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Recombinant enzymes in the food industry: A new era of innovation (Review article)

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Abstract

The food industry is undergoing a transformative paradigm shift with the integration of recombinant enzymes, ushering in a new era of innovation. This review article comprehensively explores the recent advancements and applications of recombinant enzymes in various facets of the food industry. The utilization of genetic engineering techniques has enabled the development of tailor-made enzymes with enhanced functionalities, stability, and specificity, thereby revolutionizing traditional food processing methods.

The review delves into the diverse roles of recombinant enzymes in improving food quality, safety, and sustainability. Emphasis is placed on their application in the modification of texture, flavor, and nutritional content of food products. Furthermore, the article investigates the role of recombinant enzymes in streamlining industrial processes such as fermentation, brewing, and baking, leading to increased efficiency and reduced production costs.

The safety and regulatory aspects of incorporating recombinant enzymes in food processing are thoroughly examined, providing insights into the challenges and opportunities associated with their widespread adoption. Additionally, the review discusses the environmental impact of recombinant enzyme technologies, highlighting their potential to contribute to sustainable practices in the food industry.

As recombinant enzymes continue to redefine the boundaries of innovation in the food sector, this review aims to serve as a comprehensive resource for researchers, industry professionals, and policymakers alike. By synthesizing current knowledge and emerging trends, it provides a holistic understanding of the transformative impact of recombinant enzymes on the food industry and offers valuable perspectives for future research directions and industrial applications.

Keywords: Recombinant enzyme, food industry, food quality, food safety

Introduction

All living things contain enzymes, which are vital for survival. Daily consumption of them includes both processed and fresh meals. Rennin (chymosin) has been extracted from the stomachs of calves since 1874 and used to make cheese. Since then, enzymes have been created for the processing of food. Recombinant deoxyribonucleic acid (rDNA) techniques have been used to incorporate the bovine pro chymosin gene into bacteria [4]. Bovine chymosin generated in Escherichia coli K-12 was the first recombinant enzyme approved for use in food by the FDA [3, 2]. Natural food enzymes frequently have limits under complex and demanding food processing circumstances. The enzymological properties of genetically modified enzymes are intended to be improved or altered, and/or purity and yield of expression may be increased. These changes can be attributed to the altered amino acid sequence that results from altering the gene sequence. This article examines the fundamental methods for creating genetically altered enzymes, including carbohydrates, proteases, lipases, and others, as well as their current and potential applications in food processing. Recombinant proteins provide difficulties and safety issues when used in food processing, however genetically modified enzymes hold promise due to possible advantages for the food business, consumers, and the environment. Endogenous enzymes derived from plants, animals, and microbes continue to be the market's main source for non-genetically modified enzymes. Modern food processing is often intricate and exact, and it occasionally necessitates the use of solvents and extreme temperatures, pressures, pHs, and salinities. However, native enzymes frequently contain flaws that must be fixed to accommodate particular food processing settings. By rationally enhancing enzyme properties such as purity, yield, specificity, catalytic efficiency, stability, surface property, and multifunctionality, genetic modification intends to enable cost-effective production and sustainable food processing development [1]

Recombinant Enzymes in the Food Industry

Enzyme preparations in the food industry must undergo premarket approval by the FDA, unless they are designated as GRAS by qualified experts. Manufacturers can self-affirm or notify the FDA's determination of GRAS status. The determination should evaluate host strain, genetic material, and modifications used. Recombinant enzymes designated as GRAS have been released, with many promising future applications in the food industry [5]. The following are some applications for recombinant enzymes in the food industry

1. Dairy Industry

Urbanization drives increased demand for processed dairy foods, including cheese varieties and low-lactose milk, due to lactose intolerance. For improving the quality of milk and milk products, a number of different enzymes are used.

1.1 Chymosin (Rennet)

Chymosin is an enzyme traditionally obtained from the stomach lining of calves. However, recombinant chymosin, also known as recombinant rennet, is now widely used in cheese production. It is produced by genetically modified microorganisms, such as bacteria or yeast, and has the same coagulating properties as animal-derived chymosin. Recombinant chymosin offers several advantages, including consistent enzyme activity, reduced environmental impact, and cost-effectiveness [26]. Due to their reduced cost when compared to calf chymosin, the market for aspartic proteases extracted from *Mucor spp.* has also grown. Regarding recombinant enzymes, a *Rhizomucor miehei* aspartic pro- tease from *A. oryzae* has been produced and sold under the brand name Novoren (Novo Nordisk). However, since the early 1980s, a significant amount of engineering research has concentrated on the recombinant expression of calf chymosin in microbial hosts, such as the yeast of the enzyme, due to the development of off-flavors and a bitter taste associated with the use of microbial chymosin and the short age of calf stomach. The three-dimensional structure of a similar enzyme that has a high degree of sequence homology with the target enzyme can be used to create a structural model of the target enzyme in the absence of structural information. The most effective and popular method for precisely replacing a particular amino acid with an amino acid's residue is site-directed mutagenesis [2, 6].

1.2 Proteases

Protein-degrading enzymes are known as proteases. Recombinant proteases are employed in the dairy sector to speed up the ripening and flavor development of cheese. They make it easier for complicated proteins to break down into simpler peptides and amino acids, which helps give cheese its distinctive flavor and texture.

Proteases and peptidases contribute to the production of volatile compounds and the quickening of cheese ripening. Proteolysis is primarily catalysed by the remaining coagulant enzymes contained in the curd, milk proteases, lactic bacteria, and other starters added during cheese production. Moreover, externally administered noncoagulant proteases may also be utilised because the cheese ripening process takes a lengthy time. These industrial enzymes are typically produced from native enzymes found in lactic acid bacteria [8], Bacillus species [7, 9] and Aspergillus species. Recombinant lactic acid bacteria strains that overexpress one or more proteolytic enzymes have also been created, nevertheless [5].

1.3 Lactase

The enzyme lactase converts lactose, the sugar found in milk, into glucose and galactose. Lactose-free or low-lactose dairy products, like lactose-free milk and yoghurt, are made using recombinant lactase. This makes it possible for people who are lactose intolerant to consume dairy products without feeling ill.

The dairy industry successfully uses lactase's hydrolytic action to lower the lactose content of milk and its derivatives. The yeasts *Kluyveromyces fragilis* and *K. lactis* are used to extract lactases for commercial use.

However, because fungal strains recovered from nature typically express lactase at low levels, a number of lactases have been created by recombinant methods. *A. oryzae* lactase expressed in *A. nige*r (DSM, GRAS Notice No. 510, 2014) and *Bifidobacterium bifidum* lactase expressed in *B. licheniformis* (Novozymes, GRAS Notice No. 572, 2015) are two specific recombinant lactases that have been granted GRAS certification. In *S. cerevisiae* or *K. lactis*, numerous other lactases from *A. niger* and *K. lactis* have also been expressed.

Additionally, thermostable lactases that might be employed during pasteurisation have been found using a metagenomic method, which eliminates the need to add additional enzymes after pasteurisation.

Thermophilic bacteria *Bacillus stearothermophilus* and *Alicyclobacillus acidocaldarius*, hyperthermophilic archeon *Pyrococcus furiosus*, and a metagenomic library from soil samples were used to isolate lactases with an optimal activity between 70°C and 100°C. Alternately, it has recently been suggested that lactose hydrolysis should be carried out at chilled temperatures to preserve nutrients and flavour. *Planococcus sp*-L4's cold active lactase was extracted and recombinantly expressed in *P. pastoris*. The enzyme has the potential to catalyse the breakdown of lactose at low temperatures and can be rendered inactive by pasteurisation because it

was discovered to be active between 0°C and 55°C and inactive above 60°C [5].

1.4 Lipases

The enzymes known as lipases are responsible for converting lipids into fatty acids and glycerol. In order to produce flavour, lipolysis is desired for making specialty cheeses, which is why they are utilized. It is possible to regulate and improve the lipolysis process while cheese ageing by using recombinant lipases.

In the dairy industry, lipases are typically utilised to selectively hydrolyze milkfat triacylglycerols during the ripening of cheese [12]. Although various microbial lipases have also been utilised successfully, they are primarily derived from a bovine or porcine pancreas or from pregastric tissues of juvenile ruminants. In particular, the dairy sector uses a lipase from *R. miehei* that was recombinantly expressed in *A. oryzae* under the brand name Palatase M (Novozymes) to enhance the flavour of cheese. A lipase (Est_p6) that was discovered in a metagenomic library of marine sediments from the South China Sea was also expressed in *E. coli* and used to effectively hydrolyze milkfat and give milk products a distinct and enticing flavour [10].

Due to the partial hydrolysis of milk phospholipids, the usage of phospholipases in the dairy sector is associated with an increase in cheese yield. Majority of commercial phospholipases come from microbial sources. Particularly, the *Fusarium venenatum* phospholipases A1 from recombinantly expressed in *A. oryzae* is commercially available under the trade name Novozym 46016 [11, 5].

1.5 Transglutaminase

The use of transglutaminase (TGase) up to 0.5% has been found to improve the functional properties of yogurt made from goat milk. Enzymatic cross-linking enhances gel consistency and reduces whey separation. However, no significant differences were observed between enzyme-treated and control samples [13]. Stirred yogurt was prepared through covalent cross-linking, and no adverse effects were observed. TGase reduced syneresis and increased viscosity of yogurt [14].

However, a concentration of 0.3 g L-1 was found to be optimal for fat- free yogurt production. TGase was found to be more effective in developing physical properties when whey was added to yogurt. The addition of TGase did not significantly change the chemical characteristics of yogurt, but after pasteurization, it enhanced gel stability and reduced syneresis [25].

1.6 Other related dairy enzymes

Dairy food applications involve the use of enzymes like protease and lipase to reduce allergic properties of bovine milk products and improve flavor in cheese. Caesins, which are acid-soluble, are suitable for beverages and acidy foods due to their limited proteolysis [15].

Microbial proteases are valuable due to their easy availability, use, and recovery. Lipolysis plays a significant role in the flavor of Swiss cheese, with the peppery flavor of blue cheese produced by short-chain unsaturated fats and methyl ketones. Microbial lipases are used in industries like Amano, Gis-Brocades, and Novozymes [16, 17].

Medium-aged cheeses are emulsified, homogenized, and pasteurized to produce enzyme-modified cheese (EMC), which provides 'palatase'.

EMC technology has been developed to deliver various cheese flavors and intensities in Blue, Cheddar, Swiss, Romano, and Provolo-Nemor. Exogenous enzymes have been successful in increasing aging, but their widespread use has been limited due to high costs and challenges in uniform curd and over-ripening. Minor enzymes with limited application in dairy processes include sulphydryl oxidase, lactoperoxidase, glucose oxidase, catalase, lysozyme, and superoxide dismutase. These enzymes are essential for better dairy production and the future of dairy technology [25].

2. Baking Industry

In order to enhance the texture and appearance of bread, with appetizing flavour and aroma, enzymes such as α-amylases, lipases, xylanases, and oxidoreductases can be used individually or in combinations.

2.1 α-amylase

α-Amylases are endoenzymes that break down α-1,4-glycosidic bonds in amylose or amylopectin chains, producing oligosaccharides and α-limit dextrins. They can be found in cereal, fungal, bacterial, and biotechnologically altered bacterial sources. The number of binding sites and catalytic regions determine substrate specificity, oligosaccharide fragment length, and carbohydrate profile. Different forms of α- amylases have different thermal stability profiles. Maltogenic α-amylase and other maltooligosaccharide-forming amylases are part of the GH13 family, while debranching enzymes like pullulanase and isoamylase hydrolyze α-(1,6)-bonds, removing side-chains from amylopectin [18, 19, 20].

2.2 Lipases

Lipases are enzymes that hydrolyze triacylglycerols (TAG) to produce monoacylglycerols (MAG), diacylglycerols (DAG), glycerol, and free fatty acids. They are present in all cereal grains but are usually low enough to avoid rancidity due to hydrolysis of native lipids and baking fat. The use of lipases in baking is more recent than α-amylases and proteases. The first generation of commercial lipase preparations was introduced in 1990, and a third generation was recently available. These enzymes are protein engineered and have lower affinity for short chain fatty acids, reducing the risk of off-flavour formation.

The first generation is 1,3-specific, removing fatty acids from positions 1 and 3 in TAG, improving dough rheology, strength, and stability [21]. The second generation acts simultaneously on TAG, diacylgalactolipids, and phospholipids, producing more polar lipids, increasing volume, stability, and a fine, uniform bread crumb structure. Lipases may also be used for the development of specific flavors in bakery products.

third generation lipase has been evaluated for its beneficial effects on high-fibre enriched brewer's spentgrain breads, positively affecting loaf volume, staling rate, and crumb structure [18].

2.3 Xylanases

Xylanases, also known as endoxylanases, are enzymes found in various microorganisms, including bacteria, archaea, and fungi. They are mainly classified in glycosyl hydrolase (GH) families 10 and 11, with GH10 xylanases having broader substrate specificity and shorter fragments [22]. Different endogenous xylanase inhibitors exist in cereals, such as Triticum aestivum L. xylanase inhibitor (TAXI), xylanase inhibitor proteins (XIP-type inhibitors) [23], and TLXI-type (thauma-tin-like endoxylanase inhibitors) [24]. Xylanases are used in baking to improve the rheological properties and organoleptic properties of dough and bread. The most favorable xylanases for breadmaking are those that preferentially act on WU-AX and are poorly active on WE-AX. This results in more stable, flexible, and easy-to-handle dough, improved oven spring, larger loaf volume, and a softer crumb with improved structure. The addition of xylanases during dough processing is expected to increase the concentration of arabinoxylo-oligosaccharides in bread, which have beneficial effects on human health [18].

2.4 Oxidoreductases

Glucose oxidases are essential enzymes in breadmaking, converting glucose into hydrogen peroxide and gluconic acid. This process creates stronger, drier, and more elastic dough. Common glucose oxidases include native enzymes from *A. niger* and *Penicillium chrysogenum*, as well as recombinant ones like Gluzyme Mono BG (Novozymes). Recent studies have shown successful expression of glucose oxidase from A. niger in yeast hosts like *Yarrowia lipolytica* and *P. pastoris.* Site- directed mutagenesis has also been used to modify the enzyme's FAD- and substrate-binding sites, resulting in a strong catalytic capacity and stability [18].

2.5 Other enzymes

Asparaginase, a enzyme found in living organisms, has potential for use in bakery products by reducing the formation of acrylamide during baking. It catalyzes the hydrolysis of asparagine to aspartic acid and ammonium, removing the precursor of acrylamide formation.

Acrylamide, a probable human carcinogen, forms in heated foods via Maillard reaction between asparagine and a carbonyl source.

Transglutaminases from microbial sources can modify food proteins, resulting in textured products, protecting lysine from chemical reactions, encapsulating lipids, forming heat and water-resistant films, improving elasticity and water-holding capacity, modifying solubility and functional properties, and producing higher nutritive food proteins.

Laccase, a copper-containing enzyme, catalyzes the oxidation of phenolic compounds via one-electron removal, generating reactive phenolic radicals. It can improve crumb structure, softness, strength, stability, and reduced stickness of dough, improving machinability [18].

3. Beverage Industry

3.1 Fruit juices

The fruit juice industry relies on two main groups of enzymes: pectinases and amylases. Amylases are crucial biotechnologically for various industries, such as textiles, pulp and paper, leather, detergents, beer, spirits, bread production, cereals, starch liquefaction, saccharification, animal feed, and chemical pharmaceuticals. Since 1970, the juice industry has processed large quantities of unripe fruits, causing turbidity and gelatinise during processing. The demand for amylolytic enzymes, particularly glucoamylase, has increased in the sector. Pectinases, which account for around 20% of the worldwide enzyme market, are responsible for the degradation of long, complex molecules called pectin.

They are classified into three groups based on their hydrolytic or trans eliminative cleavage of glycosidic bonds, endo or exo mechanism of action, and preference for substrates like pectic acid or pectin. Other enzymes, such as hemicellulases and cellulase, are used to optimize fruit juice production, acting on soluble pectin hydrolysis and cell wall components. Enzymatic liquefaction technology degrades cell wall polysaccharides, releasing soluble compounds like D-galacturonic acid and neutral sugars. In pulp liquefaction, pectin and cellulose hydrolysis occur due to the activity of polygalacturonases, pectin lyases, pectinesterases, and cellulases, releasing neutral sugars like D-arabinose, D-galactose, L-rhamnose, and D-xylose [28].

The preparation of fruit juice is complicated by turbidity and viscosity caused by pectins and hemicellulose, which are mostly represented by xylans. Pectolytic enzymes can aid in resolving these issues while also enhancing yield and scent release. Pectolytic enzymes that have been isolated from Aspergillus species are combined in commercial compositions. However, manufacturing various enzyme types independently and then combining them would result in commercial formulations that were better suited to each use. Different hosts have successfully generated recombinant pectolytic enzymes like pectate lyases, pectin methylesterases, xylanases, and polygalacturonases.

Bifunctional pectolytic enzymes have been discovered, including one with pectin methylesterase and pectate lyase activities in *Bacillus KSM- P358* and one with polygalacturonase and pectin methylesterase and activity in *Penicillium oxalicum* [27].

3.2 Beer

In the process of brewing, pectins, xylans, and beta-glucans must be clarified and filtered. Pectolytic and glucanolytic enzyme activity can be found in commercial brewing enzyme preparations. Research has been done to find xylanases and glucanases that can withstand high temperatures. By expressing the xylanase gene from *Talaromyces leycettanus*, a thermotolerant species, in *T. reesei*, a GRAS xylanase enzyme preparation has been created Alternative methods for creating recombinant brewer's yeast strains that express -glucanase genes from barley, *B. subtilis, and T. reese*i include genetic engineering techniques. These strains make the brewing mash less viscous and improve filterability, pointing to brewing as a possible use for them. A crucial enzyme in the creation of low-calorie light beer is glucosemylase. Brewer's yeast strains that have undergone genetic manipulation to exhibit amylolytic activity have been created; these strains have a higher capacity to metabolise saccharides and contain fewer calories [5].

3.3 Wine

Recombinant wine yeast strains that express the right levels of pectinolytic and/or glucanolytic enzymes can be advantageous for winemaking. Several enzymes, including *Fusarium solani* pectate lyase,

S. cerevisiae endopolygalactic lacturonase, *Erwinia chrysanthemi* pectate lyase, and *Butyrivibrio fibrisolvens* endo--1,4-glucanase, have been expressed to create these strains. These strains can also extract bound aromatic precursors that are vulnerable to degradation by commercially available enzymes or glycosidases generated by yeasts during fermentation. In comparison to control wines, wines made employing these recombinant strains as starters had higher levels of aromatic components and more floral and fruity scents.

Recombinant wine yeast strains that overexpress glucose oxidase, glycerol-3-phosphate dehydrogenase, and NADH oxidase have also been created for the production of low-alcohol wine. These strains frequently accumulate undesirable sensory-important metabolites, surpassing allowed amounts for wine products, which poses a serious issue for the composition of final wines [18].

3.3.1 Pectinases

Pectin is broken down by pectinase (polygalacturonase), which randomly hydrolyzes the (1-4)-D-galactosiduronic links in pectate and other galacturonans. Pectin is not a single chemical, unlike the majority of polysaccharides. A large family of soluble heterogenous polysaccharides is referred to as pectins. They are a component of the basic cell walls. In the middle lamella, where they help to glue the cells together, pectins are also present between the cells. Pectinase, which is mostly used on red grape types, works by dissolving the red grape skins' cell walls and releasing anthocyanins (the red pigment found in red grapes) and tannin. By enabling the anthocyanins to link with tannin and the wine's structure, this serves to enhance the wine's overall colour intensity and colour stability [7].

3.3.2 Cellulase

In the presence of cellulase, cellulose decomposes into either simple glucose or glucose-disaccharide. A polysaccharide of glucose is cellulose. The enzyme hemicellulose degrades hemicellulose [7].

Polysaccharides known as hemicelluloses are made up of a variety of simple sugar monomers, including as glucose, xylose, arabinose, galactose, mannose, and rhamnose. Compared to cellulose chains (7,000–15,000 sugar units), hemicellulose chains (500–3,000 sugar units) are significantly shorter [7].

3.3.3 Other enzymes

Glucanase breaks down α-glucans, such as dextran, glycogen, and starch, while glycosidases attack glycosidic bonds in carbohydrates, glycoproteins, and glycolipids. These enzymes can produce wine with more intense aromatics in a shorter time, compared to acid hydrolysis, which releases bound aromatics at a slower rate. β-glucosidase cleaves β-D-glucosides, while terpenes are released by rhamnosidase, apiosidase, and arabinofuranosidase [7].

4. Meat Industry

The meat industry uses enzymes for meat tenderization, aroma development, and cross-linking. Commercial proteases are extracted from plant sources like bromelain, papain, and ficin, or microbial sources like *B. subtilis* [31] and *A. oryzae*. subtilisin YaB, produced extracellularly by Bacillus YaB, is promising as a meat tenderizer due to its high specificity for alanine residues in connective tissue proteins.

Engineering approaches have been applied to improve the enzyme's catalytic properties. Site-directed mutagenesis and an artificial promoter sequence were designed to enhance the enzyme's extracellular production [29, 30]. The engineered enzyme has higher specificity for connective tissue proteins and optimal activity in the temperature range of 10-50°C, suggesting potential use at refrigeration and room temperatures. Recently, a GRAS notification was submitted for the use of subtilisin from *B. amyloliquefaciens* produced in *B.subtilis.* The protease EPg222, produced by *P. chrysogenum* from dry-cured hams, has been expressed in *P. pastoris*, delivering commercially viable quantities of the enzyme and exhibiting similar activity against myofibrillar proteins under dry-cured meat product conditions.

Transglutaminase is a protein cross-linking enzyme used in the meat industry to enhance texture, flavor, and shelf-life of meat products.

Streptomyces spp. produces high yields, making strains like Streptomyces mobaraensis suitable for industrial production. Studies have developed efficient heterologous systems for high-yield production, and engineering approaches have been applied to generate new, improved variants. For instance, deletion of amino acids in the N-terminus and Glu5Asp substitutions have led to enzyme variants with 1.85-fold higher specific activity compared to the wild-type enzyme.

Linker peptide additions have also resulted in higher specific activity. Ser199Ala substitutions and random mutagenesis have identified thermostable and heat-sensitive variants, potentially useful for various meat industry applications [5].

5. Sweetener Production

Recombinant enzymes are essential in the production of various sweeteners to improve efficiency and enhance the process. Examples include glucose isomerase, invertase, α-amylase, xylanase, and stevia biosynthesis enzymes. Glucose isomerase converts glucose into fructose, while invertase hydrolyzes sucrose into glucose and fructose.

Recombinant invertase enzymes are engineered to improve activity, stability, and specificity. α-amylase breaks down starch into smaller sugar molecules, while xylanase hydrolyzes xylan, releasing xylose for xylitol production. Stevia biosynthesis enzymes enhance the production of sweet compounds like steviol glycosides. The specific enzymes used in sweetener production may vary depending on the desired sweetener and the production method used by different manufacturers.

Recombinant enzyme technology optimizes enzyme properties to improve efficiency and cost-effectiveness in sweetener production processes [5].

6. Emulsifiers

Emulsifiers can be endogenously produced or externally added to processed foods. Lysolecithin, an endogenous emulsifier, is produced from egg yolk hydrolysis with phospholipases, which can be used in mayonnaise and sauce processing. Commercial porcine pancreas phospholipases A2 are commonly used. However, enzymes from microbial sources have gained popularity, with the gene encoding phospholipase A2 from pig pancreas being expressed in A. niger, and a recombinant enzyme called Maxapal A2 (DSM) commercialized. Other recombinant enzymes have been obtained from Streptomyces violaceoruber and *T. reesei*.

Mono- and diacylglycerols and sugar esters make up majority of the list of emulsifiers that are applied externally. By esterifying glycerol with free fatty acids, which lipases prefer over other partial glycerides, mono- and diacylglycerols are created. When oleic acid was used as an acyl donor, a recombinant mono- and diacylglycerol lipase from *Penicillium cyclopium* [32] was found to be more effective for the synthesis of mono- and diacylglycerols than the commercial Lipase G, suggesting its potential for food emulsifier preparation. By es-terifying a sugar with free fatty acids, which is catalysed by lipase, sugar esters are created [33]. The commercial enzyme Novozym 435, a Candida antarctica immobilised lipase expressed in *A. niger*, has been utilised to successfully make sugar esters. *P. pastoris* has also been found to express and display *C. antarctica* lipase, and the whole-cell system has successfully been employed as a biocatalyst for the synthesis of both glucose and fructose laurates [34, 35].

Conclusion

Recombinant enzymes have revolutionized the food industry by offering numerous benefits and applications. These genetically engineered enzymes, derived from microorganisms or other sources, enhance functionality and specificity in various food-related processes. They improve efficiency and quality of food production by tailoring functions, reducing production time, and enhancing product quality. Recombinant enzymes also offer cost-effectiveness and sustainability, replacing traditional methods and making them economically viable for industrial- scale food production. They have expanded the range of food products available to consumers, enabling the development of new formulations, dietary alternatives, and improved versions of existing products.

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