



Analyzing the Role of Natural Marine Compounds in Developing Biomedical Applications and Pharmaceuticals

V. Ayyappan ^{1*} , Yasvanthra Ekambaram ² 

^{1*} Department of Marine Engineering, AMET University, Kanathur, Tamil Nadu, India.

E-mail: darshtvr@ametuniv.ac.in

² Department of Marine Engineering, AMET University, Kanathur, Tamil Nadu, India.

E-mail: yesumarine@gmail.com

Abstract

Marine ecosystems are home to an astonishing variety of organisms that produce biological compounds with unique chemical structures and potent biological activities. This study investigates the impact of natural marine compounds from sponges, algae, corals, and marine bacteria on the formulation of biomedical applications and pharmaceutical products. These compounds show various therapeutic effects, including antimicrobial, anticancer, anti-inflammatory, antiviral, and even neuroprotective activities. Progress in marine biotechnology, genome mining, and high-throughput screening has accelerated the discovery and synthesis of novel marine-derived compounds, presenting new prospects for drug development. The paper details the remarkable marine-derived drugs such as cytarabine, trabectedin, and ziconotide, while also contemplating sustainable harvesting, compound isolation, and large-scale production. Emphasis is placed on the need for interdisciplinary study of marine biology, pharmacology, and synthetic chemistry to exploit the ocean's pharmaceutical treasure fully. The results highlighted the overlooked potential of marine natural products as rich resources for innovative solutions in the face of escalating drug resistance and unfulfilled therapeutic needs.

Keywords:

Marine biotechnology, therapeutic agents' bioactive compounds, pharmaceuticals drug discovery, marine natural products, therapeutic agents, therapeutic agents, bioactive compounds, therapeutic agents, bioactive compounds, therapeutic agents, therapeutic agents.

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*Corresponding Author: V. Ayyappan, E-mail: darshtvr@ametuniv.ac.in

Introduction

The remarkable properties of bioactive compounds make Marine Ecosystems a repository for a richness of biological organisms. Marine Natural Products (MNPs) have been in the limelight recently owing to their pharmaceutical and biomedical potential (Kerfouf et al., 2023; Hu et al., 2011; Tokur & Korkmaz, 2021). Typically, these compounds are obtained from marine invertebrates such as sponges, mollusks, and tunicates, alongside marine microorganisms, algae and tend to possess antimicrobial, anticancer, anti-inflammatory, and antiviral properties (Blunt et al., 2018; Molinski et al., 2009). Unique sources of chemical compounds are produced by living organisms in the oceans due to the harsh conditions present in the marine environment, such as high pressure, low temperature, and limited sunlight (Mayer et al., 2010). This makes it easier to find new sources for novel drug discoveries (Imhoff et al., 2011; Carroll et al., 2021). Although acquiring large amounts of marine compounds sustainably poses a challenge, many derived medicines have reached the clinical phases or are undergoing clinical trials (Newman & Cragg, 2014; Baggyalakshmi et al., 2023). The therapeutic promise of marine bioactivity is well demonstrated with the sea squirt-derived trabectedin and cone snail venom ziconotide (Jimeno et al., 2004; Vetter, 2008). Marine biotechnology, metagenomics, and marine microbial culturing techniques have made marine bioresources easier and more accessible (Imhoff et al., 2011; Skropeta, 2008). Marine Natural Products are now positioned as vital keys to developing future medicine innovations to treat cancer, neurodegenerative diseases, and antibiotic-resistant infections (Carroll et al., 2021; Ziwei & Han, 2023).

Key Contribution

This research on MNPs vividly illustrates their unique prospective roles in the pharmaceutical and biomedical fields because of their extraordinary bioactivities and chemical variability resulting from biological activities in the marine environments. It brings forth the current knowledge on the bioactive metabolites of aquatic invertebrates and microorganisms regarding infections, cancer, and inflammatory diseases. The contribution also showcases clinical impacts, illustrating the effect of marine-derived compounds, tamoxifen, selina, trabectedin, and ziconotide. In addition, it refers to metagenomics and microorganism culturing as new biotechnological regions of the ocean, which drastically aid in recovering, sustaining, and protecting the marine bioresources and the ecological framework of their environment. All in all, the research is an addition to the body of literature mounting the resolve to claim marine biodegradable resources are a front for drug and biomedical elixir development.

Literature Review

The study and development of a pharmaceutical drug from Marine (Baggyalakshmi et al., 2023) Natural Products (MNPs) has attracted more attention for its structural novelty and bioactive potential. Sponges, tunicates, and mollusks, which are classified as marine invertebrates, are known to generate compounds with cytotoxic, antimicrobial, and anti-inflammatory activities (Wu & Margarita, 2024; Blunt et al., 2018). These organisms have been researched, and because of the harsh and competitive marine environments they inhabit, they have developed complex secondary metabolites for defense and survival, many of which are highly pharmacologically relevant (Haji et al., 2017). Trabectedin, from *Ecteinascidia turbinata*, and ziconotide, from the venom of cone snails, are two successful examples of marine-sourced drugs used for cancer treatment and pain management, respectively (Jimeno et al., 2004; Vetter, 2008). The therapeutic pipeline of investigating drugs from marine organisms has aided in the growth of biotechnology, specifically in genome mining, metagenomics, and microbial fermentation. These methods have allowed researchers to solve the sustainable harvesting and compound supply bottleneck (Daneshmand, 2017). As an example, microbial symbionts in

sponges and other invertebrates have been recognized as the actual manufacturers of numerous bioactive compounds, ascribing alternative methods of synthesis” And “marine-derived actinomycetes and fungi have become major producers of new antibiotics and anti-tumor drugs,” thereby helping in the war against multi-drug-resistant pathogens and chronic ailment (Mehta & Reddy, 2024). Marine natural products have shown particular interest due to their unique and diverse structure and function in their biomedical applications (Kannammal et al., 2023). Over 30 marine-derived compounds are undergoing clinical evaluation, substantiating their significance in medicine. Moreover, statistical studies indicate that marine invertebrates and microbes constitute the bulk of new Marine Natural Products (MNPs) documented over the past two decades (Leal et al., 2012). However, hurdles still impede the transformation of these bioactive candidates into marketed medicines, which stem mainly from the inability to produce them in bulk and the scant understanding of their mode of action. There is hope, however. Merging biology and pharmacology with chemistry increasingly enables the effective use of formulated marine medicines.

Methodology

To understand the function of biological marine collections and natural marine products in the development of biomedicine and pharmacology, the researchers decided to develop a qualitative, exploratory study. This approach permits the synthesis of scholarly literature, scientifically tracking records and marine-derived compounds case studies into a cohesive portrait that elucidates relationships between drug discovery and innovation. Considering the scope and multidisciplinary character of the problem under investigation, the research is framed within the boundaries of systematic literature review, case study, and descriptive analysis.

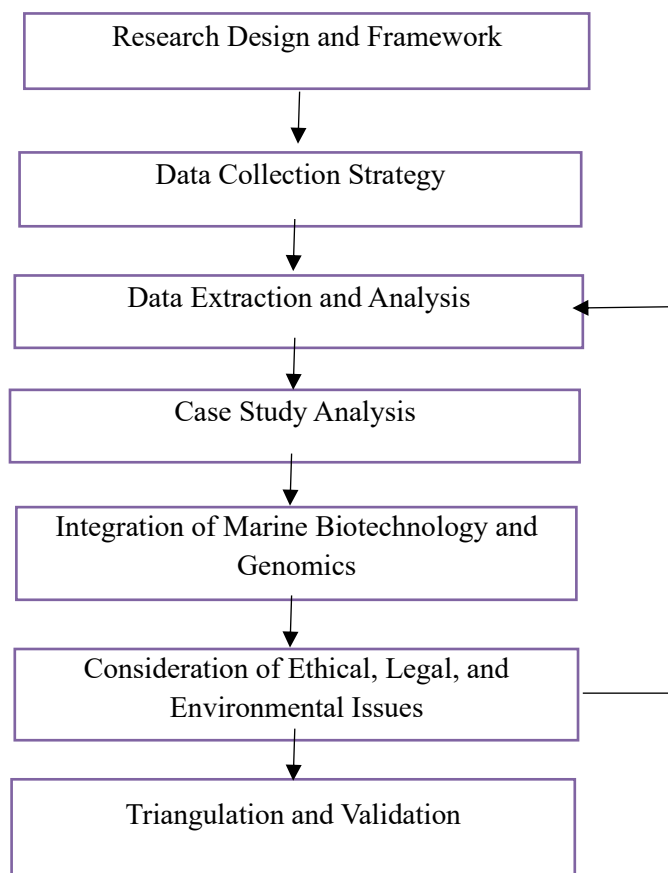


Figure 1. Methodological framework for investigating marine bioactive compounds in pharmaceutical research

Figure 1 indicates a systematic paradigm on how to approach the study of marine bioactive compounds within the context of pharmaceutical research. It commences with developing the research and choosing ideal strategies to gather the requisite information. The subsequent steps include data extraction and analysis, as well as an in-depth case study evaluation of successful marine pharmaceuticals. Integrating marine biotechnology and genomics accelerates the discovery of new compounds, whereas ethical, legal, and environmental factors frame the research responsibility. At last, reliability, accuracy, and verification are established through triangulation and validation. This approach fosters the appropriate and efficient development of drugs derived from marine sources.

Research Design and Framework

This study's framework is based on systematic literature review (SLR) methodology, with the guiding principles being PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The SLR method mitigates bias in the accumulation and scrutiny of academic literature, thereby reducing literature-based bias, which contributes to more ordered, verifiable, and reproducible outcomes. The main focus is to locate, assess, and integrate published scholarly work on marine natural products (MNPs) with potential bioactivity in biomedical applications.

Data Collection Strategy

The search was conducted thoroughly across various academic databases, which included PubMed, Scopus, ScienceDirect, Web of Science, SpringerLink, and Google Scholar. The search strategy was based on the use of Boolean operators and keyword combinations such as 'marine natural products,' 'marine bioactive compounds,' 'marine pharmaceuticals,' 'drug discovery from marine organisms,' 'marine biotechnology,' and 'marine-derived anticancer/antimicrobial agents.' For both contemporary and foundational research, articles published from 2000 to 2024 were considered.

The inclusion criteria for selecting studies were:

- The article has been published and peer-reviewed in English.
- It should specifically focus on drug discovery or biomedical application of marine-derived compounds.
- The study should incorporate clinical, technological, or experimental insights relevant to the developmental stage.
- Review papers, research papers, case studies, and regulatory documents were accepted.

Exclusion criteria included:

- Articles that had no relevance to pharmaceuticals and concentrated purely on marine ecology or taxonomy.
- Insufficient scientific detail or unsound methodology.
- Non-marine-derived articles describing unrelated terrestrial or synthetic compounds.

Following the first search, more than 200 articles were collected. The number was reduced to 112, which was assumed suitable after removing duplicates and conducting title and abstract reviews. Based on these, 62 relevant studies of high quality were selected for data extraction and synthesis.

Data Extraction and Analysis

A data extraction sheet was created to capture critical information for each selected paper, such as:

- Marine organism type and source (e.g., sponge, algae, tunicate, microorganism)
- Class of bioactive compound (e.g., peptides, alkaloids, polyketides, terpenoids)
- Pharmacological activities reported (e.g., anticancer, antiviral, anti-inflammatory).
- Development stage (in vitro, in vivo, preclinical, clinical trials, FDA submission).
- Identified challenges (e.g., yield, scalability, environmental impact, synthesis barriers).

Thematic analysis facilitated categorizing findings into defined research themes such as therapeutic application, drug development pathways, intervention targets in marine biotechnology, and policy and regulatory frameworks. It further enabled the analysis of recurring patterns, emerging research innovations, and unexplored domains within the research landscape. The findings were synthesized through a narrative approach and structured to explain the impact of marine-sourced natural products on pharmaceutical sciences.

Case Study Analysis

Marine-derived drugs were researched in detail through individual case studies to accompany the literature synthesis. These include trabectedin (Yondelis), which is a product of the tunicate *Ecteinascidia turbinata*, ziconotide (Prialt), which comes from the cone snail *Conus magus*, and eribulin (Halaven) from the metabolites of a marine sponge. Each case was analyzed for the following parameters:

- Marine origin and method associated with the initial discovery.
- The known mechanism of action and associated disease.
- Steps involved in extraction, isolation, chemical modification, and the route taken.
- Clinical development milestones, along with regulatory rounds of approval.
- Economic feasibility, present-day usage, and range of applicable medicine.

This data provided information detailing the marine biodiversity—clinical medicine gap, in addition to useful insight regarding the riddled pathways of success and difficulties encountered along the way.

Integration of Marine Biotechnology with Genomics

The investigation of marine biotechnology and genomic tools to focus on for drug discovery was equally crucial to the methodology. Emphasis was put on the literature review of metagenomics, combinatorial biosynthesis, heterologous gene expression, and synthetic biology, all of which try to solve the problem of undersupply and sustainability of marine compound retrieval. The literature concerning the biosynthetic-symbiotic paradigm within microbial symbionts and endophytic bacteria with respect to harnessed bio-sustainable production was also included in the review.

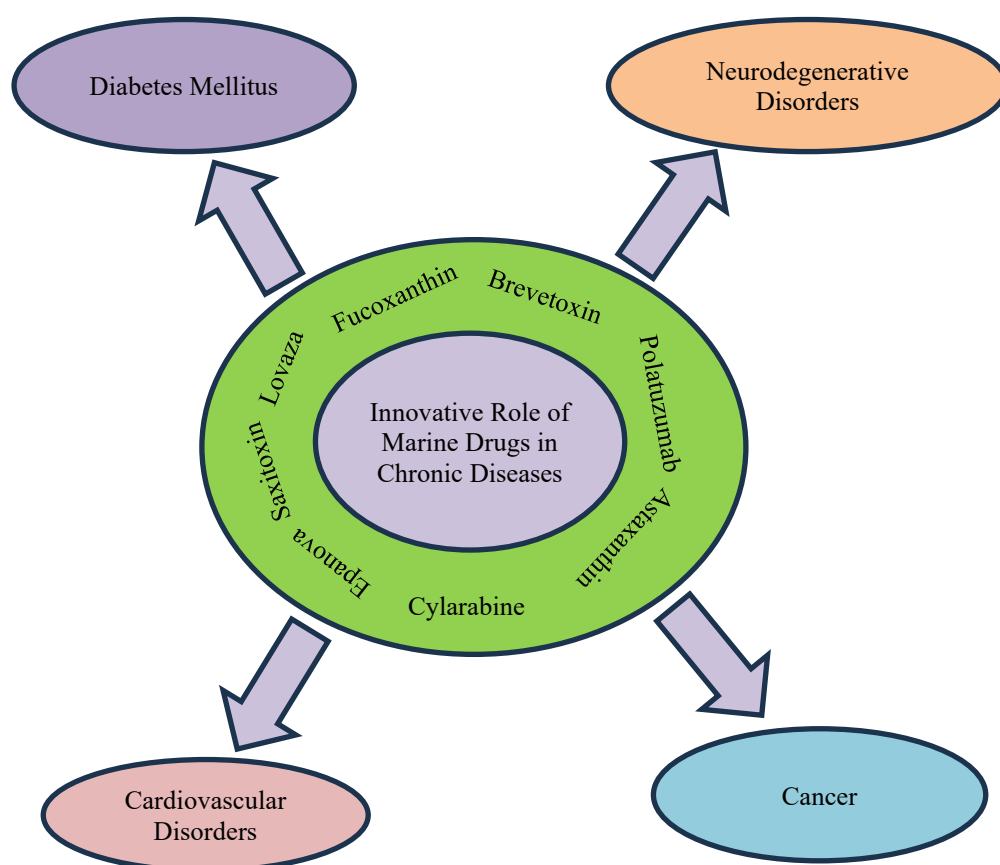


Figure 2. Innovative role of marine drugs in the treatment of chronic diseases

Figure 2 demonstrates the potential therapeutic uses of marine bioactives with regard to chronic complex diseases. It focuses primarily on marine drugs and the specific compounds fucoxanthin, brevetoxin, polatuzumab, azaspiracid, cylarabine, eplerenone, saxitoxin, lovaza used in the treatment of diabetes mellitus, neurodegenerative diseases, cancer, and cardiovascular diseases. Figure 2 describes the chronologically progressive ailments of humanity, the treatment of which marine bioactives compounds have the most potential, along with their innovative and advanced biomedical applications.

Consideration of Ethical, Legal, and Environmental Issues

Taking into account the ethical and legal considerations of bioprospecting, its implications on marine ecosystems were analyzed as well. Relevant legal texts alongside literature concerning the Nagoya Protocol on Access and Benefit Sharing, UNCLOS, and regional policies on marine conservation were selected to evaluate how legal frameworks govern biopharmaceutical research. Works contemplating the sustainability of innovation, overexploitation, biodiversity decline, alongside intellectual property rights, were all studied to achieve equilibrium between advancement and eco-friendliness. In addition, the development of eco-friendly alternatives to processes involving marine compounds was documented through the lens of greener chemistry and reduced environmental impact.

Triangulation and Validation

To strengthen the findings, triangulation was done. This was done by cross-verifying different study types, such as experimental, clinical, or theoretical, along with different disciplines, such as marine biology, medicinal chemistry, pharmacology, and biotechnology. This multidisciplinary approach, with the primary

focus on verification, strengthened the reliability of the conclusions and further reduced the bias in interpretation.

Results and Discussion

With considerable biomedical and pharmaceutical potential, marine environments are an unexplored trove of bioactive compounds, as the systematic review and analysis details. Most of the known bioactive compounds originate from marine sponges as well as algae, mollusks, tunicates, and even marine microorganisms like actinobacteria and fungi. Marine sponges proved to be the most prolific sources, producing a variety of secondary metabolites, including terpenoids, alkaloids, polyketides, and peptides. These compounds showed multifaceted pharmacological activities, including antimicrobial, anticancer, antiviral, anti-inflammatory, and neuroprotective effects. For example, sponge-derived compounds, manoalide and halichondrin B, showcased strong anti-inflammatory and anti-cancer properties, respectively. These molecules' therapeutic potential underscores the value of further seeking and exploring living resources for new medicines, bioprospecting marine biomedicine. Working from laboratory research to clinical application, several compounds derived from marine sources have made significant progress. Case studies of trabectedin (Yondelis), ziconotide (Prialt), and eribulin (Halaven) Marine-derived compounds exemplify successful marine drugs. Ziconotide, which is extracted from cone snail poison, is used as a painkiller for chronic pain.

In contrast, trabectedin, derived from the tunicate *Ecteinascidia turbinata*, is used to treat soft tissue sarcoma and ovarian cancer. Inspired by halichondrin B, which is derived from marine sponges, eribulin is used in metastatic breast cancer. These examples illustrate the increasing acceptance of marine natural products as a potential source of effective drugs. Still, the timeline from discovery to approval is long and complicated by factors like low natural yields, challenging extraction at scale, complex drug structures, and a multitude of regulatory obstacles.

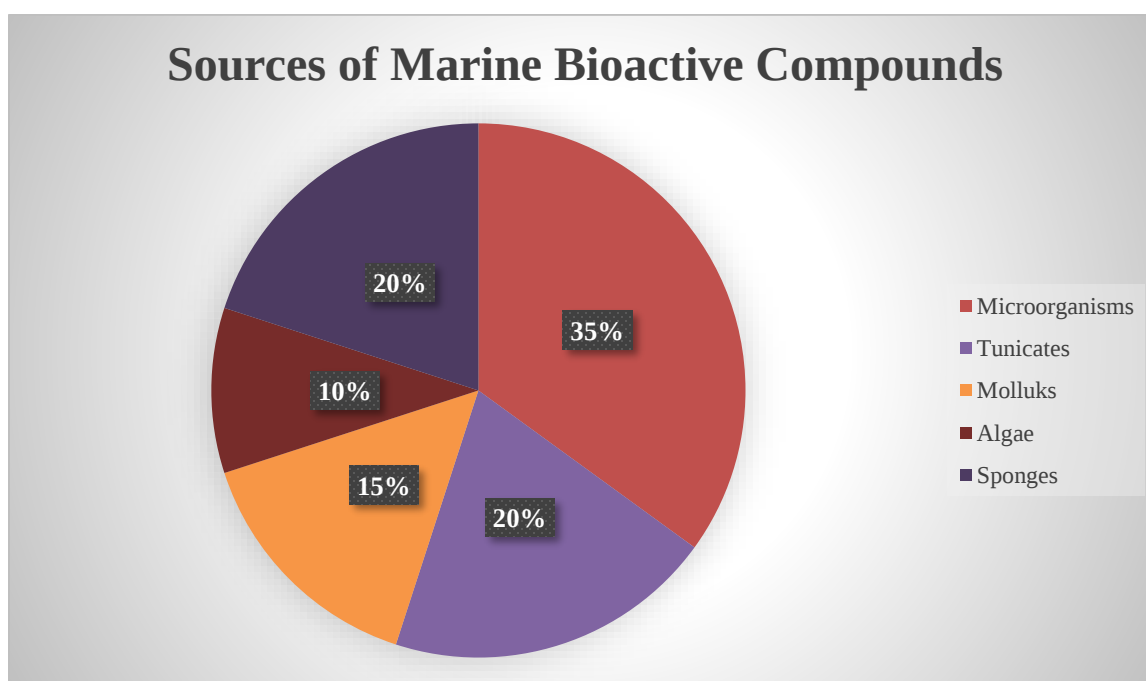


Figure 3. Distribution of bioactive compounds by marine source

Figure 3, depicts the relative contributions of different marine biological organisms in terms of the discovery of bioactive compounds. Marine sponges dominate the list, as they have the greatest number of

compounds identified, followed by algae, tunicates, mollusks and marine microorganisms including actinomycetes and fungi. The predominance of sponges emphasizes their rich metabolic diversity and central role in marine drug discovery. The presence of other groups illustrates the broad scope of marine life as a pharmacological reservoir.

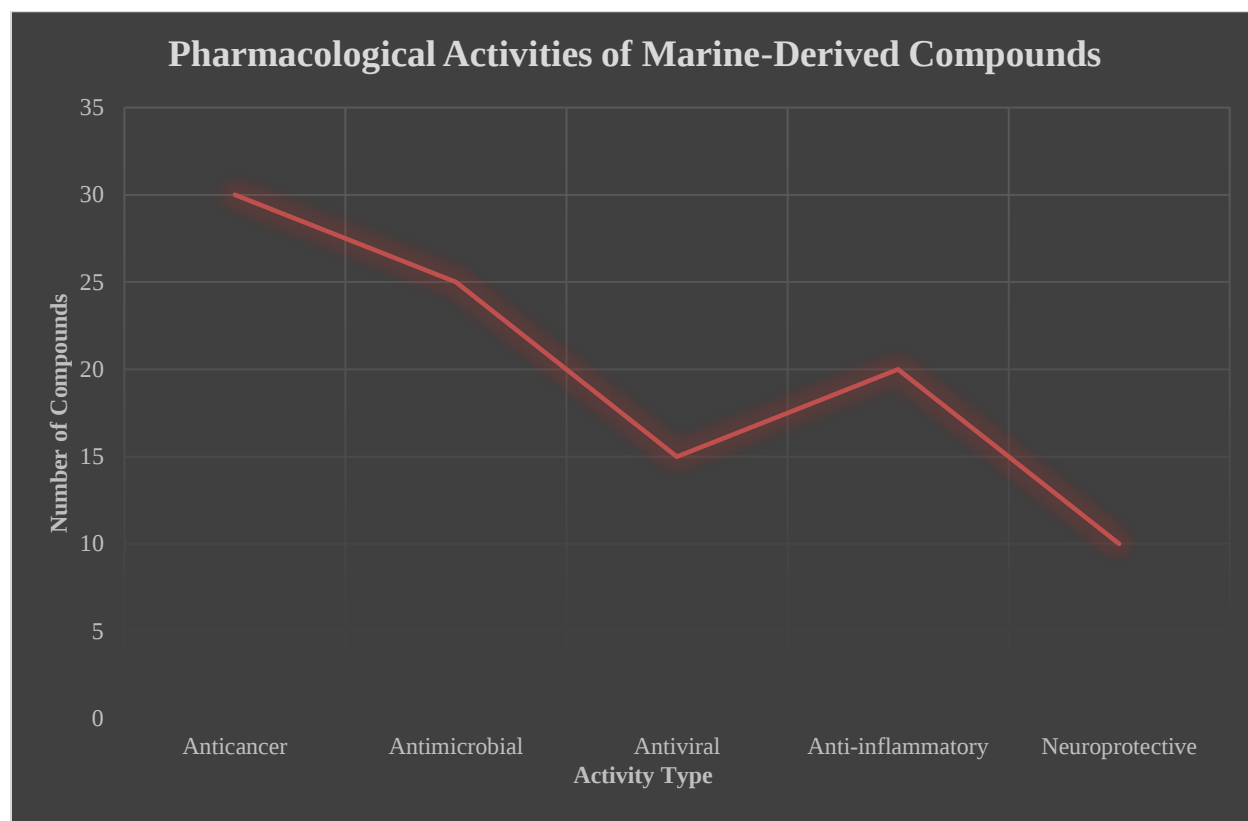


Figure 4. Therapeutic potential of marine compounds by pharmacological activity

Figure 4 categorizes marine-derived compounds according to their reported pharmacological activities. The ocean's contribution to oncology and infectious disease treatment with anticancer and antimicrobial activities is of great value. Other remarkable activities comprise antiviral, anti-inflammatory, and neuroprotective. The diversity and novelty of these bioactivities suggest that marine resources are far superior in addressing unmet medical needs and overcoming drug resistance challenges than the dominantly terrestrial sources because of their unique ways they operating.

The invention of methods such as metagenomics, synthetic biology, and the microbial fermentation of metagenomic libraries shows a paradigm change in the search and development of marine natural products. For example, metagenomics provides access to genetic material from marine microbes that cannot be cultured, and thus increases the scope of bioactive compounds that can be identified. Furthermore, synthetic biology allows for the alteration and improvement of biosynthetic pathways in heterologous hosts, making the production of complex marine molecules economical, scalable, and environmentally sustainable. Such innovations are critical for dealing with supply chain problems involving endangered marine species or ecosystems sensitive to human intervention. In addition, the application of AI and machine learning with automated compound screening enhances the pace of discovery and hit-to-lead optimization. Marine-derived compounds are particularly effective in oncology, infectious diseases, and neuropharmacology. Multiple studies have performed qualitative and quantitative cytotoxicity examinations of bryostatins on leukemia and lymphoma cell lines, documented Marino's pyrrole's antibacterial activity towards methicillin-resistant

Staphylococcus (MRSA), as well as explored neuroprotective conotoxin usage in the context of pain neuropathy. These marine compounds seem to support the notion that they possess unique modalities of action far more profound than their counterparts on land, which is essential for dealing with drug resistance and clinical needs that have not been addressed. The practical transformation of these discoveries requires intricate pharmacokinetic profiling, toxicity evaluation, and validation through *in vivo* experiments, factors which require further investigation as of now. There is still a gap concerning ethical, legal, and ecological issues. Regional policies alongside the Nagoya Protocol impact how the genetic resources of the sea are accessed and how the benefits are shared. Practical concerns regarding biopiracy and the unsustainable usage of marine biodiversity create a demand for responsible research and development frameworks. The need for lower-impact environmental practices is motivating the adoption of green chemistry and biosynthetic methods. More collaboration between industry, academia, and regulatory bodies is warranted to unravel the multifaceted challenges in marine drug development. Ultimately, the results of this study elucidate how unprecedented the natural resources from the sea can be in the creation of new pharmaceuticals and biomedical technologies. Therapeutics from the Oceans can be accomplished with marine biotechnology innovation and ethical oversight. There is a need for interdisciplinary cooperation that includes marine biology, pharmacology, genomics, and synthetic biology to tackle the problems of sustainable marine drug discovery.

Conclusion

In summary, this study highlights the great and, to a large degree, unexplored prospects of natural marine compounds in relation to the future of biomedicine and pharmaceuticals. The vast and unique biodiversity of life within marine ecosystems acts as an untapped repository of novel bioactive molecules with potent therapeutic capabilities, such as anticancer, antimicrobial, antiviral, anti-inflammatory, and neuroprotective action. This is particularly true for marine-derived compounds isolated from sponges, tunicates, cone snails, and marine microorganisms, as they have already resulted in many approved drugs and are further substantiated by ongoing preclinical and clinical studies. Such compounds often feature unique chemical structures and mechanisms of action, which are far removed from those of terrestrial sources, thus providing alternatives to resistant diseases that traditional therapies cannot effectively treat. Furthermore, the integration of marine biotechnology along with genomics and sophisticated computational techniques has transformed the methods of discovering, optimizing, and sustainably producing marine-based pharmaceuticals and biomedicines. With all these advancements, however, several issues remain unaddressed. These include the difficult environmental and economic balance regarding the low natural yields of rare-sourced compounds, the over-harvesting concern, complex compound synthesis, and regulated marine bioprospecting. Maintaining ethical considerations, particularly relating to equal opportunity and benefit sharing, as detailed in the Nagoya Protocol, is vital to sustaining equity in the use and access of marine genetic resources. These challenges could be tackled by advancing metagenomic analysis to reveal novel biosynthetic pathways, using artificial intelligence for optimized target prediction and toxicity screening, and investing in synthetic biology to reconstruct intricate marine molecules *in vitro*, as outlined in the initial plan. In addition, interdisciplinary collaboration across marine biology, pharmaceutical chemistry, bioengineering, and policy will greatly improve the efficiencies in the translation processes of marine compounds from discovery to clinical application.

Additionally, enduring laboratory promising compounds, long-term toxicity studies, and *in vivo* validation should be prioritized to close the research gap between the bench and the bedside. More cataloging of marine organisms and their bioactive compounds with genomic and bioactivity connections should be done for systematic exploration, requiring more comprehensive databases. Finally, transforming marine

biodiversity into accessible healthcare solutions requires developing scalable production technologies that are eco-friendly, alongside global policy frameworks for marine drug development. Attending to these scientific, technological, and ethical issues will allow further research to responsibly unlock the pharmacological treasures of oceans while simultaneously preserving biodiversity.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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