

Marine Microbial Enzymes: A Sustainable Frontier in Food Biotechnology

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Introduction

Marine ecosystems represent one of the richest reservoirs of microbial diversity, harboring bacteria, fungi, and archaea that are adapted to extreme environmental conditions, including high salinity, low temperatures, variable pressure, and nutrient limitation. The enzymes produced by these microorganisms exhibit unique catalytic properties that distinguish them from their terrestrial counterparts, including salt tolerance, cold activity, thermostability, and the ability to act on complex marine polysaccharides (Tricone A, 2011, Ghosh et al., 2005). These properties have attracted significant interest in food biotechnology, where milder, environmentally sustainable, and efficient processing tools are increasingly demanded.

Functional Properties of Marine Microbial Enzymes

The distinctive biochemical traits of marine microbial enzymes stem from evolutionary adaptation to oceanic niches.

- **Cold-active enzymes** (e.g., proteases, lipases) display high catalytic efficiency at low and moderate temperatures, enabling food processing under refrigeration with reduced energy inputs and minimal nutrient degradation (Santiago, 2016).
- **Salt-tolerant enzymes** retain stability in brined or saline matrices, which is particularly relevant for seafood fermentation, fish sauce production, and salted product processing (Yao et al., 2023).
- **Polysaccharide-degrading enzymes** such as alginate lyases, carrageenases, and agarases target marine hydrocolloids and produce oligosaccharides with prebiotic and textural applications in food formulation (Michael et al., 2013).
- **Chitinases and chitosanases** hydrolyse crustacean shell wastes into chitin and chitosan derivatives, widely studied for their functional roles as dietary fibres, antimicrobial agents, and food packaging materials (Jahromi et al., 2018).

Current Applications in Food Technology

Several marine microbial enzymes have been successfully used in experimental or commercial settings:

1. **Proteases** – used in the generation of fish protein hydrolysates enriched in bioactive peptides with antioxidant, antihypertensive, and antimicrobial properties. These hydrolysates are increasingly studied for incorporation into functional foods and nutraceuticals.
2. **Lipases** – are involved in a key role in flavour development and lipid modification, especially in the recovery of polyunsaturated fatty acids (PUFAs) and in synthesizing structured lipids.
3. **Carbohydrate-active enzymes** – facilitate the production of marine oligosaccharides with proven health-promoting properties, including immunomodulation and microbiota modulation in the gut.
4. **Waste valorisation** – enzymatic hydrolysis of fish processing by-products (heads, frames, viscera, shells) allows recovery of proteins, oils, and chitin derivatives, supporting circular bioeconomy approaches in the fisheries sector.

Challenges and Research Gaps

Despite their great potential, several challenges limit the widespread adoption of marine microbial enzymes, which include the following

- **Production cost:** Many enzymes are produced in low yield by native marine microbes, necessitating heterologous expression systems and optimization of fermentation conditions.
- **Stability and scalability:** At room temperature or during processing, cold-active enzymes frequently exhibit structural instability. To improve stability, immobilisation techniques and protein engineering are being used.
- **Regulatory hurdles:** Before being approved for use in food, new enzyme preparations must undergo safety evaluations that include toxicological and allergenicity testing.
- **Integration into existing processes:** Industrial processors require robust data on enzyme

performance under variable food matrices, pH, and storage conditions.

Future Prospects

The discovery and use of marine microbial enzymes is being accelerated by developments in protein engineering, synthetic biology, and metagenomics. Without requiring culture separation, novel biocatalysts can be obtained from metagenomic libraries derived from marine microbes that cannot be cultured. Enzyme stability and specificity can be fine-tuned by directed evolution and computational protein design. Additionally, the viability of food-grade applications is increased by recombinant expression in GRAS (Generally Recognised as Safe) hosts like *Saccharomyces cerevisiae* and *Bacillus subtilis*. Marine microbial enzymes are positioned to be a key component of the upcoming generation of food processing technologies, as sustainability, waste reduction, and functional food innovation gain more attention.

Conclusion

Marine microbial enzymes are a special kind of biocatalyst that is designed to work in harsh oceanic environments. For food biotechnology, their cold activity, halotolerance, and polysaccharide-degrading properties provide clear benefits, especially in waste valorisation, functional component development, and seafood processing. While technical and regulatory difficulties exist, breakthroughs in biotechnology are progressively closing the gap between discovery and industrial use. By incorporating these enzymes into food systems, the global aim for sustainable and

circular bioeconomy practices is supported in addition to innovation.

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