CHAPTER 1

INTRODUCTION

Ohmic heating (OH) is a novel thermal technology that works on the principle of Ohm's law, in which food samples are placed between two electrodes, and the current is passed through them. The food sample, acting as resistance, is heated up rapidly, uniformly, and volumetrically because of the joules effect depending on the electrical conductivity (EC) and electric field strength (EFS) applied (Sastry and Barach, 2000). In OH, the processing time is gradually reduced because of the volumetric heating and internal resistance effect, resulting in a negligible temperature gradient. Due to rapid heating and an overall reduction in processing time, OH has several advantages in terms of lower damage to physico-chemical properties, higher enzyme and microbial inactivation, and higher retention of phytochemicals as well as a higher energy-efficient process compared to conventional method (Ramaswamy et al., 2014). On the other hand, conventional thermal treatment, like hot water and steam blanching, is appropriate for enzyme inactivation. However, this method causes non-homogeneity of heat transfer and a more significant temperature gradient within the food matrix. This also results in uneven processing of food samples and takes longer overall processing time. This negatively affects a finished product's nutritional, sensory quality, and physicochemical properties (Barros et al., 2021; Barron-Garcia et al., 2019).

The effect of OH parameters on the come-up time (CUT), heating rate (HR), EC behaviour, and system performance coefficient (SPC) has been studied on the different types of fruit juices such as orange, tomato, and apple. It was observed that EFS had a significant influence on the heating of juice samples, and the CUT period significantly reduced with an increase in the EFS; thus, a higher HR was achieved at a higher EFS value (Al-Hilphy et al., 2020; Bozkurt and Icier, 2010; Darvishi et al., 2021; Jo and Park, 2019; Norouzi et al., 2021). EC is one of the critical parameters of food samples, which significantly affects the heating behaviour during ohmic heating. It was observed that EC increased linearly with temperature (Norouzi et al., 2021; Sabanci and Icier, 2017). Moreover, food composition also plays a crucial factor in EC during OH. The reduction in the ionic movement in the food samples is due to low current flow within samples exhibiting high sugar concentration and low acid content (°Brix/Acid), resulting in a significant reduction of EC. This results in a higher CUT period and lower HR (Icier and Ilicali, 2005; Sabanci and Icier, 2017). Since OH utilises the internal resistance of the food materials, heat is internally generated within the food matrix, resulting in high energy efficiency (90 % or more). However, system parameters must be critically analysed to achieve high energy efficiency. Moreover, EFS affects overall system performance; therefore, it should be optimised to achieve higher energy-efficient operation (Icier and Ilicali, 2005; Jo and Park, 2019; Srivsatav, 2016). In addition, an understanding of HR and EC is required to design an ohmic system to achieve a high-quality product (Norouzi et al., 2021).

Pineapple juice is the most widely accepted fruit product because of its refreshing and thirst-quenching properties and nutritional benefits. It is a rich source of minerals and vitamins and is appreciated widely for its aroma and taste. The fruit is seasonal and perishable, so processing is needed to prolong its shelf life and ensure its availability during the off-season (Hajare et al., 2006). Traditionally, the conventional mode of heat transfer is mainly employed for pineapple juice processing. Also, the sugar and acid content of the pineapple varies significantly depending on the cultivar, geographical location, seasonal variations, temperature, and harvesting time. Therefore, the standardization of juice is required before processing it from a consumer-industrial point of view. It is mainly done by maintaining a constant °Brix/Acid ratio of the juice as it has a more significant influence on the consumer's acceptability than sugar or acidity alone (Jayasena and Cameron, 2008).

For any juice industry, the main aim of processing is to inactivate the spoilage enzymes and microorganisms and maintain their nutritional quality. Total bacterial load, or the total microbial load, is a fundamental and commonly practised method to study microbial stability during any pasteurisation of food materials (Makroo et al., 2020). During processing, the juice comes into direct contact with atmospheric air, causing a browning reaction. This results in the undesirable colour change of the juice (Makroo et al., 2022). This enzymatic browning is mainly caused by the two oxidoreductase enzymes, polyphenol oxidase (PPO) (EC.1.10.3.1) and peroxidase (POD) (EC.1.11.1.7), that affect food quality parameters like colour, texture, and flavour. PPO, a copper-containing enzyme, catalyzes the oxidation of phenolic compounds into quinones in oxygen availability. These quinones then react non-enzymatically with other compounds like phenols and amino acids to form a complex brown polymer called melanin. On the other hand, POD catalyzes the oxidation of many compounds like phenols, amines, ascorbic acid, and indole in the company of hydrogen peroxide, which is an electron acceptor and is also accountable for the discolouration in various fruits and vegetables. POD is also accountable for black-heart development in pineapple (Pipliya et al., 2022). Thus, the oxidation by PPO and POD results in not only undesirable colour change but also enhanced deterioration of nutritional and flavour quality, leading to the development of off-flavour in due course of time. These two enzymes interchangeably are used as the marker enzymes depending on their thermal stability for juice processing and are used in optimization and process design (Pipliya et al., 2022; Barron-Garcia et al., 2019; Icier et al., 2008).

Bromelain is widely reported for its significant medicinal and therapeutic values and is highly valued in the pharmaceutical and food industries. Commercially, the bromelain is mainly extracted and purified from the pineapple stem rather than juice. The enzymes were reported to be highly thermal sensitive, and degradation often occurs due to temperature-induced denaturation (Zhou et al., 2021; Bala et al., 2012; Poh and Majid, 2011; Chakraborty et al., 2014; Bala et al., 2013). While bromelain in pineapple juice has various health benefits, its presence can also have a negative impact from a consumer acceptability standpoint. It can lead to changes in texture, causing a breakdown of proteins and potentially resulting in a less desirable mouthfeel or texture alteration in the juice. In some cases, bromelain can impart a slightly bitter taste to the juice, which might not align with consumer's flavour preferences. Also, it is believed to cause soreness and discomfort in the mouth while drinking. In more severe circumstances, for individuals allergic to bromelain, consuming pineapple juice containing significant amounts of this enzyme can lead to allergic reactions, impacting consumer safety and acceptability. Apart from this, bromelain's proteolytic activity might affect other ingredients in the juice, potentially leading to changes in taste, colour, or stability of added components, which consumers might not receive well. Therefore, while bromelain offers health benefits, its presence in pineapple juice can sometimes pose challenges regarding taste, texture, potential allergic reaction, and consumer perception of quality and safety (Sriwatanapongse et al., 2000). Therefore, the inactivation of undesirable enzymes and reducing the total microbial load to a safer limit is essential to extend the self-life of juice.

Enzyme and microbial inactivation using ohmic heating in various food samples has also been reported (Ramaswamy et al., 2014; Doan et al., 2023). However, most of the work has been reported mainly on the static mode of OH treatment. But for fruit juice processing in an industrial setup, a continuous mode of operation is required to align with other unit operations like heat regeneration, cooling, and chilling section and finally to an aseptic packaging system. For this, a prototype lab-scale continuous ohmic heating (COH) system was developed for pineapple juice processing. Apart from a high energy efficient process and reduced processing time, COH provides precise temperature control, minimising heat exposure and preserving the flavour, colour, and nutritional content of the fruit juice, and can be designed for high throughput, making them suitable for large-scale industrial production and improving overall production efficiency. The scalability of the technology allows for integration into existing processing lines with minimal modifications. However, the capital investment required to implement the COH system may be higher than that required by traditional methods. However, the long-term operational cost savings, energy efficiency and improved product quality can contribute to the overall cost-effectiveness. Precise temperature control can also contribute to minimising waste and optimising resource utilisation.

During COH, the processing occurs in two phases, one during the CUT period and the other during isothermal holding (Chakraborty et al., 2015; Barron-Garcia et al., 2019; Brochier et al., 2016). Enzyme and microbial inactivation occur in both phases mainly due to the thermal effect of the protein denaturation in the first phase and the rupturing of their cell membranes in the second phase (Doan et al., 2023). The non-thermal impact of the electric field also affects the enzyme and microbial inactivation by influencing the biochemical reactions, structural changes, and alteration of the surface charge by ionizing the solution and mechanical effects, leading to electroporation (Barros et al., 2021; Kanjanapongkul and Baibua, 2021; Makroo et al., 2022). The inactivation rate mainly depends on the source, type of enzymes, microbial internal properties, and mode of applied process technologies. Enzymes and microbial inactivation greatly depend on the temperature-time combination and electric field strength (Kanjanapongkul and Baibua, 2021; Icier et al., 2008). Suitable model development sometimes becomes necessary for designing and optimizing process conditions. It is used to predict microbial and enzyme inactivation other than those performed experimentally in deciding the pasteurization and sterilization level (Hashemi et al., 2019).

Thermal kinetics of enzymes and microbes is the basic requirement for the effective design of the enzyme inactivation process. The kinetic modelling of enzyme and microbial inactivation helps predict their behaviour and determine their thermal stability. Various kinetic models have been employed for kinetic modelling like the first order, distinct isozymes, Weibull distribution, sigmoidal logistic, fractional conversion, and two fraction model (Icier et al., 2008; Sulaiman et al., 2015b; Sulaiman et al., 2015a; Brochier et al., 2016). The best fit kinetic model was determined based on goodness of fit parameters like high R^2 values and low RMSE, SSE, and residuals. However, these parameters are sometimes insufficient in deciding the best-fit model, as several models fit equally well for a specific data set. To overcome this, the accuracy factor (A_f) and bias factor (B_f) are used for the model's performance and validation. The Akaike information criteria (AIC) is also used to rank the several competing models that have been used (Pipliya et al., 2022).

Although the OH technology seems promising and highly effective, few studies have been reported on the heating performance during COH treatment of fresh fruit juices. Also, research work on COH treatment of standardized pineapple juice based on different °Brix/Acid is not reported. Therefore, the main aim of the present research work is to design and develop a lab-scale COH system, study its heating performance with different fruit juices, optimize the process parameters for enzyme and microbial inactivation, kinetic modelling, and storage study of COH-treated pineapple juice. The detailed objectives of the research work are summarised below.

Objectives

The proposed research aimed to develop a lab-scale COH system for the thermal processing of fruit juice. To achieve the aim, the following objectives were carried out:

1. To develop a lab-scale continuous ohmic heating system and its performance evaluation with different fruit juices.
2. To standardize pineapple juice (°Brix/Acid) for continuous ohmic heating performance.
3. To standardize the process parameters for thermal processing of pineapple juice by continuous ohmic heating.
4. To model inactivation kinetics of enzymes, microbes, and quality attributes during continuous ohmic heating of pineapple juice.
5. To study the shelf-life of continuous ohmic heat-treated pineapple juice under different storage conditions.