CHAPTER-V

SUMMARY AND CONCLUSIONS

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5.1 Summary

The present research was undertaken to develop nutritionally enriched and shelf-stable pineapple powder using **dielectric barrier discharge (DBD) cold plasma pre-treatment** in combination with **foam-mat drying**. The work systematically addressed four objectives:

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 the pineapple pulp foam rheology with foam characteristics and powder attributes.
4. To study the storage behaviour of pineapple pulp foam dried powder.

5.1.1 Cold Plasma Pre-treatment and Enzyme Inactivation

Enzyme inactivation kinetics revealed that PPO and POD, responsible for enzymatic browning, were significantly inactivated by DBD plasma. At 25 kV for 15 min exposure, PPO activity was reduced by ~85% and POD by ~66%. Plasma treatment also improved brightness (L*) and preserved color attributes (ΔE and hue angle remained stable), while enhancing antioxidant activity (DPPH inhibition) and total phenolic content (TPC).

Among tested models, **Peleg's kinetic model** provided the best fit ($R^2 < 0.99$, RMSE < 0.32), accurately describing enzyme inactivation behavior. The Two-fraction model also showed acceptable performance, though less consistent. These results demonstrate that DBD plasma is an effective non-thermal method for enhancing pineapple pulp quality prior to drying.

5.1.2 Foam Formation and Drying Behavior

Pineapple pulp was successfully foamed using skim milk powder (SMP) as a foaming agent. Foaming standardization indicated that **6% SMP with 120 s whipping time** yielded the most stable foams, with higher expansion volume (EV), reduced drainage volume (DV), and improved foam stability (FS). SMP proteins contributed to strong viscoelastic films at the air–liquid interface, resulting in smaller, more stable foam bubbles.

Foam-mat drying of optimized foams at 60 °C produced powders with good rehydration ability, low stickiness, and improved nutritional value. **Page's drying model** best described drying kinetics ($R^2 \geq 0.984$), with coefficient *n>1*, confirming a **super-diffusion phenomenon** indicative of rapid moisture removal. SMP incorporation significantly enhanced protein and ash content in the powders, contributing to nutritional fortification.

5.1.3 Rheological Properties and Interrelationships

Rheological characterization revealed that pineapple pulp foams exhibited **shear-thinning, time-dependent, and viscoelastic behavior**. Steady shear studies showed decreasing viscosity with increasing shear rate, while time-dependent studies confirmed thixotropic behavior. Models by Weltman, Hahn, and Figoni–Shoemaker effectively described the rheological data, with high correlation coefficients ($|r| \leq 0.998$).

Structural breakdown coefficients (B and M) decreased with shear rate and were influenced by SMP concentration, making them reliable indices of foam stability. Dynamic rheology demonstrated that the **storage modulus (G′) exceeded the loss modulus (G″)**, confirming elastic dominance and foam stability. Principal component analysis (PCA) established strong interrelationships among foam stability indices, rheological parameters, and powder quality attributes, validating the role of rheology as a predictor of powder functionality.

5.1.4 Sorption Isotherms and Storage Stability

Moisture sorption studies conducted at 30–50 °C showed **Type-II isotherm behavior** (sigmoid curves), typical for sugar-rich powders. Among the fitted models, the **Smith model** best described sorption data (lowest RMSE <0.005, highest $R^2 \leq 0.974$), followed by GAB. Monolayer moisture content (M_G) values remained below 0.12, indicating maximum stability and minimal risk of deterioration.

Thermodynamic analysis showed that the net isosteric heat of sorption (Qst) decreased with increasing moisture content, reflecting reduced binding energy at higher hydration levels. Sorption entropy trends supported these findings, and PCA biplots successfully correlated Qst with entropy, providing deeper insight into water–solid interactions in pineapple powders. Packaging trials demonstrated that **aluminum laminate pouches (ALP)** provided superior barrier properties compared to polyethylene (PP), with powders retaining phenolics, antioxidant activity, and physicochemical stability during accelerated storage.

Minor titratable acidity changes were observed in PP packaging, which were attributed to constituent interactions.

5.2 Integrated Findings

This research demonstrated that integrating cold plasma pre-treatment with foam-mat drying and SMP fortification offers a robust approach for producing **nutritionally enriched, shelf-stable pineapple powders**. Cold plasma preserved bioactives and color, foam-mat drying enabled efficient dehydration of viscous pulp, and SMP improved both processability and product nutrition. The study advances theoretical modeling and applied food engineering for tropical fruit valorization.

5.3 Conclusions

- Cold plasma effectively inactivated PPO (85%) and POD (66%), reducing enzymatic browning and improving pulp stability for drying. Peleg's model was most suitable for describing inactivation kinetics.
- Incorporation of 6% SMP and whipping for 120 s produced the most stable foams, resulting in high-quality powders with improved protein content and low moisture. Drying followed Page's model with high predictive accuracy.
- Pineapple pulp foams exhibited shear-thinning and viscoelastic behavior, with SMP enhancing foam stability. Rheological indices correlated strongly with powder attributes, making rheology a reliable predictor of product performance.
- Sorption isotherms confirmed Type-II behavior, with Smith's model providing the best fit. Powders in aluminum laminate packaging exhibited superior stability, maintaining nutritional and functional qualities during storage.
- Integration of DBD plasma treatment and foam-mat drying with SMP fortification offers an effective strategy for producing stable, enriched pineapple powders suitable for industrial-scale applications.

5.4 Future Scope

- Sensory evaluation to assess consumer acceptability of plasma-treated foam-mat dried powders.
- Exploration of alternative foaming agents (e.g., plant proteins, hydrocolloids) for broader applications and reduced SMP dependence.
- Scale-up and techno-economic analysis of plasma-assisted foam-mat drying for commercial production.

- Long-term bioactive retention studies under realistic distribution and storage conditions.
- Extension of the combined approach to other fruits, dairy-based formulations, and nutraceutical blends.

5.5 Contribution to Knowledge

- First systematic integration of **DBD plasma pre-treatment** with **foam-mat drying** for pineapple pulp.
- Development and validation of predictive models (Peleg, Page, Smith) for enzyme inactivation, drying, and sorption behavior.
- Identification of **optimal foaming parameters (6% SMP, 120 s whipping)** for stable foam formation and superior powder quality.
- Demonstration that cold plasma preserves **nutritional quality and color** while inactivating browning enzymes.
- Establishment of **aluminum laminated packaging** as the most effective for long-term stability.
- Provided integrated insights linking processing conditions, modeling outcomes, and product quality, contributing to the commercial applicability of pineapple powder production.