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Application of Biotechnology in the Dairy Industry: A Review

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Abstract:

Biotechnology has become an important tool in the dairy industry by improving milk production, product quality, processing efficiency, and environmental sustainability. It has enabled the development of advanced starter cultures, microbial enzymes, probiotics, and genetically modified microorganisms that enhance the production of cheese, yogurt, fermented milk products, and other value-added dairy foods. Biotechnological approaches such as accelerated cheese ripening, designer milk production, and the development of functional dairy products have improved nutritional quality, shelf life, and consumer health benefits. In addition, biotechnology plays a significant role in the effective utilization of whey and dairy waste by converting them into valuable products, thereby reducing environmental pollution. Recent research has also demonstrated the potential of probiotic and prebiotic dairy products in improving human health and supporting specialized nutrition. Despite these advancements, challenges such as high production costs, biosafety concerns, ethical issues, regulatory requirements, and consumer acceptance continue to limit large-scale adoption. Overall, biotechnology offers tremendous opportunities for developing innovative, safe, and sustainable dairy products while supporting the future growth of the dairy industry.

Keywords: Biotechnology, Dairy Industry, Probiotics, Dairy Enzymes, Functional Dairy Products, Designer Milk, Whey Utilization, Sustainability.

1. Introduction

The dairy industry plays a vital role in global agriculture by providing nutritious foods, supporting rural livelihoods, and contributing to national economies. Increasing demand for safe, nutritious, and value-added dairy products has encouraged the adoption of advanced technologies, particularly biotechnology. Advances in microbial biotechnology, genetic engineering, molecular biology, enzyme technology, and fermentation have created opportunities to improve milk production, animal health, product quality, processing efficiency, and resource utilization (Nikbalkar *et al.*, 2021).

Recent technological developments have improved dairy farming and processing through precision dairy farming, automated milking, herd monitoring, and advanced preservation techniques such as high-pressure processing, pulsed electric fields, microfiltration, UV treatment, and microwave processing. These technologies help improve product quality, extend shelf life, reduce microbial contamination, and enhance processing efficiency (Gebeyeh *et al.*, 2023).
Biotechnology has further contributed to dairy production through recombinant enzymes, genetically improved starter cultures, probiotics, bacteriocins, vaccines, molecular diagnostics, and functional dairy products. These applications improve nutritional quality, sensory characteristics, safety, and shelf life. Microbial biotechnology, particularly the use of *Lactobacillus*, *Bifidobacterium*, *Streptococcus*, and *Saccharomyces*, plays an important role in fermented dairy products by enhancing flavor, texture, nutritional value, and probiotic benefits**.** Bacteriocins produced by lactic acid bacteria also act as natural antimicrobials, improving food safety and extending product shelf life.

2. What is Biotechnology?

The term **biotechnology** literally refers to the study and application of tools and techniques derived from living organisms. It is derived from the Greek words **"bios"** meaning *life*, **"teuchos"** meaning *tool*, and **"logos"** meaning *study*. Biotechnology can be defined as "any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use."

3. Scope of Biotechnology in the Dairy Industry

Biotechnology combines molecular biology, microbiology, biochemistry, genetic engineering, and bioinformatics to develop innovative products and processes. In the dairy industry, it improves milk production, animal health, product quality, food safety, processing efficiency, and waste management**.** Advances in genetic engineering and microbial biotechnology have enabled the use of microorganisms such as *E. coli*, *Kluyveromyces lactis*, *K. marxianus*, *Aspergillus niger*, *A. oryzae*, and *Mucor miehei* for the production of industrial enzymes and metabolites (Enitan-Folami and Swalaha, 2020).

Table 1. Enzymes Produced by Genetically Modified Microorganisms for the Dairy Industry

Enzyme	**Microorganism**	**Major Application**
Phytase	*Aspergillus niger*	Dairy animal feed
Lipase	*Aspergillus oryzae*	Cheese flavor development and Cheddar cheese production
Chymosin	*Escherichia coli* K-12	Cheese manufacture
Microbial rennet	*Mucor miehei*	Cheese manufacture and milk coagulation
Protease	*Aspergillus usamii*	Milk coagulation, brewing, meat tenderization, and bread quality improvement
β-Galactosidase (Lactase)	Lactic acid bacteria (LAB)	Production of lactose-free dairy products and prebiotic food ingredients

4. Key Areas of Biotechnology Application in the Dairy Industry

Biotechnology has improved the dairy industry by enhancing manufacturing efficiency, product quality, nutritional value, and food safety. Genetic engineering improves starter cultures and industrial microorganisms by increasing metabolic activity, bacteriophage resistance, flavor production, and enzyme synthesis. A major application is the genetic improvement of lactic acid bacteria used in cheese and yogurt production. Enhanced lactose metabolism promotes faster fermentation, while improved proteolytic activity accelerates cheese ripening and flavor development.
Improved citrate metabolism increases the production of diacetyl and acetoin, providing desirable buttery flavors. Bacteriophage-resistant cultures ensure consistent fermentation and reduce production losses. Biotechnology also enables the production of bacteriocins, which inhibit spoilage microorganisms and pathogens and extend shelf life. Recombinant rennet, proteases, and lipases are used in cheese manufacture to accelerate ripening, improve flavor, and reduce production time and cost.

Table 2. Major Areas of Genetic Manipulation in Dairy Biotechnology

Target Area	Major Microorganisms	Industrial Importance
Lactose utilization	*Lactococcus* spp., *Lactobacillus* spp.	Rapid lactic acid production
Proteolytic activity	*Lactococcus* spp., *Lactobacillus* spp.	Enhanced cheese ripening and flavor development
Citrate utilization	*Lactococcus lactis* biovar *diacetylactis*, *Leuconostoc* spp.	Increased flavor production
Bacteriophage resistance	*Lactococcus* spp., *Lactobacillus* spp.	Prevention of fermentation failure
Bacteriocin production	*Lactococcus* spp., *Lactobacillus* spp.	Bio-preservation and food safety
Microbial rennet production	*Aspergillus niger*, *Kluyveromyces lactis*, *Mucor miehei*	Alternative to calf rennet
Proteolytic and lipolytic enzyme production	*Bacillus subtilis*	Accelerated cheese ripening

5. Important Enzymes Used in the Dairy Industry

Enzymes are important biotechnological products used in dairy processing to improve processing efficiency, product quality, flavor, texture, and nutritional value. Recombinant DNA technology has enabled large-scale production of purified microbial enzymes.

1. Chymosin (Rennet)

Chymosin coagulates milk during cheese manufacture by hydrolyzing κ-casein and initiating curd formation. Recombinant chymosin produced using microorganisms is widely used due to its high purity, consistent quality, and reliable coagulation.

2. Lactase (β-Galactosidase)

Lactase hydrolyzes lactose into glucose and galactose, producing lactose-free dairy products. It also improves digestibility, sweetness, and prevents lactose crystallization in products such as ice cream.

3. Catalase

Catalase breaks down hydrogen peroxide into water and oxygen. It is used to remove residual hydrogen peroxide and protect starter cultures during cheese manufacture.

4. Lipases

Lipases hydrolyze milk fat into glycerol and free fatty acids, producing characteristic flavors during cheese ripening. They are especially important in strongly flavored cheeses, although excessive activity may cause rancidity or off-flavors.

5. Gene Probes and Immunological Assays

Gene probes, PCR-based methods, and monoclonal antibody assays are biotechnological tools used for rapid and sensitive detection of foodborne pathogens. They improve microbial quality control, food safety, and disease surveillance in the dairy industry.

6. Biotechnological Approaches in the Dairy Industry

1. Accelerated Cheese Ripening

Cheese ripening is a complex biochemical and microbiological process responsible for the development of the characteristic flavor, aroma, and texture of cheese. Since it may take several months, ripening is one of the most expensive stages of cheese production. The major biochemical changes include glycolysis, proteolysis, and lipolysis, with proteolysis playing an important role in flavor development. Traditional methods, such as increasing ripening temperature or moisture, can shorten ripening time but may cause undesirable flavors and quality defects. Therefore, biotechnological approaches offer better control over the process.

The addition of exogenous enzymes such as β-galactosidase, proteinases, peptidases, and lipases accelerates lactose metabolism, protein breakdown, and fat hydrolysis. Adjunct and attenuated starter cultures also enhance proteolysis and flavor development. Genetically engineered starter cultures with improved enzymatic activity and flavor-forming ability can further reduce ripening time while maintaining cheese quality.

2. Designer Milk

Designer milk refers to milk whose composition has been modified through biotechnology, genetic engineering, selective breeding, or nutritional interventions to improve its nutritional and technological properties. The objective is to produce milk that better meets consumer health needs and enhances dairy processing.

Biotechnological modification of milk aims to increase beneficial unsaturated fatty acids, reduce lactose for lactose-intolerant individuals, and modify milk proteins to improve nutritional quality. From a technological perspective, designer milk can improve casein composition, increase protein content, enhance cheese yield, shorten coagulation time, and support the production of functional dairy products enriched with bioactive compounds and nutraceuticals.

3. Biotechnology in Whey and Dairy Effluent Management

The dairy industry generates large quantities of whey and wastewater containing lactose, proteins, fats, and minerals, resulting in high biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Instead of treating whey as waste, biotechnology enables its conversion into valuable products while reducing environmental pollution.

Microorganisms such as *Kluyveromyces* spp., *Saccharomyces cerevisiae*, *Lactobacillus helveticus*, and *Lactococcus lactis* are widely used for lactose utilization, β-galactosidase production, bioethanol production, exopolysaccharide (EPS) synthesis, and single-cell protein production. Biotechnology is also applied in wastewater treatment through microbial biosensors, biological fuel cells, heavy metal removal, and immobilized cell technology, contributing to sustainable dairy waste management.

Some of the notable areas of applications of specially designed or genetically manipulated strains of microbes for utilization of whey or disposal of dairy waste in more economical way are summarized below:

1. **BOD Reduction:** *Kluyveromyces* yeasts utilize lactose and produce β-galactosidase, helping reduce lactose and BOD in whey and dairy waste.
2. **Single Cell Protein (SCP):** *Kluyveromyces* species convert whey lactose into microbial biomass, reducing pollution and producing valuable protein.
3. **Bioethanol Production:** Engineered *Saccharomyces cerevisiae* strains can utilize lactose to produce bioethanol from whey**.**
4. **Exopolysaccharides (EPS):** Modified lactic acid bacteria such as *Lactobacillus helveticus* and *Lactococcus lactis* produce EPS used in food formulations**.**
5. **Removal of Toxic Metals:** Bacteria such as *Bacillus licheniformis* produce extracellular polymers that bind and remove metals such as iron, copper, cadmium, and nickel**.**
6. **Biological Fuel Cells:** Microorganisms such as *Rhodoferax ferrireducens* convert biodegradable organic matter into electrical energy.
7. **BOD Sensors:** Immobilized microorganisms such as *Bacillus subtilis* and *Pseudomonas putida* are used in biosensors to measure BOD**.**
8. **Biodegradation of Oil:** Genetically engineered *Pseudomonas putida* can degrade several petroleum compounds, helping in oil-spill treatment.
9. **Immobilized Cell Technology**: Nitrifying bacteria such as *Nitrosomonas* and *Nitrobacter* help reduce ammonia in wastewater by converting it into nitrate.

7. Challenges in Dairy Biotechnology

- **High cost:** Advanced technologies require expensive equipment, laboratories, and skilled professionals.
- **Biosafety concerns:** Strict measures are needed to protect human health, animal health, and the environment.
- **Ethical issues:** Genetic modification and animal cloning raise concerns about animal welfare and food safety.
- **Consumer acceptance:** Consumers may hesitate to accept genetically modified dairy products due to safety concerns.
- **Regulatory requirements:** Strict safety testing and approval processes are often lengthy and expensive.
- **Technical limitations:** Maintaining microbial stability, product quality, and large-scale production can be challenging.
- **Skilled manpower and infrastructure:** Biotechnology requires trained professionals, modern laboratories, and advanced processing facilities.

- **Public awareness:** Limited knowledge may cause misconceptions and resistance toward biotechnology-based dairy products.

Conclusion

Biotechnology has become a key driver of innovation in the dairy industry by improving milk production, product quality, processing efficiency, and environmental sustainability. The application of microbial enzymes, probiotics, genetically modified microorganisms, and advanced fermentation technologies has enhanced the production of cheese, yogurt, functional dairy products, and designer milk. In addition, biotechnological approaches have enabled the efficient utilization of whey and dairy effluents, converting dairy waste into valuable products while reducing environmental pollution.

Overall, biotechnology has significantly contributed to the development of safe, high-quality, and value-added dairy products while supporting sustainable dairy processing. Continued research and technological advancements are expected to further expand its applications, improving resource utilization, food safety, and environmental management. These innovations will play an important role in ensuring the sustainable growth and competitiveness of the dairy industry.

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