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Ohmic Heating: Enhancing Microbial Inactivation and Nutritional Retention in Liquid Dairy Products

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Ohmic heating, also known as Joule heating or electrical resistance heating, is an emerging thermal processing technology that offers uniform and rapid heating of food materials through the application of electric current. In liquid dairy products such as milk, flavored milk, cream, and whey beverages, ohmic heating has demonstrated significant potential in achieving effective microbial inactivation while preserving nutritional and sensory quality. Compared to conventional thermal pasteurization and sterilization methods, ohmic heating reduces processing time, minimizes thermal gradients, and enhances retention of heat-sensitive nutrients. This review discusses the principles of ohmic heating, its mechanisms of microbial inactivation, effects on nutritional components, processing parameters, and industrial applicability in dairy systems. The integration of ohmic heating into modern dairy processing represents a promising strategy for improving product safety, quality, and energy efficiency.

Introduction

Liquid dairy products are highly nutritious but equally susceptible to microbial contamination due to their rich composition of proteins, lactose, fats, vitamins, and minerals. Conventional thermal treatments such as pasteurization and ultra-high temperature (UHT) processing are widely used to ensure microbial safety. However, these methods rely on heat transfer through conduction and convection, which often results in non-uniform temperature distribution, prolonged heating times, and potential degradation of heat-sensitive nutrients. In recent years, the dairy industry has explored alternative processing technologies that improve safety without compromising quality. Ohmic heating has gained considerable attention because it enables rapid and uniform heating throughout the product volume. Instead of transferring heat from an external source, ohmic heating generates heat internally as electric current passes through the food material. This unique mechanism significantly reduces processing time and thermal damage.

Principle of Ohmic Heating

Ohmic heating operates on the principle of electrical resistance. When an alternating electric current is applied across electrodes placed in a conductive food material, the inherent electrical resistance of the product generates heat uniformly within the matrix. The rate of heat generation depends on electrical conductivity, voltage gradient, and product composition. Liquid dairy products such as milk possess adequate ionic content, making them suitable for ohmic processing. The homogeneous nature of milk allows uniform distribution of electric current, reducing the risk of localized overheating. Unlike conventional heating, where heat must travel from the surface inward, ohmic heating ensures simultaneous volumetric heating, leading to faster temperature rise and shorter exposure time.

Mechanisms of Microbial Inactivation

The primary objective of thermal processing in dairy products is microbial safety. Ohmic heating enhances microbial inactivation through both thermal and potential non-thermal mechanisms. The rapid temperature increase achieved during ohmic processing effectively inactivates pathogenic and spoilage microorganisms such as *Escherichia coli*, *Listeria monocytogenes*, *Salmonella* spp., and *Staphylococcus aureus*. The uniform heating minimizes cold spots, which are common in conventional systems and can allow microbial survival. In addition to thermal effects, electric field exposure may contribute to microbial cell membrane disruption. The applied electric current can induce electroporation, increasing cell membrane permeability and leading to leakage of intracellular contents. Although the dominant inactivation mechanism remains thermal, the synergistic effect of electric fields may enhance microbial lethality at comparatively lower temperatures.

Studies have shown that ohmic heating can achieve microbial reduction comparable to pasteurization and UHT processing while reducing overall thermal load.

Nutritional Retention in Liquid Dairy Products

One of the significant advantages of ohmic heating is improved retention of heat-sensitive nutrients. Milk contains essential vitamins such as vitamin C, B-complex vitamins, and bioactive proteins that are susceptible to thermal degradation. Because ohmic heating reduces processing time and limits exposure to high temperatures, it minimizes nutrient loss. Research indicates improved retention of vitamin C and thiamine compared to conventional heating methods. Furthermore, protein denaturation is reduced due to shorter heating duration, preserving functional properties such as solubility and emulsification capacity. Lipid oxidation, which can lead to off-flavors and nutrient loss, is also minimized under controlled ohmic conditions. The reduced thermal gradients prevent excessive localized overheating, thereby protecting sensitive components.

Effects on Physicochemical and Sensory Properties

Beyond safety and nutrition, dairy product quality depends on physicochemical stability and sensory attributes. Ohmic heating maintains desirable color, flavor, and texture in liquid dairy products due to reduced Maillard browning and caramelization reactions. Protein coagulation and sedimentation are minimized because uniform heating prevents localized protein aggregation. In flavored milk and dairy beverages, improved flavor retention has been reported due to lower thermal stress. Additionally, ohmic heating may improve emulsion stability in products containing fat, as rapid heating reduces the time available for phase separation.

Energy Efficiency and Industrial Application

Ohmic heating is considered energy-efficient because electrical energy is directly converted into thermal energy within the product. This reduces heat loss to surrounding equipment and enhances process efficiency. The technology also allows precise control of temperature and processing time, making it suitable for continuous dairy processing systems. Industrial-scale implementation requires careful selection of electrode materials to prevent corrosion and metal ion migration. Stainless steel and inert conductive materials are commonly used to ensure food safety and durability. While initial equipment costs may be higher than conventional systems, long-term benefits include energy savings, improved product quality, and reduced processing time.

Challenges and Future Perspectives

Despite its advantages, several challenges must be addressed before widespread adoption of ohmic heating in the dairy industry. These include optimization of electrical conductivity for different dairy formulations, electrode fouling prevention, regulatory approval, and validation of microbial safety standards. Further research is needed to understand the combined thermal and electrical effects on microbial inactivation kinetics. Additionally, integration of ohmic heating with other emerging technologies such as high-pressure processing or pulsed electric

fields may further enhance safety and quality. Future developments in automation and process control systems will likely improve scalability and commercial feasibility.

Conclusion

Ohmic heating represents a promising alternative to conventional thermal processing in liquid dairy products. By enabling rapid and uniform volumetric heating, it enhances microbial inactivation while preserving nutritional and sensory quality. Improved retention of heat-sensitive vitamins, reduced protein denaturation, and enhanced energy efficiency position ohmic heating as a transformative technology in modern dairy processing. Continued research and industrial optimization will further establish its role in producing safe, high-quality dairy products with minimal nutritional compromise.

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