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Review

# Dairy processing using supercritical carbon dioxide technology: Theoretical fundamentals, quality and safety aspects

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A B S T R A C T

*Background:* Non-thermal food processing is configured as an interesting alternative for the food industry due to the increased nutrient retention and minimal sensory changes in processed products.
*Scope and approach:* The aim of this review is to address the potential of supercritical carbon dioxide technology, emphasizing milk and dairy processing, including the historical aspects, main advantages, microbial inactivation mechanisms, as well as effects in some quality parameters of dairy products.
*Key findings and conclusions:* The use of supercritical carbon dioxide technology (SC-$CO_2$) presents great potential application in dairy processing, since it is effective to reduce microbial load when compared to the pasteurization process, thus obtaining a product with greater shelf life and better organoleptic properties with minimal and sometimes positive changes in the intrinsic quality parameters.


## 1. Introduction

Milk and dairy products have high nutritional value, being consumed worldwide, and considered as healthy choices by consumers, associated with quality of life (North America Milk Market, 2016; FAO, 2016). In fact, it is estimated that the global consumption of dairy products will increase by around 36% by 2024 (Tetra Pak, 2016).

In many countries, raw milk is required to undergo thermal processing so that the milk is safe to consume (Clayes et al., 2013; Yoon, Lee, & Choi, 2016). Thermal treatments are the most common means of ensuring food safety and shelf-life stability of milk and dairy products (Gulsun, 2015). However, it is known that the high temperatures of conventional heat treatments lead to changes in nutritional (for example, degradation of vitamins) and organoleptic characteristics (aroma, flavor and texture) of the processed products (Barba, Zhu, Koubaa, Sant'Ana, & Orlen, 2016).

Recent interest in the consumption of raw milk and raw milk products has led to the consideration of alternative dairy processing technologies that will not compromise milk quality and safety (McAuley, Singh, Haro-Maza, Williams, & Buckow, 2016). Currently, many studies have addressed the emerging non-thermal technologies in food processes to minimize the deleterious effects of thermal conventional process, like, pulsed electric field (Odriozola-Serrano, Aguiló-Aguayo, Soliva-Fortuny, & Martín-Belloso, 2013), ohmic heating (Jaeger et al., 2016), ultraviolet light (Guneser & Yuceer, 2012), pulsed-light technology (Abida, Rayees, & Masoodi, 2014; Miller, Sauer, & Moraru, 2012), ultrasound (Chandrapala & Leong, 2014), cold plasma (Mir, Shah, & Mir, 2016), high hydrostatic pressure (Yang et al., 2012) and ultra-high pressure homogenization (Valsasina et al., 2015).

Supercritical carbon dioxide technology (SC-$CO_2$ technology) utilizes pressure in combination with carbon dioxide to destroy microorganisms without affecting the nutritional content, organoleptic attributes, being a promising alternative for pasteurization of bioactive compounds in food and medicine (Jiménez-Sanchez,

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Lozano-Sanchez, & Fernández-Gutiérrez, 2017) in which compounds would be destroyed by conventional thermal processes (Vigano, Machado, & Martínez, 2015). However, the high cost of the equipment and operation of supercritical systems can be an obstacle to the application of supercritical processes on an industrial scale (Ceni et al., 2016).

Jermann, Koutchma, Margas, Leadley, and Ros-Polski (2015) developed a study involving researchers and CEOs (Chief Executive Officer) of North America, about the trends of utilizing an emerging technology in food process and reported that supercritical carbon dioxide technology has a great commercial potential for the next ten years. Regarding dairy foods processing, SC-$CO_2$ technology would aim to control the raw material and minimize the use of heat treatment to inactivate the bioactive compounds. Also, it would improve economic and technical efficiency focus on value-added processing of milk and dairy products (Maubois, 2011).

Consumers crave for food with better nutritional quality, coupled with food safety and use of green technology (Barba et al., 2016). Therefore, this review aims to discuss the use of SC-$CO_2$ technology as an innovative method of dairy products processing, exploring the historical perspectives on technology, main advantages, limitations, microbial inactivation mechanisms, and relevance of milk matrix issues will be assessed.

## 2. Theoretical and fundamentals aspects

The term "supercritical" refers to a substance in a non-condensing and single-phase fluid when brought above its critical temperature ($T_c$) and critical pressure ($P_c$). Beyond this point, there is a supercritical region where the substance shows some typical physicochemical properties of gases or liquids, such as high density, intermediate diffusivity and low viscosity and surface tension (Table 1) (Cavalcanti & Meireles, 2012).

The application of supercritical fluid is directly related to its physicochemical properties. The high-density values combined with the pressure dependent solvent power provides high solubility and selectivity to the supercritical fluid. In addition, low viscosity values and intermediate values of diffusivity combined with the absence of surface tension of these fluids allow its rapid penetration into the cells and particles of the sample matrix extracting their interior material (Osorio-Tobón, Silva, & Meireles, 2016; Silva & Meireles, 2014). These characteristics facilitate process of extraction and inactivation of vegetative cells.

In some cases, similar effects to the supercritical state can be reached at temperatures near to its critical, the liquid state of a substance, with $P > P_c$ and $T < T_c$ characterizing the subcritical state (Ceni et al., 2016). Subcritical fluids exhibit physicochemical properties similar to supercritical fluids and have been suggesting as a practical advantage, once relatively high densities can be found at moderate pressures guaranteeing similar solvent extracting power. For example, subcritical $CO_2$ density at 20 °C is 0.818 g $cm^{-3}$ at 7.5 MPa, while for supercritical $CO_2$ similar density (0.816 g $cm^{-3}$) only will be achieved at 32 °C and 13.5 MPa (NIST, 2005). This indicates use of subcritical $CO_2$ is highly advantageous in respect to investment cost and thermal degradation once similar solvent power is achieved at more moderated conditions of temperature and pressure.

Various substances in the supercritical state could be used in the food industry, such as ethylene, water, ammonia. However, most of the studies using supercritical fluid technology use carbon dioxide ($CO_2$) as supercritical fluid aiming extraction and processing (Zabot, Moraes, Carvalho, & Meireles, 2015). Carbon dioxide is considered a chemically inert, non-corrosive, non-flammable, non-toxic, cheap, readily available, and GRAS (generally recognized as safe) solvent (Khosravi-Darani, 2010). Also, it can be recirculated into the system making this technology safe and environmentally friendly, due to the fact $CO_2$ can be easily removed from food matrix by pressure reduction, to obtaining a solvent-free product. Furthermore, its low critical temperature (31.04 °C) allows application at near room temperature, which prevents degradation of thermosensitive and volatile compounds, minimizing changes in the physicochemical, sensorial and nutritional characteristics of the food, thus obtaining high quality products. Besides, its moderate critical pressure (7.38 MPa) provides minor energetic and investment costs when compared with other supercritical substances, for example supercritical water (373,95 °C and 22.064 MPa) (Cavalcanti & Meireles, 2012; Cavalcanti, Albuquerque, & Meireles, 2016; Vigano et al., 2015).

Indeed, SC-$CO_2$ technology has many applications in food processing, with relevance in the fractionation, extraction, microencapsulation, pasteurization, sterilization, and chromatograph techniques, among others (Kulkarni, Kar, & Singhal, 2017; Moraes, Zabot, & Meireles, 2015; Osorio-Tobón et al., 2016; Santos & Meireles, 2013; Silva & Meireles, 2014).

## 3. Dairy processing by SC-$CO_2$Technology

### 3.1. General aspects

Generally, fluids in their supercritical state possess various advantages, including higher diffusion coefficient and lower viscosity, absence of surface tension, allowing rapid penetration into the pores of heterogeneous matrices, and simple control of temperature and pressure, which directly affects the solubility of the fluid (Sanli, Bozbag, & Erkey, 2012).

The main difference between high hydrostatic pressure (HHP) and supercritical carbon dioxide technology (SC-$CO_2$) processes applied in microbial and enzymatic inactivation processes is that SC-$CO_2$ technology can be as efficient as HHP but at lower pressures, i.e., much lower processing pressure is employed with supercritical carbon dioxide. Indeed, $CO_2$ pressure applied for preservation purposes is in the range of 10–20 MPa, which is almost two orders of magnitude lower than HHP pressure (50–1000 MPa). This reduces the cost of investment and facilitates the handling of the pressurized $CO_2$ system. Furthermore, use of SC-$CO_2$ improves mass transfer due to higher diffusivity resulting in shorter processing time with consequent preservation of essential food elements, which means minimal degradation of nutritional

**Table 1**
Physical properties of carbon dioxide according to the state of aggregation*.

| Property | Gas 1 atm, 15 - 30 °C | Supercritical Fluid | | Liquid 15 - 30 °C |
|---|---|---|---|---|
| | | $T_c$, $P_c$ | $T_c$, $4P_c$ | |
| Diffusivity, D ($cm^2.s^{-1}$) | 0.1–0.4 | $0.7 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $(0.2–2) \times 10^{-5}$ |
| Viscosity, η ($g.cm^{-1}.s^{-1}$) | $(1–3) \times 10^{-4}$ | $(1–3) \times 10^{-4}$ | $(3–9) X 10^{-4}$ | $(0.2–3) \times 10^{-2}$ |
| Density, ρ ($g.cm^{-3}$) | $(0.6–2) \times 10^{-4}$ | 0.2–0.5 | 0.4–0.9 | 0.6–1.6 |

*Source: Tzia & Liadakis, 2003.