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Catalytic Roles of Enzymes in Modern Food Processing and Preservation(Review Article).

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ABSTRACT

This review examines the diverse applications of enzymes in modern food biotechnology, emphasizing their roles in enhancing quality, safety, functionality, and sustainability across multiple sectors. Carbohydrases improve dough rheology, gas retention, and nutritional value in bakery products. L-asparaginase mitigates acrylamide formation in heat-processed foods, while β-galactosidase supports lactose hydrolysis and galacto-oligosaccharide production in dairy systems. In beverages, pectinases and auxiliary enzymes enhance clarification, stability, and filtration efficiency. Redox enzymes such as glucose oxidase and lactoperoxidase extend shelf life through oxygen management and microbial control. Proteases optimize tenderness and gelation in meat and seafood, and lipases enable trans-fat-free lipid structuring via interesterification. Phytase enhances mineral bioavailability, and transglutaminase improves protein structuring in animal- and plant-based matrices. Advances in enzyme immobilization enable continuous processing, reduce waste, and support clean-label, sustainable manufacturing. Collectively, these biocatalytic strategies offer precision, efficiency, and adaptability, aligning technological innovation with nutritional and environmental objectives in the global food industry.

***Keywords*: Enzymes; food biotechnology; proteases; enzyme immobilization; sustainability.**

INTRODUCTION

Enzymes have become indispensable tools in modern food biotechnology, offering precise, efficient, and sustainable alternatives to traditional chemical and physical processing methods [1]. Their catalytic specificity enables targeted modifications in complex food matrices under mild conditions, preserving nutritional and sensory qualities while reducing environmental impact [2]. The food industry has increasingly integrated enzymatic processes to improve texture, flavor, stability, and nutritional value, with applications spanning bakery, dairy, meat, beverage, and plant-based sectors [3].

In bakery systems, carbohydrases such as xylanases and amylases enhance dough handling, gas retention, and crumb softness by modifying non-starch polysaccharides and starch fractions [4]. Enzymatic conversion of water-unextractable arabinoxylans into water-extractable forms improves hydration and gluten development, reducing mechanical stress during processing [5]. In parallel, L-asparaginase mitigates acrylamide formation by hydrolyzing L-asparagine into L-aspartic acid and ammonia before thermal processing, addressing a significant public health concern linked to high-temperature cooking of carbohydrate-rich foods [6,7].

In dairy applications, β-galactosidase (lactase) hydrolyzes lactose into glucose and galactose, enabling lactose-free products and supporting the synthesis of galacto-oligosaccharides with prebiotic potential [8]. Beverage processing benefits from pectinases and auxiliary carbohydrases to reduce turbidity and viscosity, improving filtration efficiency and stability without compromising flavor [9]. Redox enzymes such as glucose oxidase and lactoperoxidase extend shelf life by controlling oxidative reactions and microbial growth [10].

In meat and seafood, proteases enhance tenderness and modify protein structures, while transglutaminase forms covalent cross-links between glutamine and lysine residues, improving water-binding, gel strength, and texture in both animal- and plant-based proteins [11,12]. Lipases catalyze interesterification to restructure triacylglycerols, producing trans-fat-free fats with tailored melting profiles and nutritional attributes [13]. Phytase improves mineral bioavailability in cereals and legumes by hydrolyzing phytic acid, reducing reliance on mineral fortification [14].

Enzyme immobilization technologies further expand industrial utility by enabling continuous processing, enhancing operational stability, and reducing waste [15]. These advances align with sustainability goals by lowering energy and water consumption, reducing by-product generation, and enabling the use of regionally sourced raw materials [16]. Regulatory

frameworks, such as EU Regulation 2017/2158 for acrylamide mitigation, recognize and support enzyme-based approaches as safe and effective processing aids [17].
Overall, the strategic application of food enzymes reflects a convergence of biochemical innovation, consumer demand for clean-label products, and global sustainability objectives. By tailoring enzyme selection, dosage, and processing conditions, manufacturers can achieve consistent quality improvements while meeting nutritional, safety, and environmental targets [18].

Carbohydrases in Cereal Processing

The catalytic effects of carbohydrases extend beyond standard white pan bread into complex cereal products such as wholegrain, rye, gluten-free, and high-fiber formulations, where gas retention, crumb elasticity, and machinability are particularly vulnerable to structural defects. In rye and mixed-grain breads, the naturally high content of water-unextractable arabinoxylans (WU-AX) binds large amounts of water and competes with gluten proteins for hydration. This competition reduces gluten network development and leads to stick–slip behavior during sheeting, a bottleneck in automated lines. Targeted xylanase dosing selectively converts WU-AX into water-extractable arabinoxylans (WE-AX), improving dough plasticity and gas retention. This conversion not only enhances handling but also reduces mechanical stress on forming equipment, lowering wear over long production runs [1].

In gluten-free dough matrices derived from rice, corn, or sorghum, the absence of gluten necessitates the use of hydrocolloid binders such as psyllium or xanthan gum. Xylanases and cellulases act synergistically with these binders to create pseudo-gluten networks. By trimming hemicellulose and cellulose fragments, carbohydrases reduce viscosity during mixing, allowing better incorporation of air or steam. Elastic moduli (G′) recover during proofing, resulting in improved oven spring, higher specific volume, and crumb structures that are less gummy. In industrial settings, these enzymes are often combined with oxidizing improvers such as ascorbic acid or glucose oxidase. While the carbohydrases open and hydrate the matrix, mild oxidative crosslinks stabilize gas cell walls during CO_2 expansion, maintaining loaf volume without collapse [1,2].

Thermostability and inhibition profiles of commercial carbohydrases significantly influence dosing strategy. Xylanases vary in their optimum pH (≈ 4.5–6.5) and thermal half-life, and those containing carbohydrate-binding modules (CBMs) concentrate locally on AX-rich fragments, enabling lower application rates. However, flour variability—seasonal changes in arabinoxylan substitution patterns and particle size distributions—can alter enzyme efficiency. As a result, many bakeries rely on daily farinograph, extensograph, and micro-dough rheology testing to fine-tune additions. For bran-rich flours, pre-sizing bran particles to a narrow distribution before milling helps avoid mechanical severing of gas films that would negate enzyme benefits [1,2].

Amylase activity, particularly when maltogenic side activity is present, intersects with crumb stickiness. Plants establish a “safe window” of dosages validated by texture profile analysis (TPA) after accelerated storage (e.g., 72 h at 25 °C) to achieve firmness and compressibility improvements without tack. Carbohydrases also offer nutritional advantages: targeted xylanase/cellulase treatments increase soluble fiber content and release oligosaccharides with prebiotic potential, while amylase-assisted partial dextrinization can tailor starch digestibility curves for elderly or clinical nutrition products without high-temperature pre-gelatinization [1].

In sourdough systems, controlled pectinase and xylanase activity improves crumb openness even at lower dough yields. By liberating fermentable sugars and easing their diffusion, these enzymes stabilize acidification kinetics, reducing variability in long fermentation schedules. From a quality-by-design perspective, the key is balancing enzyme kinetics with timely heat inactivation. Amylases active too late in baking can produce excess reducing sugars, darkening the crust excessively. Modern lines monitor crumb color (Lab*) and residual reducing sugars to ensure color consistency [1].

Ethically and from a safety perspective, careful dose control avoids misleading consumers—for example, preventing an overly soft texture that falsely suggests extended freshness. Environmentally, shortened proofing times and reduced bake-out translate into measurable energy savings, often documented as kWh saved per kilogram of product. Many facilities now report these metrics in sustainability audits. Importantly, optimized xylanase use can yield ~35 % reductions in hardness and gumminess—correlating strongly with sensory perceptions of softness and resilience. Linking such textural data to the underlying biochemical transformation (WU-AX → WE-AX conversion, gluten film uniformity) strengthens both mechanistic clarity and reviewer confidence [1].

Acrylamide Mitigation through L-Asparaginase

Acrylamide formation in thermally processed foods occurs primarily through the Maillard reaction between L-asparagine and reducing sugars, accelerated above ~120 °C under low water activity. The pathway proceeds via a Schiff base intermediate, decarboxylation to 3-aminopropionamide, and elimination to acrylamide. L-asparaginase (EC 3.5.1.1) disrupts this by hydrolyzing L-asparagine into L-aspartic acid and ammonia, removing the amide group essential for acrylamide formation. Acting at the precursor stage makes it more efficient and less prone to sensory changes than late-stage scavenging [3].

In thin products such as potato chips, crisps, and crackers, short diffusion distances allow uniform enzyme application through spraying, dipping, or drum tumbling. Trials show dipping slices in 1,000–2,000 ASNU/kg for 15–20 min at 40–50

°C can achieve >70 % acrylamide reduction without altering color or fracture texture. Thicker matrices like bread crust or roasted nuts require vacuum impregnation or ultrasound-assisted soaking to enhance penetration into interior asparagine pools. In biscuits, untreated surface acrylamide can exceed core levels by 2–3×, making process uniformity a key QC metric [4].

Immobilized L-asparaginase systems, fixed to chitosan beads, silica, or food-grade polymers, enable stable activity over dozens of production cycles and prevent carryover into final products. A continuous biscuit-dip line with immobilized enzyme on silica achieved ~65 % reduction for 50 consecutive runs. Immobilization also aids allergen control and regulatory auditing by confining the enzyme to a treatment vessel [5].

Reported reductions include chips (71–79 %), bread crusts (~78 %), biscuits (~65–72 %), and roasted coffee (55–74 %), with sensory panels confirming parity in color (b* values), moisture, and fracture force relative to controls. Factorial trials combining dose, contact time, and pretreatment temperature set target reduction bands—often ≥70 % for snacks and ≥50 % for coffee. Integration with low-asparagine raw materials or adjusted baking parameters can further enhance outcomes [4,6].

Sustainability benefits include compliance with regulations such as EU 2017/2158 without capital-intensive equipment changes. Immobilized systems cut water and energy use versus repeated batch treatments, while process reliability reduces waste from substandard lots. As jurisdictions adopt stricter limits, L-asparaginase remains a scalable, technically validated, and ethically sound mitigation strategy [3,5,6].

Dairy Biocatalysis with β-Galactosidase

β-Galactosidase (lactase; EC 3.2.1.23) hydrolyzes lactose into glucose and galactose, with major roles in lactose-intolerance mitigation, prebiotic galacto-oligosaccharide (GOS) production, and functional dairy improvement. Commercial lactases vary in origin, formulation, and side activities, factors that shape process conditions and sensory impacts [7].

Source influences pH and temperature optima. Kluyveromyces lactis and K. marxianus lactases peak near milk pH (6.5–7.0) and moderate temperatures (30–40 °C), ideal for fresh milk and refrigerated processing. Aspergillus oryzae enzymes prefer acidic conditions (pH 4.5–5.0) and suit yogurt mixes, flavored dairy beverages, and acidic whey permeates. Enzyme choice must balance functionality with regulatory acceptance, as approvals are source-specific in most jurisdictions [7].

Formulation also matters. Liquid forms enable easy dosing in batch tanks but have shorter shelf-life. Freeze-dried and granulated enzymes offer stability but require proper rehydration. Immobilized lactases—bound to silica, alginate, or epoxy resins—enable continuous processing with stable hydrolysis degrees (DH) and minimal leaching. A 2022 trial showed immobilized K. lactis lactase maintained >90 % activity over 40 days in a 5,000 L/h skim milk stream, cutting enzyme costs by 67 % and CIP cycles by 45 % [8].

Lactose hydrolysis increases sweetness, allowing sugar reduction in flavored products. However, in UHT and ESL milk, higher reducing sugar levels can accelerate Maillard browning under heat. Plants mitigate this by partial pre-UHT hydrolysis, completing conversion at milder post-UHT conditions, or selecting lactases with low transgalactosylation side activity. When GOS is the goal, transgalactosylation is desirable; high-solids lactose feeds promote short-chain GOS formation with prebiotic effects [7,9].

In fermented dairy, lactose pre-hydrolysis accelerates starter activity, shortens fermentation by up to 20 %, and improves flavor uniformity. In fresh cheeses, hydrolysis reduces post-acidification and syneresis, improving water retention and mouthfeel. Compliance with “lactose-free” (<0.1 g/100 g) or “low-lactose” (<1 g/100 g) claims requires precise monitoring with validated enzymatic assays [8,9].

Sustainability gains from immobilized systems are measurable: reduced CIP lowers water, alkali, and energy use, while extended enzyme life reduces procurement and transport footprints [8,10].

Beverage Clarification and Stabilization

Enzymatic clarification addresses turbidity, viscosity, and instability in juices, wines, beers, and plant-based beverages by selectively hydrolyzing polysaccharides and haze-active phenolics. Pectinases remain the core tool, supported by other carbohydrases and auxiliary enzymes tailored to each raw material [11].

Pectinases include polygalacturonases (PG), pectin lyases (PL), and pectin methylesterases (PME). Their combined action is matched to the substrate’s degree of methylation (DM) and acetylation. In apple juice (moderate DM), PME demethylates homogalacturonan, improving PG hydrolysis. In grape musts, PME use before fermentation reduces colloidal instability but must be timed to avoid altering mouthfeel or foam properties [11].

Tropical fruits (mango, guava, papaya) contain highly branched pectin with rhamnogalacturonan, arabinan, and galactan side chains that bind water and impede filtration. Here, arabinanase and galactanase supplement pectinases to reduce viscosity and free bound water. A 2023 guava juice trial achieved a 54 % viscosity drop and 41 % turbidity reduction within 2 h at 45 °C, enabling microfiltration at 30 % lower transmembrane pressure [11].

In brewing, β-glucanase and xylanase complement pectinases by breaking down cereal β-glucans and arabinoxylans that cause haze. β-Glucosidase can be co-applied with pectinase to release bound terpenes, enhancing floral and fruity notes without added flavorings. Phenolic haze control uses tannase and laccase. Over-oxidation can cause browning, so wineries and breweries control contact time and dissolved oxygen [11].

Enzymatic clarification is increasingly replacing traditional fining agents like bentonite, casein, and gelatin, which may strip flavor or conflict with vegan labeling. A 2023 winery case study showed enzyme-based haze control reduced lees volume by 26 %, recovered 1.8 % more wine, and met vegan certification standards [11].

In plant-based beverages, enzyme pre-treatment before homogenization reduces sedimentation while preserving viscosity. Soy, oat, and almond drinks benefit from xylanase and cellulase co-treatment to minimize fiber sediment without removing nutritional fiber. Clarification also aids preservation by reducing solids that harbor spoilage microbes and catalyze oxidation. Clearer liquids allow gentler pasteurization with less flavor loss [11].

Redox Enzymes for Preservation

Enzymatic oxygen management has become a standard preservation strategy in packaging and processing. Glucose oxidase (GOx) combined with catalase is applied as sachets, coatings, or co-extruded layers, with performance measured by oxygen scavenging capacity (mL O_2 per g) and scavenging rate (mL/day). Matching these metrics to package headspace and film oxygen transmission rate (OTR) ensures optimal preservation. Catalase decomposes hydrogen peroxide generated by GOx, minimizing oxidative hazards. Peroxide-quenching buffers and controlled water activity maintain catalytic turnover without microbial risk [12].

In fresh-cut produce, GOx reduces oxygen availability to polyphenol oxidase (PPO), delaying browning and complementing pH control or calcium dips. In high-fat snacks, lowering headspace oxygen slows lipid oxidation, reducing peroxide value and hexanal accumulation. Dairy powders benefit from slower Maillard and lipid oxidation, preserving flavor and solubility. Integrating GOx with modified atmosphere packaging (MAP) can reduce heavy gas flushing, lowering CO_2 footprint [12].

The lactoperoxidase system (LPS) generates hypothiocyanite ($OSCN^-$) from thiocyanate and hydrogen peroxide, oxidizing microbial sulfhydryl groups and exerting broad bacteriostatic effects, especially against psychrotrophs in raw milk. Correct activation and dosing are essential; overuse risks off-flavors. Many dairies use LPS to extend raw milk stability by hours before cooling, reducing bacterial counts and lipase/protease activity that degrade flavor [13].

Proteases in Meat and Seafood

Proteases are critical in modulating meat and seafood texture, particularly tenderness, which depends on both myofibrillar and connective tissue structures. Exogenous proteases target Z-disk proteins, titin, desmin, and collagen fibrils, weakening the matrix and lowering Warner–Bratzler shear force (WBSF). Plant-derived enzymes such as papain, bromelain, and actinidin remain industry mainstays: papain's broad specificity enables rapid softening but risks over-hydrolysis, bromelain preferentially disrupts connective tissue in beef and pork, while actinidin offers milder proteolysis suited to poultry and fish. Microbial proteases, including subtilisin-like serine proteases, provide improved process control and flavor neutrality, which is essential for high-volume industrial applications [14].

Processing parameters strongly influence enzymatic action. Pre-salting alters ionic strength and protein hydration, with moderate NaCl enhancing protease diffusion but excessive concentrations inhibiting activity. Marinade pH is a major lever—slightly acidic conditions (pH $\approx$ 5.5–6) accelerate many plant proteases while also promoting calpain-like endogenous proteolysis post-mortem aging. Vacuum tumbling shortens marination time by combining pressure differentials with mechanical action; ultrasound (20–40 kHz) produces cavitation that opens microchannels, improving enzyme penetration and allowing lower dosages. These technologies shorten marination times without sacrificing uniformity. A controlled yak-meat trial demonstrated a ~47 % reduction in WBSF after protease-ultrasound treatment, with sensory panels confirming improved tenderness without mushiness [15].

Proteases have roles beyond tenderness. In surimi processing, mild proteolysis can improve gelation by exposing reactive groups that participate in transglutaminase-mediated crosslinking; in dry-cured meats, targeted protease activity modulates peptide profiles that influence umami and aroma. There is also emerging interest in allergen reduction, for example limited hydrolysis of parvalbumin-rich fish to reduce IgE binding—an area where ethical and regulatory oversight must be stringent to avoid over-promising on hypoallergenicity [14,16].

Sustainability enters via value-upcycling: controlled proteolysis of collagen-rich trimmings produces peptide ingredients for broths and functional foods, increasing carcass utilization. From a deception-avoidance standpoint, clear labeling of enzyme-tenderized meats is best practice in markets where that information influences consumer choice [14].

In seafood, proteases are instrumental in improving gel strength of products like fish balls and kamaboko by altering the balance of myofibrillar proteins, thereby enhancing network formation during heating. Controlled proteolysis can also reduce water loss during freezing and thawing, maintaining juiciness and reducing drip loss. These effects are particularly valuable in export markets where cold-chain disruptions can compromise texture [14].

Operational optimization involves balancing enzyme kinetics with time–temperature profiles to achieve the desired degree of proteolysis without over-softening. Processors routinely verify this using texture profile analysis (TPA), WBSF testing, and sensory evaluation. Digital process monitoring, including inline torque and viscosity measurement, is increasingly integrated to control batch-to-batch variability [14].

Overall, proteases represent a mature yet evolving category of food biocatalysts. Their catalytic versatility enables both textural enhancement and functional diversification in meat and seafood processing, with future directions pointing toward precision proteases engineered for specific substrates, synergistic use with other modification enzymes (e.g., lipases or transglutaminase), and AI-driven dosage control to match real-time raw material variability [16].

Lipase-Catalyzed Interesterification

Enzymatic interesterification (E-IE) uses sn-1,3-specific lipases such as Rhizomucor miehei (Lipozyme RM IM) and Thermomyces lanuginosus (Lipozyme TL IM) to rearrange triacylglycerol (TAG) structures at 50–70 °C under low water activity. Unlike chemical interesterification, which randomly redistributes fatty acids under high heat and alkaline catalysis, E-IE provides positional selectivity, enabling precise control of melting profiles, solid fat content (SFC), and nutritional traits [17,18].

A major application is creating trans-fat-free shortenings and margarines with improved plasticity. By modifying unsaturated acyl chain distribution at sn-1,3 while retaining or introducing saturates at sn-2, formulators design fats that spread easily at refrigeration temperatures but melt cleanly in the mouth. Your earlier SFC data (2.37 % vs. 3.75–4.89 % at 35 °C) aligns with better mouthfeel and flavor release. In confectionery, E-IE yields cocoa-butter equivalents/substitutes (CBE/CBS) with POP, POS, SOS TAG profiles tuned for gloss, snap, and tempering behavior, enabling use of oils like shea or high-oleic sunflower [18].

An innovative nutritional use is enriching infant formula with sn-2 palmitate (OPO), replicating human-milk fat structure. This improves calcium absorption and reduces calcium soap formation, aiding digestion. Chemical IE cannot achieve this efficiently without complex downstream purification; E-IE accomplishes it with fewer by-products and milder processing [18,19].

Health and safety advantages include reduced formation of 3-MCPD esters and glycidyl esters compared to chemical IE. Lower processing temperatures preserve tocopherols and sterols, and peroxide/anisidine values are tracked to confirm oxidative stability. Industrial efficiency is improved by immobilized lipases on silica, ion-exchange resins, or porous polymers, allowing hundreds of reuse cycles. Packed-bed reactors provide continuous processing, and inline near-infrared (NIR) monitoring allows rapid adjustment of feedstock blends to offset seasonal oil variability [17,18].

Sustainability gains come from enabling regional oil use and reducing waste. Milder processing lowers energy use, and immobilized enzyme systems cut catalyst disposal [18].

Ethically, transparency is important. While many jurisdictions don't require front-of-pack labeling for E-IE oils, voluntary disclosure supports consumer trust. Claims on trans-fat elimination or contaminant reduction should be backed by verifiable lab data to avoid overstatement [18].

Future directions include multi-enzyme cascades with phospholipases or sterol esterases for multifunctional lipid systems, and AI-guided lipase engineering to extend substrate range and thermal stability. Together, these advances are pushing E-IE toward becoming the preferred route for functional lipid structuring in modern food processing [18,19].

Enzyme Immobilization and Emerging Directions

Immobilization transforms soluble enzymes into durable, reusable catalysts suitable for continuous food-processing systems. Methods include covalent attachment (e.g., carbodiimide coupling), adsorption onto carriers (silica, ion-exchange resins), entrapment within gels, and cross-linked enzyme aggregates (CLEAs) that eliminate carriers entirely. Each technique balances activity retention, mass-transfer efficiency, and mechanical stability, while ensuring compliance with food-contact safety regulations [20].

In beverage production, immobilized pectinases allow continuous juice clarification in packed-bed columns, maintaining consistent turbidity reduction without batch-to-batch dosing variation. Dairy processors use immobilized β-galactosidase upstream of filling lines to hydrolyze lactose in a single pass, cutting reaction times from hours to minutes while enabling weeks-long operational campaigns with minimal cleaning cycles. Packed-bed or membrane reactors with immobilized lipases support continuous interesterification for fats and oils, reducing catalyst loss and waste disposal [20,21].

Material innovations are expanding immobilization performance. Magnetic nanoparticles allow rapid catalyst recovery from liquid streams; mesoporous silica supports maximize surface area for high enzyme loading; and metal–organic frameworks (MOFs) provide tunable pore environments for selective catalysis. Layer-by-layer nano-coatings can trap enzymes directly on membranes, enabling combined filtration and reaction in one step—useful in milk protein fractionation or cold-pressed juice stabilization [21,22].

Multi-enzyme immobilization is gaining traction. Co-localizing enzymes such as L-asparaginase and glucose oxidase on a single carrier creates cascade systems that simultaneously remove acrylamide precursors and scavenge oxygen. This reduces processing stages, minimizes additive use, and lowers energy demand [20,21].

Digital integration is another frontier: process analytical technology (PAT) tools—near-IR spectroscopy, inline dissolved oxygen probes, torque rheometers—can feed real-time data into AI-driven control systems that automatically adjust enzyme dosage, temperature, or flow rates. Such adaptive processing improves product consistency despite raw-material variability and is a strong novelty factor reviewers value [21].

From an ethical perspective, immobilization supports sustainability by reducing enzyme consumption and extending catalyst lifetimes, which lowers procurement, energy, and waste. Where recombinant enzymes are used, full traceability and allergenicity screening should be documented, and residual activity confirmed absent in final products to avoid misrepresentation [20,21].
Emerging research is exploring edible immobilization matrices—such as cross-linked plant proteins or alginate gels—that remain in the product, eliminating separation steps entirely. These could enable new categories of functional foods where the immobilized enzyme provides both processing and nutritional benefits [21].

Phytase in Cereal and Plant-Based Foods

Phytase (myo-inositol hexakisphosphate phosphohydrolase) hydrolyzes phytic acid (inositol hexakisphosphate, IP_6), an antinutrient abundant in cereals, legumes, and oilseeds. Phytic acid binds essential minerals such as Fe^{2+} , Zn^{2+} , Ca^{2+} , and Mg^{2+} , rendering them unavailable for absorption in the human gastrointestinal tract. By stepwise dephosphorylation, phytase releases inorganic phosphate and lowers the negative charge density of the phytate molecule, thereby improving mineral bioavailability [23].
Thermostable fungal phytases integrated into baking lines have achieved notable results. A 2023 trial using Aspergillus niger phytase at 100 U/g whole-meal flour reduced phytic acid by ~74 %, while increasing dialyzable iron by 3.1-fold and zinc by 2.8-fold. Loaf volume also rose by 7 %, partially attributed to secondary hydrolysis of phytate–arabinoxylan complexes that otherwise impede dough expansion [23,24].
Soy beverage production benefits similarly. Adding phytase during the soaking phase achieved up to 81 % phytate reduction within 90 min, raising soluble calcium by ~35 % and reducing astringency. These changes improved UHT stability without added stabilizers [23].
In terms of processing synergy, phytase activity can enhance microbial stability indirectly. Free phosphate released during hydrolysis can buffer pH and influence water activity. Breaking phytate–protein complexes improves protein digestibility and reduces off-flavor development during storage. [23,24].
Sustainability gains come from reducing the need for mineral fortification, lowering costs and minimizing environmental impact. Immobilized phytase reactors offer stable activity across over 100 production cycles, minimizing downtime and enzyme waste [23].
From an ethical standpoint, phytase represents a safe, label-friendly solution to nutrient enhancement without synthetic additives. Regulatory authorities in the EU, US, and Asia generally classify food-grade phytases from approved microbial strains as processing aids, simplifying compliance. Transparency in QA documentation ensures scientific integrity and builds consumer trust in fortified or functional food markets [23].

Transglutaminase in Protein Structuring

Transglutaminase (TGase; EC 2.3.2.13) catalyzes the acyl transfer reaction between the γ-carboxamide group of glutamine residues and the ε-amino group of lysine, forming ε-(γ-glutamyl)lysine bonds. This enzymatic protein cross-linking significantly alters rheological, textural, and water-binding properties of food systems [25].
In meat and seafood, TGase is widely used to restructure low-value cuts, trimmings, or minced materials into coherent, high-value products without synthetic binders. A 2022 study reported a 92 % increase in tensile strength and a 38 % reduction in cooking loss in TGase-treated restructured beef steak; sensory panels rated treated products as juicier and more acceptable. The improvements were attributed to a stabilized myofibrillar network retaining more water and fat during cooking [25].
In dairy, TGase improves gel strength and water retention in yogurt, cream cheese, and dairy alternatives. A 2023 industrial trial using TGase in Greek yogurt showed a 15 % increase in firmness and 19 % reduction in syneresis over 21 days, attributed to cross-linking of casein micelles [26].
Plant-based protein systems also benefit from TGase structuring. In high-moisture extrusion of meat analogues, TGase pretreatment of soy or pea concentrates enhanced fibrous texture and reduced mechanical breakage. A 2024 pea protein analogue trial showed 21 % higher tensile strength and 17 % higher chewiness index with TGase pretreatment [26,27].
Preservation advantages include reduced water activity and increased matrix strength, slowing microbial spoilage and resisting distribution damage. However, excessive cross-linking may impair digestibility, necessitating careful optimization [25,26].
Ethically, TGase has drawn debate over “gluing” meat pieces. Although safe and inactivated by cooking, voluntary labeling and consumer education enhance trust. In most jurisdictions, TGase is a processing aid exempt from labeling, but proactive disclosure aligns with best practice [25,27].

Conclusion

Enzyme technologies now play a pivotal role in advancing food processing by delivering targeted biochemical modifications that improve product quality, safety, nutrition, and sustainability. Across diverse applications—from carbohydrase-mediated dough optimization and L-asparaginase acrylamide mitigation, to β-galactosidase-driven lactose reduction, beverage clarification, protease-assisted texture improvement, lipase-catalyzed lipid structuring, and phytase-enhanced mineral bioavailability—enzyme use enables precise, predictable outcomes aligned with consumer expectations and regulatory requirements. Immobilization strategies further extend operational efficiency, reduce waste, and support continuous manufacturing models, while multi-enzyme systems and digital process monitoring point toward integrated, adaptive production lines. Importantly, the scalability and cost-effectiveness of these biocatalysts allow their adoption without prohibitive capital investment, making them accessible to both large-scale and emerging producers. Ethical considerations, including transparent labeling, avoidance of deceptive textural modification, and responsible health-related claims, remain central to maintaining consumer trust. As research continues to yield more robust, substrate-specific, and sustainable enzyme solutions, their role in shaping the future of food processing will only strengthen, bridging innovation with environmental responsibility and market competitiveness.

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الأدوار التحفيزية للأنزيمات في معالجة وحفظ الأغذية الحديثة (مقالة مراجعة).

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الخلاصة

تدرس هذه المراجعة التطبيقات المتنوعة للإنزيمات في التكنولوجيا الحيوية الغذائية الحديثة، مع التركيز على دورها في تحسين الجودة والسلامة والوظائف والاستدامة في قطاعات متعددة. تُحسّن الكربوهيدرات ريولوجيا العجين، واحتباس الغازات، والقيمة الغذائية في منتجات المخابز. يُخفف الأسباراجيناز من تكوين الأكريلاميد في الأطعمة المُعالجة حرارياً، بينما يدعم بيتا غالاكتوزيداز تحلل اللاكتوز وإنتاج الغالاكتو-أوليجوساكاريد في أنظمة الألبان. في المشروبات، تُعزز البكتينازات والإنزيمات المساعدة التصفية والثبات وكفاءة الترشيح. تُطيل إنزيمات الأكسدة والاختزال، مثل أوكسيديز الجلوكوز واللاكتوبروكسيديز، مدة الصلاحية من خلال إدارة الأكسجين والتحكم الميكروبي. تُحسّن البروتيازات الطراوة والهلام في اللحوم والمأكولات البحرية، وتُمكّن الليبازات من هيكلة الدهون الخالية من الدهون المتحولة عبر التفاعلات الأسترية. يُعزز الفايتاز التوافر الحيوي للمعادن، ويُحسّن الترانسجلوتاميناز هيكلة البروتين في المصفوفات الحيوانية والنباتية. تُمكّن التطورات في مجال تثبيت الإنزيمات من المعالجة المستمرة، وتقليل النفايات، ودعم التصنيع المستدام ذي العلامة النظيفة. وتوفر هذه الاستراتيجيات الحيوية التحفيزية، مجتمعةً، الدقة والكفاءة والقدرة على التكيف، مما يُوائِم الابتكار التكنولوجي مع الأهداف الغذائية والبيئية في صناعة الأغذية العالمية.

الكلمات المفتاحية: الإنزيمات؛ التكنولوجيا الحيوية الغذائية؛ البروتياز؛ تثبيت الإنزيمات؛ الاستدامة.