0.56	0.61	0.43	0.52	0.24	0.21	0.06	0.21	0.63	1.32	1.14	0.58	0.71	0.83	0.34	0.19	0.15
Chlorophyll a (mg/m^3)	1.44	4.06	2.35	1.29	3.47	2.37	1.47	17.64	3.30	1.62	1.06	1.86	1.12	1.21	2.93	0.81	1.51	1.98
Rainfall (mm)	0.2	1.2	14.1	0.2	1.2	14.1	0.2	1.2	14.1	0	0	7.4	0	0	7.4	0	0	7.4
Temperature (°)	29.49	29.06	29.11	29.61	28.95	29.14	29.73	29.52	28.89	29.71	29.39	29.39	29.71	29.52	29.24	29.91	29.49	29.69
Salinity (%)	38.1	33.2	33.4	37.8	34.5	33.5	38.2	34.6	33.8	32.8	33.8	34.3	32.9	33.9	34.0	32.5	33.7	33.5

	Rainy season																	
	June/22									**July/22**								
	Sewer			**100m**			**Reference area**			**Sewer**			**100m**			**Reference area**		
Variable	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**	**Day 15**	**Day 7**	**Day 0**
NH_4^+ (µmol/L^{-1})	0.61	0.11	23.69	0.47	0.00	0.37	0.13	0.00	0.33	0.59	0.41	0.19	0.45	0.58	0.20	0.10	0.43	0.26

NO_2 (µmol/L^{-1})	0.61	0.21	2.42	0.57	0.17	0.18	0.40	0.23	0.09	0.39	0.44	0.31	0.44	0.44	0.31	0.66	0.44	0.24
NO_3^- (µmol/L^{-1})	8.86	1.26	5.95	8.92	1.08	0.57	4.51	3.33	2.63	2.87	4.86	8.09	2.79	4.21	5.74	6.04	3.63	2.20
PO_4^{3-} (µmol/L^{-1})	0.62	0.24	21.27	0.56	0.18	0.25	0.46	0.12	0.13	0.76	0.45	0.55	0.39	0.37	0.45	0.33	0.35	0.29
Chlorophyll a (mg/m^3)	1.97	1.66	1.07	1.15	1.42	0.77	1.92	1.54	0.95	0.86	0.93	1.14	1.95	1.63	1.40	0.59	1.15	0.79
Rainfall (mm)	18	5.2	2.2	18	5.2	2.2	18	5.2	2.2	7.2	21.2	0	7.2	21.2	0	7.2	21.2	0
Temperature (°)	28.39	28.52	28.55	28.33	28.47	28.93	27.93	28.46	28.97	26.96	27.07	28.00	26.86	27.02	27.54	27.07	26.58	27.90
Salinity (%)	28.3	31.9	31.4	28.6	32.2	30.9	29.2	32.2	32.3	32.9	31.5	31.6	32.3	31.1	32.2	32.7	31.2	32.3

Tabela 3: PERMANOVA results for environmental parameters considering season (SE) and sewage (SI) factors, and their combination.

Source	**df**	**SS**	**MS**	**Pseudo-F**	**P(MC)**
SE	1	15.34	15.34	3.3759	**0.028**
SI	2	20.013	10.006	2.2022	0.058
SExSI	2	8.5612	4.2806	0.94206	0.465
Res	42	190.84	4.5439		
Total	47	235			

DF: Dregree of freedom; SS: Sun of square; MS: Mean of square.

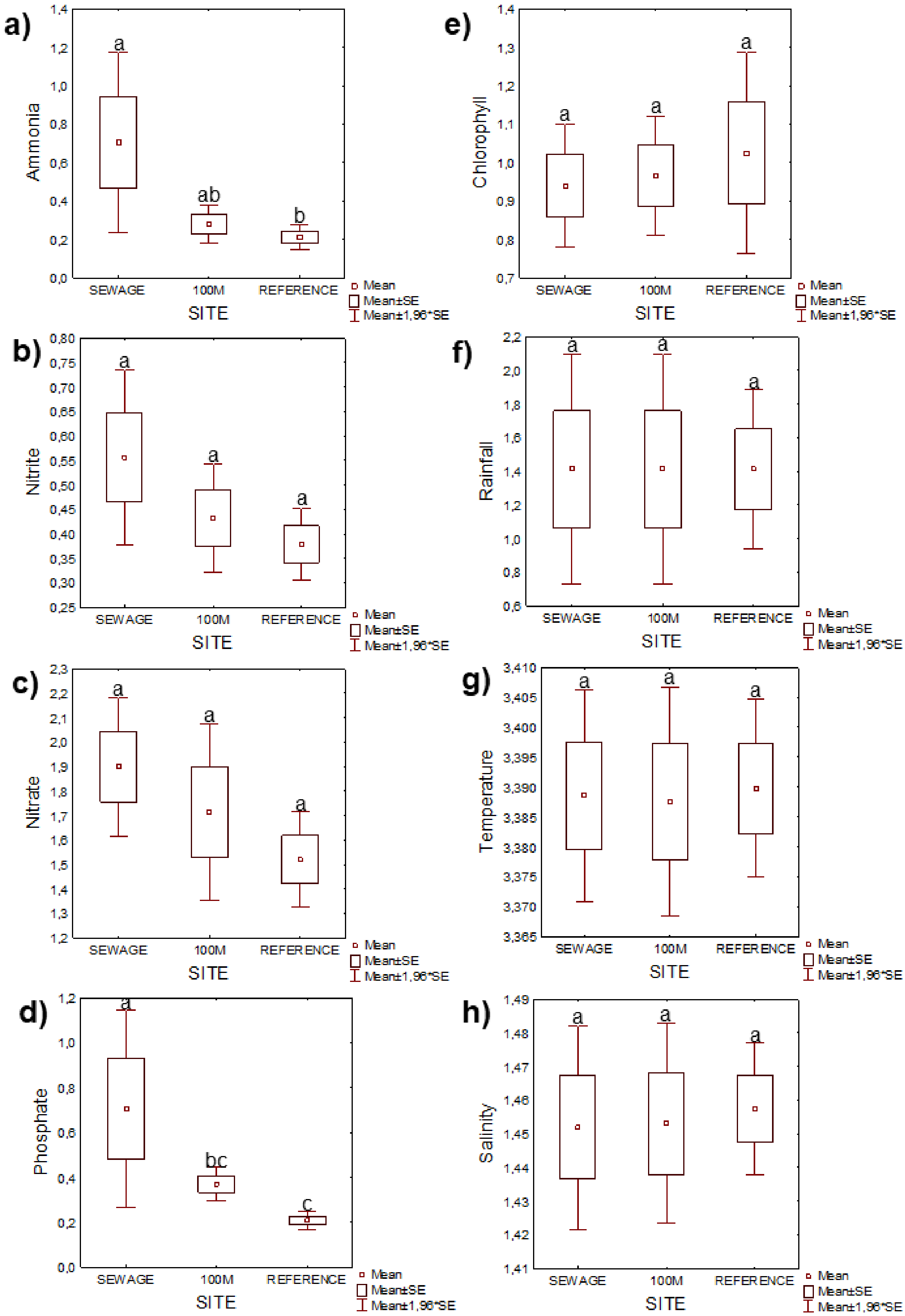


Figure 3: Boxplot for environmental parameters under sewage discharge, <100m from outfall and reference area.

3.2. Macroalgae responses to sewage discharge

36 taxa of macroalgae were identified in a total of 319 samples, which were taxonomically distributed in Rhodophyta (24), Chlorophyta (9) (Ulvophyceae) and Ochrophyta (Phaeophyceae) (3). Rhodophyta was the Phylum with highest coverage during dry and rainy seasons in all study areas, followed by Chlorophyta and Ochrophyta (table 3). Brown algae showed minimal coverage values, being absent in areas under sewage discharge (table 4). Total coverage of algae was significantly higher in reference areas than in other areas, showing differences between sewage discharge area and reference area ($p < 0.0001$) and between <100m of sewage and the reference area ($p < 0.0001$) (figure 4a). However, total coverage did not respond to seasonality, no differences were found between the dry and rainy seasons (figure 4d).

Richness (S), Pielou's evenness (J') and Simpson's diversity (1-Lambda') responded significantly to sewage discharge (figure 4b-d). The richness, evenness, and diversity differed between the area under sewage discharge and the reference area (S: $p < 0.0001$; J': $p < 0.05$; 1-Lambda': $p < 0.0001$; figure 4b-d), while <100m from the sewer and the reference area showed differences for richness and diversity (S: $p < 0.0001$; 1-Lambda': $p < 0.0001$; figure 4b-d). No statistical differences were observed for diversity descriptors between the sewage discharge area and <100m of sewage ($p > 0.05$; figure 4b-d). Overall, values for richness, diversity and evenness were higher in reference areas than in areas under sewage discharge and <100m from the outfall. Seasonality had no individual effects on diversity descriptors ($p > 0.05$; figure 4e-h).

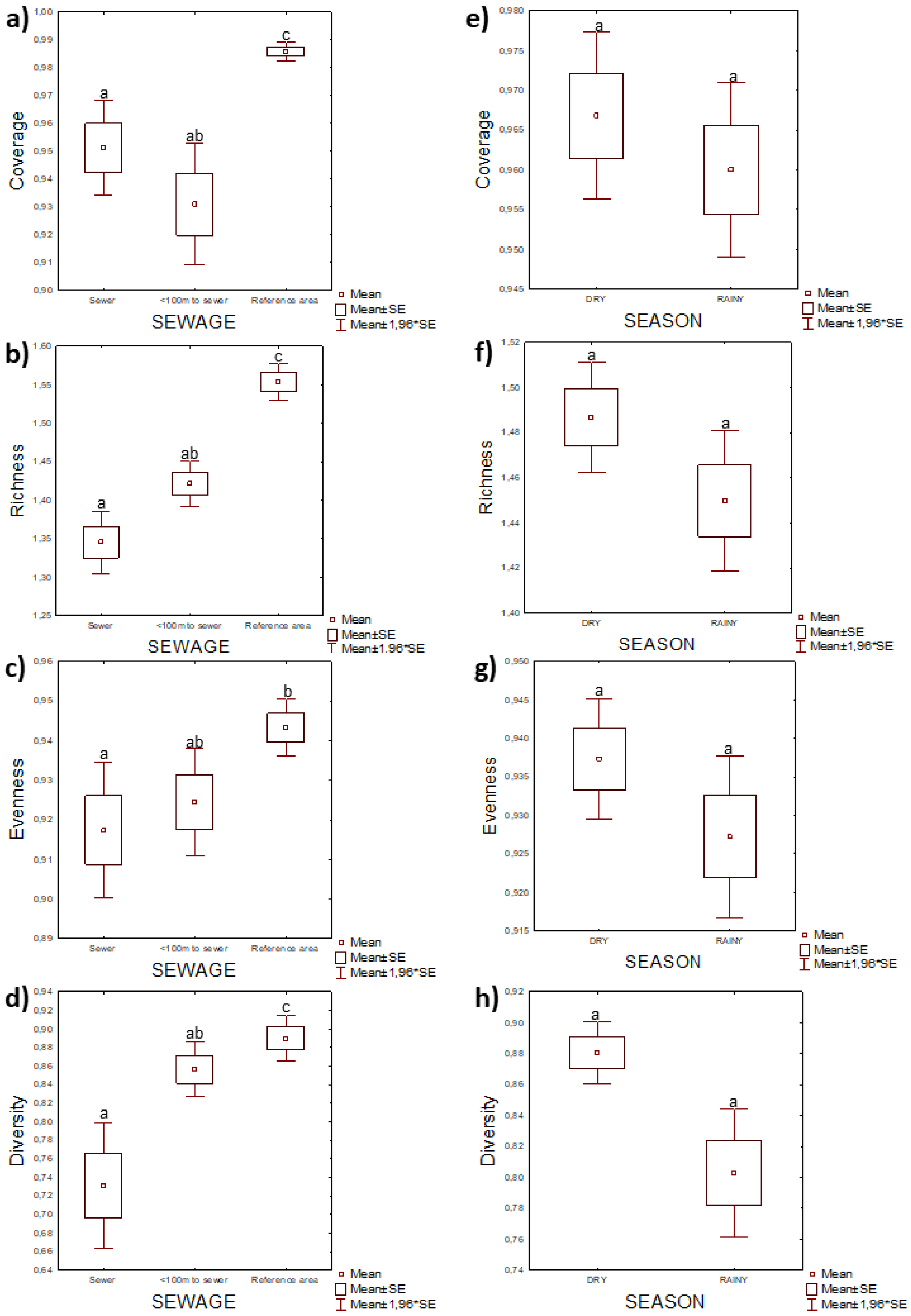


Figure 4: Boxplot for the diversity descriptors for the sewage and season factors indicated by Kruskal-Wallis analysis.

Table 4: List of macroalgae taxa and their respective relative abundances in areas under direct influence of sewage, < 100m from the outfall and reference site throughout the dry and rainy seasons. "-" indicates absence of the taxon.

	Sewer		**< 100m to sewer**		**Reference site**	
	Relative abundance (%)		**Relative abundance (%)**		**Relative abundance (%)**	
Composition	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**
Chlorophyta						
Bryopsis sp.	1.9	0.8	3.9	6.8	14.9	6.5
Caulerpa cupressoides (Vahl) C. Agardh	-	-	-	-	6.8	1.6
Caulerpa fastigiata Montagne	-	-	-	1.6	0.3	0.2
Caulerpa mexicana Sonder ex Kützin	-	-	-	-	8.1	1.3
Chaetomorpha antennina (Bory) Kützing	-	0.6	0.6	0.9	-	-
Cladophora sp.	0.3	1.4	1.6	1.5	1.1	0.3
Rhizoclonium sp.	9.6	5.8	-	-	-	-
Ulva lactuca L.	11.3	1.9	14.5	19.1	4.7	6.1
Ulva flexuosa Wulfen	1.5	1.3	-	-	0.1	-
Phyllum coverage	**24.6**	**11.8**	**20.6**	**29.9**	**36.0**	**15.8**
Rhodophyta						
Acanthophora spicifera (M.Vahl) Børgesen	-	-	-	-	0.2	0.2
Alsidium seaforthii (Turner) J. Agardh	1.2	0.8	-	-	0.1	0.1
Amansia multifida J. V. Lamouroux	-	0.1	-	-	0.1	0.3
Centroceras clavulatum (C.Agardh) Montagne	0.2	0.1	0.6	-	0.1	-
Ceramiaceae	0.5	-	1.4	-	-	0.2
Ceratodictyon variabile (J.Agardh) R. E. Norris	8.9	4.0	5.0	2.1	2.0	5.8
Chondracanthus acicularis (Roth) Fredericq	13.6	3.9	12.4	6.0	4.5	10.1
Corallina officinalis L.	2.3	3.0	8.6	8.5	16.4	21.5
Cryptonemia spp.	1.1	4.7	-	-	1.0	0.2

Gelidiella acerosa (Forsskål) Feldmann & Hamel	0.3	-	4.0	4.3	4.6	5.9
Gelidium spp.	17.0	43.9	21.0	19.2	8.4	11.7
Gelidium lineare Iha & Freshwater	0.9	-	-	-	-	-
Gracilaria spp.	6.7	2.5	2.3	3.5	7.0	10.3
Gracilaria caudata J. Agardh	-	-	-	-	0.1	-
Gracilaria domingensis (Kützing) Sonder ex Dickie	0.2	-	-	-	0.1	-
Grateloupia sp.	-	-	-	-	-	0.2
Hypnea spp.	5.3	0.8	0.6	0.7	5.5	5.4
Jania sp.	2.0	3.1	0.6	1.2	-	-
Laurencia sp.	-	-	-	-	0.1	-
Laurencia dendroidea J. Agardh	0.5	-	-	-	0.3	0.6
Palisada furcata (Cordeiro-Marino & M. T. Fujii) Cassano & M. T. Fujii	-	-	-	-	0.1	-
Palisada perforata (Bory) K.W.Nam	0.3	-	1.1	0.7	4.4	3.6
Vidalia obtusiloba (Mertens ex C. Agardh) J. Agardh	-	0.1	-	-	0.2	0.4
Non-articulated calcareous algae	1.7	3.3	3.1	1.5	2.2	1.9
Phyllum coverage	**62.7**	**70.3**	**60.7**	**47.7**	**57.1**	**78.0**
Ochrophyta						
Dictyopteris sp.	-	-	-	-	1.6	0.9
Dictyota sp.	-	-	-	-	-	0.1
Padina sp.	-	-	0.1	-	0.1	0.1
Phyllum coverage	**-**	**-**	**0.1**	**-**	**1.6**	**1.0**
Macroalgae total coverage	**87.3**	**81.4**	**94.7**	**82.1**	**77.6**	**94.8**

PERMANOVA indicated that algal abundance responded to sewage discharge and short-term seasonal variations (table 5). Differences were verified between under sewage discharge area and <100m from the outfall ($p < 0.001$), between <100m from the outfall and reference area ($p < 0.001$), and between under sewage discharge area and reference area ($p < 0.001$) (table 6). SIMPER analysis shown *Gelidium* spp. (56.2%), *Ulva lactuca* (11.4%) and *Chondracanthus acicularis* (11.3%) were most abundant taxa in areas under sewage discharge, while *U. lactuca* (30.1%), *Gelidium* spp. (23.8%) and *C. acicularis* (18.1%) in <100m of the outfall, and *Corallina officinalis* (18.9%), *Gracilaria* spp. (14.1%) and *Gelidium* spp. (13.1%) in the reference area. CAP explained 66.77% of the total data variation, in which it was possible to observe *Gelidium* spp. were more related to samples from the environment that receives direct demands from sewage, while *U. lactuca* showed a strong interaction with the area <100m from outfall, characterized by receiving less intermediate influence from sewage water. Finally, *C. officinalis* and *Gracilaria* sp. showed strong interaction with the reference site, which is not under the sewage outfall regime (figure 5).

The combination of sewage and season factors showed significant interactions, indicating changes in algal abundance between the dry and rainy seasons in areas under sewage discharge, <100m from the outfall and reference (table 6). Throughout the dry season, SIMPER analysis revealed *U. lactuca* (32.7%), *Gelidium* spp. (26.4%) and *C. acicularis* (16.2%) as the most abundant species in the area under sewage discharge, while *Gelidium* spp. (29.4%), *C. acicularis* (22.8%) and *U. lactuca* (20.9%) in <100m from outfall, and *Bryopsis* spp. (23%), *C. officinalis* (16.5%) and *Gelidium* spp. (11.6%) in reference areas. On the other hand, during the rainy season, *Gelidium* spp. (81.5%) and *C. acicularis* were more dominant in areas under sewage discharge, while *U. lactuca* (40%), *Gelidium* spp. (18.3%) and *C. acicularis* (13.6%) in <100m from outfall, and *C. officinalis* (20.4%), *Gracilaria* spp. (16.1%) and *Gelidium* spp. (14%) in reference areas.

Table 5: PERMANOVA results for data on frequency of occurrence of macroalgae communities. SEW = Sewage; SEA = Season.

Source	df	SS	MS	Pseudo-F	P(perm)
SEW	2	94838	47419	21.884	**0.001**
SEA	1	4705.5	4705.5	2.1716	**0.039**

SEWxSEA	2	33102	16551	7.6383	**0.001**
Res	313	6.78E+05	2166.8		
Total	318	8.11E+05			

DF: Dregree of freedom; SS: Sun of square; MS: Mean of square.

Table 6: Result of Pairwise tests (PERMANOVA) for the factors sewage (SEW), season (SEA) and the interaction between these (SEWxSEA) along the sites under direct influence of the sewage (Sewer), < 100m from the outfall (<100m) and reference area (Reference).

PAIR-WISE TESTS			**Term 'SEWxSEA'**					
Term 'SEW'			**Level 'DRY'**			**Level 'RAINY'**		
Groups	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**	**Groups**	**t**	**P(perm)**
Sewer, <100m	3.06	**0.001**	Sewer. <100m	1.63	**0.029**	Sewer. <100m	3.88	**0.001**
Sewer, Reference	5.67	**0.001**	Sewer. Reference	3.94	**0.001**	Sewer. Reference	5.24	**0.001**
<100m, Reference	4.56	**0.001**	<100m. Reference	3.54	**0.001**	<100m. Reference	3.56	**0.001**

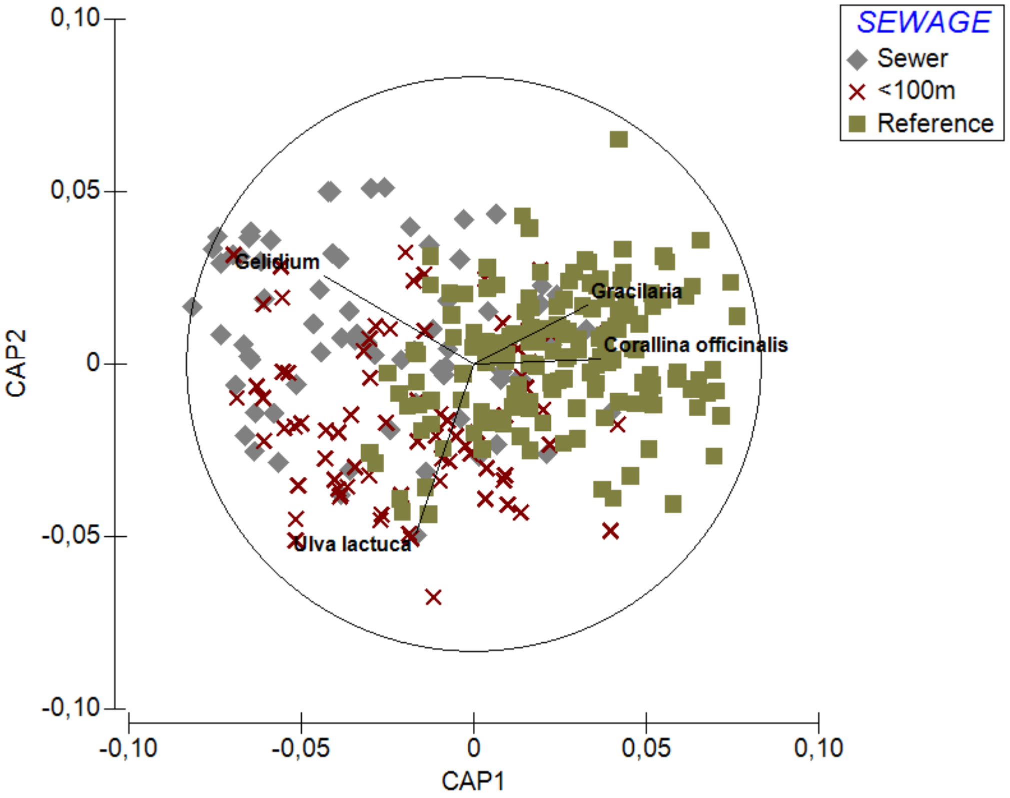


Figure 5: Plot of the Canonical Analysis of Principal Coordinates (CAP) from sites under direct sewage discharge (sewer), <100m away from the outfall (<100m) and reference area (Reference). Vectors show taxa indicated by Pearson's correlation (>0.4).

To identify environmental variables inserted in a sampling delay of 15, 7 and 0 days best relate to macroalgal communities, marginal and sequential tests were performed using a distance-based linear model (DistLM). The results of marginal tests show how much each variable explains when taken alone, ignoring all other variables. Here, we see (Table7) that in Day 15 the Phosphate explains a significant amount of about 32% of the variation in the macroalgae communities (p = 0.002). Sequential are the conditional testes of individual variables done in the order specified. The Day 15 delay, ammonia, nitrite, nitrate and phosphate contributes to explain about 59% of the macroalgae communities variation (Table 8). In other hand, in the Day 7 delay the temperature was the significant variable and with ammonia, nitrite, nitrate, phosphate and Rainfall explains 68% of total variation in macroalgal communities. The dbRDA ordination graph was applied to determining how much of the fitted model variation is captured by the two axes of the plot. The physical-chemical variables of water 15 before biological sampling explained 58.21% of the total data variation and 81,6% of adequacy of the plot to fitted model, where it is possible to observe a sewage impact gradient from left to right, with samples from impacted environments on the left, more susceptible to high concentrations of phosphate and ammonia, the samples from non-impacted areas on the right.

Table 7: Result of marginal tests of DistLM for environmental variables collected 15, 7 and 0 days before sampling the macroalgae communities.

DAY 15				
Variable	**SS(trace)**	**Pseudo-F**	**P**	**Variation (%)**
Ammonia	967.85	1.63	0.161	14%
Nitrite	897.29	1.49	0.178	13%
Nitrate	697.21	1.12	0.307	10%
Phosphate	2208.6	4.70	**0.002**	32%
Rainfall	261.15	0.39	0.865	4%
Temperature	451.66	0.70	0.622	7%
Salinity	429.57	0.66	0.675	6%
DAY 7				
Variable	**SS(trace)**	**Pseudo-F**	**P**	**Variation (%)**
Ammonia	305.49	0.46	0.82	4%
Nitrite	190.39	0.28	0.96	3%
Nitrate	282.8	0.43	0.85	4%
Phosphate	752.72	1.22	0.29	11%
Rainfall	457	0.71	0.64	7%
Temperature	345.65	0.53	0.80	5%
Salinity	387.54	0.59	0.72	6%
DAY 0				
Variable	**SS(trace)**	**Pseudo-F**	**P**	**Variation (%)**
Ammonia	549.83	0.86	0.429	8%
Nitrite	766.16	1.25	0.258	11%
Nitrate	1275.6	2.26	0.052	18%
Phosphate	584.14	0.92	0.389	8%
Rainfall	537.12	0.84	0.488	8%

Temperature	419.05	0.65	0.678	6%
Salinity	489.38	0.76	0.576	7%

SS: Sun of square.

Table 8: Sequential tests (DistLM) for predictive environmental variables of macroalgae communities.

DAY 15						
Variable	**AIC**	**SS(trace)**	**Pseudo-F**	**P**	**Variation (%)**	**Cumulative (%)**
Ammonia	78.46	967.85	1.63	0.17	14%	14%
Nitrite	78.24	1002.80	1.83	0.12	15%	29%
Nitrate	78.48	673.32	1.26	0.28	10%	38%
Phosphate	75.51	1448.40	3.60	**0.02**	21%	59%
Rainfall	76.23	284.43	0.67	0.63	4%	63%
Temperature	77.63	123.14	0.26	0.92	2%	65%
Salinity	77.31	423.83	0.85	0.51	6%	71%
DAY 7						
Variable	**AIC**	**SS(trace)**	**Pseudo-F**	**P**	**Variation (%)**	**Cumulative (%)**
Ammonia	79.73	305.49	0.46	0.82	4%	4%
Nitrite	81.11	332.31	0.48	0.81	5%	9%
Nitrate	82.05	527.28	0.73	0.58	8%	17%
Phosphate	80.98	1298.9	2.04	0.10	19%	36%
Rainfall	82.14	298.82	0.43	0.77	4%	40%
Temperature	76.77	1904.4	4.25	**0.02**	28%	68%
Salinity	77.38	245.83	0.49	0.72	4%	71%
DAY 0						
Variable	**AIC**	**SS(trace)**	**Pseudo-F**	**P**	**Variation (%)**	**Cumulative (%)**
Ammonia	79.28	549.83	0.86	0.40	8%	8%
Nitrite	80.29	503.53	0.77	0.54	7%	15%
Nitrate	78.76	1491.4	2.73	0.07	22%	37%
Phosphate	79.42	460.3	0.83	0.52	7%	43%
Rainfall	80.36	330.21	0.55	0.74	5%	48%
Temperature	80.88	415.92	0.66	0.61	6%	54%

Salinity	77.43	1152.1	2.30	0.13	17%	71%

SS: Sun of square.

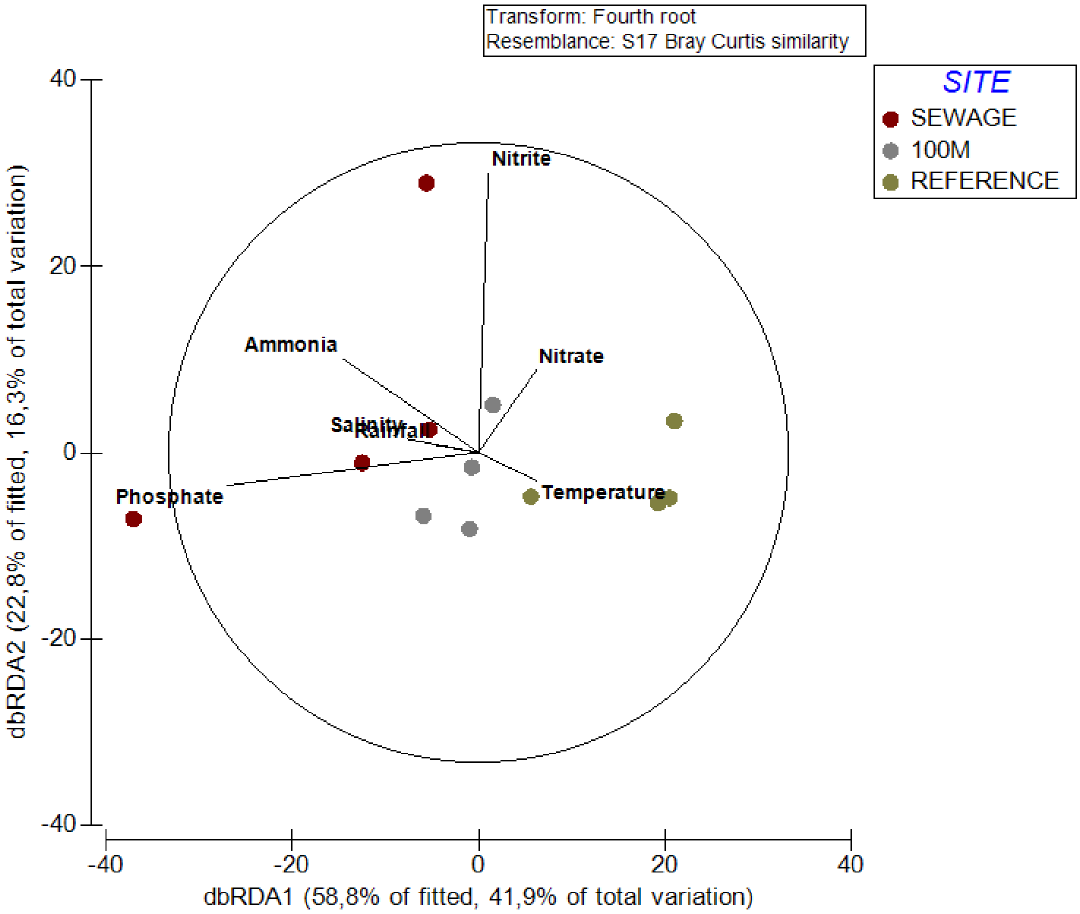


Figure 6: Distance-based redundancy analysis (dbRDA) illustrating the DistLM model based on environmental variables collected 15 days before biological sampling for the sewage (site) factor.

4. Discussion

Environmental parameters responded to short-term seasonal variations, showing differences between the dry and rainy seasons. Temperature, rainfall, salinity, and chlorophyll were the variables that best reflected these variations. Despite located in the tropics, the climate in Northeast Brazil changes substantially between seasons, with high rainfall and low temperatures and salinity during the winter, and low rainfall and high temperatures and salinity during the summer (Barros et al., 2011; Cordeiro et al., 2014). Chlorophyll showed a distinct pattern between seasons, with higher concentrations during dry season than in rainy season. Similar findings were observed by Cordeiro et al. (2014) in areas of Pernambuco near the port of Recife. High temperatures associated with availability of nutrients can stimulate phytoplankton growth and photosynthesis, resulting in high levels of chlorophyll (Häder & Gao, 2015).

Our results indicated ammonia and phosphate contents varied significantly between environments that receive different impacts from sewage discharge. Brauko et al. (2020) pointed that the increase in the human population associated with low sewage treatment favors the increase of nutrients and organic matter. The input of organic components rich in macromolecules, such as proteins and nucleic acids, may favor the increase in the levels of ammonia available in ecosystems through ammonification processes (Herbert, 1999). Similarly, Tayeb et al. (2015) indicate that inadequate sewage treatment contributes to increased concentrations of phosphorus in the aquatic environment, which certainly influenced the increase in phosphate in areas under sewage discharge and <100m from the outfall.

Macroalgae communities responded significantly to sewage release, showing changes in total coverage, richness, evenness, and diversity along a distance gradient from the polluting source. In general, reference areas had higher values of coverage, richness, evenness, and diversity than areas under direct and intermediate impact of sewage. Algae respond to a eutrophication gradient, showing changes in species abundance according to the level of proximity to the sewer point (Pinedo et al., 2015). Areas close to sewers tend to have lower species richness and high abundance of opportunistic algae such as *Ulva* spp., with nutrient concentrations being one of the main predictors of algal abundance (Arévalo et al., 2007). Additionally, our data revealed seasonal effects on macroalgae species abundance, with differences between areas under direct sewage discharge, <100m from the outfall and reference areas. Changes in precipitation between dry and rainy seasons can alter the volume, dilution, and residence time of wastewater, contributing to availability of nutrients (Barile, 2018). In addition, the input of fresh water can decrease salinity, causing a reduction in the growth of macroalgae species (Fong et al., 1996; Martins et al., 1999).

Dissolved nutrient concentrations, especially phosphate, were positively related to algal communities in environments that receive interference from sewage discharge (direct discharge and <100m from the outfall), exhibiting high dominance of opportunistic species. Pinedo et al. (2015) observed that a phosphate input via domestic sewage caused an increase in macroalgae abundance off the coast of Spain. The presence of sewage outfalls in urban centers close to marine regions facilitates the enrichment of nitrogen and phosphorus, causing changes in the structure of benthic communities (Alter et al., 2020). Thus, the coverage and taxonomic composition of macroalgae communities are strongly influenced by the concentrations of nutrients present in the water column, and areas close to sewers have a high abundance of opportunistic algae (Bellgrove et al., 1997; Arévalo et al., 2007; Bellgrove et al., 2017).

Throughout the study, *Gelidium* was the most representative taxon in areas under direct sewage discharge. Orfanidis et al. (2003) include *Gelidium* in a class of opportunistic organisms characterized by foliose or filamentous morphology, with fast growth and short life history. Brown et al. (1990) observed high abundances of *Gelidium pusillum* in areas near sewage discharges off the coast of Australia. Terlizzi et al. (2002) describe *Gelidium* and *Pterocladiella* as typical algae from waters rich in organic pollutants. *U. lactuca* had high contributions to the total abundance of communities in areas <100m from outfall. *U. lactuca* is a fast-growing species with high nutrient assimilation rates and, because it has a large surface area composed of thin cell layers, it can have good interactions with chemical components present in seawater (Areco et al., 2021). Teichberg et al. (2010) and Barr et al. (2020) indicate that nitrogen and phosphorus concentrations can cause changes in *Ulva* spp., with higher coverage values in areas rich in nutrients. *C. acicularis* was co-abundant on reefs under direct sewage discharge and <100m from the outfall. Scherner et al. (2013) and Vasconcelos et al. (2019) observed high abundances of *C. acicularis* in ecosystems under the impact of organic pollutants. In reference areas, *C. officinalis* was the most representative species. Brown et al. (1990) and Bellgrove et al. (1997) observed higher abundances of *C. officinalis* in areas do not close to sewers. Studies indicate that factors such as pH and CO_2 concentrations cause changes in the growth rate and physiology of *C. officinalis* (Hoffmann et al., 2012). Bellgrove et al. (2017) suggest that *C. officinalis* has better growth rates in intermediate impact environments, as the release of effluents with high phosphate loads can affect the process of calcification of cell walls, compromising the survival of populations.

5. Conclusions

Macroalgae communities responded to sewage discharge, showing differences in total coverage, evenness, diversity, and species richness between under discharge areas and reference areas. The abundance of macroalgae species showed strong variations between the dry and rainy seasons, so it is possible to infer that the impact of sewage discharge is reflected in short-term seasonal variations. The composition of dominant species was different between the studied areas, *Gelidium* spp. showed high contribution in the environment under sewage discharge, while *Ulva lactuca* and *Corallina officinalis* in locations <100m from the outfall and reference, respectively.

Multivariate analyzes showed that environmental parameters did not differ between sites under direct effluent discharge, <100m from the outfall and reference site. However, it was found that ammonia and phosphate differed significantly between areas under direct sewage discharge and the reference site, showing higher concentrations in regions receiving effluent disposal. Certainly, the input of untreated wastewater rich in organic components contributed to increase in ammonia and phosphate levels. Still, environmental parameters varied between the dry and rainy seasons. Rainfall, temperature, salinity, nitrite, and chlorophyll were variables that best responded to short-term seasonal changes. Additionally, the abundance of macroalgae from areas under sewage discharge and <100m from the outfall showed strong significant relationships with the available phosphate concentrations in a sample space of 15 days before biological collection. Thus, we can infer that benthic macroalgae communities may respond more slowly to variations in phosphate levels.

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5 CONSIDERAÇÕES FINAIS

O presente estudo revelou que a urbanização costeira causa mudanças na estrutura das comunidades de macroalgas de recifes tropicais, havendo reduções acentuadas na cobertura de algas pardas e de espécies menos tolerantes conforme o nível de urbanização aumenta. Atrelado a isto, regiões de urbanização consolidada mostraram ser mais susceptíveis a ocorrência em elevadas abundâncias de algas oportunistas como *Ulva lactuca*, *Gelidium* e *Chondracanthus acicularis*, isto por apresentar um ambiente com condições que favorecem o rápido assentamento e crescimento desses organismos, resultando, dessa forma, no desaparecimento de espécies sensíveis e na posterior homogeneização da comunidade. Ainda, foi possível constatar que as comunidades podem variar ao longo dos anos, bem como entre as estações seca e chuvosa. Entretanto, mudanças na composição de espécies em áreas menos impactadas são menos sutis, como observado para *Palisada perforata* e *Gelidiella acerosa*, que se mantiveram dominantes durante as estações seca e chuvosa dos anos de 2014, 2021 e 2022.

O lançamento de esgotos domésticos é um dos principais problemas relacionados ao crescimento de centros urbanos em regiões próximas ao mar. A descarga de esgotos provocou uma alta dominância de *Gelidium* spp. e *Ulva lactuca*, espécies conhecidas pelo rápido crescimento e histórico de vida curto, capazes de crescer em ambientes com elevadas cargas de contaminantes. As macroalgas de áreas sob o despejo direto de esgotos estiveram positivamente relacionadas com os teores de nitrito, nitrato, amônia e fosfato, apresentando interações significativas com as concentrações de fosfato. A disponibilidade de nutrientes é um dos fatores que controlam o desenvolvimento das comunidades algais, dessa forma, o fluxo de águas eutrofizadas carreadas pelos esgotos certamente favoreceu o desenvolvimento desordenado de espécies oportunistas, resultando em declínios da riqueza e diversidade das comunidades.

Embora resultados importantes tenham sido obtidos acerca dos impactos da urbanização sobre macroalgas bentônicas de recifes tropicais, pesquisas experimentais e observacionais ainda são necessárias, especialmente considerando características bioquímicas e fisiológicas (como a diversidade química e o potencial antioxidante), e os efeitos das interações interespecíficas (competição e pressão de herbivoria, p.e) na distribuição das espécies.

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