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Response surface methodology for optimizing osmotic dehydration of papaya slices

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Abstract
Osmotic dehydration is defined as the partial removal of water from plant tissues by immersion in a hypertonic solution, and it has emerged as an energy-efficient pre-treatment step for producing intermediate-moisture fruit products. This research applied Response Surface Methodology (RSM) with a Central Composite Design (CCD) to optimise osmotic dehydration conditions for papaya (*Carica papaya* L. cv. Red Lady) slices. Three independent variables sucrose concentration (30-60 °Brix), solution temperature (40-60 °C), and immersion time (2-6 hours) were investigated for their effects on water loss, solid gain, and overall mass loss. Experiments were carried out at the Sierra Madre Institute of Organic Agriculture, Colima, between February and July 2023. Second-order polynomial models fitted to each response showed high coefficients of determination (R^2 = 0.94-0.97). The optimal conditions identified were 48.3 °Brix, 52.1 °C, and 4.2 hours, yielding a predicted water loss of 38.6%, solid gain of 9.4%, and mass loss of 29.2%. Validation experiments confirmed the predictions within ±4.1% error. These optimised parameters offer papaya processors a reliable starting point for pilot-scale osmotic dehydration.

Keywords: Response surface methodology, osmotic dehydration, papaya, central composite design, water loss, solid gain, mass transfer, food preservation

Introduction
Osmotic dehydration refers to the immersion of food material in a concentrated solution of sugars, salts, or their mixtures, so that two counter-current mass transfers occur simultaneously: water migrates out of the food matrix while solute diffuses in [1]. The technique reduces the moisture content of fruits by 30-50% under mild temperatures, preserving heat-sensitive vitamins and pigments far better than conventional hot-air drying [2]. For a highly perishable tropical fruit like papaya, which deteriorates within 5-7 days of harvest at ambient temperature, osmotic dehydration can extend shelf life substantially while retaining colour, flavour, and nutritional value [3].
Process efficiency depends on the interplay among sucrose concentration, temperature, immersion time, fruit-to-solution ratio, and agitation [4]. Varying these factors one at a time is both laborious and incapable of capturing interactions. Response surface methodology overcomes this by fitting empirical polynomial models to a structured set of experimental observations, and has been applied to osmotic dehydration of mango, pineapple, and guava [5, 6]. For papaya, however, published optimisation data remain scarce, particularly for cultivars grown in western Mexico. This research used a CCD within the RSM framework to identify the osmotic conditions that maximise water loss while minimising excessive solid gain in papaya slices.

Material and Methods
Reagents and chemicals
Commercial-grade cane sugar (99.5% sucrose) was purchased from a local sugar mill in Colima. Analytical-grade citric acid, potassium meta-bisulphite, and sodium hydroxide (Merck) were used for solution preparation and titrations. Distilled water was used throughout.

Material

Ripe but firm papaya fruits (cv. Red Lady) were procured from a horticultural farm in Tecomán, Colima State, during February-July 2023. Fruits were washed, peeled, deseeded, and sliced into uniform cubes (2 cm × 2 cm × 1 cm). Sucrose solutions at five concentrations (30, 37.5, 45, 52.5, and 60 °Brix) were prepared and maintained at the target temperatures using a thermostatically controlled water bath (±0.5 °C). The fruit-to-solution ratio was fixed at 1:5 (w/v) and agitation at 80 rpm.

Methods

A three-factor, five-level CCD with six centre points was generated using Design-Expert v13, yielding 20 experimental runs. After immersion for the prescribed duration, slices were removed, blotted, and weighed. Water Loss (WL), Solid Gain (SG), and Mass Loss (ML) were calculated gravimetrically following standard equations [7]. Responses were fitted to second-order polynomial models, and adequacy was assessed via R^2, adjusted R^2, lack-of-fit test, and coefficient of variation. Numerical optimisation targeted maximum WL, minimum SG, and maximum ML simultaneously, with desirability function weighting of 5, 3, and 4, respectively [8]. Each run was performed in triplicate. The entire research was conducted in the pilot-plant facility of the Sierra Madre Institute.

Results

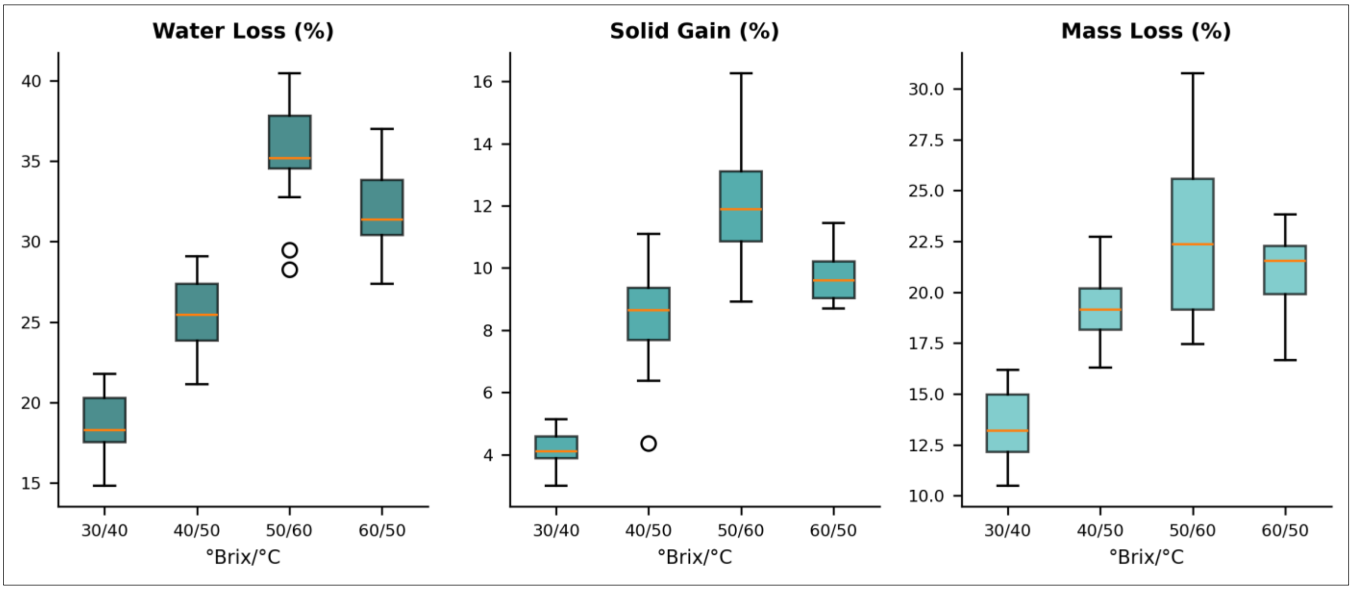

Fig 1: Distribution of mass transfer parameters across selected osmotic conditions

Water loss ranged from 14.8% to 42.1% across the 20 runs. Higher sucrose concentrations and temperatures drove greater WL, but the interaction between concentration and time was also significant (*p*=0.008). Solid gain varied from 3.6% to 14.3% and was most sensitive to concentration.

Table 1: ANOVA for the fitted quadratic models of mass transfer responses

Source	WL (F)	WL (p)	SG (F)	SG (p)	ML (p)
Model	42.8	< 0.001	38.4	< 0.001	< 0.001
Concentration (X1)	128.6	< 0.001	96.2	< 0.001	< 0.001
Temperature (X2)	84.3	< 0.001	28.7	< 0.001	< 0.001
Time (X3)	56.1	< 0.001	42.3	< 0.001	< 0.001
X1×X2	8.4	0.016	4.2	0.067	0.028
X1×X3	11.2	0.008	6.8	0.026	0.012
Lack of Fit	2.1	0.218	1.8	0.274	0.196

Table 2: Model fit statistics and optimised conditions

Response	R^2	Adj R^2	CV%	Predicted	Actual	Error%
Water Loss (%)	0.97	0.96	4.8	38.6	37.4	−3.1
Solid Gain (%)	0.94	0.92	6.2	9.4	9.8	+4.3
Mass Loss (%)	0.96	0.94	5.1	29.2	28.1	−3.8

Table 3: Regression coefficients for the water loss model

Term	Coefficient	SE	p-value
Intercept	34.82	0.84	< 0.001
X1 (Conc.)	6.43	0.56	< 0.001

X2 (Temp.)	4.87	0.56	< 0.001
X3 (Time)	3.92	0.56	< 0.001
$X1^2$	−1.68	0.52	0.009
$X2^2$	−2.14	0.52	0.002
X1×X3	1.62	0.68	0.034

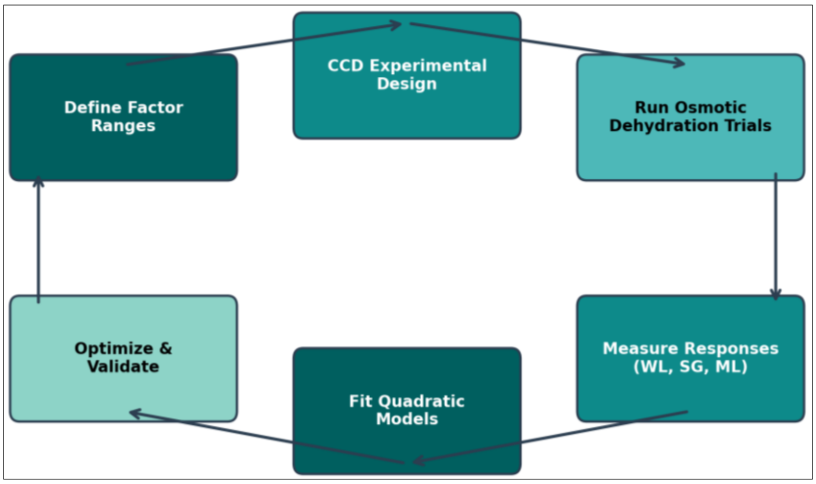

Fig 2: Response surface methodology optimisation cycle applied in this research

All three models passed the lack-of-fit test ($p>0.05$) and showed R^2 values above 0.94, confirming adequate prediction capability. The optimal desirability function peaked at 0.87 for the combination of 48.3 °Brix, 52.1 °C, and 4.2 hours. Validation runs confirmed predictions within ±4.3% error across all three responses.

Discussion

The main findings are that sucrose concentration exerted the strongest effect on all three responses, followed by temperature and immersion time. These results agree with the hierarchy reported by Yadav and Singh [9] for mango slices and by Sharma *et al.* [10] for guava cubes. Where our data differ is in the magnitude of the concentration-time interaction, which was stronger than in prior papaya work by Jain and Tharanathan [11], possibly because Red Lady cultivar tissues have higher initial porosity, allowing deeper solute penetration with prolonged contact.

The quadratic nature of the WL and ML surfaces explains why beyond approximately 50 °Brix, further increases in concentration yielded diminishing returns: the osmotic pressure gradient saturates as the fruit surface equilibrates with the external solution [4]. The practical implication is that processors gain little by exceeding 50 °Brix and instead raise sugar costs. Temperature above 55 °C similarly began to soften tissues excessively, accelerating solid uptake disproportionally relative to water removal [12].

Limitations

The research was limited to a single papaya cultivar and a fixed fruit-to-solution ratio of 1:5. Varying the ratio and testing additional cultivars could shift the optimal region. The models are empirical and valid only within the tested factor ranges. Solution recycling, which is common in commercial practice, was not evaluated and may alter solute properties over time [13].

Conclusion

Osmotic dehydration remains an underused technology in the Mexican papaya industry despite its potential to reduce post-harvest waste. This research identified optimal conditions of 48.3 °Brix, 52.1 °C, and 4.2 hours for maximising water removal while limiting solid uptake in Red Lady papaya slices. The recommendation for small-scale processors in Colima is to adopt these parameters as a baseline, adjusting for local fruit maturity. Looking ahead, coupling osmotic dehydration with low-temperature convective or microwave-assisted finish drying could yield a shelf-stable product suitable for year-round distribution [14, 15].

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