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Non-thermal pasteurization of milk by an innovative energy-saving moderate electrical field equipped with elongated electrodes and process optimization

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ABSTRACT

Environmental concerns and consumer demand necessitate alternative pasteurization techniques that sustainably produce safe and high-quality milk. To this end, a new non-thermal (<42 °C) moderate electric field (MEF) system was developed with elongated electrodes and a reduced electrode gap. Response surface methodology optimized technical and thermo-physical attributes, including viscosity, density, freezing point, solid non-fat (SNF), temperature, power usage, and specific energy consumption (SEC), by altering electrical field intensities (EFI) and mass flow rates ($\dot{m}$) from 25 to 30 V/cm and from 0.017 to 0.033 kg/s, respectively. The results were then compared with the conventional thermal pasteurization (CP, 63 °C for 30 min). Besides, process cost analysis in terms of electricity consumption was performed to identify cost reduction opportunity for the industry, and milk samples were analyzed by scanning electron microscopy to elaborate on the mechanisms involved. MEF optimal processing conditions were 29.8 V/cm EFI and 0.018 kg/s $\dot{m}$, which reduced 98.58% of energy consumption, 98.51% of SEC, and 99.09% of processing time in comparison with CP. Also, MEF possessed higher productivity than CP. D-value for total count bacteria (TCB) in MEF was significantly lower than CP (0.06 *vs.* 14.80 min), and MEF and CP reduced TCB by 99% and 88.61%, respectively. Compared with the previously reported MEF milk pasteurizer, the MEF system developed in this study saved energy, cost, and time by 99.2%, 99.0%, and 78.4%; therefore, this emerging technology could further contribute to sustainable manufacturing of foods.

1. Introduction

Milk contains macro- and micro-nutrients necessary for human health, with a well-balanced composition of protein, fat, lactose, minerals, and vitamins (Liu & Rochfort, 2023). Therefore, dietary guidelines include milk and dairy products as essential sources of daily nutrition in many countries (Cimmino et al., 2023). However, fresh raw milk has a limited shelf-life and could contain spoilage and pathogens from people, animals, soil, air, feed, water, and milking equipment (Al-Hilphy, Abdulstar, & Gavahian, 2021; Martin, Evanowski, & Wiedmann, 2023); Therefore, it should be pasteurized.

The conventional milk pasteurization approach is based on a batch thermal process (e.g., 63 °C for 30 min) followed by refrigeration to assure safety and extend shelf-life (Lott, Wiedmann, & Martin, 2023). Such a harch heating process can change milk flavor, composition, and other characteristics unpleasantly (Yang et al., 2018); therefore, it cannot meet the expectation of 21st Century's customers who are looking for safe, healthy, and minimally processed food with "fresh-like" flavor and taste. These market needs have triggered fierce competition in the food industry to create alternative processing methods (Al-Hilphy, Abdulstar, & Gavahian, 2021; Liu et al., 2020). At the same time, those emerging technologies are expected to consider sustainability and environmental concerns as specified in guidelines for sustainable development goals by United Nations. Machado, Pereira, Martins, Teixeira, and Vicente (2010) used MEF to inactivate *Escherichia coli* below 25 °*C*. They observed significant microbial inactivation at an

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