ABSTRACT

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Pineapple (*Ananas comosus*) is a nutritionally rich tropical fruit, but its high moisture content and enzymatic activity make it highly perishable, leading to substantial postharvest losses. Conventional thermal processing often degrades heat-sensitive nutrients, highlighting the need for non-thermal approaches coupled with effective drying technologies to ensure quality retention, value addition, and extended shelf life.

The present study was undertaken to develop stable and nutritionally enriched pineapple powder using foam-mat drying in combination with dielectric barrier discharge (DBD) cold plasma pre-treatment. The specific objectives were: (i) to investigate the effect of cold plasma on enzyme inactivation and pulp characteristics, (ii) to evaluate the foaming and powder properties of treated pulp, (iii) to examine the rheological behavior of pineapple pulp foam and its correlation with foam and powder attributes, and (iv) to assess the storage stability of the dried powder through sorption and accelerated shelf-life studies.

The present investigation mathematically modeled the Polyphenol oxidase (PPO) and peroxidase (POD) inactivation in pineapple pulp. The pineapple pulp was exposed to dielectric barrier discharge (DBD) plasma at 15, 20, and 25 kV with treatment times of 3, 6, 9, 12, and 15 min. The cold plasma treatment at 25 kV for 15 min achieved up to 85% and 66% inactivation of polyphenol oxidase (PPO) and peroxidase (POD), respectively, with Peleg's kinetic model providing the best fit for enzyme inactivation data ($R^2 > 0.90$). Plasma treatment also improved color attributes and antioxidant activity of the pulp.

Following this, the foaming behaviour of pineapple pulp foam (PPF) with the varying skimmed milk powder (SMP) [2-6%] for different whipping times (WT) [60-120 s] was investigated. PF's behavior [expansion and drainage volume, foam density, and stability] was studied. Prepared foam was dried at 60 ^{o}C, and its powder physicochemical properties were determined. Incorporation of skim milk powder (SMP, 6%) and whipping for 120 s during foaming enhanced expansion volume, reduced drainage, and improved foam stability, resulting in powders with desirable physicochemical properties, including higher protein content and low moisture levels. The good stability of the pulp foam may be attributed to holding the interfaces of the foam bubbles, which exhibited a good foam-dried powder. Hydrocolloids of SMP produce smaller foam bubbles with a strong

viscoelastic film. Protein in SMP helps to bind gas/liquid interfaces and form thick, hard, solid-like films that can stop coarsening. Drying kinetics were well described by Page's model ($R^2 \geq 0.984$). In all cases, the Page's model coefficient $n>1$ showed its super-diffusion phenomena.

A Rheological study of the foam was conducted with the varying shear rates of 1, 10, and 50 s^{-1}. It fitted the data with various mathematical models, viz., the Weltman model, the Hahn model, and the Figoni and Shoemaker model, to understand the flow behavior of the foam. The investigations obtained from the study suggest the pineapple pulp foam's shear-thinning behaviour with the shear rates. Time-dependency of the pulp foam can be explained by Hahn and Figoni-Shoemaker models ($|r| \leq 0.998$). Structural breakdown coefficients (B and M) varied due to foam properties (stability, expansion, and drainage volume) and SMP (%). These coefficients could be suitable indices to judge the stability of the foam. While dynamic rheological characteristics at 25°C were significantly varied with SMP ($p<0.05$), and a higher storage modulus (G') exceeded loss modulus (G"), indicating the foam's viscoelastic behavior. Rheological characterization revealed shear-thinning and viscoelastic behavior of the foam, with structural breakdown parameters correlating strongly with foam stability and powder quality. Principal component analysis (PCA) confirmed significant interrelationships between foaming, rheological, and powder attributes. The physical properties of the powder were also influenced. The higher stability of foam could hold the air-liquid phase for a longer time to dry the product, and reach the equilibrium moisture content in a shorter time.

To ensure long-term product stability, sorption isotherm studies of the pineapple pulp powder (PPP) were performed using Polyethylene (PP) and Aluminum laminate (AL) packaging under accelerated storage conditions at 30, 40, and 50 °C. After every 3-day interval, the powder's moisture adsorption, thermodynamic properties, and physicochemical properties were analyzed. The sorption values fit with the various mathematical models. Estimating the thermodynamic properties (Net Isosteric heat (Q_{st}) and sorption entropy) provides an idea about the properties of water and energy requirements associated with the sorption isotherm. The downward concavity of the curve obtained in the present investigations showed a type-II isotherm. The GAB and Smith model fit well with the experimental values, with $R^2 \leq 0.974$ and the lowest RMSE<0.005. However, model validation parameters (A_f and B_f values) suggest the Smith model was

best for the sorption isotherm of PPP. Model selection parameter AIC also suggests the Smith model was best selected for the isotherm study of the PPP. The Q_{st} value significantly decreased with increased moisture content. Slight changes were observed in the TPC or DPPH scavenging activity value throughout the study of the pineapple pulp powder. Monolayer moisture content obtained below the critical limit (<0.12) showed the powder's maximum shelf-life stability. Powder packed in AL materials showed more stability during storage. The titratable acidity of the powder packed in PP material showed slight changes that might be due to the interaction of the various constituents present in the PPP. PCA biplot suitably correlates the Sorption entropy and isosteric heat of PPP.

Overall, combining cold plasma pre-treatment with foam-mat drying and SMP fortification proved effective in producing shelf-stable, nutritionally enhanced pineapple powder. The findings contribute to process optimization for tropical fruit valorization, offering potential for industrial-scale applications in functional foods and nutraceuticals.

Keywords: Pineapple pulp, cold plasma, foam-mat drying, skim milk powder, rheology, sorption isotherm, shelf life.