CHAPTER-I

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1.1 Importance of Pineapple

Pineapple (*Ananas comosus*) is one of the most important tropical fruits cultivated in India and worldwide. It is valued for fresh consumption and industrial processing due to its attractive flavor, high nutritional content, and versatile applications. India ranks among the top producers, with an annual production exceeding 1.7–1.8 million tonnes in recent years. The major producing states include Assam, West Bengal, Tripura, Meghalaya, Manipur, Kerala, and Karnataka, with Assam alone contributing nearly one-fifth of the total national output. Pineapple cultivation provides small and marginal farmers with significant livelihood opportunities and supports domestic and export markets.

Nutritionally, pineapple is rich in carbohydrates, dietary fiber, and minerals such as calcium and potassium. It is also an excellent source of vitamin C, a potent antioxidant that promotes iron absorption and collagen synthesis, thereby supporting the immune system and structural health of tissues. The fruit contains bromelain, a proteolytic enzyme with multiple therapeutic benefits, including improved digestion, anti-inflammatory activity, and potential cardiovascular protection (Hossain et al., 2015). These nutritional and functional qualities make pineapple an economically significant fruit with growing applications in nutraceutical and functional food sectors.

1.2 Perishability and Postharvest Challenges

Despite its importance, pineapple is highly perishable due to its high moisture content and sensitivity to enzymatic and microbial activity. Postharvest losses in India are estimated at 20–30%, mainly because of inadequate processing facilities and cold-chain infrastructure. In addition, pineapple pulp contains oxidative enzymes such as polyphenol oxidase (PPO) and peroxidase (POD), which catalyze browning reactions upon exposure to oxygen, leading to undesirable changes in color, flavor, and nutritional quality. PPO converts monophenols to o-quinones, while POD catalyzes the single-electron oxidation of phenols, ultimately forming melanins responsible for darkening and deterioration (Panigrahi et al., 2021). Such enzymatic browning remains a major challenge during processing and storage.

1.3 Processing Needs and Non-Thermal Alternatives

Conventional thermal treatments (e.g., pasteurization) are widely employed to inactivate enzymes and microorganisms. However, heat-sensitive bioactives such as vitamin C, phenolic compounds, and aroma volatiles are often degraded during these treatments, compromising quality (Chakraborty et al., 2014). To address this limitation, non-thermal technologies have been investigated for fruit processing. Among these, cold plasma has emerged as a promising technique due to its ability to inactivate enzymes and pathogens at low temperatures, thereby minimizing nutrient and flavor losses.

Dielectric barrier discharge (DBD), a commonly used cold plasma configuration, generates reactive species that disrupt enzyme structures and microbial membranes, leading to effective inactivation. Cold plasma has been successfully applied to extend the shelf life of various fruits and juices, including apples, tomatoes, and strawberries, while preserving sensory and nutritional attributes (Illera et al., 2019; Misra et al., 2014). Its low energy requirement, environmental sustainability, and scalability enhance its relevance for fruit processing industries.

1.4 Drying of Pineapple Pulp

Processing pineapple into dehydrated products provides a viable strategy to reduce postharvest losses, extend shelf life, and improve value addition. Pineapple is widely processed into canned slices, juices, jams, and powders. Among these, powdered forms have gained attention due to their long storage stability, reduced transportation costs, and convenient incorporation into beverages, confectionery, and functional foods.

Several drying techniques are available for converting pulp into powder, including spray drying, tray drying, vacuum drying, freeze drying, and foam-mat drying. Though widely used, spray drying is less suitable for low molecular weight sugar-rich and viscous products like pineapple pulp due to stickiness and low yield (Chandrasekar et al., 2015). Freeze drying provides high-quality powders but is prohibitively expensive for large-scale operations. Foam-mat drying, in contrast, is simple, cost-effective, and particularly suited to viscous, sugar-rich pulps. It enables drying at relatively low temperatures and short drying times, thereby retaining flavor, color, and nutrients while minimizing stickiness.

1.5 Principles of Foam-Mat Drying

Foam-mat drying involves whipping juice or pulp with foaming agents and stabilizers to form a stable foam, which is then dried into thin layers. Foam stability is critical because it influences drying rate, powder texture, rehydration properties, and product quality. Additives such as maltodextrin, starch, carboxymethyl cellulose (CMC), and glycerol monostearate are often incorporated to improve foam stability and reduce hygroscopicity of the final powder (Muzaffar et al., 2018; Asokapandian et al., 2016). Rheological properties, particularly time-dependent behavior, are pivotal in determining foam stability and processing performance. Shear-thinning behavior, commonly observed in fruit pulps and concentrated juices, indicates viscosity changes over time under constant shear (Ibarz et al., 2010). A food foam consisting of air bubbles in a fruit juice or pulp matrix is obtained before drying (Lobo et al., 2017). Thus, the characteristics of the foam and its stability during the drying phase are helpful for the standardization of the drying process, dry product attributes, and scaling-up purposes. In foam-mat drying, the foam is suitably dried to obtain a powder. Thus, the rheology of foam is a critical issue that can affect the downstream processes. The stability of foam is of prime importance as it may also facilitate the drying rate by maintaining the foam structure during the drying process. However, studies in this direction, particularly using fruit juice or pulp, are scarce.

The time-dependent characteristics reflect changes in apparent viscosity and related indices concerning shearing time. For various fruit pulps and concentrated juices (such as banana puree, mango pulp, and date syrup), a typical shear-thinning behavior is observed, where apparent viscosity decreases over time under constant shear rate (Ibarz et al., 2010; Mohamed & Hassan, 2016). The reverse trend is seen in rare cases, known as anti-thixotropy, which is uncommon in food systems. Several time-dependent flow models have been developed to predict shear stress or apparent viscosity and better describe such behavior. Examining the suitability of these models helps understand the rheological characteristics of raw materials such as fruit juice, pulp, or foam. While this chapter places significant emphasis on data modeling, which is essential for predicting parameters and gaining a deeper understanding of the underlying process, it is equally important to highlight the practical applications of the property data. Linking the modeling results to industrial relevance, such as process optimization, quality control, cost reduction, and product development, would not only strengthen the discussion but also demonstrate the scientific importance and potential contribution of this study to addressing real-world challenges in the food processing industry.

1.6 Role of Skim Milk Powder (SMP)

While various foaming agents have been explored, using skim milk powder (SMP) in pineapple pulp foam remains limited. SMP is an attractive additive due to its high-quality proteins, nutritional fortification potential, and foaming ability (Hoppe et al., 2008). It is widely used in fortified foods for infants and vulnerable populations. Incorporating SMP into pineapple pulp foams could improve foam formation and stability and enhance the final powder's protein content and consumer acceptability (Watharkar et al., 2021). However, systematic studies on SMP-stabilized pineapple foams in relation to drying behavior and powder quality are lacking.

1.7 Storage Stability and Sorption Characteristics

Beyond drying, ensuring the long-term stability of the powder is essential. Moisture uptake during storage can trigger caking, microbial growth, and quality deterioration. Moisture sorption isotherms describe the relationship between equilibrium moisture content and water activity under different conditions, offering valuable insights into storage stability, packaging requirements, and shelf-life prediction (Aviara & Ajibola, 2002; Iglesias et al., 1976). Thermodynamic parameters derived from sorption studies help estimate the energy required for moisture removal and the molecular interactions between food solids and water (Al-Muhtaseb et al., 2004). These data are crucial for designing stable powdered products with consistent quality.

1.8 Research Gaps

Although foam-mat drying has been successfully applied to fruits such as banana, mango, and muskmelon, research on pineapple pulp remains limited. In particular, the following gaps are evident:

- Limited studies on the combined application of cold plasma pre-treatment and foam-mat drying of pineapple pulp.
- Lack of systematic investigation on the role of SMP as a functional foaming and stabilizing agent in pineapple foam.

- Scarcity of data on the rheological behaviour of pineapple pulp foam and its correlation with foam stability, drying kinetics, and powder attributes.
- Inadequate information on the moisture sorption and storage behaviour of foam-mat dried pineapple powder.

1.9 Objectives of the Present Study

In view of the above research gaps, the present study was undertaken with the aim of developing nutritionally enriched, shelf-stable pineapple powder using foam-mat drying technology. The specific objectives are:

1. To study the effect of cold plasma pre-treatment on pineapple pulp characteristics, enzyme inactivation, and kinetic modelling.
2. To study the foam and powder properties prepared from cold plasma-treated pulp.
3. To investigate and correlate pineapple pulp foam rheology with foam characteristics and powder attributes.
4. To study the storage behaviour of pineapple pulp foam-dried powder.

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