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EDITORA

MARINE BIOTECHNOLOGY IN NORTHEAST BRAZIL: BIODIVERSITY'S POTENTIAL FOR INNOVATION IN HEALTH AND ENVIRONMENTAL SUSTAINABILITY

BIOTECNOLOGIA MARINHA NO NORDESTE BRASILEIRO: POTENCIAL DA BIODIVERSIDADE PARA A INOVAÇÃO EM SAÚDE E SUSTENTABILIDADE AMBIENTAL

BIOTECNOLOGÍA MARINA EN EL NORDESTE DE BRASIL: EL POTENCIAL DE LA BIODIVERSIDAD PARA LA INNOVACIÓN EN SALUD Y SOSTENIBILIDAD AMBIENTAL

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ABSTRACT

Marine biotechnology has established itself as one of the most innovative fronts in the sustainable bioeconomy, offering promising solutions to global challenges in the areas of health, food, energy and the environment. In the Brazilian context, the Northeast region stands out for being home to some of the greatest marine biodiversity in the South Atlantic, representing a veritable natural laboratory for the development of biotechnologies based on aquatic resources. The aim of this chapter is to analyze the biotechnological potential of marine organisms from the Brazilian Northeast, highlighting their applications in the areas of health and environmental sustainability, as well as identifying the main challenges and opportunities for the advancement of marine biotechnology in the region. The methodology adopted consisted of a systematic bibliographic review of scientific articles, technical reports and institutional documents published in recent years, with an emphasis on contemporary authors and recognized databases such as Scopus, Web of Science and SciELO. The results indicate that, although there are relevant initiatives underway, the sector still faces barriers such as lack of investment, regulatory gaps, weaknesses in the scientific infrastructure and insufficient training of specialized professionals. On the other hand, strategic areas with high potential for innovation were identified, such as the use of microalgae to produce biofuels and bioactive compounds, the use of marine organisms for pharmaceuticals and cosmetics, and the development of technologies for the bioremediation of coastal environments. The study concludes that the consolidation of marine biotechnology in the Northeast depends on the articulation of integrated public policies, the strengthening of research networks, the encouragement of cooperation between scientific institutions and the productive sector, and the valorization of regional human capital. These actions are essential for transforming the region's marine wealth into a vector for economic, sustainable and inclusive development.

Palavras-chave: Marine Biotechnology. Biodiversity. Regional sustainability.

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RESUMO

A biotecnologia marinha tem se consolidado como uma das frentes mais inovadoras da bioeconomia sustentável, oferecendo soluções promissoras para os desafios globais nas áreas da saúde, alimentação, energia e meio ambiente. No contexto brasileiro, a região Nordeste se destaca por abrigar uma das maiores biodiversidades marinhas do Atlântico Sul, representando um verdadeiro laboratório natural para o desenvolvimento de biotecnologias baseadas em recursos aquáticos. Este capítulo tem como objetivo analisar o potencial biotecnológico dos organismos marinhos do Nordeste brasileiro, com destaque para suas aplicações nas áreas de saúde e sustentabilidade ambiental, além de identificar os principais desafios e oportunidades para o avanço da biotecnologia marinha na região. A metodologia adotada consistiu em uma revisão bibliográfica sistemática de artigos científicos, relatórios técnicos e documentos institucionais publicados nos últimos anos, com ênfase em autores contemporâneos e bases de dados reconhecidas como Scopus, Web of Science e SciELO. Os resultados indicam que, embora existam iniciativas relevantes em curso, o setor ainda enfrenta barreiras como escassez de investimentos, lacunas regulatórias, fragilidade na infraestrutura científica e insuficiência na formação de profissionais especializados. Por outro lado, foram identificadas áreas estratégicas com alto potencial de inovação, como a utilização de microalgas para produção de biocombustíveis e compostos bioativos, o aproveitamento de organismos marinhos para fármacos e cosméticos, e o desenvolvimento de tecnologias para a biorremediação de ambientes costeiros. O estudo conclui que a consolidação da biotecnologia marinha no Nordeste depende da articulação de políticas públicas integradas, do fortalecimento das redes de pesquisa, do incentivo à cooperação entre instituições científicas e setor produtivo, e da valorização do capital humano regional. Essas ações são essenciais para transformar a riqueza marinha da região em um vetor de desenvolvimento econômico, sustentável e inclusivo.

Palavras-chave: Biotecnologia Marinha. Biodiversidade. Sustentabilidade Regional.

RESUMEN

La biotecnología marina se ha consolidado como uno de los frentes más innovadores de la bioeconomía sostenible, ofreciendo soluciones prometedoras a los desafíos globales en los ámbitos de la salud, la alimentación, la energía y el medio ambiente. En el contexto brasileño, la región Nordeste se destaca por albergar una de las mayores biodiversidades marinas del Atlántico Sur, representando un verdadero laboratorio natural para el desarrollo de biotecnologías basadas en recursos acuáticos. El objetivo de este capítulo es analizar el potencial biotecnológico de los organismos marinos del Nordeste de Brasil, destacando sus aplicaciones en las áreas de salud y sostenibilidad ambiental, así como identificar los principales desafíos y oportunidades para el avance de la biotecnología marina en la región. La metodología adoptada consistió en una revisión bibliográfica sistemática de artículos científicos, informes técnicos y documentos institucionales publicados en los últimos años, con énfasis en autores contemporáneos y bases de datos reconocidas como Scopus, Web of Science y SciELO. Los resultados indican que, aunque existen iniciativas relevantes en marcha, el sector aún enfrenta barreras como la falta de inversión, vacíos regulatorios, debilidades en la infraestructura científica e insuficiente formación de profesionales especializados. Por otro lado, se identificaron áreas estratégicas con alto potencial de innovación, como el uso de microalgas para producir biocombustibles y compuestos bioactivos, la utilización de organismos marinos para productos farmacéuticos y cosméticos, y el desarrollo de tecnologías para la biorremediación de ambientes costeros. El estudio concluye que la consolidación de la biotecnología marina en el Nordeste depende de la articulación de políticas públicas integradas, del fortalecimiento de las redes de

investigación, del fomento de la cooperación entre las instituciones científicas y el sector productivo, y de la valorización del capital humano regional. Estas acciones son esenciales para transformar la riqueza marina de la región en un vector de desarrollo económico, sostenible e inclusivo.

Palabras clave: Biotecnología marina. Biodiversidad. Sostenibilidad regional.

1 INTRODUCTION

Marine biodiversity represents one of the most promising sources of biological resources that are still little explored on the planet, especially with regard to microorganisms and their potential biotechnological applications. These organisms, adapted to extreme environmental conditions, produce a diversity of bioactive compounds with great value for sectors such as health, the pharmaceutical industry, agriculture, and the environment (Imhoff, 2020). In the Brazilian context, and particularly in the Northeast, this biological wealth remains largely underutilized, despite the extensive coastline and the remarkable diversity of marine and coastal habitats, such as coral reefs, estuaries, mangroves and abyssal zones.

The northeastern coast is home to unique ecological conditions that favor the proliferation of a specialized microbiota, with biotechnological potential relevant to the discovery of new antibiotics, industrial enzymes, biosurfactants, pigments and antioxidant agents. These natural products are strategic in the face of contemporary global challenges, such as the growing microbial resistance to conventional drugs and the urgent need to replace industrial inputs with sustainable alternatives (Sánchez & Demain, 2017; Newman & Cragg, 2020). In addition, environmental biotechnology applied to the marine microbiota can contribute significantly to the remediation of contaminated areas and the development of more sustainable practices in the agricultural and fisheries sectors.

Despite the high potential, the development of marine biotechnology in Brazil still faces structural, legal and financial obstacles. In the Northeast, these challenges are accentuated by the scarcity of specific public policies for the blue bioeconomy, the lack of laboratory infrastructure for advanced microbiological studies, and the fragmentation of initiatives between universities, research centers, and the productive sector (Melo & Torres, 2023). Such a context highlights the need to systematize the knowledge already produced, identify critical gaps and promote strategic guidelines that consolidate the region as a reference in innovation based on marine biodiversity.

In view of this panorama, this study aims to analyze the biotechnological potential of marine organisms in the Brazilian Northeast, with emphasis on their applications in the areas of health and environmental sustainability, in addition to identifying the main challenges and opportunities for the advancement of marine biotechnology in the region. The proposal consists of critically reviewing the most recent national and international scientific production, highlighting advances, challenges and opportunities, both from a scientific and strategic point of view.

The methodology adopted was based on a systematic literature review of a qualitative nature, with a time frame between the years 2010 and 2024. The search was carried out in

the Scopus, PubMed, Web of Science, SciELO and Google Scholar databases, using combined descriptors such as "marine microbiota", "bioprospecting", "marine biotechnology", "bioactive compounds", "Northeast Brazil" and their respective translations into Portuguese. Peer-reviewed articles addressing tropical marine microbiota with biotechnological applications in health or the environment were included, and duplicate studies, with a purely chemical scope or without a compatible geographic cut, were excluded. In addition, theses, dissertations and technical reports from research institutions in the Northeast were also analyzed, with emphasis on the production of UFC, UFRN, UFPE, Fiocruz-CE and Embrapa.

The data analysis followed a thematic approach, organizing the contents into four main axes: microbial biodiversity, identified bioactive compounds, bioprospecting techniques and potential applications. From this structure, it seeks to contribute to the strengthening of marine biotechnology as a vector of sustainable development and scientific innovation in the Brazilian Northeast.

2 THEORETICAL FOUNDATION

The theoretical foundation of this work aims to present and discuss the main concepts, scientific approaches and recent advances related to marine biotechnology, especially highlighting the vast biotechnological potential of the marine microbiota in the context of the Brazilian Northeast. This region, of enormous ecological and economic importance, offers a unique setting for scientific, technological and innovative development. To this end, this section is structured into five main sub-themes: marine microbiota and its diversity; techniques and methodologies of marine bioprospecting; biocompounds of biotechnological interest; environmental applications, with an emphasis on sustainability and bioremediation; and applications in human health, including pharmaceutical and cosmetic development.

2.1 MARINE MICROBIOTA: CONCEPT AND DIVERSITY

The marine microbiota represents an extremely diverse and complex set of microorganisms, which includes bacteria, archaea, viruses, protozoa, and fungi, which colonize practically all niches of the marine environment, from the surface of surface waters to the abyssal depths. These organisms are fundamental for the maintenance of ecological and biochemical processes in the ocean, acting in essential biogeochemical cycles, such as the carbon, nitrogen, and sulfur cycle (Sunagawa et al., 2015).

It is estimated that more than 99% of marine microbial species are still unknown and not cultivable in the laboratory, a fact that highlights the enormous untapped potential of this diversity (Sunagawa et al., 2015). The marine microbiota not only contributes to oxygen

production — through photosynthesis carried out by cyanobacteria and other microalgae — but also acts as a regulator of ecosystems, influencing primary productivity, the decomposition of organic matter, and the balance of biological populations (Danovaro et al., 2020).

On the Brazilian northeastern coast, which includes varied environments such as coral reefs, mangroves, estuaries, algae banks, and tidal zones, the microbiota is influenced by very specific environmental conditions, such as high solar radiation, daily and seasonal thermal variations, as well as significant fluctuations in salinity (Silva et al., 2021). These conditions encourage the development of highly adapted microbial communities, which have unique biochemical and genetic mechanisms to survive and thrive.

Environments such as coral reefs, for example, have a complex symbiotic relationship between microorganisms and host organisms, which results in a rich source of genes and bioactive metabolites with biotechnological applications that are still underexplored (Thomas et al., 2020). These ecosystems function as true hotspots of microbial biodiversity, offering a window for the development of new technologies based on the sustainable exploitation of marine life.

2.2 MARINE BIOPROSPECTING: METHODS AND APPROACHES

Marine bioprospecting is an interdisciplinary field that involves the systematic search for organisms and their bioactive molecules, with potential industrial, medical, environmental, and cosmetic uses. Traditionally, bioprospecting has depended on the isolation and cultivation of microorganisms in the laboratory, a method that has significant limitations for the marine microbiota, as most organisms do not grow under conventional artificial conditions (Zhou et al., 2015).

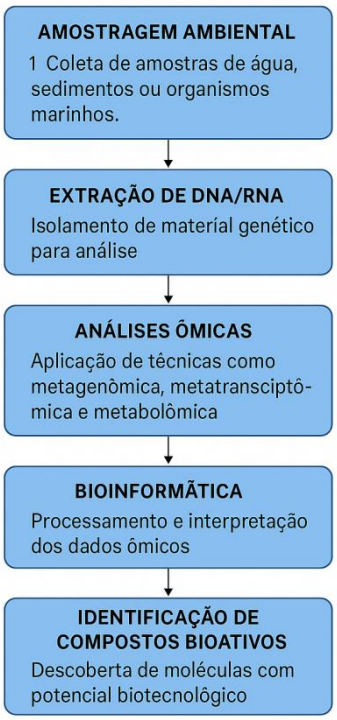
To overcome this barrier, advanced molecular techniques have revolutionized the field, especially metagenomics, which allows access to the complete genetic material present in environmental samples, without the need for cultivation. Metagenomics enables the identification and analysis of genes and metabolic pathways of microorganisms that are still unknown, greatly expanding the potential for the discovery of novel bioactive compounds (Handelsman, 2004).

In addition to metagenomics, other "omics" approaches such as transcriptomics, proteomics, and metabolomics have been incorporated to map gene expression, protein profiles, and metabolites produced by marine microorganisms under different environmental conditions (Della Sala et al., 2022). These tools enable integrated understanding of microbial functionality and facilitate the selection of promising candidates for biotech applications.

Bioinformatics plays a crucial role in the analysis of the large volumes of data generated, enabling the prediction of gene functions and the modeling of metabolic routes, accelerating the development of final products and optimization strategies. The combination of these advanced technologies has contributed significantly to the sustainable and efficient exploitation of the marine microbiota, paving the way for innovations in multiple industrial sectors.

To understand in a clearer and didactic way the steps involved in marine bioprospecting, especially those based on omics tools, the following flowchart summarizes the process from environmental collection to the technological development of bioactive compounds. The image illustrates how different areas of knowledge integrate to transform marine biodiversity into applied innovation.

Figure 1 – Flowchart of the stages of marine bioprospecting based on omics tools.



Source: Prepared by the author based on Della Sala et al. (2022).

2.3 BIOCOMPOUNDS OF BIOTECHNOLOGICAL INTEREST

Marine microorganisms are very rich sources of secondary metabolites, bioactive compounds that exert protective, signaling or defensive functions, and that have enormous potential for biotechnological applications. Among the main productive groups are marine actinobacteria, known for synthesizing potent antibiotics and enzymes with high stability under extreme conditions, such as salt variations and elevated temperatures (Newman & Cragg, 2020).

In addition to actinobacteria, microorganisms associated with marine organisms such as sponges and corals have revealed unique and complex compounds, such as salinosporamides (with anticancer activity), didenniins, and halichondrins, which demonstrate therapeutic potential in treatments against various diseases (Hughes & Fenical, 2019). These compounds have attracted worldwide attention for their unique chemical structure and efficacy in preclinical models.

In addition to the pharmaceutical sector, enzymes produced by marine microorganisms, such as lipases, proteases, and amylases, have been used in industrial processes, especially in the food, cosmetics, and energy sectors (Trincone, 2020). Their high stability in harsh environments makes them ideal for applications that require robustness and efficiency, for example in biofuel production processes, natural cosmetics formulation and waste biodegradation.

The potential of these biocompounds is vast and requires greater investment in research to isolate them, characterize them and scale their production, especially from the little explored biodiversity of the Brazilian Northeast.

Several marine microorganisms have been studied for their ability to synthesize bioactive compounds with relevant industrial applications. The table below presents representative examples of these organisms and their respective applications, demonstrating the functional diversity and potential of the marine microbiota to generate innovation in the pharmaceutical, environmental, and cosmetic sectors.

Table 1 – Examples of marine microorganisms and their biocompounds with industrial applications.

Marine Microorganism	Biocompost Produced	Main Application
Salinispora tropica	Salinosporamide A	Anticancer drug
Alcanivorax borkumensis	Biosurfactants	Petroleum bioremediation
Coral actinobacteria	Antibiotics	Human health
Cyanobacteria	Bioactive peptides	Cosmetics and antivirals
Endophytic marine fungi	Degrading enzymes	Wastewater treatment

Source: Adapted from Hughes & Fenical (2019); Martins et al. (2020); Silva et al. (2021).

2.4 ENVIRONMENTAL APPLICATIONS: BIOREMEDIATION AND SUSTAINABILITY

The marine microbiota is recognized for its ability to degrade organic and inorganic pollutants, positioning itself as an essential tool in environmental bioremediation strategies. Microorganisms adapted to extreme environments, such as tidal zones contaminated by oil or heavy metal spills, have efficient biochemical mechanisms for the degradation of toxic compounds, aiding in the recovery and preservation of coastal ecosystems (Das & Chandran, 2011).

Biosurfactant-producing bacteria, such as those of the genus Alcanivorax, have stood out in studies and practical applications for the remediation of areas contaminated by petroleum-derived hydrocarbons. These biosurfactants act by reducing the surface tension of water, increasing the solubility and bioavailability of pollutants for their subsequent degradation (Venosa & Holder, 2007).

In addition to bioremediation, the marine microbiota is used in industrial effluent treatment processes, biological control of harmful algal blooms, and restoration of degraded marine habitats, such as coral reefs (Melo & Torres, 2023). Brazilian institutions, such as Embrapa Environment and Fiocruz-CE, lead initiatives that combine biotechnology and environmental conservation, developing solutions that combine technology, sustainability, and regional development.

2.5 APPLICATIONS IN HUMAN HEALTH: THERAPIES AND COSMETICS

Marine biotechnology has been consolidated as a promising frontier for the development of new drugs and therapies, especially in a scenario of growing antibiotic resistance and the search for more effective and sustainable treatments. Products derived from the marine microbiota include antibiotics, antivirals, anti-inflammatories, and immunomodulators that demonstrate potential in several therapeutic areas (Jiménez, 2018).

In the cosmetic field, the use of marine microbial extracts has increased due to their antioxidant, moisturizing, regenerative, and anti-aging properties. The demand for natural and sustainable products drives investment in this sector, with formulations that value biocompatibility and low environmental impact (Martins et al., 2020).

Recent advances also indicate a convergence between marine biotechnology and nanotechnology, resulting in the production of functional nanoparticles for medical applications, such as intelligent controlled drug release systems and cell regeneration therapies, expanding the spectrum of clinical applications of the marine microbiota (Dias et al., 2022).

3 THE REALITY OF THE BRAZILIAN NORTHEAST

The Brazilian Northeast is a region marked by an extensive coastline that exceeds 3,000 km of coastline, positioning itself as one of the largest and most biodiverse marine environments on the planet. This vast coastline is home to a unique ecological diversity, composed of varied ecosystems such as coral reefs, mangroves, estuaries, kelp beds, and intertidal zones, which together offer ideal conditions for the proliferation and development of highly diverse and metabolically active microbial communities (MMA, 2023). The complexity

and heterogeneity of these environments promote ecological interactions that sustain biogeochemical cycles essential for the health of marine ecosystems and for regional environmental balance.

The biological richness of the northeastern coast is not restricted only to macrofauna and flora, but includes a vast microbiota that plays essential roles in ecological processes, such as nutrient cycling, decomposition of organic matter, and production of bioactive substances. Given the ecological and economic importance of these environments, the region has significant potential for the development of blue biotechnology, an area that seeks to exploit marine resources for innovative applications in the pharmaceutical, environmental, industrial, and agricultural sectors.

3.1 REGIONAL BIOTECHNOLOGICAL POTENTIAL

Despite its undeniable natural and biological richness, the biotechnological potential of the marine microbiota of the Brazilian Northeast is still largely underexplored, configuring itself as a significant gap in national research. According to recent data from the National Council for Scientific and Technological Development (CNPq, 2022), less than 15% of marine bioprospecting projects funded in Brazil are mainly focused on the Northeast region, which shows an imbalance in the distribution of scientific and technological efforts. This underutilization of local potential is associated with several factors, including the insufficiency of modern and adequate laboratory infrastructure in the coastal areas of the region, the scarcity of specific programs to foster and encourage local scientific research, and the absence of robust and integrated public policies that stimulate innovation and research in the area of blue biotechnology.

However, there is a gradual and promising growth in the development of centers of excellence that have boosted regional scientific and technological training. Notable examples include the Marine Biotechnology Laboratory at the Federal University of Rio Grande do Norte (UFRN) and the Graduate Program in Biotechnology at the State University of Ceará (UECE), which have been playing a crucial role in training qualified human resources and generating scientific knowledge about local marine microorganisms (Silva et al., 2022). Such initiatives are fundamental for building an environment conducive to innovation and for strengthening applied research in the region.

In addition, the biodiversity of the northeastern coast is characterized by its uniqueness, harboring endemic species and microbial communities adapted to peculiar environmental conditions, such as high solar radiation, high salinity and wide natural thermal variations. These factors exert selective pressure on microorganisms, promoting the development of unique biochemical and metabolic mechanisms, responsible for the synthesis

of metabolites with innovative properties and potential biotechnological applications, such as the production of antibiotics, industrial enzymes, natural cosmetics, and bioremediation agents (Almeida et al., 2021). Thus, the coast of the Northeast represents a strategic and untapped source of biotechnological raw material that can contribute to the economic and sustainable diversification of the region.

Although the potential of marine biotechnology in the Brazilian Northeast is still underutilized, some teaching and research institutions have stood out in the generation of knowledge and technical training in the area. The following table summarizes the main institutions in the region working in marine biotechnology, highlighting their areas of specialization and contribution to local scientific advancement.

Table 1 – Main institutions in the Northeast operating in marine biotechnology.

Institution	State	Main Area of Expertise
Federal University of Ceará (UFC)	EC	Microalgae bioprospecting
Federal University of Rio Grande do Norte (UFRN)	RN	Genomics and metabolomics of marine microorganisms
Federal University of Pernambuco (UFPE)	PE	Bioactive compounds for cosmetics and pharmaceuticals
Fiocruz-CE	EC	Environmental biotechnology and public health
Embrapa Tropical Agroindustry	EC	Enzymes and bioremediation with microorganisms

Source: Prepared by the author based on technical reports (2023).

3.2 TERRITORIAL INEQUALITY IN SCIENCE AND TECHNOLOGY

Scientific and technological production in Brazil has an unequal regional distribution, marked by a significant concentration in the South and Southeast regions, which historically hold most of the investments and infrastructure for research. According to a survey by the Brazilian Institute of Geography and Statistics (IBGE, 2021), approximately 72% of public and private investments in science, technology, and innovation are directed to these hubs, while the Brazilian Northeast receives about 12% of this amount, evidencing a disparity that directly impacts local scientific development and the appreciation of its marine biodiversity.

This territorial inequality limits the potential of the Northeast to consolidate itself as a protagonist in marine biotechnology, in addition to contributing to the exodus of scientific talent and the devaluation of regional knowledge. Researchers such as Dagnino (2019) argue that it is necessary to adopt a development model that prioritizes contextualized innovation, that is, that takes into account the territorial, environmental, cultural, and socioeconomic specificities of each region, thus promoting fairer, more sustainable development that is aligned with local demands.

In this context, marine biotechnology appears as a strategic opportunity to boost the economy of the sea in the Northeast, promoting locally-based science that has a global impact. Valuing regional marine biodiversity and integrating multidisciplinary efforts can leverage the development of innovative products, processes, and services, strengthening local production chains and contributing to the generation of employment, income, and environmental sustainability.

3.3 LOCAL INITIATIVES AND EMERGING PUBLIC POLICIES

In recent years, several initiatives have emerged aimed at reversing the situation of scientific and technological underdevelopment in the Northeast, especially in the field of marine biotechnology. Programs such as Pró-Mar Semiárido, a partnership between northeastern universities and federal institutions, aim to stimulate applied research and entrepreneurship in the area of blue biotechnology, with a specific focus on the Coastal Semi-Arid Region. These actions seek to foster regional innovation and the generation of scientific knowledge aligned with local environmental and socioeconomic characteristics (Melo & Torres, 2023).

At the same time, national public policies, such as the National Bioeconomy Strategy and the National Innovation Policy, have been incorporating the valorization of marine biodiversity as a strategic axis for the sustainable development of the country. However, the effectiveness of these policies strongly depends on their regionalized implementation, which considers the specificities of the Northeast, as well as on the strengthening of local research and cooperation networks between academia, the productive sector, and public authorities (Barbosa & Lima, 2022).

To consolidate the Northeast as a reference hub in bioprospecting and blue innovation, it is essential to expand investments in scientific and technological infrastructure, promote the continuous training of specialized human resources and foster the creation of coastal innovation hubs integrated with local production chains. Such measures can catalyze regional development, raising the potential of the marine microbiota in the Northeast to levels of international competitiveness and contributing to the advancement of the sustainable bioeconomy in Brazil.

4 RECENT SCIENTIFIC AND TECHNOLOGICAL ADVANCES IN THE AREA

In the last two decades, marine biotechnology has consolidated itself as one of the most dynamic and promising fields of contemporary science, benefiting significantly from the advancement of technologies associated with molecular biology, next-generation genetic

sequencing and bioinformatics tools. Such progress has allowed access to a marine microbial universe largely unknown until then, expanding the frontiers of knowledge about the genetic and functional diversity of these organisms. The potential for the development of new bioactive products has aroused enormous interest in the pharmaceutical, cosmetic, environmental, and food industries, configuring marine biotechnology as a strategic axis for innovation and sustainable development (LEAL et al., 2023).

4.1 DISCOVERIES OF NEW MICROORGANISMS AND FUNCTIONAL GENES

One of the most revolutionary advances in this field was the development of environmental metagenomics, which makes it possible to directly analyze the genetic material present in natural samples, without the need to cultivate the microorganisms in the laboratory. This method has been essential in overcoming the historical challenge that more than 99% of marine microbial species are not cultivable by traditional techniques, limiting access to their functional metabolites and genes (IMHOFF, 2022). Metagenomics, along with other "omics" – such as transcriptomics and proteomics – enables the in-depth study of the structure and function of microbial communities, revealing genes that encode enzymes, antibiotics and antioxidant molecules that were previously unknown.

Concrete examples include the discovery of new strains of Actinobacteria and Proteobacteria in tropical coastal regions, organisms with high potential for the biosynthesis of bioactive substances. These bacteria have specialized metabolic mechanisms, which have been exploited for the development of drugs capable of fighting infections resistant to traditional antibiotics, one of the major current public health crises (MOURA et al., 2022). In addition, the identified genetic diversity provides a basis for the development of industrial enzymes with high efficiency and stability under extreme conditions, essential for innovative biotechnological processes.

4.2 BIOACTIVE PRODUCTS OF MARINE ORIGIN

Marine biotechnology is not restricted to the discovery of microorganisms, but also encompasses the extraction and study of bioactive compounds with diverse therapeutic properties. Compounds with anti-inflammatory, antitumor, antiviral, and immunomodulatory actions have been isolated and characterized, demonstrating promising efficacy in preclinical and clinical models. An emblematic example is Salinosporamide A, a potent proteasome inhibitor derived from the bacterium Salinispora tropica, which is currently in the advanced stages of clinical trials for the treatment of multiple myeloma, an aggressive form of cancer (FENICAL et al., 2021).

In addition, other molecules extracted from marine microorganisms, such as epsilomycin, Halaven® (eribulin mesylate), and peptides from cyanobacteria, have been investigated for their ability to inhibit tumor cells and emerging viruses, including HIV and SARS-CoV-2. These findings underscore the strategic role of marine bioprospecting in the search for new drugs, especially in the face of global challenges posed by infectious diseases and increasing microbial resistance (GOMES et al., 2023).

4.3 TECHNOLOGICAL ADVANCES IN MARINE BIOPROCESSES

Technological advances are not restricted to the genetic area, but also include the development of systems and processes for the large-scale production of the compounds of interest. The engineering of specific bioreactors, capable of reproducing the extreme conditions of marine environments — such as pressure, salinity, temperature, and pH — has allowed the feasibility of large-scale cultivation of microorganisms with biotechnological potential. New co-culture or mixotrophic cultivation methodologies, which combine different sources of carbon and energy, have been tested to maximize the yield and efficiency of the processes (ZHAO et al., 2022).

At the same time, the advancement of gene editing techniques, especially CRISPR-Cas9, has been applied to modify marine microorganisms, enhancing the production of secondary metabolites with industrial and pharmaceutical applications. This metabolic engineering allows not only the optimization of the biosynthesis of already known compounds, but also the creation of variants with enhanced properties (ZHAO et al., 2022).

Another key innovation is the integration of artificial intelligence (AI) into biotechnological processes, enabling computational modeling to predict molecular interactions, virtual screening of thousands of bioactive compounds, and optimization of metabolic pathways. This has accelerated the discovery and development of new products, significantly reducing the time and costs involved (RODRIGUES; FURTADO, 2023).

4.4 SUSTAINABILITY AND THE BLUE ECONOMY

Marine biotechnology is also deeply aligned with the principles of sustainability and the so-called blue economy, which seeks to reconcile the rational use of ocean resources with environmental preservation and social inclusion. The sustainable exploitation of marine microorganisms is not limited to the extraction of bioactive compounds, but also involves biotechnological processes that contribute to the mitigation of environmental impacts.

Examples of this include the bioremediation of polluted areas, where marine microorganisms are employed to degrade toxic contaminants, the treatment of wastewater

using microalgae and bacteria, and the development of biodegradable materials, such as bioplastics and biofertilizers (UNESCO, 2022). Such applications reinforce the potential of marine biotechnology as a tool for the circular economy and for reducing environmental damage.

In Brazil, several startups and research centers have stood out by investing in innovative solutions. The use of microalgae to capture atmospheric CO_2, produce renewable energy biomass, and develop agricultural bioinputs are concrete examples of technologies that contribute to climate change mitigation and the transition to more sustainable and cleaner production models (SOUZA et al., 2023).

5 CHALLENGES AND FUTURE PERSPECTIVES FOR MARINE BIOTECHNOLOGY IN THE NORTHEAST

Although scientific and technological advances in the area of marine biotechnology in Brazil represent relevant milestones, especially in the last two decades, the sector is still far from reaching its full potential — especially in the Northeast region. This disparity does not stem from natural limitations, as the region is privileged by an extensive coastline, rich biodiversity, and unique ecosystems. What is observed, in fact, is the presence of historical, structural, political, and financial obstacles that compromise the systematic and sustainable development of this strategic front of the blue bioeconomy.

However, the scenario is not exclusively discouraging. The existence of academic centers in consolidation, the emergence of specialized research groups, and the growing interest of young scientists in marine biotechnology suggest a possible transition route— provided that it is accompanied by consistent public policies, structuring investments, and strategies for regional articulation.

5.1 STRUCTURAL AND FUNDING CONSTRAINTS

Among the main obstacles faced by marine biotechnology in the Northeast is the chronic deficiency of scientific and technological infrastructure. Most research centers in the region, especially those linked to public universities, still operate with outdated equipment and without adequate conditions to carry out cutting-edge studies in areas such as marine genomics, mass spectrometry, advanced molecular biology, and the cultivation of extremophile microorganisms from marine environments (Pereira et al., 2021).

This shortage compromises the ability to compete internationally and attract talent, in addition to limiting Brazil's participation in global scientific consortia. It is important to highlight that countries that lead in marine biotechnology — such as Japan, Norway, and the United

States — have established, over decades, policies for continuous funding for science, focusing on strategic areas and a long-term vision.

In addition, there is a considerable vacuum of specific policies aimed at the economy of the sea in Brazil. The few existing incentives still do not adequately contemplate startups, coastal technology parks, incubators and accelerators aimed at the sustainable use of marine resources. The absence of credit lines directed to marine biotechnology and tax relief mechanisms for innovative companies drives away potential investors and limits the emergence of local ventures (Silva & Andrade, 2022).

5.2 DISCONTINUITY OF POLICIES AND LACK OF REGIONAL INTEGRATION

Another critical challenge is the institutional instability of science, technology, and innovation (ST&I) policies in the country. Changes in government and recurrent budget cuts negatively affect the continuity of strategic projects and discourage researchers who depend on public notices and research grants with precarious validity.

In addition, there is a significant fragmentation among the various actors involved in northeastern marine biotechnology. Universities, federal institutes, research centers, and companies act, to a large extent, in isolation, which makes it difficult to create synergies, collaborative networks, and knowledge and technology transfer flows (Lopes et al., 2023). This lack of articulation makes it more difficult to consolidate local production chains based on marine biotechnology, in addition to preventing the creation of specialized regional hubs that could leverage innovation in the sector.

The absence of an integrated strategy among the states of the Northeast reinforces these limitations. Although they share similar geographic and social characteristics, state governments have not, to date, articulated common policies that promote the strengthening of the blue bioeconomy as an axis of sustainable regional development.

5.3 ETHICAL, LEGAL AND ACCESS TO GENETIC HERITAGE CHALLENGES

The regulation of access to genetic heritage, especially that associated with marine biodiversity, represents another neuralgic point. The Biodiversity Law (Law No. 13,123/2015) was created with the objective of preserving natural resources and ensuring a fair and equitable sharing of benefits. However, its implementation has faced criticism due to the complexity of bureaucratic procedures and the legal uncertainty it imposes on companies and research centers interested in carrying out bioprospecting activities (Araújo et al., 2021).

These legal obstacles, even if well-intentioned, may end up discouraging applied research and hindering the entry of private investments, especially in areas that require agility

and constant innovation, such as the discovery of bioactive compounds from marine algae, bacteria, and fungi. It is also necessary to advance the debate on the ethics of the exploitation of sensitive marine resources and on the mechanisms for protecting traditional knowledge associated with coastal biodiversity.

5.4 FUTURE OPPORTUNITIES AND STRATEGIES

Despite the difficulties faced, the Brazilian Northeast is positioned as one of the most promising regions for the advancement of marine biotechnology in the country. The combination of natural wealth and scientific potential creates an environment conducive to the flourishing of innovative initiatives. Coral reefs, mangroves, estuaries, kelp beds and upwelling zones form a mosaic of unique ecosystems, whose microbiological and chemical diversity is still largely unexplored.

Another positive factor is the growing training of trained human resources, with the expansion of undergraduate and graduate courses in strategic areas such as Biological Sciences, Fisheries Engineering, Biotechnology, Oceanography and Pharmacy. This critical mass could be decisive for the development of a new generation of scientists, entrepreneurs, and managers focused on the blue economy (Carvalho & Bezerra, 2023).

Among the strategies that can be adopted in the coming years, the following stand out:

- Creation of centers of excellence in marine biotechnology, integrating universities, research institutes and companies focused on technological innovation and sustainability;
- Encouragement of public-private partnerships, with specific calls for proposals for the development of marine biotechnological products, such as cosmetics, biopharmaceuticals, food supplements and biofuels;
- Promotion of the internationalization of research, through collaborative networks, scientific exchanges, participation in international congresses and double degree programs; and
- Incorporation of environmental education and scientific literacy in schools and coastal communities, valuing local knowledge and promoting a culture of appreciation and care for the ocean.

The consolidation of marine biotechnology in the Northeast will require a multidisciplinary approach, capable of integrating diverse knowledge and dialoguing with the principles of sustainability, social inclusion and technological innovation. As Amaral (2022) points out, "the sea is not only a source of resources, but also of knowledge, solutions, and

paths for the future". Turning this vision into practice depends on political choices, institutional commitments, and the continued engagement of society and the scientific community.

6 FINAL CONSIDERATIONS AND RECOMMENDATIONS

Marine biotechnology represents a promising frontier for the scientific, technological, economic and environmental development of the Brazilian Northeast. With one of the greatest coastal biodiversity on the planet, associated with unique ecosystems such as coral reefs, mangroves, estuaries and upwelling zones, the region has exceptional conditions to lead sustainable initiatives based on the intelligent use of marine resources. However, the full use of this potential requires overcoming historical, structural and institutional challenges that still limit the consolidation of this strategic area.

The present analysis showed that the bioprospecting of marine organisms — especially microalgae, cyanobacteria, extremophile bacteria, and invertebrates — has generated high value-added compounds with pharmacological, nutraceutical, cosmetic, and energy applications (Araújo et al., 2021; Pereira et al., 2021). These advances, however, remain concentrated in specific initiatives, often isolated, and lack an institutional environment that favors the articulation between science, the market, and society.

In addition to the scarcity of laboratory infrastructure and continuous funding, the Brazilian legal framework, although oriented towards the protection of biodiversity, imposes bureaucratic obstacles that discourage innovation and hinder the engagement of private actors (Silva & Andrade, 2022). Likewise, the fragmentation between teaching and research institutions in the region, added to the absence of integrated public policies among the northeastern states, prevents the formation of a robust ecosystem of marine innovation (Lopes et al., 2023).

Faced with this scenario, this study proposes a set of strategic recommendations, aimed at strengthening the scientific base, expanding institutional cooperation, and boosting the insertion of the Northeast in global chains of the blue bioeconomy:

- Structured and lasting promotion of scientific and technological research, with specific calls for proposals for marine biotechnology, coordinated by regional and national development agencies, ensuring predictability and continuity of investments;
- Creation of inter-institutional collaborative networks, bringing together universities, federal institutes, research centers and companies, with a focus on applied projects, data exchange, shared infrastructure and dissemination of knowledge;

- Technical training of professionals and strengthening of scientific education, with emphasis on the training of researchers, technicians and entrepreneurs specialized in bioprospecting, cultivation of marine organisms and biochemical analysis;
- Review and simplification of legal and regulatory frameworks, based on public consultations and intersectoral dialogue, in order to ensure legal certainty, environmental protection, and encourage responsible innovation (Araújo et al., 2021); and
- Incorporation of traditional knowledge and participation of coastal communities, promoting sustainable use practices, socio-environmental justice, and respect for the cultural diversity of peoples who have historically lived in contact with the sea (Carvalho & Bezerra, 2023).

The importance of environmental education and scientific literacy policies as central elements to build a sustainable ocean literacy is also reinforced. The sea must be recognized not only as a source of resources, but as a generator of interdisciplinary solutions and knowledge, with the capacity to guide a new model of regional development, more resilient, inclusive, and environmentally balanced (Amaral, 2022).

In summary, investing in marine biotechnology is betting on the Northeast's ability to become a world reference in blue innovation, contributing to the fight against global crises — such as climate change, food insecurity, and biodiversity loss — and opening paths for a just transition towards the economy of the future.

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