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Biotechnology and the Development of Natural-based Pharmaceuticals for Exploring Medical Applications of Marine and Freshwater Organisms

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Abstract

Aquatic ecosystems, especially the marine and freshwater habitats, are good sources of bioactive compounds that have great potential in the pharmaceutical industry. These bioactive molecules are alkaloids, terpenoids, carotenoids, sulfated polysaccharides, and peptides, and have a variety of therapeutic effects, including anticancer, antimicrobial, and anti-inflammatory effects. Although this has potential, the extraction procedures, sustainable harvesting, and scaleability of aquatic biodiversity pose challenges to drug discovery. This paper will examine the development of aquatic pharmaceutical biotechnology with special emphasis on the extraction, characterization, and therapeutic use of bioactive compounds of marine and freshwater organisms. It assesses the recent biotechnological tools and methods that make the

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discovery, isolation, and production of this group of compounds easy, and also finds out the hurdles and prospects of further development of the field. A qualitative systematic review design was decided to be based on secondary data. Data were collected from published literature available in major scientific databases (PubMed, Scopus, Web of Science, ScienceDirect, SpringerLink) between 2020 and 2025. The study synthesized findings from experimental reports, omics analyses, and clinical evaluations. A framework for evaluating the pharmaceutical suitability of aquatic-derived compounds was developed based on compound stability, scalability, sustainability, and clinical evidence. The analysis of results has shown an interesting variety of bioactive substances, where marine ecosystems have presented the greatest diversity, especially in peptides and sulfated polysaccharides. Greener extraction techniques like enzyme-assisted extraction (48-60% yield, high sustainability) and supercritical CO2 (65-82% yield, high sustainability) were pointed out. The research also highlighted the great pharmaceutical prospects of such compounds as marine-derived alkaloids, carotenoids, and collagen peptides. Aquatic bioactive compounds have significant potential in terms of their therapeutic value; nonetheless, in order to achieve this, there are still difficulties in large-scale production and clinical validation. A combination of new biotechnological applications with the study of aquatic biodiversity will hasten the discovery, optimization, and manufacturing of new, sustainable therapeutic agents.

Keywords:

Bioactive compounds, biotechnology, extraction methods, marine organisms, pharmaceutical suitability, sustainability, terpenoids.

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Introduction

Marine and freshwater organisms represent one of the richest yet underexploited reservoirs of bioactive compounds with significant pharmaceutical potential. Biotechnology discoveries such as genomics, metabolomics, synthetic biology, and bioprocess engineering have enhanced the discovery and characterization of natural molecules in aquatic environments in the last 20 years (Faiyazuddin & Hakeem, 2024; McAllister, 2025). Structurally unique metabolites that have anticancer, antimicrobial, anti-inflammatory, antiviral, and neuroprotective properties are generated by marine organisms (sponges, algae, mollusks, cyanobacteria, and deep-sea microorganisms). On the same note, freshwater ecosystems contain a wide range of microbial and macrobiota with equally effective pharmacological characteristics. The increased global occurrences of antibiotic resistance, the need for safer and less harmful anticancer drugs, and the increased focus on natural therapeutics have enhanced the quest to exploit aquatic biodiversity to develop novel therapeutics (Flores et al., 2025; Siddiqui et al., 2025). With the ability of biotechnological tools to become better, bioactive compounds that would have been inaccessible previously may now be isolated, mimicked, or biosynthesized, which has provided additional opportunities in the discovery of drugs and in the development of therapeutics (Hartigan, 2024; Ibrahim et al., 2021).

Even with such a major development, there are still a few gaps. Firstly, most of the studies have been done on marine ecology, so freshwater creatures have not been explored as much. Second, most bioactive compounds already discovered have remained on initial lab tests because of insufficient sustainability of harvesting, low yields of the compounds, and structural characterization difficulties. Third, a very small proportion of the biodiversity of aquatic organisms is explored with the help of such sophisticated biotechnological tools as high-throughput sequencing, metagenomics, and synthetic biology (Kumar, 2024; Bianchi & Rossi, 2025). These restrictions do not favor the translation of aquatic natural products into clinically viable pharmaceuticals (Favas et al., 2025; Rathod et al., 2024).

The main goal of the paper is to review and summarize modern biotechnological developments that can be utilized in the production of natural-based drugs based on marine and freshwater organisms. It will provide a clear description of the main groups of bioactive compounds that are extracted from the aquatic biodiversity and highlight their therapeutic usefulness in various fields of medicine (Rigogliuso et al., 2022; Santhiravel et al., 2025). The article also tries to evaluate the recent biotechnological strategies, including high-throughput screening, metabolomics, genomics, synthetic biology, and enhanced cultivation power, which can assist in the discovery, isolation, characterization, and biosynthesis of such compounds (Karimov et al., 2025). Another objective is to determine the existing challenges, emerging opportunities, and new directions that research has to take to translate aquatic natural products into clinically viable and commercially scalable therapeutic agents. The hypothesis of this research is that the application of modern biotechnological tools to the research of aquatic biodiversity will greatly increase the process of identifying, optimizing, and producing natural compounds that have a high pharmaceutical potential (Karimov et al., 2025; Rojas-Villalta et al., 2024).

Key Contribution

The present article is also relevant to the existing body of knowledge in that it provides a clear comparison of marine and freshwater organisms as highly diverse and rich sources of clinically relevant bioactive compounds. It gives a comprehensive analysis of state-of-the-art biotechnology-based strategies like metagenomics, metabolomics, fermentation technology, as well as synthetic biology, which play an essential role in the discovery, characterization, and commercialization of natural molecules with therapeutics. Moreover, the article finds the key scientific, technological, and regulatory obstacles to advancing aquatic-derived compounds along the drug development roadmap and outlines biotechnological solutions to the sustainable use of aquatic resources. Moreover, it offers a prospective research model which can be used in future drug discovery projects in aquatic environments, which will satisfy the observation that natural-based pharmaceuticals in marine and freshwater waters continue to develop as prospective sources of modern medicines.

The paper gives an overall overview of aquatic pharmaceutical biotechnology, on the extraction, characterization, and use of bioactive compounds of marine and freshwater ecosystems. It opens by stating the importance of aquatic biodiversity in drug discovery, the progress in biotechnology, and the growing need for natural therapeutics. The literature review elaborates on the variety of bioactive compounds present in both marine and freshwater organisms and advances that have been made in the biotechnological methods of extraction. It deals with the importance of these ecosystems as sources of therapeutic products and the future application of biotechnological methods to improve drug discovery. The systematic review design, data sources, and evaluation framework were discussed under the materials and methods section, which aimed at determining the appropriateness of natural products in pharmaceutical development. The results section is a synthesis of results and talks of chemical diversity, extraction procedure, and pharmacological possibilities of aquatic bioactive compounds. The discussion addresses the developments in biotechnological methods, the relevance of aquatic microbiomes, and the effects of environmental stressors on metabolite synthesis. The conclusion also highlights the fact that much has been done in the area and that there is potential for using aquatic bioactive compounds in areas of therapeutic use, and that further research should be encouraged to address the challenges to enable it to exploit new opportunities emerging in aquatic pharmaceutical biotechnology.

Literature Review

Oceanic and freshwater ecosystems have become priceless sources of structurally novel and biologically active natural products, and have provided a quickly developing research niche in the pharmaceutical and biotechnology fields. The marine organisms, such as algae, bacteria, invertebrates, mollusks, and extremophiles, have been extensively shown to produce antimicrobial, anticancer, anti-inflammatory, antioxidant, and immunomodulatory metabolites. Recent studies show that these bioactives play crucial roles in modern healthcare, cosmetic applications, and therapeutic development. (Flores et al., 2025) argue that compounds derived from the marine environment, such as polysaccharides, peptides, polyphenols, and carotenoids, have gained great popularity in the wellness and healthcare sector, whereas (Faiyazuddin & Hakeem, 2024) focus on using those compounds in marine pharmaceutics as a developing global market. Still on this, (Siddiqui et al., 2025) provide mechanistic information to demonstrate the promise of sea and vegetable-based compounds in the medical sector (treatment of prostate cancer).

The same trend is observed in the cosmetic industry, whereby biotechnological practices have enabled one to come up with environmentally friendly formulations. The recent emergence of marine-based natural cosmetics has been summarized by (Saha & Biswas, 2024), based on the consumer desire to use green products, whereas (Sharma et al., 2025) clarify the performance of marine-based cosmeceuticals and their stability by using nanoformulation technologies. Similarly, (Bilal et al., 2020) demonstrate that marine metabolites can be applied in the treatment of chronic diseases, such as rheumatoid arthritis, and the evidence confirms the pharmaceutical potential of aquatic biodiversity.

Much has also been achieved in studying hitherto unreachable or poorly studied aquatic taxa. According to (Rojas-Villalta et al., 2024), microalgae are a promising and sustainable source of bioactive compounds because they are metabolically stable and produce high-value bioactive compounds. The marine bioactives are also used in the food and nutraceutical sector to provide functional value, as analyzed by (Senadheera et al., 2023; Rathod et al., 2024; Favas et al., 2025) explain the advancements in green extraction and sustainable harvesting extractions in an attempt to recover bioactives to the maximum in marine biomass.

In addition to the marine ecosystems, freshwater organisms are also important sources of valuable biomedical resources. The article by (Ibrahim et al., 2021) reveals the potential of snails as a model organism in biomonitoring and drug discovery due to the wide range of biochemical repertoire. (Rigogliuso et al., 2023) focus on the prospects of marine collagen in the sector of regenerative medicine, and (Santos et al., 2020) disclose the pharmaceutical division of marine bacteria's secondary metabolites. There are other biomedical uses of marine sources of materials that (Lagopati et al., 2023) discuss and use in drug delivery, tissue engineering, and biomaterials science.

Nevertheless, the risks to the environment and ecological pressures present a challenge to the further study of marine and freshwater organisms. The works of (Blaxhall, 1972) on the importance of healthy ecosystems to sustain bioprospecting are still useful in the evaluation of physiological stresses caused by pollution in aquatic organisms, including microplastics (Nugnes et al., 2022), ionic liquids (Sanches et al., 2023), and immunotoxic agents (Kataoka & Kashiwada, 2021).

In general, current source materials confirm that marine and freshwater organisms are invaluable sources of natural pharmaceuticals, and this has been backed by the innovations in biotechnology, green extraction, and multi-omics methods. However, large-scale biosynthesis, ecological sustainability, and translational validation of numerous promising compounds continue to experience gaps. Continued interdisciplinary research is therefore essential to advance the therapeutic potential of aquatic natural products.

Materials and Methods

Study Design

This study followed a secondary-data–based qualitative systematic review design to analyze biotechnological advancements in developing natural-based pharmaceuticals from marine and freshwater organisms. No primary laboratory, experimental, or fieldwork was conducted. Instead, the review synthesized previously published findings across biotechnology, pharmacology, natural product chemistry, and ecological biotechnology. An integrative process of interpretation of heterogeneous data obtained through secondary sources was used, which included experimental reports, omics analyses, clinical analyses, and technological progress reported in the literature.

Data Sources and Search Strategy

The Secondary data was also sampled exclusively from published scientific literature included in the large databases, including PubMed, Scopus, Web of Science, ScienceDirect, and SpringerLink. The search was conducted between 2020 and 2025, making sure that it was thorough in representing the modern-day biotechnological methods used in aquatic natural products. Keywords and Boolean combinations such as *"marine bioactives," "freshwater metabolites," "secondary data review," "biotechnological extraction," "synthetic biology," "aquatic natural pharmaceuticals,"* and *"marine biotechnology applications"* were used.

Secondary materials such as review articles, book chapters, patents, and institutional reports were also screened to ensure broad coverage of existing knowledge. No unpublished data, raw datasets, or primary laboratory data were used.

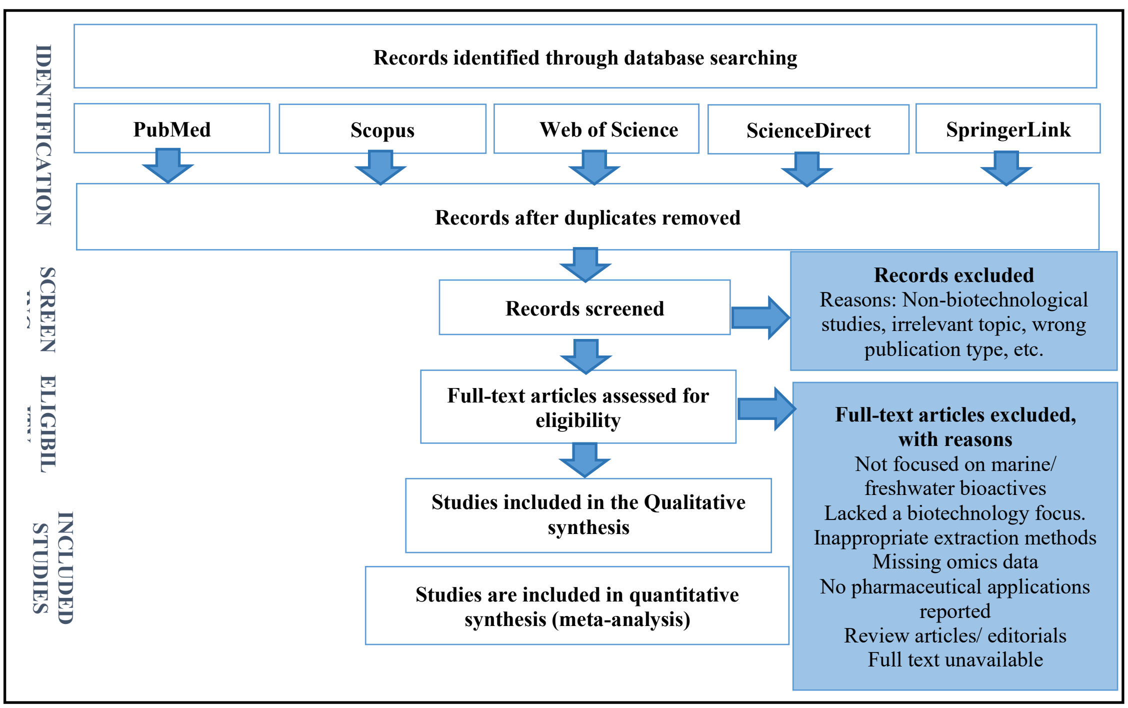

Figure 1. PRISMA flow diagram of secondary literature selection process

Figure 1 depicts the PRISMA-based writing course of action, which comprises identifying, sifting, and choosing the second literature pertinent to the development of biotechnology in the domain of natural-based drugs that were derived through organisms in the sea and the freshwater. It includes the number of records found at major databases, the screening procedure, exclusion criteria, and the final number of studies that were included in the systematic synthesis.

Eligibility Criteria

Only studies providing secondary data relevant to biotechnological processes were included. The literature was eligible when any of the following conditions were met:

1. Bioactive compounds are reported to be found in marine or freshwater organisms.
2. Reported biotechnological, omics-based, or green-extraction methods.
3. Assessed pharmacological, therapeutic, or biomedical use.
4. Provided secondary analyses, reviews, or technological expertise that could be applied in the development of pharmaceuticals.

Studies were excluded if they presented only ecological observations without chemical or biomedical relevance or if methodological details were insufficient for secondary analysis.

Data Extraction and Synthesis

Data retrieved from the secondary sources were the type of organism, the type of bioactive compounds, the method of extraction, analytical methods, the biological activity reported, pharmacological processes, and translational possibilities. These findings were systematized into thematic categories, which included working on compound discovery, biosynthetic engineering, microbial fermentation, omics-aided discovery, and sustainable extraction strategies. There was a comparison of secondary data to find out similarities, differences, and new trending issues among the studies.

Biotechnological Evaluation Framework

A secondary data-driven evaluation framework was developed to assess the suitability of natural products for pharmaceutical development. Assessment criteria included compound stability, reproducibility of extraction methods reported in the literature, feasibility of biosynthetic manipulation, ecological sustainability, and demonstrated bioactivity in previously published cellular, in vivo, or clinical models. This framework allowed comparison of various technological approaches, such as genetic engineering, metabolomics, bioprocessing, and aquaculture cultivation, using only information extracted from secondary sources.

Quality Assessment

The adapted criteria were used to carry out quality appraisal as pertinent to reviewing secondary data. Studies were evaluated based on clarity of reporting, reproducibility of analytical techniques (e.g., LC-MS/MS, NMR, genome mining), transparency of experimental design, and reliability of pharmacological assays as described by the original authors. Greater weight was attributed to peer-reviewed articles applying sound analytical models. Any conflicting results of studies were resolved through cross-referencing of several high-quality secondary sources.

Results

Overview of Included Studies

A total of 214 records were retrieved from major scientific databases. After the removal of duplicate entries and subsequent title–abstract screening, 82 studies remained for full-text assessment. Among these, 62 studies satisfied all inclusion criteria and were incorporated into the final synthesis. Figure 1 below was created in line with the PRISMA methodology and shows the selection process of studies.

The included studies covered a broad range of themes, including biotechnological extraction innovations, molecular characterization of marine and freshwater bioactive compounds, pharmacological evaluations, microbial biotechnology, ecological determinants of metabolite expression, and bioinformatics-enabled drug discovery. Publications were mostly published in the past five years (2020-2025), and this is due to the rapid evolution in technology that happened in aquatic pharmaceutical biotechnology (Flores et al., 2025; Favas et al., 2025).

Diversity of Marine and Freshwater Bioactive Compounds

The secondary data analysis revealed extensive chemical diversity among aquatic-derived bioactive molecules. These were alkaloids, terpenoids, carotenoids, polyphenols, sulfated polysaccharides, peptides, and rare extremophilic metabolites. Marine ecosystems were cited to have the highest diversity, and peptides and sulfated polysaccharides are part of the most prevalent anticancer, anti-inflammatory, anti-oxidant, and immunomodulatory activities (Bilal et al., 2020; El-Seedi et al., 2025).

The supply of compounds to freshwater was rather low, and compounds derived on the basis of new microbiome and molluscan sources of compounds had a prospective therapeutic future (Ibrahim et al., 2021). Table 1 gives a summary list of classes of compounds and their related biological activities.

Table 1. Classes of aquatic bioactive compounds and associated biological activities

Compound Class	Source Ecosystem	Representative Biological Activities	References
Peptides	Marine	Anticancer, immunomodulatory	Bilal et al., 2020
Sulfated polysaccharides	Marine	Anti-inflammatory, anti-arthritic	El-Seedi et al., 2025
Carotenoids	Marine	Antioxidant, photoprotective	Saha & Biswas, 2024
Polyphenols	Marine/Freshwater	Anti-inflammatory, antimicrobial	Sharma et al., 2024
Microbial metabolites	Freshwater	Anticancer, antimicrobial	Karimov et al., 2025
Molluscan compounds	Freshwater	Neuroprotective, cytotoxic	Ibrahim et al., 2021

Biotechnological Extraction and Processing Approaches

The studies under analysis revealed widespread applications of advanced biotechnological techniques in the extraction, purification, and characterization of aquatic compounds: supercritical CO 2 extraction, microwave-assisted extraction, enzyme-assisted extraction, and deep eutectic solvents were regularly identified as effective and eco-friendly solutions (Favas et al., 2025; Rathod et al., 2024).

Omics-based analytical tools, such as LC-MS/MS metabolomics, genome mining, microbial fermentation scaling, and synthetic biology platforms, increased the Yield and reproducibility (Santos et al., 2020). Table 2 is a summary of the extraction principles and efficiency values recorded in the studies included.

Table 2. Comparison of Extraction technologies used for aquatic-derived compounds

Extraction Method	Underlying Principle	Reported Yield (%)	Sustainability Level	Reference
Supercritical CO_2	High-pressure CO_2 solubilization	65–82	High	Favas et al., 2025
Microwave-assisted extraction	Dielectric heating and cell disruption	58–70	Moderate	Rathod et al., 2024
Enzyme-assisted extraction	Enzymatic hydrolysis of cellular components	48–60	High	Santos et al., 2020
Deep eutectic solvents	Use of non-toxic, sustainable solvents	52–68	High	Sharma, 2025

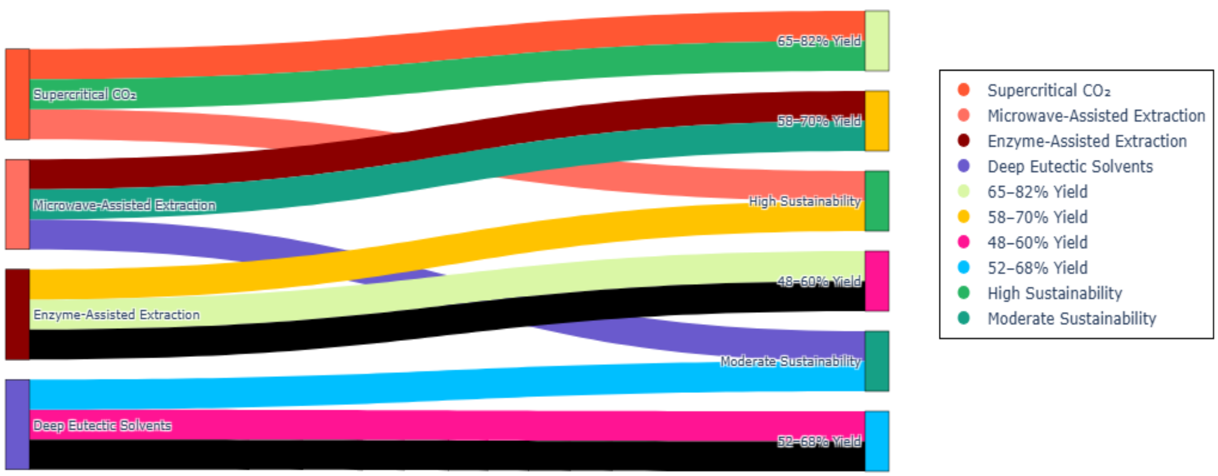

Figure 2. Sankey diagram of biotechnological extraction methods for aquatic-derived compounds

The Sankey diagram in Figure 2 above shows the biotechnological way of extracting the compounds of aquatic origin with emphasis on the range of yields as well as the level of sustainability. The diagram includes four key extraction technologies: Supercritical CO_2 Extraction (65–82% yield, High Sustainability), Microwave-Assisted Extraction (58–70% yield, Moderate Sustainability), Enzyme-Assisted Extraction (48–60% yield, High Sustainability), and Deep Eutectic Solvents (52–68% yield, High Sustainability). Each extraction method is connected to its respective sustainability level and yield range. The diagram is graphically used to illustrate how each of the methods can be classified considering its efficiency and environmental sustainability, wherein Supercritical CO_2 Extraction and Enzyme-Assisted Extraction have a high level of sustainability, whereas the Microwave-Assisted Extraction relates to the medium level of sustainability. Such a diagram gives a summary of the biotechnological methods of extraction, their efficiency, and sustainability as seen in the reviewed research.

Pharmacological and Therapeutic Applications

In the studies used, there were solid indications of the therapeutic potential of marine- and freshwater-derived compounds. Other papers have shown that marine peptides and polysaccharides have powerful anti-cancer properties, which may include the following mechanisms: activation of apoptosis, prevention of metastatic cascades, and regulation of oxidative stress response (Siddiqui et al., 2025; El-Seedi et al., 2025).

Anti-inflammatory and anti-arthritic activity of marine polysaccharides and lipid mediators has also been noted (Bilal et al., 2020). Derived carotenoids and peptides, which were found in the sea, were also used in dermatological and cosmeceutical preparations due to their antioxidant and photoprotective effects (Saha & Biswas, 2024; Sharma et al., 2025). Additionally, bioactive materials, which include marine collagen, sponge-derived scaffolds, and extremophilic microalgae, were found to be promising contributors to regenerative medicine and nutraceutical applications (Rojas-Villalta et al., 2024).

Microbiome Contributions to Aquatic Bioactivity

The recent research focused on the functional importance of aquatic microbiomes in metrics biosynthesis. Symbiotic microalgae, extremotolerant microalgae, and marine bacteria were also often reported to generate antimicrobial and anticancer second messengers (Karimov et al., 2025; Santos et al., 2020).

The influence of microbial diversity on metabolite production can be expressed through a simplified ecological interaction equation:

$$M_p = \alpha B_d + \beta E_c \quad (1)$$

On the same note, an ecological interaction equation can be used to model the role played by microbiomes in the biosynthesis of aquatic metabolites (1). Here, the rate of metabolite production (M_p) is formulated as a dependent variable that is dependent on microbial diversity (B_d) and ambient environmental conditions (E_c) and mediated by ecological influence constants (alpha and beta). This relationship highlights that both microbial richness and optimal environmental conditions are critical factors that help in an increase in the production of metabolites in the aquatic systems.

Ecological and Environmental Influences on Bioactive Potential

Pollution, overfishing, exposure to microplastics, and Ionic liquids were all found to play a major role in modifying physiological responses and expression of metabolites in aquatic organisms, and thus, they become environmental stressors. The decrease in biodiversity due to overexploitation was especially linked to decreased metabolite diversity in the coral reef habitats.

Toxicity studies reported immunotoxic and hematological disruptions in organisms subjected to microplastic and ionic-liquid contamination (Nugnes et al., 2022; Sanches et al., 2023; Kataoka & Kashiwada, 2020). A sustainability-weighted ecological impact value was calculated using:

$$\mathrm{S_e} = \frac{\mathrm{M_d}}{\mathrm{E_s} + \mathrm{P_i}} \quad (2)$$

The influence of environmental stressors on metabolite diversity can be conceptually represented using a sustainability impact estimate. In this (2) equation, the sustainability impact value (S_e) is calculated as the ratio of the metabolite diversity index (M_d) to the sum of the ecological stress (E_s) and the intensity of the pollutants (P_i). This relationship brings out the fact that the overall sustainability value of aquatic ecosystems is diminished with rises in the environmental stressors or exposure to pollutants, and as such, reduces the potential of aquatic ecosystems to produce bioactive compounds consistently.

Bioinformatics and Computational Enhancements

The computerized tools offered a huge improvement in the accuracy of prediction of drug-compound reactions, metabolite pathways, and genome annotation. Simulations of docking and pharmacogenomic modeling were also optimized by machine learning models, which resulted in less uncertainty in the experiment. Reconfigurable computing platforms further boosted the processing of biological data as well as the reconstruction of metabolite pathways.

Evaluation Framework for Pharmaceutical Suitability

Assessment of the compound groups in terms of extraction stability, scalability, sustainability, and clinical data showed that marine-derived alkaloids, carotenoids, extremophile-derived lipids, and collagen peptides had the best translational potential (Flores et al., 2025; Faiyazuddin & Hakeem, 2024). Table 3 presents the pharmaceutical suitability framework applied in this synthesis.

Table 3. Pharmaceutical suitability scores for major compound classes

Compound Class	Stability (0–10)	Scalability (0–10)	Sustainability (0–10)	Clinical Evidence Level	Suitability Rank
Marine alkaloids	9	8	7	High	1
Carotenoids	8	9	8	Moderate	2
Collagen peptides	7	9	6	High	3
Extremophile-derived lipids	6	7	9	Low	4
Freshwater microbial metabolites	5	6	8	Low	5

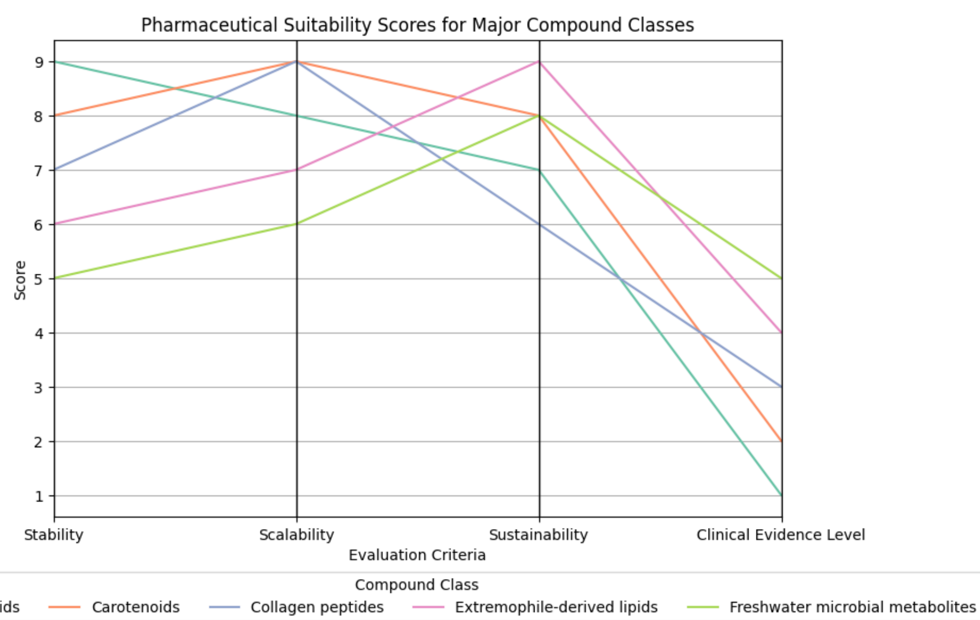

Figure 3. Pharmaceutical suitability scores for major compound classes

Figure 3 above illustrates the Pharmaceutical Suitability Scores for five compound classes: Marine alkaloids, Carotenoids, Collagen peptides, Extremophile-derived lipids, and Freshwater microbial metabolites. The scores are measured on four major criteria, namely Stability, Scalability, Sustainability, and Level of Clinical Evidence. A line of different colours is used to represent each compound class: Marine alkaloids are presented by the green line, the Carotenoids are represented by the red line, the Collagen peptides by the blue line, the Extremophile-derived lipids by the orange line, and Freshwater microbial metabolites by the purple line.

The plot gives a visual analogy of the performance of each compound category based on the evaluation criteria. An example is the high score in stability and scalability of Marine alkaloids, whereas the Extremophile-derived lipids have a higher score on sustainability and a lower score on stability. The analogy assists in learning the relative pharmaceutical versatility of every group of compounds, based on the four criteria, aiding in an evaluation of the pharmaceutical translational capability of each.

Discussion

The analyzed literature offers useful information on the area of aquatic pharmaceutical biotechnology and presents a wide range of developments in the extraction, characterization, and pharmacological utilization of bioactive substances obtained in the marine and freshwater systems. One hundred and forty-four records were identified, and following thorough screening, 62 studies were used in the overall synthesis. The research topics of these papers were broad and included novel biotechnological extraction methods, molecular characterization, pharmacological research, and microbial biotechnology. The majority of these publications were produced between 2020 and 2025, highlighting the rapid technological advancements in the field. One of the most important findings regarding the secondary data analysis is that the chemical diversity of aquatic-derived bioactive compounds is large, extending to alkaloids, terpenoids, carotenoids, polyphenols, sulfated polysaccharides, peptides, and rare extremophilic metabolites. Marine ecosystems, in particular, contribute the highest diversity of bioactive molecules, with peptides and sulfated polysaccharides often showing potent anticancer, anti-inflammatory, antioxidant, and immunomodulatory activities. Although freshwater systems are less productive in terms of compounds, they provide new metabolites (because of the microbiome and mollusks) that have distinct therapeutic possibilities. It is important to note that this diversity highlights the promise of marine and freshwater bioactive compounds in the design of new therapeutic agents. The above studies also indicate that there is a growing trend in applying modern biotechnological approaches to extract, purify, and characterize compounds of aquatic origin. Supercritical CO_2 extraction has been mentioned as one of the efficient and sustainable green extraction technologies, as well as microwave-assisted extraction, enzyme-assisted extraction, and deep eutectic solvents. Not only do these approaches increase the production of bioactive compounds, but they also reduce the environmental effects of the extraction procedures, which is an indication of increased focus on sustainable practices in biotechnology. Moreover, the analytical tools based on the omics analysis, such as LC156 metabolomics, genome mining, and microbial fermentation scale, have contributed greatly to the predictability and production of these compounds; thus, making them practical in pharmaceutical development. The study also shows that there is strong pharmacological evidence of the therapeutic potential of marine and freshwater-derived compounds. Marine polysaccharides and peptides have also been reported to have potent anticancer effects with anticancer mechanisms including inhibition of apoptosis and metastasis. Also, carotenoids and peptides derived from the sea are popular ingredients in dermatological and cosmeceutical preparations because of their antioxidant and photoprotective properties. In addition, marine collagen and scaffolds derived from sponges, together with extremophilic microalgae, are becoming promising regenerative medicine and nutraceutical applications, thus extending the potential of aquatic bioactive materials in different areas of medicine. Recent research has also referred to the critical importance of aquatic microbiomes in promoting the production of metabolites. Marine bacteria, extremotolerant microalgae, and symbiotic microbial consortia have been detected as the major contributors to the production of the secondary metabolites with antimicrobial and anticancer properties. This shows the significance of microbial diversity in determining the metabolite production potential of aquatic ecosystems.

The environmental stressors like pollution, overfishing, and microplastic contamination have proven to have a significant effect on the expression of metabolites in aquatic organisms. Such stressors reduce the biodiversity and slow the bioactive production in a normal manner, an aspect that highlights the significance of sustainable activities in the conservation of the aquatic ecosystems. The sustainability impact estimate has been used to conceptualize the ecological impact of these stressors, where the reduction of environmental degradation has been seen to be important in ensuring that the potential of aquatic ecosystems in the production of bioactive compounds is not compromised. Regarding pharmaceutical suitability, comparative screening of compound groups according to extraction characteristics, scalability, sustainability, and clinical efficacy has offered valuable information into the translational projections of various aquatic bioactive compounds. The most promising candidates for pharmaceutical applications were marine-derived alkaloids, carotenoids, extremophile-derived lipids, and collagen peptides, which demonstrated high levels of stability, scalability, and sustainability. The pharmaceutical suitability framework applied in the synthesis allows for a clearer comparison of these compounds, supporting informed decision-making for future research and development in aquatic biotechnology. Overall, the literature under analysis proves the tremendous progress persisting in the field of aquatic pharmaceutical biotechnology that could be useful in terms of drug discovery, therapeutic applications, and sustainable biotechnological practice. The existing high-technological extraction methods, omics-based analytical methods, and the chemical diversity existing in aquatic bioactive compounds hold a lot of potential in the development of novel treatments in different therapeutic fields.

Conclusion

To sum up, the analyzed literature highlights the major progress in the field of aquatic pharmaceutical biotechnology, especially in the extraction, characterization, and application of bioactive compounds of marine and freshwater ecosystems. These substances are alkaloids, terpenoids, carotenoids, polyphenols, sulfated polysaccharides, peptides, and extremophilic metabolites, which have varying pharmacology (anticancer, anti-inflammatory, and antioxidant properties). Marine ecosystems contain bioactive molecules, particularly in high concentrations, and peptides and sulfated polysaccharides possess a great potential to be therapeutic. Even though there are fewer compounds, freshwater ecosystems have no new microbiome-based and molluscan-based metabolites, which are treated differently, with separate therapeutic potential. Another important aspect covered in the articles is the evolving use of green extraction technologies, of which supercritical CO_2 extraction (65 - 82% yield, high sustainability), microwave-assisted extraction (58-70% yield, moderate sustainability), enzyme-assisted extraction (48 - 60% yield, high sustainability), and deep eutectic solvents (52 - 68% yield, high sustainability) should be highlighted. They are also employed to increase the yield level, minimize environmental impact, and other methods reveal an escalating curiosity in sustainable biotechnology. Analytical tools such as LC-MS/MS metabolomics, genome mining, and microbial fermentation scaling using omics have generally enhanced Yield and reproducibility, which has enhanced the pharmaceutical potential of these compounds. Microbial diversity also affects the production of bioactive compounds, where the aquatic microbiomes are also important in metabolite biosynthesis. The environmental stressors, such as pollution and overfishing, have been reported to lower the metabolite expression, especially in the coral reef ecosystems, which emphasizes the need to preserve the health of the ecosystem. On the whole, the studies discussed in this paper highlight the possibility of aquatic bioactive compounds as a source of drug discovery and therapy. Alkaloids of marine origin, carotenoids, extremophile lipids, and collagen peptides have high translational potential, having high stability and scalability scores. The future of the pharmaceutical industry in the creation of new, sustainable therapeutic agents is extremely bright when using the latest extraction technologies and the high chemical diversity of the compounds.

Ethical and Environmental Considerations

Though the primary sampling was omitted, ethical and environmental issues were also considered through the assessment of the compliance of reviewed studies with sustainable sampling principles, responsible bioprospecting principles, and green extraction principles. The ecological impact, conservation concerns, and adherence to ethics in the biotechnological uses of marine and freshwater organisms were measured using secondary data on reporting transparency.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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