

Marine-derived probiotic microorganisms: A review of their therapeutic applications in human health

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ABSTRACT

This narrative review summarizes current knowledge on marine-derived probiotic microorganisms and their therapeutic applications in human health. Databases such as PubMed and Scopus were searched (2000–2025) using terms related to marine probiotics, bioactive compounds, and clinical or experimental evidence of health benefits. There has been an increasing interest in marine-derived probiotics and their potential applications to humans in health care. Probiotic microorganisms derived from marine environments include a spectrum of various species of bacteria including *Lactobacillus*, *Bacillus* and *Pseudomonas*, marine yeasts and microalgae. Marine microbes produce special bioactive compounds displaying unique antimicrobial, antioxidant and anti-inflammatory capacity that developed because of their adaptation to extreme oceanic conditions. While more research is needed in this area, evidence has shown that marine probiotics can alter gut microbiota, improve immune function, and exhibit bioactive functions including antimicrobial, anti-inflammatory, and antioxidant functions. Moreover, marine probiotics also have potential for prevention of gastrointestinal illnesses, improve cardiovascular function, and aid in metabolism. The purpose of this review is to summarize marine probiotics including, origins, cellular activity, and applications, including possible therapeutic functions as a new bio-therapeutic approach to human health. However, comprehensive genomic and clinical studies are required to validate their safety and therapeutic efficacy

1. Introduction

Probiotics are "live microorganisms which, when administered in adequate amounts, confer a health benefit on the host" (FAO/WHO, 2001). Lilly and Stillwell (1965) first used the term probiotic to refer to microbial products that support the growth and health of other organisms. Traditional probiotics mainly consist of the members of the genera *Lactobacillus*, *Bifidobacterium*, *Bacillus*, and *Saccharomyces* (Fijan, 2014). Probiotics balance host flora, boost host immunity, and general health (El-Saadony et al., 2021). Probiotics are even utilized as feed additives to boost antioxidant and immune ability, increase feed conversion ratio, and improve water quality in aquaculture (Liu et al., 2022).

Marine probiotics are fungi, bacteria, or other microorganisms occurring naturally in oceans, algae, fish, and seawater. Due to their capacity to withstand fluctuating pressure, temperature, and salinity, these organisms synthesize varied metabolites with novel biological activities (Senadheera et al., 2023). The marine environment contains a diverse assemblage of organisms that have developed specialized

enzymes and metabolic pathways, making them successful in harsh environments. Such adaptation renders marine microorganisms to be promising sources of new probiotics with higher stress resistance, stability, and bioactive activity relative to terrestrial strains (Poli et al., 2017). Marine ecosystems serve as natural reservoirs of halotolerant and alkaliphilic microorganisms, including members of genera like *Bacillus* and *Actinomyces*, that are known to produce diverse bioactive compounds such as proteases, lipases, and amylases (Sadaf Wajahat, 2024).

Microorganisms from the marine ecosystem yield a wide range of functional biomolecules such as bacteriocins, antimicrobial peptides, exopolysaccharides, polyunsaturated fatty acids, carotenoids, siderophores, and hydrolytic enzymes (Olaniyan et al., 2021). These metabolites exhibit antimicrobial, antioxidant, anti-inflammatory, and anticancer activities that find applications across different industries. Marine bioactive compounds find important applications in nutraceuticals, pharmaceuticals, agrochemicals, enzyme production, cosmeceuticals, and functional food technology (Ghosh et al., 2022). Their sustainability and ecological origin make them ideal substitutes for

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chemical compounds conventionally applied in these industries.

In 2023, the global market for probiotics was valued at approximately USD 87.70 billion, and it is expected to grow at a compound annual growth rate (CAGR) of 14.1 % between 2024 and 2030 (Đurđević-Milošević et al., 2024). This growth in the market is a mirror image of the global concern with gut health and functional foods that promote better well-being and disease prevention. Probiotics are increasingly being added to food and dietary supplements to boost digestive and immune function (Champagne et al., 2018).

Conventional probiotics such as *Lactobacillus* and *Bifidobacterium* species have been consistently suggested to support gut homeostasis, functionality of the intestinal barrier, and immune modulation (Yan & Polk, 2020). On the other hand, marine probiotics have many other beneficial properties in addition to possessing preventative and therapeutic potential due to the production of antimicrobial peptides, enzymes, and anti-inflammatory compounds (Eze et al., 2023). These strains exhibit improved viability in stressful gastrointestinal environments, increased tolerance to temperature and salinity changes, and increased resistance to bile salts (Chen et al., 2017). Marine probiotics have been found to enhance gut health and immunity in higher animals and to make contributions to disease prevention in human beings. They have been linked with protective effects against gastrointestinal diseases, allergies, respiratory infections, obesity, diabetes, and cancer (Anee et al., 2021; Pratap et al., 2020).

Recent studies have also indicated their function in regulating the gut-brain -microbiota axis and treating neurological and metabolic diseases such as depression, anxiety, and metabolic syndrome (Bhatt et al., 2023; de Vos & de Vos, 2012). Marine probiotics provide multi-dimensional health benefits by regulating gut microbiota composition, inhibiting pathogens by competing for adhesion sites, improving mucosal immunity, and secreting bioactive metabolites (Pereira et al., 2022; Fusco et al., 2023).

Due to their biochemical diversity and potential therapeutic applications, probiotics derived from marine sources are being recognized as sustainable and viable alternatives to classic probiotics. This review intends to compile the modern understanding of marine-derived probiotic microorganisms, exploring their bioactive compounds, mechanisms of action and implications for therapeutic use in human health.

2. Materials and methods

2.1. Study design and review type

This review is a narrative literature review that synthesizes the research on marine-derived probiotic microorganisms and their potential application for the treatment and management of human health. While it is not a systematic review, a structured and explicit literature search was performed to extend beyond a cursory examination of the literature and establish fairly comprehensive coverage of the relevant studies.

2.2. Data sources and search strategy

A literature search was performed on the PubMed, Scopus, and Google Scholar databases for documents published between January 2000 and September 2025. The following search string and Boolean operators were used:

("marine probiotic" OR "marine-derived probiotic" OR "marine bacteria" OR "marine yeast" OR "marine microalgae") AND ("health" OR "therapeutic" OR "anticancer" OR "antimicrobial" OR "immunomodulatory" OR "gut" OR "cosmeceutical")

Searches were refined using Boolean operators (AND, OR) and filters for English-language, peer-reviewed studies. Reference lists of retrieved articles were also screened to capture additional relevant publications.

2.3. Inclusion and exclusion criteria

Inclusion criteria:

- Peer-reviewed articles published in English.
- Studies dealing with isolation, characterization, or therapeutic uses of marine probiotics.
- Experimental, observational, or review articles with clear methods written about human or animal health.

Exclusion criteria:

- Non-English papers.
- Studies unrelated to marine microorganisms or probiotic activity.
- Conference abstracts, theses, or gray literature lacking sufficient data.

2.4. Screening and selection

After duplicates were removed, titles and abstracts were screened for relevance. The full-text papers that agreed with inclusion criteria were then thoroughly read. The selection process broadly followed PRISMA guidelines for narrative reviews.

2.5. Data extraction and synthesis

For each eligible study, the sources of the microbes, bioactive compounds, experimental design, and therapeutic effects that were observed were extracted manually. The collected data were organized thematically into the following review sections: (i) sources and classification of marine probiotics, (ii) bioactive metabolites and mechanisms of action, and (iii) therapeutic applications and industrial relevance.

3. Probiotics: sources and classification

Probiotics are live microbes that provide a health benefit to the host when taken in appropriate amounts. Probiotics exist in the human gastrointestinal tract and fermented foods, in soil, and in marine environments (Zommiti et al., 2020). Probiotics consist of various genera of bacteria and yeast, but the most commonly utilized in human and animal health applications are *Lactobacillus*, *Bifidobacterium*, *Bacillus*, and *Saccharomyces* (Hatoum et al., 2012).

Marine environments have emerged as new sources of probiotic strains. Because they have adapted to harsh salinities, temperatures, and pressures, marine microorganisms are highly metabolically diverse and have the ability to tolerate stress (Lauritano et al., 2020). The marine microbes produce distinct biomolecules that are novel in their functionality, such as antimicrobial peptides, proteases, lipases, exopolysaccharides, etc., making their properties unique in health and industrial applications (Ghosh et al., 2022). The diverse origins and functional characteristics of these microorganisms are summarized in Table 1.

Probiotics can be broadly classified based on their taxonomic group, origin, or mechanism of action.

1. Taxonomic classification distinguishes bacterial (e.g., *Lactobacillus*, *Bifidobacterium*, *Bacillus*) and non-bacterial probiotics (e.g., *Saccharomyces*, *Kluyveromyces*).
2. Source-based classification includes terrestrial, food-associated, and marine-derived probiotics.
3. Functional classification focuses on their biological roles—such as antimicrobial activity, immune modulation, enzyme production, antioxidant defense, and gut microbiota regulation.

Marine probiotics, particularly *Bacillus*, *Pseudoalteromonas*, and *Vibrio* spp., have gained attention for their ability to produce bioactive molecules under saline stress, which enhances stability and therapeutic

Table 1

Representative sources and classification of probiotic microorganisms.

Source / Environment	Representative Genera or Species	Key Functional Features	Applications	Reference
Human gut microbiota	<i>Lactobacillus</i> , <i>Bifidobacterium</i>	Acid and bile tolerance, immune modulation	Gut health, digestion, lactose tolerance	Rastogi & Singh, (2022)
Fermented foods (yogurt, cheese, pickles)	<i>Lactobacillus</i> , <i>Leuconostoc</i> , <i>Pediococcus</i>	Production of lactic acid and vitamins	Food fermentation, preservation	Mani, (2018)
Soil and plant rhizosphere	<i>Bacillus</i> , <i>Streptomyces</i>	Enzyme and antibiotic production	Agriculture, biocontrol	Ryabova et al., 2022
Marine environments (fish gut, seawater, sediments)	<i>Bacillus</i> , <i>Pseudoalteromonas</i> , <i>Vibrio</i> , <i>Photobacterium</i>	Halotolerance, production of antimicrobial and antioxidant compounds	Aquaculture, pharmaceuticals	Hoseinifar et al., 2024
Yeasts and fungi	<i>Saccharomyces cerevisiae</i> , <i>Kluyveromyces marxianus</i>	Production of enzymes, vitamins, and flavor compounds	Food and beverage industries, probiotic supplements	Homayouni-Rad et al., 2020

efficacy in diverse formulations (Eze et al., 2023). With respect to aquaculture applications, these strains are associated with increased nutrient utilization, decreased pathogenesis, and overall improvements in host health, and in human applications are being investigated for immunomodulatory and metabolic properties (Wang et al., 2020).

Overall, understanding the classification and source of probiotic microorganisms provides a foundation for exploring their modes of action and therapeutic potential, which are discussed in the subsequent sections.

4. Difference between traditional and marine probiotics

The difference between traditional (terrestrial) probiotics and marine-origin probiotics comes down to the source, physiological traits, and future applications. Traditional probiotics are mostly sourced from terrestrial environments or fermented foods, while marine probiotics are sourced from oceanic environments, where they demonstrate different tolerance capabilities to extreme environments, including high salt amounts, pressure, and low temperature (Zayed et al., 2022; Hosseini et al., 2022).

Both varieties provide favorable health benefits to the host after certain doses. However, there are large differences in their source, strain diversity, stability, and functional perspectives. The table below describes the main differences between conventional and marine probiotics.

This comparison highlights the recognized efficacy of proven probiotics and the rapidly emerging potential of marine-derived strains. More research is needed to establish their safety, create an appropriate delivery mode, and explore new bioactive compounds that benefit human and environmental health. The primary distinctions in source, strain diversity, and stability between conventional and marine probiotics are detailed in Table 2.

5. Mechanisms and modes of action of probiotics

The positive influence of probiotics on the host is achieved through various biological mechanisms, including gut microbiota modulation, enhancement of the intestinal barrier, competition with pathogens, and regulation of immune and neurological responses (Raheem et al., 2021) (Fig. 1).

Probiotics function through multiple complementary mechanisms, some of which are summarized below:

5.1. Antagonism and pathogen inhibition

One of the most familiar functions of probiotics in terms of health is the inhibition of pathogenic microbes through competitive exclusion and the secretion of antimicrobial substances (Nair et al., 2017). Probiotics inhibit pathogens by competing for adhesion to the intestinal epithelium and nutrients for their growth and by secreting bacteriocins, organic acids (such as lactic, acetic, propionic acid), hydrogen peroxide,

and biosurfactants that reduce gut pH and kill pathogens including *Escherichia coli*, *Salmonella*, *Staphylococcus aureus*, and *Clostridium difficile* (Rocchetti et al., 2021). Certain sea-strains like *Bacillus* and *Pseudoalteromonas* spp. have profound antimicrobial and antifungal activity by releasing peptides and enzymes (Offret et al., 2016).

5.2. Detoxification of mycotoxins and xenobiotics

Certain probiotic strains can bind, degrade, or biotransform mycotoxins and environmental toxins into less toxic metabolites. *Lactobacillus rhamnosus* and *Bacillus subtilis*, for instance, are able to bind aflatoxins and ochratoxin A in order to reduce their gut absorption (Ghadaksaz et al., 2022). Marine probiotics have also proved to be able to break down xenobiotic substances such as heavy-metal chelates and pesticides, which helps detoxify the environment and gives a safer food chain (Reid, 2015). This is especially critical in aquaculture, where bioaccumulation of toxicants can be harmful to aquatic animals, as well as to the human consumers.

5.3. Vitamins and metabolites production

Probiotic microbes synthesize a range of significant micronutrients, such as vitamin K, riboflavin (B₂), folate (B₉) and short-chain fatty acids (SCFAs), such as acetate, propionate, and butyrate (LeBlanc et al., 2017). SCFAs are used by colonocytes as a source of energy, control lipid metabolism, and enhance the intestinal barrier. Some marine isolates also synthesize antioxidant enzymes (for example, superoxide dismutase and catalase) and anti-inflammatory agents, which have the potential for creating systemic protection against oxidative and inflammatory stress (Cheng et al., 2022).

5.4. Enhancement of gut barrier integrity

Probiotics contribute to the enhancement of intestinal barrier integrity through the stimulation of the tight-junction proteins (occludin, claudin, and ZO-1), and the increase of mucin production from goblet cells thereby decreasing pathogen translocation and gut permeability (in “leaky-gut” conditions). Probiotics also control epithelial cell turnover and ensure equilibrium between apoptosis and regeneration (Fusco et al., 2023).

5.5. Immunomodulation

The immunomodulatory effect of probiotics is that they have the ability to modulate the innate and adaptive immune systems. Probiotics have an influence on dendritic cells, macrophages and T lymphocytes through pattern recognition receptors such as Toll-like receptors (TLRs) (Yousefi et al., 2019). The downstream action is to increase the production of anti-inflammatory cytokines (IL-10, TGF- β) and decrease the production of pro-inflammatory cytokines (TNF- α , IL-6). These impacts have resulted in worse inflammatory bowel disease (IBD), allergies and

Table 2
Difference Between Traditional and Marine Probiotics.

Aspect	Traditional Probiotics	Marine Probiotics	References
Source	Derived from terrestrial environment s; commonly found in fermented foods like yogurt, cheese, and sauerkraut.	Sourced from marine environment s; include strains like <i>Pseudoalteromonas</i> and marine-derived <i>Bacillus</i> species.	(Eze et al., 2023)
Strain Diversity	Predominantly includes <i>Lactobacillus</i> , <i>Bifidobacterium</i> , and <i>Saccharomyces</i> species.	Encompasses diverse genera such as <i>Pseudoalteromonas</i> , <i>Shewanella</i> , and marine yeasts like <i>Candida</i> and <i>Pichia</i> .	(Bermúdez-Humarán and Langella, 2017)
Health Benefits	Known to enhance gut microbiota balance, improve digestion and nutrient absorption, strengthen the immune system, and alleviate symptoms of lactose intolerance.	Emerging research suggests potential anticancer and antibacterial effects, as well as modulation of the immune system.	(Eze et al., 2023)
Therapeutic Applications	Utilized in managing gastrointestinal disorders, preventing antibiotic-associated diarrhea, and supporting overall digestive health.	Potential applications in cancer therapy, infection control, and as sources of novel bioactive compounds.	(Bermúdez-Humarán and Langella, 2017)
Environmental Adaptations and Stability	Adapted to survive in the human gastrointestinal tract but may have varying stability during storage and passage through the stomach.	Certain marine-derived <i>Bacillus</i> strains have shown resilience under gastrointestinal conditions, indicating potential as stable probiotic candidates for human consumption.	(Eze et al., 2023)
Safety Profile	Generally recognized as safe for most individuals; mild digestive discomfort may occur initially.	Safety profile is under investigation; Extensive clinical studies are required to confirm both the effectiveness and safety of probiotics.	(Bermúdez-Humarán and Langella, 2017)
Mechanism of Action	Compete with pathogens for adhesion sites, produce antimicrobial substances, and modulate the host's immune response	May produce unique bioactive compounds with anticancer and antibacterial properties; mechanisms are subject to ongoing research.	(Eze et al., 2023)
Research Status	Extensive research and clinical studies supporting health benefits and safety.	Emerging field with increasing studies focusing on therapeutic potentials and safety assessments.	(Bermúdez-Humarán and Langella, 2017)

respiratory infection symptoms (Sanders et al., 2013; Amenyogbe et al., 2023). Marine-derived strains, in particular, typically elicit greater immunostimulatory effects due to the adaptation to adverse saline conditions, resulting in the production of thick extracellular polysaccharides used for immunomodulatory purposes (Liu et al., 2022).

5.6. Gut-brain axis and neuroprotective effects

New research suggests that various probiotics, called psychobiotics, may alter the gut-brain axis. These probiotics release neurotransmitters including serotonin, dopamine, and γ -aminobutyric acid (GABA), which impact mood, cognition, and stress response (Kapreliants & Zhuk, 2021; Bonham et al., 2023). These studies support the prospects of probiotics as a therapeutic agent in the context of anxiety, depression, and metabolic or neurological disorders.

All in all, probiotics support host health by engaging multiple pathways and mechanisms of action including microbial competition, metabolic regulation, immune modulation, and signaling through the gut and neural networks (Thomas & Versalovic, 2010). Effects will be species-specific and depend on strain source, dose, and host physiology. The specific interactions at the intestinal barrier and systemic signaling pathways are summarized in Fig. 2.

Cumulatively, probiotics act by (i) suppressing pathogens by competition and release of antimicrobial substances (Denkova et al., 2017), (ii) strengthening intestinal barrier function and mucus production (Gou et al., 2022), (iii) modulating host immune mechanisms (Mazziotta et al., 2023), and (iv) affecting neurotransmitter production (LaGreca et al., 2021). Marine-derived strains, in specific, have been reported to exhibit enhanced bioactivity under severe environmental stress, generating metabolites with anticancer and antibacterial activity. For example, *Pseudoalteromonas* species have exhibited strong anticancer and antimicrobial activity, and thus are useful natural therapeutic compounds (Eze et al., 2023).

6. Application of marine probiotic in human health

The increasing interest in marine-derived probiotics is due, in part, to their varied applications in the fields of health care, agriculture, aquaculture, pharmaceuticals, and functional foods (Senadheera et al., 2023) (Fig. 3). Due to their physiological stress tolerance and metabolic diversity, marine probiotics can function efficiently in adverse environmental and processing conditions, making them more advantageous than traditional probiotics based on terrestrial strains (Mbye et al., 2020). The principle application areas are briefly summarized below.

6.1. Human health and therapeutics

Marine probiotics also play a crucial role in maintaining gut homeostasis and improving digestive health. They regulate the intestinal microbiota balance, enhance immune system function, and inhibit enteric pathogens (Li et al., 2020). Clinical and preclinical studies show their potential to alleviate irritable bowel syndrome (IBS), inflammatory bowel disease (IBD), Non-Alcoholic Fatty Liver Disease (NAFLD), and metabolic disorders such as type 2 diabetes and obesity (Bonham et al., 2023; Amenyogbe et al., 2023). Psychobiotic bacteria are involved in the modulation of the gut-brain axis, promoting mental well-being and symptom relief against anxiety, stress, and depression by the production of neurotransmitters such as GABA and serotonin (Chowdhury, 2024). Marine probiotics are also researched for anticancer, antioxidant, and anti-inflammatory effects due to their ability to produce new bioactive compounds, enzymes, and peptides that inhibit oxidative and inflammatory signaling pathways (Cheng et al., 2022).

6.2. Functional foods and nutraceuticals

Due to increased consumer demand for natural health foods, marine

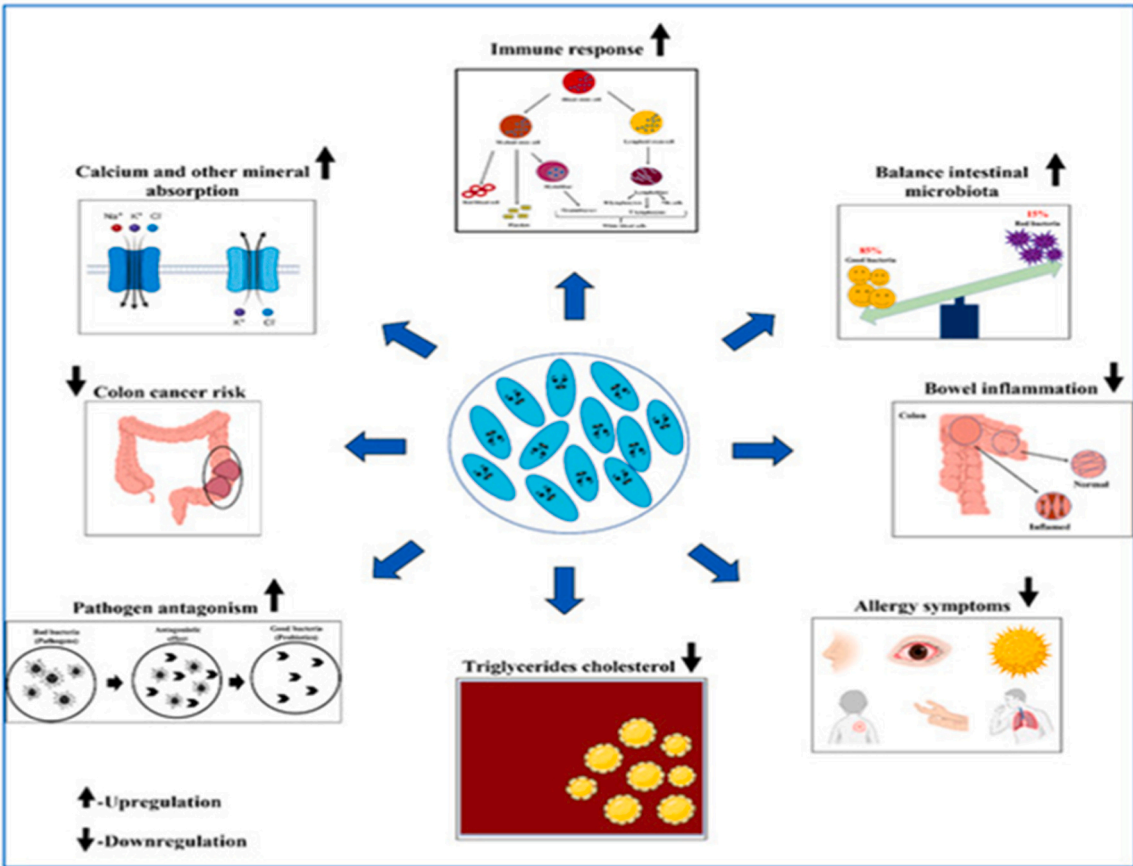


Fig. 1. Proposed modes of action of probiotics (Bhagoju & Nahashon, 2022).

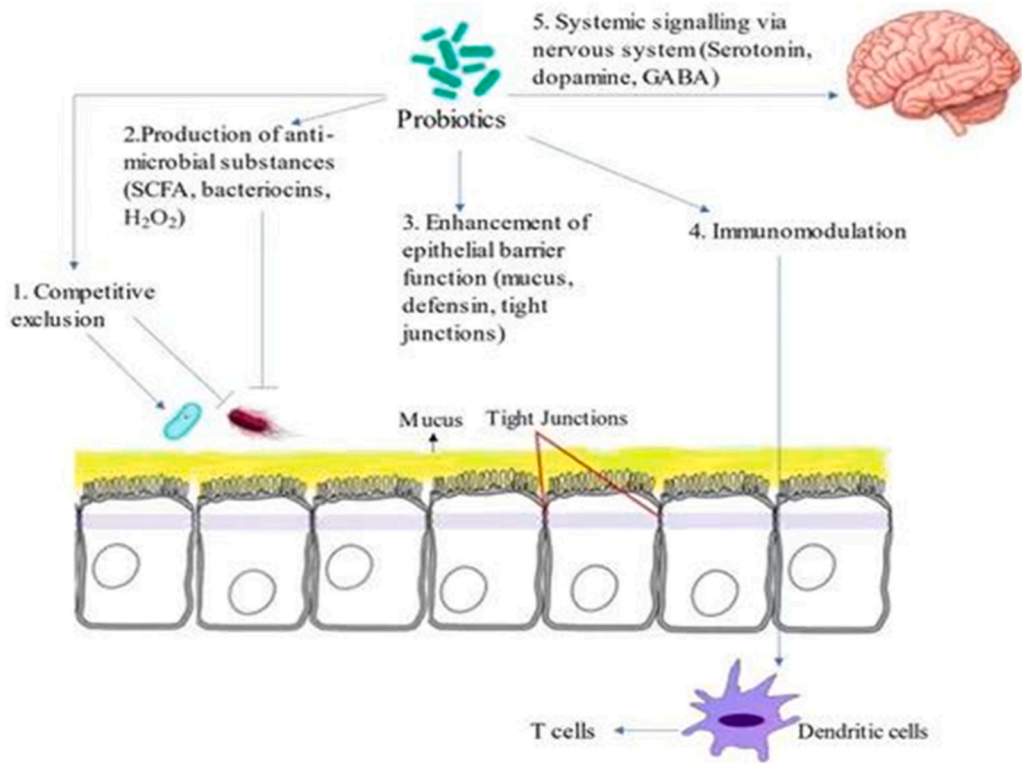


Fig. 2. Mechanisms of action of probiotics (Eze et al., 2023).

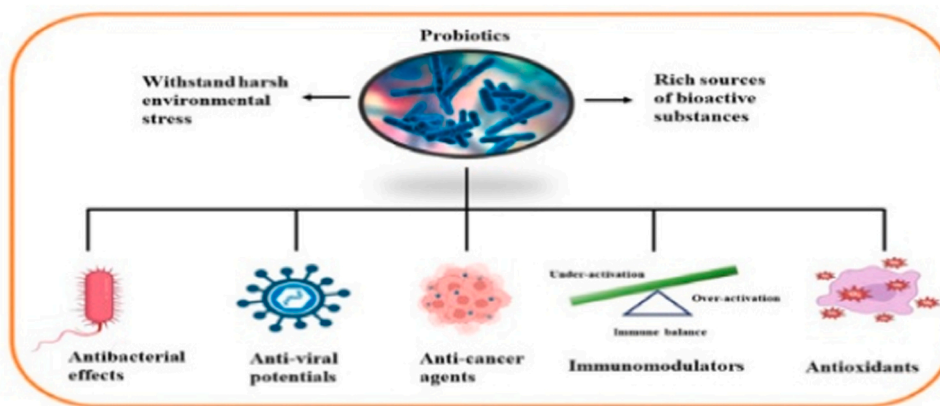


Fig. 3. Therapeutic potentials of marine probiotics (Eze and Berebon et al., 2023).

probiotics are widely added to nutraceuticals and functional foods such as fermented drinks, yogurts, and dietary supplements (Halder et al., 2021). They boost nutritional content by producing vitamins (e.g., B-complex, K), fatty acids, and enzymes. Marine-derived strains tend to demonstrate superior tolerance to stress, which means they have a longer shelf life and survive better processing and storing of the foods (Suraiya et al., 2022; Bose et al., 2023). In addition, functional foods made with marine probiotics help support gut microbiota composition and nutrient absorption, which may attract interest for preventive healthcare and wellness (Han et al., 2024).

6.3. Pharmaceutical and biotechnological uses

Bioactive metabolites isolated from marine probiotics, such as antimicrobial peptides, polysaccharides, and enzymes, are therapeutic against multi-drug-resistant pathogens (Abouelela and Helmy, 2024). New antibiotics, antifungal agents, and immune-modulating drugs are based on these metabolites. Marine strains produce industrial enzymes like proteases, lipases, and amylases for enzyme replacement therapy and biocatalysis (Abdul et al., 2019). Also, marine probiotics have gained interest as potential carriers in oral vaccine delivery systems to enhance mucosal immunity and antigen uptake (Jazayeri et al., 2021).

6.4. Aquaculture and animal husbandry

In aquaculture, marine probiotics are eco-friendly alternatives to antibiotics. It improves feed efficiency, promotes growth, improves stress resistance, and protects fish and shellfish from pathogenic infections. *Bacillus subtilis*, *Vibrio alginolyticus*, and *Pseudoalteromonas* spp. enhance nutrient uptake and reduce ammonia accumulation and enhances water quality (Liu et al., 2022, Fachri et al., 2024). The use of probiotics in fish and shrimp diets enhances immune systems and reproductive efficiency, leading eventually to higher yield and sustainability in aquaculture production (Sumon et al., 2022). Similar measures in livestock farming improve gut health, reduce the use of antibiotics, and ultimately enhance growth performance (Gadde et al., 2017).

6.5. Agriculture and environmental biotechnology

Marine probiotics and their metabolites have the potential to act as biofertilizers and biocontrol agents, improving soil health and crop resistance against phytopathogens (Harutyunyan et al., 2022). Their capacity to biodegrade pesticides, heavy metals and other xenobiotics renders them valuable for bioremediation and detoxification (Reid, 2015). Marine strains that produce enzymes can further facilitate waste recycling and the bio-production of valuable biopolymers and bio-surfactants, reinforcing circular bioeconomy frameworks (Lee et al., 2023).

6.6. Cosmeceutical and industrial uses

Because of their antioxidant and anti-aging activities, marine probiotics are increasingly used in cosmeceutical products (Resende et al., 2021). They can shield skin cells against UV-based injury, modulate microbial balance across the skin, and provoke collagen synthesis (Mujeeb et al., 2022).

Marine probiotics have various industrial uses, which span food and beverage processing, including fermentation, flavor, and bio-preservation. They are viewed as eco-friendly alternatives to synthetic additives (Rameez et al., 2024).

7. Future prospects of marine probiotics in human health

Marine probiotics are a fast-moving research field with enormous, as-yet-unrealized potential for human health, aquaculture, and biotechnology. Although their value has been proven, numerous marine strains are still uncharacterized or unexplored, and their modes of action are not yet understood. Future studies should thus focus on the isolation, genomic sequencing, and functional characterization of new strains from extremophilic and diverse marine environments, such as coral reefs, hydrothermal vents, and abyssal sediments.

Development of multi-omics technologies metagenomics, proteomics, transcriptomics, and metabolomics will speed up the identification of novel probiotic candidates and elucidate their biosynthetic pathways. Through technology, scientists can identify genes responsible for metabolite biosynthesis, stress tolerance, and immune modulation and thereby identify key biomarkers of probiotic activity.

Synthetic biology and genetic engineering also offer possibilities to enhance the activity of probiotics. Engineered marine probiotics could be designed to target the delivery of bioactive compounds, degrade specific toxins, or modulate post-activation host signaling pathways with increased safety and specificity. Similarly, AI-based bioinformatics and machine learning algorithms will likely change strain selection, as well predict host-microbiome interactions to facilitate personalized probiotic therapy.

Translational research should also focus on in vivo validation of marine probiotic efficacy utilizing animal models and large-scale human clinical trials. Establishing clearly defined parameters for safety and dosage recommendations together with regulatory pathways is essential to the integrity of the product and the trust of the public. It is critical to develop sustainable marine bioprospecting, which will allow for biodiversity conservation and ecological stability.

Surrounding this will require collaboration between several disciplines, including microbiologists, marine scientists, bioengineers, and clinicians, in order to harness the potential of marine probiotics. Novelty, along with development, in the field of biotechnology may allow for microorganisms derived from marine environments to be the future

of therapeutics, functional foods and sustainability in the environment.

8. Conclusion

Marine-origin probiotics are a developing frontier for human and animal health. Their ability to meet extreme salinity, pressure, and temperature has allowed them to generate bioactive compounds such as antimicrobial peptides, enzymes, and antioxidant molecules, with greater stability and bioactivity than their terrestrial counterparts. Thus, marine probiotics may arise as next-generation sustainable alternatives to produce therapeutics, functional foods, and nutraceuticals.

This review observed the various mechanisms of action of probiotics, including inhibition of pathogenic bacteria, detoxification of mycotoxins, biosynthesis of nutrients, strengthening the gut barrier, behaviour of the immune system, and modulation of the gut–brain axis. These mechanisms point to their applications for gastrointestinal disorders, metabolic disorders, and neuroinflammatory conditions. Nonetheless, research on marine probiotics is lagging behind terrestrial probiotics despite advancements in formulation.

Future research is needed to conduct genomics and metabolomic characterization of marine probiotic strains to discover new bioactive compounds, investigate in vivo safety and efficacy, and translate therapeutic applications to clinical practice. Opportunities for artificial intelligence and bioinformatic tools can enhance strain selection for probiotics, host–microbe interaction prediction, and optimize formulations for individual health.

From an industrial and regulatory point of view, maintaining quality control, stability, and functional consistency throughout batches of production is crucial for commercialization. Sustainable culture and harvesting methods should also be a priority to maintain marine biodiversity while facilitating large-scale probiotic production.

Suggestions for use in practice include:

- Providing probiotics on an empty stomach for maximum survival and colonization.
- Use appropriate storage conditions (e.g., refrigerate heat-dried products)
- Allowing a two-hour timeframe at minimum, from the last consumption of an antibiotic to the consumption of the probiotic.
- Carrying out a co-administration of a multi-strain probiotic to potentially achieve synergistic health benefits.

In summary, marine probiotics have enormous unexplored potential in human health management, aquaculture, and food biotechnology. Continuing interdisciplinary research integrating microbiology, marine science, and biotechnology will be critical in the processes of unlocking marine probiotics full therapeutic and industrial potential.

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Sanjana Katariya: Methodology. **Chhatrodiya Devi Jinabhai:** Writing – review & editing, Supervision. **Anjali Gadhiya:** Writing – original draft, Formal analysis. **Khushbu Khapandi:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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