High pressure technologies in dairy processing

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With the growing appeal of nonthermal processing techniques in food processing, technologies that utilize high pressure have gained more attention. These technologies can either be described as batch systems (e.g., high hydrostatic pressure) in which single samples are processed at one time, or continuous systems (e.g., high pressure homogenization) in which liquid samples continuously flow through the associated equipment. These processes have numerous applications in dairy manufacturing, and current research is still being conducted to broaden these applications.

High Hydrostatic Pressure (HHP)

HHP, synonymous with high-pressure processing (HPP), is a batch or semi-continuous pressurization technology that can be used on both solid (water containing) and liquid foods (Figure 1). To start, in the typical batch system, packaged food is loaded into a pressure vessel, and the vessel is filled with a pressure medium (typically water). This vessel is then pressurized, typically between 100-1 000 MPa, for a desired time-pressure combination based on the properties of the contained food material. This pressure increase follows the isostatic principle in which transmittance of pressure is uniform and instantaneous. Therefore, these treatments cause pressure-induced changes in every part of the product at the same time. Although this processing technique is considered “nonthermal,” there is a slight adiabatic rise in temperature (*ca.* 2-3°C per 100 MPa) caused by inner friction. When the processing is complete, the pressure relief valve is opened, the system decompresses, and the product is removed. There are several thorough reviews of this technology including Chawla et al. (2011), Ravash et al. (2022), and Voigt et al. (2015).

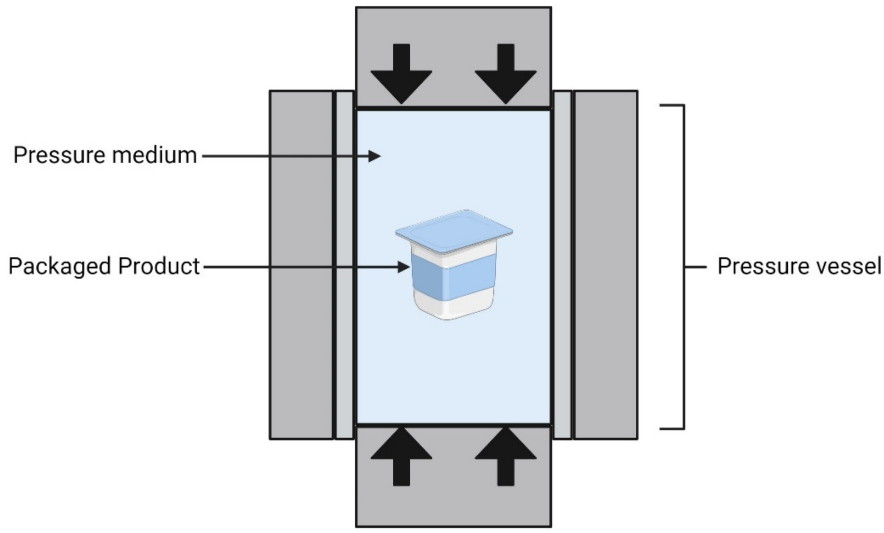

Figure 1. Schematic of batch high hydrostatic pressure (HHP) unit created with BioRender.com.

Applications of high hydrostatic pressure in dairy processing

HHP has primarily been targeted as a means of nonthermal microbial inactivation, enzymatic inactivation, and shelf-life extension. There are studies showing comparable microbial inactivation between typical high-temperature short-time (HTST) pasteurized milk and sufficiently HHP-treated milk (Liu et al., 2020). HHP has been shown to cause microbial inactivation by inducing protein and enzyme denaturation, cell membrane damage, and gas vacuole compression (Voigt et al., 2015). Although microorganisms have varying susceptibility to pressure, the impact of HHP treatment on microbial inactivation can be optimized by varying treatment duration, pressure, temperature, and food environment. A hurdle approach, combining multiple inactivation technologies (e.g., antimicrobials and HHP, temperature and HHP), has shown promising results in dairy systems (Black et al., 2005). There are current HHP-treated dairy products on the market across the world, but regulations in some countries prevent the sale of these products as they are not thermally pasteurized to legal standards.

Other applications of HHP in dairy systems include casein micelle size and functionality manipulation (Ni et al., 2021), whey protein denaturation and functionality enhancement (Huppertz et al., 2004b), milkfat globule size alterations (Huppertz et al., 2003), rennet coagulation and cheese yield improvements (Huppertz et al., 2004a; Stewart et al., 2006), residual rennet activity reduction (Riebel et al., 2024), and dairy product (e.g., yogurt, ice cream) rheological property changes (Harte et al., 2003). All of these applications are highly dependent on processing conditions and product properties.

Ultra-high-pressure homogenization (UHPH)

UHPH involves a pump forcing a liquid sample through narrow valve or orifice under incredibly high pressures (100-400 MPa; Figure 2). The orientation of these nozzles varies based on the equipment, and the size of the nozzles can be adjusted to achieve different pressures (i.e., smaller nozzle = higher achievable pressure). As the fluid sample passes through the nozzle, it transitions from high pressure (high potential energy) to high velocity (high kinetic energy) as the sample returns to atmospheric pressure (unless there is back pressure applied). With this, the sample experiences several physical phenomena including shear, friction, turbulent flow conditions, elongation, and cavitation. Additionally, there is a temperature increase associated with UHPH treatment (*ca.* 14-20°C per 100 MPa; Zamora et al., 2012); however, immediate cooling post-treatment has been shown to minimize the impact of this heating (Blayo et al., 2016). UHPH systems are often highly customizable by allowing for multiple passes, various flow cell orientations, post-treatment cooling, back pressure, and ranging nozzle sizes. Microfluidizers are specific types of high-pressure homogenizers (20-275 MPa) that involve the collision of two or more jet flow streams within a fixed interaction chamber. A thorough review of this technology can be found in Harte (2016) and Tobin et al. (2015).

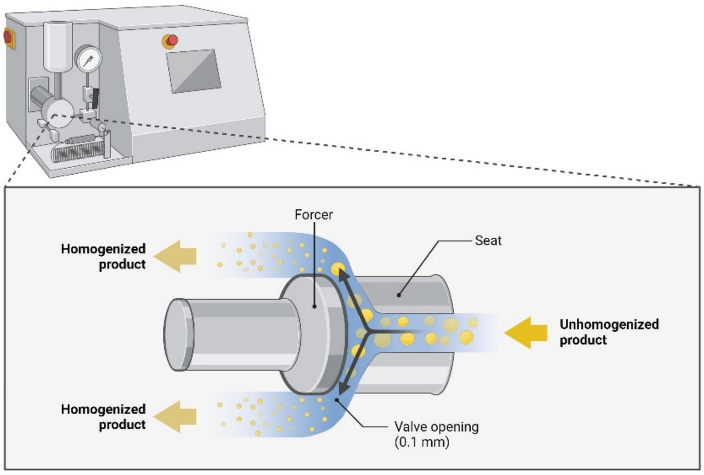

Figure 2. Schematic of ultra-high-pressure homogenization (UHPH) unit reprinted from "Working Principle of High-Pressure Homogenization", by BioRender.com (2024). Retrieved from https://app.biorender.com/biorender-templates.

Applications of ultra-high-pressure homogenization in dairy processing

UHPH has also been thoroughly evaluated for microbial inactivation applications (Bevilacqua et al., 2019). Larger microorganisms and gram-negative bacteria tend to be more susceptible to UHPH treatment, and their inactivation is likely caused by a combination of rapid pressure and velocity fluctuations, turbulence, and cavitation (Diels & Michiels, 2006).

The other physical phenomena (i.e., shear, friction, heat, etc.) caused by UHPH have been shown to cause significant alterations to dairy components, thereby influencing the functionality of dairy systems. Some of these alterations include casein micelle dissociation (Roach & Harte, 2008), whey protein denaturation (temperature and post-cooling dependent, Blayo et al., 2016), milkfat globule size reduction (D[4,3] < 0.5 µm with 200 MPa two-stage UHPH; Tobin et al., 2015, Hayes & Kelly, 2003). All of these dairy system alterations are highly dependent on sample characteristics (e.g., temperature) and processing conditions (e.g., pressure, back pressure). Some applications specific to UHPH processing include textural alterations in ice cream and other dairy products (Innocente et al., 2009), stabilization of cream liqueurs (Heffernan et al., 2009), casein nanocarrier systems (Corzo-Martínez et al., 2015), and stable emulsion formation (de Souza Queirós et al., 2020). Considering this, UHPH has received attention in both the food and pharmaceutical industries, and current investigative research is still ongoing.

The future of high-pressure technologies

With the growing interest in nonthermal, novel processing techniques, high-pressure-related research continues to be conducted and applications for these systems continue to be revealed. Additionally, new high-pressure technologies are being studied. More recently, the application of high-pressure jet (HPJ) technology in dairy systems has been evaluated (Hettiarachchi et al., 2018) and has shown promise in creating clean label, value-added dairy products such as carrageenan-free chocolate milk (Tran et al., 2021) and functionalized milk powders (Voronin et al., 2021). As this work continues, the use of these technologies in commercial dairy products could become more frequent.

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