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Microbial Enzymes in Food Processing: Biotechnological Innovations and Applications

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Abstract

Microbial enzymes have revolutionized food processing by offering efficient, sustainable, and scalable biocatalytic solutions for enhancing product quality, texture, flavor, and shelf life. This review explores the shift from traditional animal and plant-derived enzymes to microbial sources, driven by advancements in industrial biotechnology, fermentation technologies, and genetic engineering. Key enzyme classes, including proteases, glycosyl hydrolases, lipases, and extremozymes, are discussed in the context of their applications in dairy, baking, starch conversion, and beverage industries. The global market for food enzymes is projected to grow from USD 4.6 billion in 2024 to USD 6.7 billion by 2030, fueled by consumer demand for clean-label products and natural processing aids. Challenges in production methods (submerged vs. solid-state fermentation), enzyme stabilization through immobilization and directed evolution, and regulatory frameworks (FDA GRAS vs. EU EFSA) are analyzed. Emphasis is placed on sustainability, with enzymes enabling valorization of agri-food byproducts and green extraction technologies. Future prospects highlight the integration of AI-driven engineering and extremozyme discovery to address emerging industrial needs, positioning microbial enzymes as pivotal for a circular economy in food systems.

Keywords: Microbial enzymes, Food processing, Biocatalysis, Fermentation technologies, Extremozymes, Enzyme engineering, Sustainability, Regulatory frameworks, Dairy applications, Baking innovations

1. Introduction

1.1. The Critical Role of Biocatalysis in Modern Food Systems

Enzymes, as highly specific protein biocatalysts, are fundamentally important in modern industrial food systems, accelerating biochemical reactions necessary for texture modification, flavor development, and preservation (Ferreira et al., 2022). They function predominantly as processing aids, though specific examples, such as lysozyme and inverses, are used as direct food additives (Yao et al., 2024). Historically, the food industry utilizes enzymes derived from animal sources or plants (proteases from papaya). However, the development of industrial biotechnology has driven a definitive shift towards microbial enzyme production (Jan et al., 2015). This preference for microbial sources, encompassing bacteria, fungi, and yeasts, stems from their capacity to offer

unparalleled consistency, reproducibility, and high yields through scalable fermentation processes (Jan et al., 2015). Furthermore, microbial hosts allow for facile genetic manipulation, enabling the optimization of production strains and the purification of biocatalysts with highly desirable catalytic properties (Shrivastav et al., 2025).

1.2. Global Market Landscape and Economic Drivers

The economic significance of industrial enzymes underscores their strategic value. The overall global enzymes market is estimated at USD 14.0 billion in 2024 and is projected to expand robustly to USD 20.4 billion by 2029, reflecting a Compound Annual Growth Rate (CAGR) of 7.8% (The specific segment dedicated to food enzymes also exhibits rapid expansion, projected to rise from USD 4.6 billion in 2024 to USD 6.7 billion by 2030, with a CAGR of 6.3% (Yadav., et al).

This substantial market growth is propelled by converging factors that link industrial necessity with consumer trends. Changing consumer lifestyles have escalated the demand for processed foods, requiring the use of sophisticated enzymatic tools to improve product quality, texture, and shelf-life stability (kumar et al., 2024). This high growth rate confirms the success of industrial scaling efforts necessary to meet global demand, but it also reflects a deeper underlying reality modern food companies must manage complex supply chains while meeting contemporary consumer mandates for "natural" ingredients. Microbial enzymes, functioning as highly effective processing aids Serve as natural substitutes for many chemical additives, thus satisfying the dual requirements of industrial efficiency and clean label preferences. (Polizeli et al., 2008).

Beyond basic functionality, the strategic value of enzymes is rapidly evolving toward high-value enhancement. Enzymatic modification of substrates can generate highly desirable flavor enhancements, increase the digestibility of plant and animal proteins, and reduce allergenicity, yielding clean-tasting peptides and savory, umami flavors, exemplified by products like flavorpro (Dai et al., 2024). This sophisticated positioning demonstrates that enzyme innovation directly impacts financial performance and operational risk mitigation. For example, the introduction of Kerry Group plc's Biobake EgR an innovative solution that reduces egg usage in baking, illustrates that enzyme technology can directly offset major input costs. This capability positions advanced enzyme technology as a critical instrument for cost control and stability, especially when manufacturers are compelled to switch to higher-cost inputs, such as organic or free-range eggs (Yi, J., 2025).

2. Fundamentals of Microbial Enzyme Diversity and Production

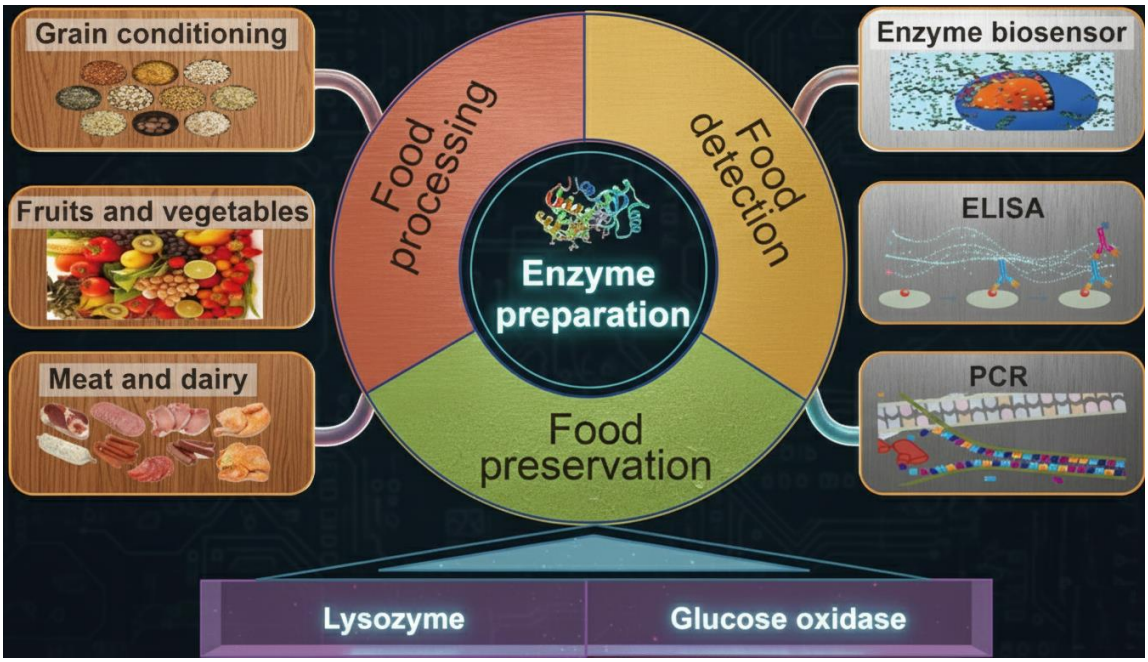
2.1. Classification, Nomenclature, and Major Enzyme Classes

Microbial enzymes used in food processing primarily function as hydrolases, a class that catalyzes the cleavage of chemical bonds through the addition of water Their wide functional diversity allows them to specifically target the major components of food: proteins, carbohydrates, and lipids. (Gautam et al., 2018).

2.1.1. Proteases

Proteases (proteinases or peptidases) constitute the largest and most widely utilized product segment in the global industrial enzyme market, due to their extensive applications across food, detergent, leather, and pharmaceutical fields (Yao et al., 2024: Shrivastav et al., 2025). These enzymes are categorized based on their cleavage mechanism: Endopeptidases hydrolyze internal peptide bonds, producing shorter peptides; conversely, exopeptidases cleave terminal peptide bonds from either the C-terminal or N-terminal ends, releasing free amino acids (L. M. et al., 2023). The robust market position of proteases is intrinsically linked to the high-yield production

capabilities of their microbial sources (*Bacillus* spp.), which are efficiently cultivated via submerged fermentation methods (L. M. et al., 2023).



2.1.2. Glycosyl Hydrolases

This essential group includes biocatalysts that modify carbohydrate structures:

- **Amylases:** This class includes alpha-Amylases and Glucoamylases, which are fundamental for the industrial conversion of starch (Gautam et al., 2018).
- **Lactase (beta-Galactosidase):** Catalyzes the hydrolysis of lactose into glucose and galactose, representing a key biotechnological process for producing lactose-reduced dairy products (Gautam et al., 2018; S. A. G. et al., 2021).
- **Pectinases:** These enzymes are extensively used for hydrolyzing pectic substances, which is critical in fruit and vegetable processing (Ferreira et al., 2022; Gautam et al., 2018).
- **Xylanases:** Vital in baking, these enzymes hydrolyze the beta-1, 4 backbones of arabinoxylans (cereal xylans), improving dough rheology (Polizeli et al., 2008).

2.1.3. Lipolytic and Oxidoreductase Enzymes

Lipolytic enzymes include Lipases, which hydrolyze long-chain triglycerides to release free fatty acids for flavor development, and Phospholipases, which specifically break down phospholipids (Gautam et al., 2018; S. A. G. et al., 2021). Oxidoreductases, such as Glucose oxidase, Laccase, Catalase, and Peroxidase, are employed for targeted functions like oxygen scavenging and color stability (Gautam et al., 2018).

2.2. Industrial Production: Comparative Analysis of Fermentation Technologies

Commercial microbial enzyme production largely relies on two distinct cultivation methods: submerged fermentation (SmF) and solid-state fermentation (SSF) (Hyseni et al., 2018; L. M. et al., 2023).

2.2.1. Submerged Fermentation (SmF)

SmF, involving the cultivation of microorganisms (bacteria and fungi) in liquid nutrient media, is the established standard for large-scale, industrial manufacturing of enzymes and other valuable metabolites (L. M. et al., 2023). SmF is generally preferred for high-volume enzyme production due to the relative ease of controlling parameters such as temperature, pH and dissolved oxygen, and its simplified downstream handling compared to solid media (Hyseni et al., 2018).

2.2.2. Solid-State Fermentation (SSF)

SSF involves cultivating microorganisms, particularly filamentous fungi, on a solid or semi-solid substrate this technology can offer significantly more concentrated enzyme solutions than SmF, especially when subsequent extraction steps are performed in counter-current mode. SSF is also described as a simple fermentation process that minimizes foam formation and simplifies the control of bacterial contamination (Hyseni et al., 2018).

However, SSF presents distinct operational challenges. It necessitates enzyme extraction as the critical first downstream processing step technical hurdles exist in managing mixing and mass transfer within the solid substrate, and difficulties persist in maintaining steady aeration and monitoring growth kinetics. Furthermore, the lack of efficient heat dissipation in solid beds can lead to excessive temperature rises, potentially destroying the target product or halting microbial growth entirely (Sánchez et al., 2018).

Despite these inherent engineering challenges, SSF is strategically important because of its strong connection to sustainability and circular economy objectives. The ability to use low-cost agricultural byproducts and residues as the growth substrate allows manufacturers to align production with valorization goals this deliberate choice suggests that the environmental and economic advantages derived from waste utilization are often sufficient to justify the increased complexity and capital expenditure required for SSF downstream processing. (Romero et al., 2024).

3. Applications in Core Food Processing Sectors

Microbial enzymes catalyze essential transformations across the food industry, optimizing texture, enhancing nutritional profiles, and improving process efficiency. (Hassoun et al., 2024).

3.1. Dairy Technology: Flavor, Texture, and Digestibility

Enzymes are central to dairy processing, from coagulation to flavor maturation. Proteases accelerate cheese aging and are employed to modify milk protein structure to reduce allergic effects, a crucial function in specialized infant formulas (S. A. G. et al., 2021).

Flavor signature in cheese is largely determined by lipolytic enzymes. Lipases, including microbial sources like *Mucor miehei*, hydrolyze milk fat to release free unsaturated fatty acids The required specificity dictates enzyme choice; animal-source enzymes preferentially hydrolyze short- and medium-chain fats, which produce highly desirable flavors. Microbial lipases, while effective, can be less specific, and the hydrolysis of longer chain fats may result in flavor neutrality or soapiness (Chen. et al., 2024).

Lactase (beta-galactosidase) remains critical, catalyzing lactose hydrolysis into sweeter, more soluble glucose and galactose, enabling the production of lactose-free dairy items beyond fundamental chemistry, modern enzymatic solutions are designed for sophisticated product enhancements. Products like flavorpro improve protein functionality, increase digestibility, and generate savory, umami flavor profiles, demonstrating the transition of enzymes from simple aids to advanced functional ingredients (Manoj Kuma et al., 2024).

3.2. Starch Conversion and High-Fructose Syrup Production

This sector is highly resource-intensive and relies heavily on processes where liquefaction and saccharification occur at temperatures often exceeding 100c This requirement for extreme heat necessitates the use of robustly thermostable, or thermophilic, enzymes to maximize starch solubility and ensure a sterile operating environment (Ndochinwa et al., 2024).

Thermostable \alpha-Amylases, such as Termamyl™ derived from *Bacillus licheniformis*, are foundational for starch liquefaction Candidates like \beta-Amylases from *Thermoanaerobacterium thermosulfurigenes* are valued for their high-temperature activity during saccharification (Jan et al., 2015).

Glucose (xylose) isomerases convert glucose into fructose for syrup preparation, with optimal conversion rates achieved at high temperatures, typically between 60 and 90c (Jan et al., 2015). Sweetzyme®, an immobilized glucose isomerase from *Streptomyces murinus*, is commercially effective in the 55 to 60c range (Nnaji, et al., 2025)

Amylopullulanases are gaining prominence due to their dual functionality—catalyzing both debranching and liquefying reactions and their calcium independence. This bi-functionality allows them to replace multiple conventional amylases, offering a consolidated and more cost-effective production process (Jan et al., 2015).

3.3. Baking Technology and Dough Rheology

In baking, enzymes, including amylases, xylanases, and proteases, are employed to enhance dough flexibility, stability, loaf volume, and crumb structure are crucial for quality improvement and shelf-life extension. Cereal xylans, or arabinoxylans, significantly influence bread quality due to their water absorption capacity Xylanases, typically sourced from *Aspergillus* and *Trichoderma* species, hydrolyze these pentosans. This action optimizes dough properties, improves loaf volume, reduces crumb stickiness, and plays a significant role in minimizing bread staling, thereby increasing shelf life (Polizeli et al., 2008).

Enzymatic solutions directly address logistical and financial concerns. The use of thermostable maltogenic amylase (Novamyl® from *B. stearothermophilus*) commercially improves bread freshness by delaying staling, these enzymes reduce food waste and minimize inventory holding time for retailers and manufacturers, effectively serving as a substitute for capital tied up in slow-moving inventory. (Jan et al., 2015).

An emerging area of research focuses on low-temperature processing utilizing psychrophilic enzymes. Psychrophilic xylanases, such as those from *P. haloplanktis* TAH3A, can effectively convert insoluble hemicellulose into soluble sugars at low temperatures. A key technical finding demonstrated that these cold-active xylanases can significantly improve dough properties and increase final bread volume by up to 28% compared to mesophilic xylanases (Ghosh et al., 2025).

3.4. Beverage and Fruit Processing

In the beverage sector, amylases, pectinases, and cellulases are heavily utilized processing aids Pectinases are vital for reducing viscosity and clarifying juices, musts, and wines The quality of these products is highly sensitive to heat; therefore, the application must prioritize preserving volatile flavor compounds and color integrity. (Ferreira et al., 2022).

The optimal strategy involves using psychrophilic (cold-adapted) pectinases, such as Lallzyme® (derived from *Aspergillus niger*), which remain optimally active in the 5 to 20c range This necessity for temperature specialization utilizing cold-active enzymes to prevent thermal damage is a core feature of high-quality beverage processing. (Jan et al., 2015).

Furthermore, glycosidases are employed to enhance the sensory profile by cleaving glycosidic bonds and releasing volatile aroma compounds from their precursors (Ferreira et al., 2022). While

many commercial beverage enzymes are mass-produced using fungal hosts (filamentous fungi and yeasts), Lactic Acid Bacteria (LAB) are a source of valuable enzymes. However, the typically slow growth of LAB strains often makes direct inoculation of the microorganisms, rather than the use of a purified enzyme preparation, the more common strategy in applications like wine production (Yao et al., 2024).

4. Advanced Biotechnological Optimization: Engineering and Stabilization

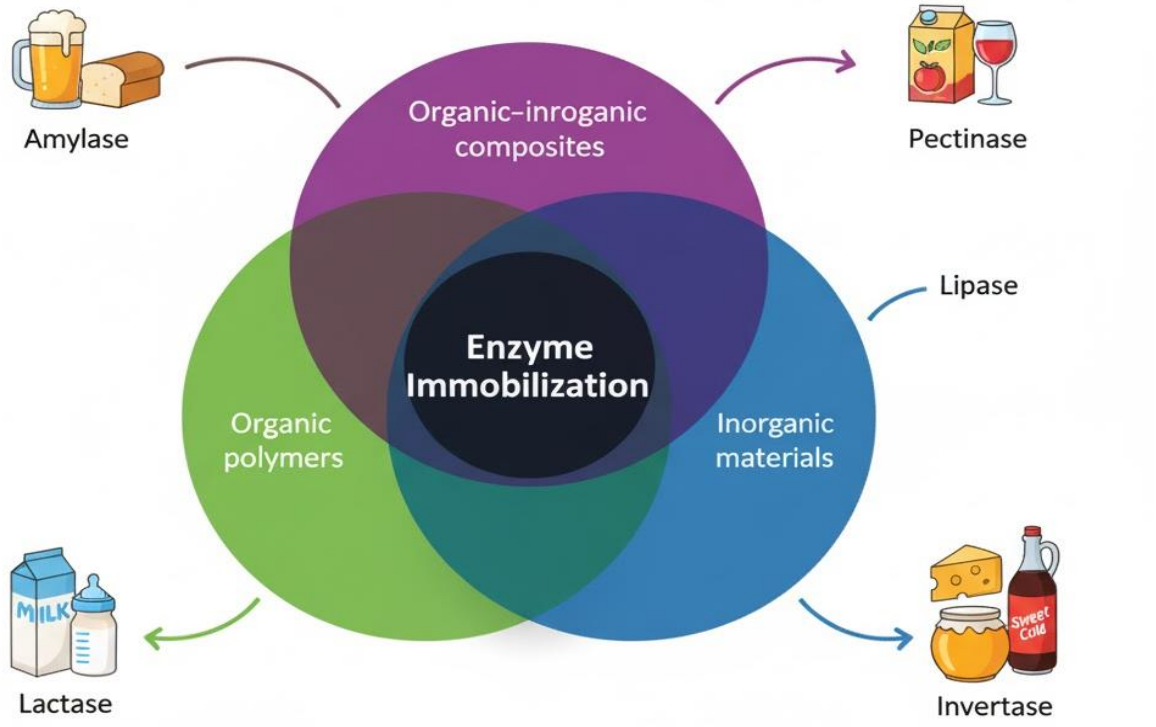
To overcome the inherent limitations of native enzymes and meet the escalating demands of industrial processes, extensive research is dedicated to enzyme engineering. This field employs rational design, directed evolution, and advanced computational simulation to create biocatalysts with superior operational characteristics, including enhanced thermal stability, altered substrate specificity, and robust tolerance (Liu et al., 2023; G. M. W., 2001).

4.1. Rational Design and Computational Modeling

Rational redesign is a systematic engineering strategy requiring extensive structural knowledge of the enzyme. It utilizes computational tools to predict the precise effect of specific amino acid substitutions on the enzyme's function and stability. This approach aims for iterative improvement based on a detailed understanding of the molecular mechanisms involved (Liu et al., 2023).

The efficiency of rational design is being augmented by advanced computation. The integration of computational tools and methods, including artificial intelligence and machine learning (ML), enables the development of sophisticated predictive models. These models guide the construction of optimized mutation libraries and accelerate the process of identifying highly efficient structural modifications (Ding et al.2020,).

Figure 4.1 Strategies for Enzyme Immobilization in Food Processing: Overlapping Supports Using Organic Polymers, Inorganic Materials, and Organic-Inorganic Composites with Key Microbial Enzyme Examples



4.2. Directed Evolution Strategies

Directed evolution offers an exploratory approach, particularly useful when detailed structural or mechanistic data are limited It is an iterative, laboratory-based process involving the creation of vast libraries of enzyme variants through mutagenesis, followed by high-throughput screening to select variants exhibiting the desired functional improvement Traditional methods laid the groundwork, including random techniques like error-prone PCR and DNA shuffling Modern approaches now include more targeted strategies to enhance precision (Liu et al., 2023).

Focuses random mutation specifically at the enzyme's active site, leveraging preliminary structural insight systematically saturates specific, pre-determined regions of the protein structure with mutations Combine the systematic nature of rational design with the broad search space of directed evolution, leading to efficient, iterative functional enhancement (Jamtsho et al., 2024).

While the literature details these methodologies meticulously, confirming the maturity of enzyme engineering techniques (such as ISM, CAST, OrthoRep, and PACE) (Liu et al., 2023), publicly available documentation lacks specific, detailed examples of directed evolution or rational design applied to *food enzymes* to improve their stability and activity This suggests that the successful application of these highly technical modifications is predominantly retained within industrial R&D programs as proprietary commercial advantage. (Ndochinwa et al 2024).

4.3. Stabilization via Immobilization

Operational stability is a critical economic factor in industrial biocatalysts. Enzyme immobilization the process of anchoring the enzyme to an inert solid matrix is a fundamental strategy for enhancement immobilization significantly enhances the enzyme's stability against environmental stresses heat changes and allows for its application in continuous processes. This method ensures greater sustainability by facilitating enzyme recovery and reuse, minimizing the overall operational expenditure, and simplifying enzyme removal post-processing (Liu et al., 2023).

5. The Role of Extremozymes in Extreme Processing Environments

Extremozymes are biocatalysts derived from extremophilic microorganisms that thrive in harsh habitats. These enzymes are uniquely adapted to maintain optimal activity and structure under extreme industrial conditions (high temperature, high salinity, or extreme These robust characteristics enable biocatalytic chemical reactions under conditions previously considered prohibitive, driving the development of environmentally friendly and highly efficient industrial technologies (Jan et al., 2015).

5.1. Thermostable and Hyperthermophilic Enzymes

High heat is unavoidable in many industrial food processes, often required to maximize substrate solubility (starch) or eliminate biological contamination Thermostable enzymes are mandatory in these environments. Examples include the reliance on alpha-Amylases from *Bacillus licheniformis* for starch liquefaction, and Glucose (Xylose) Isomerases from candidates like *Thermotoga neapolitana* and *Thermus aquaticus* for efficient isomerization at elevated temperatures The use of these enzymes minimizes contamination risk and increases throughput efficiency (Kudalkar et al., 2024).

5.2. Psychrophilic (Cold-Adapted) Enzymes

Psychrophilic enzymes, optimally active between 5 and 20c , offer distinct advantages Their utility is defined by their ability to enable processing at refrigeration temperatures, which inhibits the growth of mesophilic spoilage organisms and prevents the loss of crucial quality attributes like

flavor, nutrients, and color integrity that occur during thermal processing This specificity is crucial in the beverage industry, where cold-active pectinases (Lallzyme®) are used for juice and wine clarification (Chapadgaonkar et al., 2024).

Despite the proven capabilities of selecting thermophiles and psychrophiles, the full potential of biocatalysis offered by the wider range of extremozymes is still far from being completely realized This untapped resource pool, encompassing enzymes from alkaliphiles, acidophiles, and piezophiles, represents a significant opportunity for future enzyme discovery aimed at highly specialized or unconventional processing demands. (Atif et al., 2024)

Extremozyme Type	Example Enzyme	Source Microorganism	Optimal Conditions	Industrial Benefit
Thermophilic	alpha-Amylase (Termamyl™)	*Bacillus licheniformis*	T > 90°C, high stability	Starch liquefaction; reduced contamination risk in high-heat processes (Jan et al., 2015)
Thermophilic	Glucose Isomerase (Sweetzyme®)	*Streptomyces murinus*	T: 55–70°C	Efficient conversion of glucose to fructose for syrup production (Jan et al., 2015)
Psychrophilic	Pectinase (Lallzyme®)	*Aspergillus niger*	T: 5–20°C	Clarification of juices and musts; preserves flavor and color (Jan et al., 2015)
Psychrophilic	Xylanase	*P. haloplanktis* TAH3A	T: 5–20°C	Improved dough quality and volume at low, controlled temperatures (Jan et al., 2015)

6. Microbial Enzymes in Sustainability and Circular Economy

The application of microbial enzymes is fundamental to adopting green chemistry principles and establishing a circular economy within the food industry by maximizing resource recovery and minimizing waste. (Nargotra et al., 2024)

6.1. Valorization of Agri-Food Byproducts

Enzymatic conversion offers a sustainable pathway for transforming agricultural residues and food processing waste (e.g., spent grains, fruit peels) into functional, high-value-added ingredients This practice of valorization generates new revenue streams and simultaneously mitigates the financial and environmental costs associated with the disposal of large volumes of industrial waste (T. F. S. et al., 2023).

This circular business model reduces dependence on virgin raw materials and contributes to the preservation of ecosystems, water, and energy resources by linking enzyme production (often via SSF on agricultural residues) with the goal of creating marketable high-value extracts, the industry establishes a virtuous cycle of sustainable production that drives innovation and competitiveness (Orakzai et al., 2024).

6.2. Green Extraction Technologies

Enzyme-assisted Green Extraction (EAGE) techniques represent a sophisticated use of biocatalysts to obtain high-purity compounds. Enzymes are applied to specifically degrade cellular structures, facilitating the selective release of targeted bioactive compounds, such as nutraceuticals, from complex plant matrices (O. S. et al., 2023).

EAGE techniques surpass conventional methods by offering higher yields, improved selectivity, lower energy consumption, and a reduced reliance on harsh organic solvents When combined with innovative physical methods like Microwave-Assisted Extraction (MAE), EAGE further enhances efficiency and aligns perfectly with green chemistry protocols In this context, the high selectivity inherent to enzymatic catalysis is crucial, as it defines the purity and market quality of the functional ingredient being extracted. (Shrivastav. et al., 2024).

7. Regulatory Landscape and Commercial Strategy

Global suppliers of microbial food enzymes must navigate highly divergent regulatory frameworks, presenting significant strategic challenges (Elazzazy et al., 2024).

7.1. Global Regulatory Frameworks for Food-Grade Enzymes

7.1.1. United States (FDA/GRAS)

In the United States, regulation is primarily managed by the FDA through the Generally Recognized as Safe (GRAS) provision Safety status can be established based on a history of common use or by scientific consensus supported by sufficient public data Manufacturers can independently determine GRAS status, or they may choose to submit a voluntary GRAS Notice to the FDA for notification This system offers a relatively flexible pathway for market entry. (Lau et al., 2025)

7.1.2. European Union (EFSA/EC)

The EU enforces a strict, mandatory authorization system, considered among the world's most demanding regulatory regimes Under EU rules, all food enzymes require a compulsory risk assessment conducted by the European Food Safety Authority. Following EFSA's scientific advice, the European Commission (EC) grants final approval for inclusion in a unified EU list of authorized food enzymes (Palou et al., 2024)

A crucial component of the EU system is the assessment of the production organism itself for status. QPS assessment requires that the microbial species used as the host is taxonomically well-defined, has sufficient established safety knowledge, is confirmed to lack pathogenic properties, and has a clearly described intended use This high regulatory focus on the safety of the host strain, rather than solely on the purity of the final enzyme, dictates that future innovation involving novel or engineered microorganisms must incorporate substantial investment in host genomics and non-pathogenicity testing. (Mirsalami et al., 2024)

The mandatory, centralized EFSA review process and the ongoing status of the unified EU list create a long, highly stringent authorization timeline (EC, 2023). This extensive regulatory lead time functions as a competitive barrier, making market entry challenging for small biotech innovators and favoring large firms capable of sustaining prolonged regulatory review periods (Epskamp et al., 2025).

Table 3: Comparison of Key Regulatory Pathways for Food Enzymes

Regulatory Aspect	United States (FDA)	European Union (EFSA/EC)
Primary Mechanism	Generally Recognized as Safe (GRAS) (FDA, 2023)	Mandatory Safety Evaluation and Authorization (EC, 2023)
Review Process	Manufacturer self-determination or voluntary FDA notification (Biosafe, 2023)	Mandatory risk assessment by EFSA, followed by EC approval (EC, 2023)
Microorganism Safety	Historical safety data considered; reviewed under GRAS (FDA, 2023)	Requires Qualified Presumption of Safety (QPS) status for host strains (Biosafe, 2023)
Current Market Access	GRAS ingredients can be marketed upon determination	Subject to varied national laws until the unified EU list is established (EC, 2023)

8. Conclusion and Future Outlook

Microbial enzymes have fundamentally transformed food processing by providing highly specific, scalable, and reproducible biocatalytic agents. They have enabled the optimization of critical industrial processes, from achieving high-yield starch conversion through thermostable amylases to maintaining flavor integrity using psychrophilic pectinases in cold-chain processes. (Ferreira et al., 2022).

The future trajectory of this field will be defined by the successful integration of advanced engineering strategies. The sophisticated merging of rational design, machine learning-driven computation, and directed evolution is essential for creating next-generation biocatalysts capable of operating under increasingly specific and demanding industrial conditions (Liu et al., 2023; G. M. W., 2001). This includes improving stability, reducing necessary dosages, and eliminating unwanted side reactions. Simultaneously, innovation requires tapping into novel biological resources. Despite the existing industrial reliance on a few robust strains, the extensive potential of extremozymes derived from diverse microbial habitats is largely undeveloped (Jan et al., 2015). Unlocking this potential necessitates sustained research into extremophilic biodiversity to secure novel biocatalysts for new food applications. Finally, strategic commercialization must anticipate and incorporate complex global regulatory requirements, particularly the stringent QPS assessments demanded by the European Union. Future research and development must not only aim for catalytic efficiency but also for compliance readiness, ensuring transparent and documented safety profiles for the microbial host strains. By aligning biotechnological mastery with proactive regulatory strategy and environmental imperatives, microbial enzymology will continue to be the definitive driver of sustainable and high-quality innovation in the global food supply chain. (Palou et al., 2024)

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