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Perspective

Beyond Heat: Emerging Technologies for Preserving Food Quality and Safety

Suhail Usman*

Department of Food Technology and Bioprocessing, National Institute of Food Sciences, Norway

DESCRIPTION

Non-Thermal Processing (NTP) refers broadly to food-processing approaches that achieve preservation, extraction, modification, or microbial control without relying primarily on conventional high-temperature treatment. These technologies have become increasingly important because consumers and manufacturers seek foods that retain fresh-like sensory characteristics and heat-sensitive nutritional components

Conventional thermal processing remains essential for many food products, particularly where robust microbial safety is required. However, excessive heat can influence vitamins, pigments, flavors, texture and other quality attributes. Non-thermal approaches attempt to address these limitations through physical mechanisms such as pressure, electrical fields, acoustic energy, or reactive species.

High-Pressure Processing (HPP) is one important NTP. It subjects foods to high hydrostatic pressure and can reduce microbial populations while limiting direct thermal exposure. Pulsed Electric Field (PEF) processing represents another approach. PEF applies short electrical pulses that can create electroporation of microbial cell membranes. Depending on the process conditions, PEF can also facilitate extraction or modification of plant tissues.

Ultrasound is another widely investigated technology. High-intensity ultrasound generates acoustic cavitation, in which microscopic bubbles form, grow and collapse. The resulting mechanical effects can improve mass transfer, extraction, mixing and certain processing operations. Ultrasound-assisted extraction has attracted interest for recovering bioactive compounds from plant materials.

Cold plasma is a further NTP technology. It produces reactive species capable of interacting with microbial cells and surface contaminants. Applications include microbial reduction, surface treatment and potentially modification of food functionality. Research has identified antimicrobial, pesticidal, functionalization and waste-treatment applications for plasma technologies.

NTP technologies are not necessarily interchangeable. Each has distinct mechanisms, equipment requirements, limitations and food applications. HPP is particularly suited to pressure-tolerant foods and packaged products, while PEF is often investigated for liquid or semi-liquid systems. Ultrasound is frequently applied to extraction and mass-transfer operations, whereas cold plasma has strong potential for surface decontamination.

One of the major scientific challenges is process optimization. The intensity and duration of a treatment must be sufficient to achieve the desired effect but not so severe that quality deteriorates. Researchers therefore study relationships between processing parameters and microbial inactivation, nutrient retention, texture, color, flavor and bioactive stability.

Food composition also influences treatment response. Proteins, carbohydrates, lipids, salts and suspended particles can alter the effectiveness of physical treatments. Microorganisms themselves differ in resistance because of differences in cell structure and physiological state.

NTP can also contribute to extraction. Plant tissues contain valuable compounds that may be trapped within cellular structures. Ultrasound, PEF and other physical treatments can increase cell permeability, potentially improving recovery of phenolic compounds, pigments, proteins, or other substances. Recent reviews emphasize the growing interest in non-thermal extraction for reducing damage to nutrients and sensory components.

Combination processing is an important future direction. Rather than depending on a single technology, processors can use multiple mild treatments. This approach, known as hurdle technology, may achieve microbial control with lower intensity from each individual treatment.

Commercial adoption requires more than laboratory effectiveness. Equipment cost, throughput, maintenance, energy consumption, operator safety, process validation and regulatory acceptance must be evaluated. Scale-up can also introduce challenges because physical phenomena observed at laboratory scale may behave differently in industrial equipment.

Correspondence to: Suhail Usman, Department of Food Technology and Bioprocessing, National Institute of Food Sciences, Norway

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Another important area is consumer acceptance. Although "non-thermal" may suggest freshness and nutritional preservation, consumers may have limited understanding of the underlying technologies. Clear communication regarding safety, benefits and processing methods can influence acceptance. The integration of NTP with sensors and computational modeling could further improve process control. Real-time monitoring may allow processors to determine whether a treatment has reached the required endpoint.

CONCLUSION

Non-Thermal Processing therefore represents a broad technological platform rather than one individual method. Its future lies in selecting the appropriate technology for each food matrix and combining physical processing with microbiology, food chemistry, engineering and data science. Properly optimized NTP systems may support safer foods with improved quality retention while reducing dependence on severe thermal treatments. Emerging food preservation technologies are transforming the way safety and quality are maintained. Methods such as high-pressure processing, pulsed electric fields, cold plasma, ultraviolet light and irradiation can reduce harmful microorganisms while minimizing nutrient and sensory losses. These innovative approaches extend shelf life, reduce chemical preservatives and support the production of safer, fresher and higher-quality foods.