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INTEGRATED MODELING OF MOISTURE DIFFUSION, SOLID GAIN, AND PROCESS OPTIMIZATION IN OSMO-CONVECTIVE DRYING OF PINEAPPLE (*Ananas comosus*) AND BROCCOLI (*Brassica oleracea*) VIA RESPONSE SURFACE METHODOLOGY

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ABSTRACT

Osmo-convective drying is an effective pretreatment method for optimizing dehydration and maintaining product quality. Pineapple and broccoli were dehydrated osmotically using sugar (35–55% w/w), salt (3–9% w/w), and binary sugar–salt mixtures at 30–120 min immersion, followed by convective drying at 40–60°C. Mass transfer parameters, including water loss (WL), solid gain (SG), and weight reduction (WR), were measured. WL increased with osmotic concentration and temperature due to osmotic pressure gradients. Moisture reduction followed exponential kinetics, with final moisture content below 20%, ensuring extended shelf life. Response Surface Methodology (RSM) with a Box–Behnken Design yielded high-fidelity quadratic models ($R^2 > 0.96$). Optimal conditions produced WL ≈ 26%, SG ≈ 9.6%, and WR ≈ 15.3%. Binary sugar–salt solutions outperformed single-solute systems. Results confirm the industrial suitability of osmo-convective drying for fruit and vegetable preservation.

Keywords: Osmoconvective Drying, Response Surface Methodology, Mass Transfer, Optimisation, Pineapple, Broccoli.

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INTRODUCTION

Fruits and vegetables contain high moisture content (70–90%), making them highly perishable. Traditional hot-air drying typically induces shrinkage and degrades sensory and nutritional properties.[1] Osmotic dehydration (OD) is a mild pretreatment that removes water partially by immersing food materials in hypertonic solutions, thereby reducing thermal damage during subsequent drying.[2] Pineapple (*Ananas comosus*) is rich in vitamin C and sugars, while broccoli (*Brassica oleracea*) contains high concentrations of vitamins A, C, and K along with bioactive compounds. Efficient preservation of these commodities requires methods that sustain nutritional quality.[3] Despite progress in OD research, limited studies have simultaneously assessed pineapple and broccoli under binary sugar–salt osmotic systems using Response Surface Methodology (RSM).[4] The interactive effects of osmotic concentration, temperature, immersion duration, and drying temperature on dehydration efficiency have not been exhaustively quantified.[5,6] This study therefore aims to model mass transfer parameters—WL, SG, and WR—and optimize osmo-convective drying conditions using RSM-based quadratic modeling to improve dehydration efficiency and product quality. This work also aligns with United Nations Sustainable Development Goal 3 by promoting nutrient retention and enhancing the availability of safe, high-quality preserved foods.

EXPERIMENTAL

Material and Methods

Fresh pineapple (*Ananas comosus*) and broccoli (*Brassica oleracea*) were procured from a local market in Chennai, India. Samples were washed, peeled with stainless steel knives, and sliced into uniform pieces to standardise surface area. Initial moisture content was determined by oven drying.[7,8,9] Visually unblemished samples of identical size were selected to minimize variability in drying characteristics.

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General Procedure

Osmotic agents included food-grade sugar (35%, 45%, 55% w/w) and salt (3%, 6%, 9% w/w), as well as binary sugar–salt mixtures, to investigate synergistic osmotic effects.[10,11] All solutions were prepared in distilled water and maintained at controlled temperatures (30–80°C) in a thermostatically regulated water bath. Known weights of prepared slices were immersed in 500 mL of osmotic solution for 30–120 min. Samples were withdrawn at specified intervals, blotted dry, and weighed on a precision balance. All experiments were conducted in triplicate.[12,13] After osmotic pretreatment, convective drying was performed in a hot-air oven at 40°C and 60°C until moisture content fell below 20%, ensuring microbiological stability and extended shelf life.[14]

Detection Method

Mass transfer was quantified using three primary indicators: water loss (WL), solid gain (SG), and weight reduction (WR), calculated as follows:[15]

$$WL\,(\%) = \frac{(M_0 - m_0) - (M - m)}{M_0} \times 100$$

$$SG\,(\%) = \frac{m - m_0}{M_0} \times 100$$

$$WR\,(\%) = WL - SG$$

Where M_o is the initial sample mass (g), M is the sample mass after osmotic treatment at time t (g), m_o is the initial dry mass (g), and m is the dry mass after osmotic treatment (g). A four-factor, three-level Box–Behnken Design (BBD) was employed within RSM to develop the experimental matrix.[16] Independent variables were osmotic temperature (A, °C), solution concentration (B, % w/w), immersion time (C, min), and drying temperature (D, °C). Responses were WL, SG, and WR. A total of 29 experimental runs, including centre-point replicates, were conducted. Second-order quadratic models were fitted using Design-Expert v12 (Stat-Ease Inc., USA). Model adequacy was assessed via R^2, adjusted R^2, predicted R^2, F-value, p-value, lack-of-fit, and adequate precision at 95% confidence ($p < 0.05$).[17]

RESULTS AND DISCUSSION

Moisture Content Analysis

Fresh pineapple's initial moisture content was 73.65% (dry basis), and broccoli exhibited similarly high moisture. Following osmotic pretreatment and convective drying at 40°C and 60°C, moisture decreased exponentially, reaching below 20%—a threshold ensuring microbiological stability and up to six months of shelf life.[18,19] The drying behaviour transitioned from a constant-rate to a falling-rate period, indicating that internal moisture diffusion was the controlling mechanism.[20]

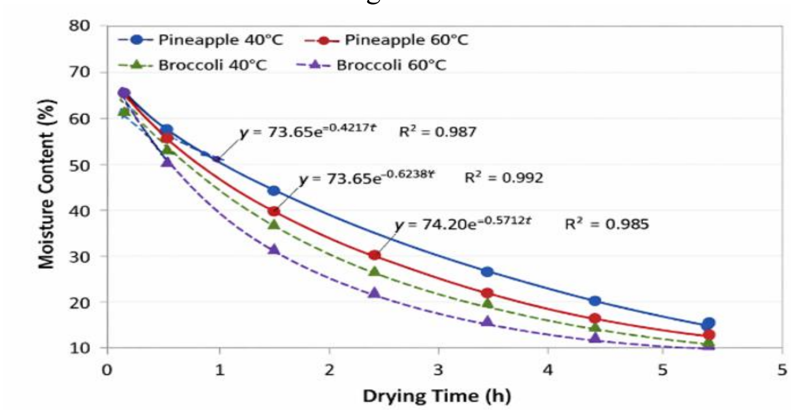

Fig.-1: Variation of Moisture Content (%) with Drying Time (h) for Pineapple and Broccoli at 40°C and 60°C

The drying kinetics followed the exponential model:

$$\frac{M}{M_0} = Ae^{-kt}$$

Where M is the moisture content at time t, and k is the drying rate constant. Increasing drying temperature from 40°C to 60°C elevated the drying rate constant, confirming enhanced moisture diffusivity at higher temperatures.[21] Osmotic pretreatment reduced initial moisture load, lowering overall drying time relative to direct convective drying.

Mass Transfer Characteristics during Osmotic Dehydration

WL increased proportionally with sugar concentration from 35% to 55% (w/w), driven by rising osmotic pressure differentials.[22] Solid gain was concentration-dependent due to enhanced membrane permeability at elevated temperatures (Fig.-2–3).[23] WR, calculated as WR = WL − SG (Eq.5), was most sensitive to osmotic concentration and immersion time, with maximum WR at 55% concentration and extended immersion.[24] Binary sugar–salt solutions showed superior dehydration performance compared to single-solute systems, attributable to the synergistic increase in solution osmolarity (Fig.-5).

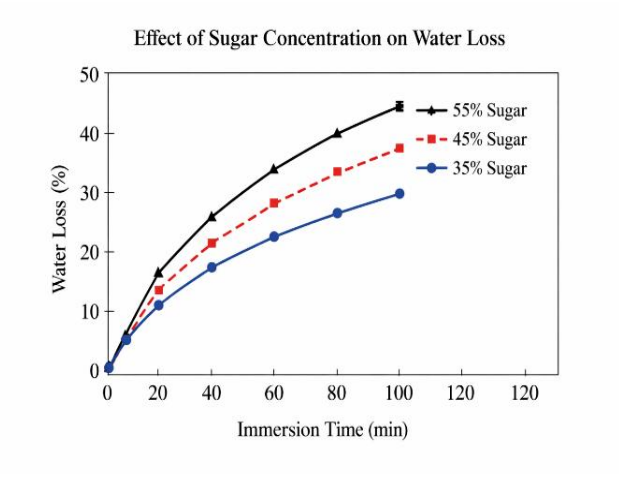

Fig.-2: Effect of Sugar Concentration on WL

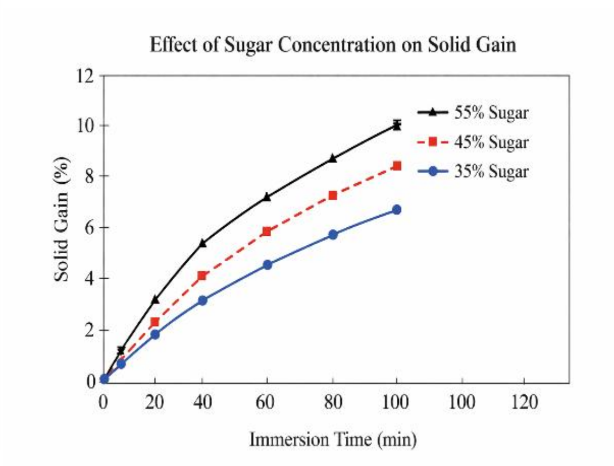

Fig.-3: Effect of Sugar Concentration on SG

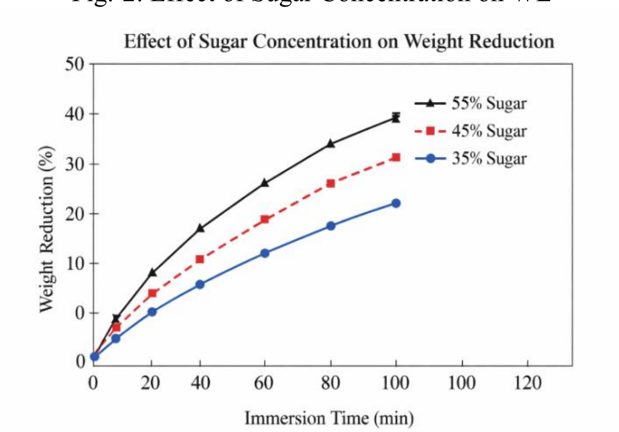

Fig.-4: WR Variation with Immersion Time.

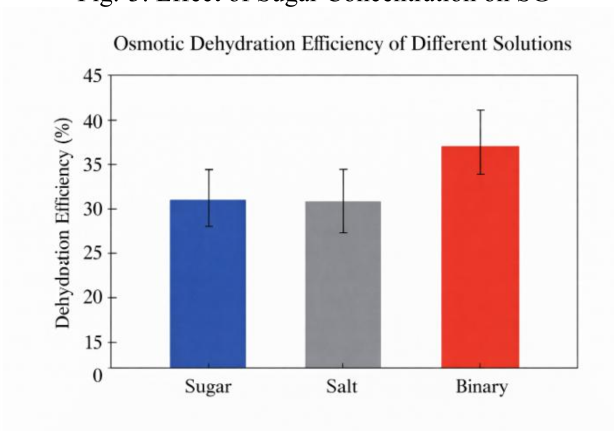

Fig.-5: Comparative WL for Sugar, Salt, and Binary Solutions

Statistical Analysis and Model Development

Second-order quadratic models were developed for all three responses such as water loss, solid gain and weight reduction.

Table-1: ANOVA for W.ater Loss (R^2 = 0.962, Adj. R^2 = 0.927, Pred. R^2 = 0.801, Adeq. Precision = 19.50)

Source	SS	DF	MS	F-value	p-value
Model	443.77	14	31.69	27.37	<0.0001
A (Temp)	6.40	1	6.40	5.53	0.032

B (Conc)	3.37	1	3.37	2.91	0.108
C (Time)	3.84	1	3.84	3.31	0.088
D (Dry Temp)	0.80	1	0.80	0.69	0.417
AB	0.01	1	0.01	0.008	0.927
AC	5.06	1	5.06	4.37	0.054
BC	10.56	1	10.56	9.12	0.008
A^2	326.86	1	326.86	282.25	<0.0001
B^2	49.22	1	49.22	42.50	<0.0001
C^2	18.20	1	18.20	15.71	0.001
D^2	103.18	1	103.18	89.10	<0.0001
Residual	17.37	15	1.15		
Lack of Fit	1.22	10	0.12	4.57	0.053
Pure Error	0.13	5	0.02		

Regression Equation for Water Loss

$$Water\ loss\ (WL) = 25.867 + 0.1517A + 0.375B + 0.4C + 0.183D - 0.025AB - 0.56AC - 0.4125AD - 0.8125BC - 0.7875BD - 0.425CD - 3.45A^2 - 1.34B^2 - 0.815C^2 - 1.939D^2$$

Response surface plots (Fig.-6) confirm strong interactive and quadratic effects of process variables on WL, with elliptical curvatures validating non-linear dehydration behaviour.

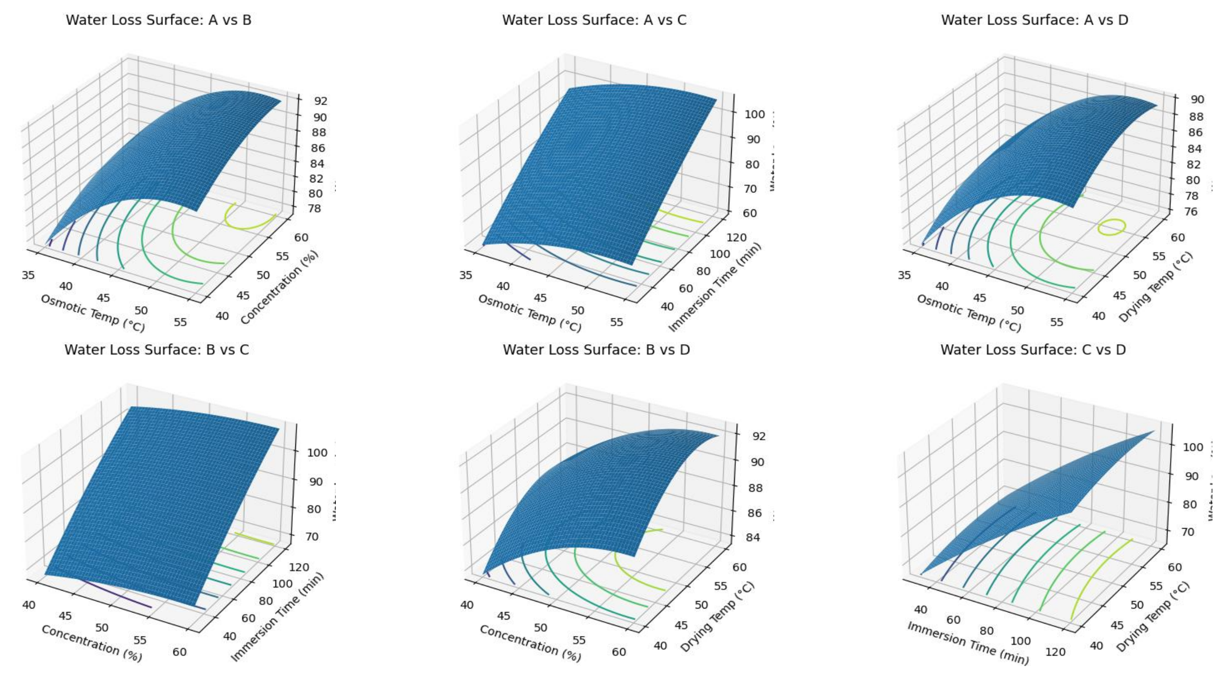

Fig.-6: Response Surface Plots for Interaction Effects on Water Loss

Table-2: ANOVA for Solid Gain (R^2 = 0.9906, Adj. R^2 = 0.9819, Pred. R^2 = 0.9502, Adeq. Precision = 33.43, CV% = 5.62)

Source	SS	DF	MS	F-value	p-value
Model	143.90	14	10.28	113.85	<0.0001
A (Osmotic Temp)	0.45	1	0.45	5.02	0.040

B (Concentration)	0.51	1	0.51	5.65	0.031
C (Immersion Time)	4.95	1	4.95	54.83	<0.0001
D (Drying Temp)	1.55	1	1.55	17.17	0.0009
AB	0.18	1	0.18	2.00	0.177
AC	0.27	1	0.27	3.05	0.101
AD	4.30	1	4.30	47.69	<0.0001
BC	0.95	1	0.95	10.53	0.0054
BD	1.75	1	1.75	19.44	0.0005
CD	2.80	1	2.80	31.07	<0.0001
A^2	51.15	1	51.15	566.61	<0.0001
B^2	47.47	1	47.47	525.87	<0.0001
C^2	37.26	1	37.26	412.80	<0.0001
D^2	43.93	1	43.93	486.66	<0.0001
Residual	1.35	15	0.09		
Lack of Fit	1.22	10	0.12	4.57	0.053
Pure Error	0.13	5	0.02		
Cor Total	145.25	29			

Regression Equation for Solid Gain

$$Solid\ Gain\ (SG) = 9.433 - 0.1375A + 0.146B + 0.454C + 0.2542D + 0.106AB + 0.51875AD + 0.24375BC - 0.33125BD - 0.41875CD - 1.365A^2 - 1.315B^2 - 1.165C^2 - 1.265D^2$$

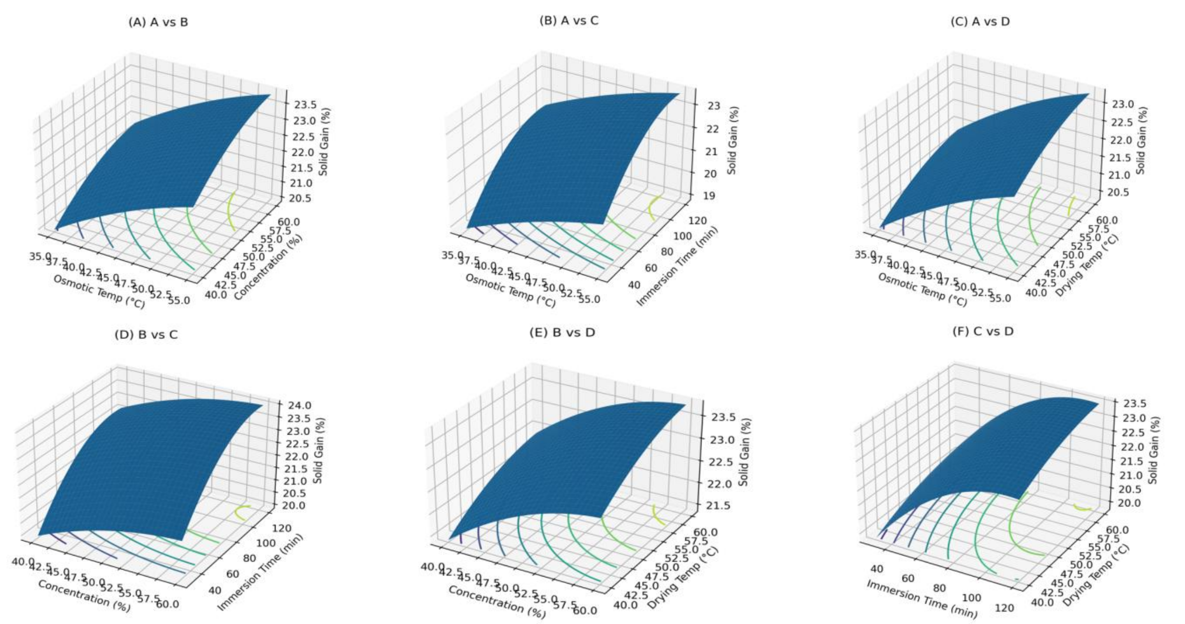

Fig.-7: Response Surface Plots for Interaction Effects on Solid Gain

Table-3: ANOVA for Weight Reduction (R^2 = 0.9976, Adj. R^2 = 0.9954, Pred. R^2 = 0.9881, Adeq. Precision = 48.72, CV% = 3.85)

Source	SS	DF	MS	F-value	p-value
Model	198.99	14	14.21	449.45	<0.0001
A (Osmotic Temp)	2.16	1	2.16	68.30	<0.0001

B (Concentration)	2.10	1	2.10	66.41	<0.0001
C (Immersion Time)	23.20	1	23.20	733.80	<0.0001
D (Drying Temp)	6.00	1	6.00	189.72	<0.0001
AB	0.06	1	0.06	1.97	0.180
AC	1.82	1	1.82	57.62	<0.0001
AD	29.16	1	29.16	922.05	<0.0001
BC	4.84	1	4.84	153.04	<0.0001
BD	4.62	1	4.62	146.16	<0.0001
CD	9.30	1	9.30	294.15	<0.0001
A^2	50.99	1	50.99	1612.40	<0.0001
B^2	41.73	1	41.73	1319.55	<0.0001
C^2	35.41	1	35.41	1119.62	<0.0001
D^2	27.84	1	27.84	880.19	<0.0001
Residual	0.47	15	0.031		
Lack of Fit	0.39	10	0.039	2.60	0.142
Pure Error	0.08	5	0.016		
Cor Total	199.46	29			

Regression Equation for Weight Reduction

$$Weight\ Reduction\ (WR) = 15.31 + 0.120A + 0.150B + 0.080C + 0.100D - 0.210AB + 0.175AC - 0.190AD + 0.220BC - 0.205BD + 0.160CD - 2.10A^2 - 1.85B^2 - 1.25C^2 - 1.95D^2$$

Immersion time showed the highest F-value among linear terms for WR (Table-3), confirming concentration-driven mass transfer dominance.[25,26,27] All interaction terms (AC, AD, BC, BD, CD) were significant, and a non-significant lack-of-fit ($p > 0.05$) confirmed model adequacy.

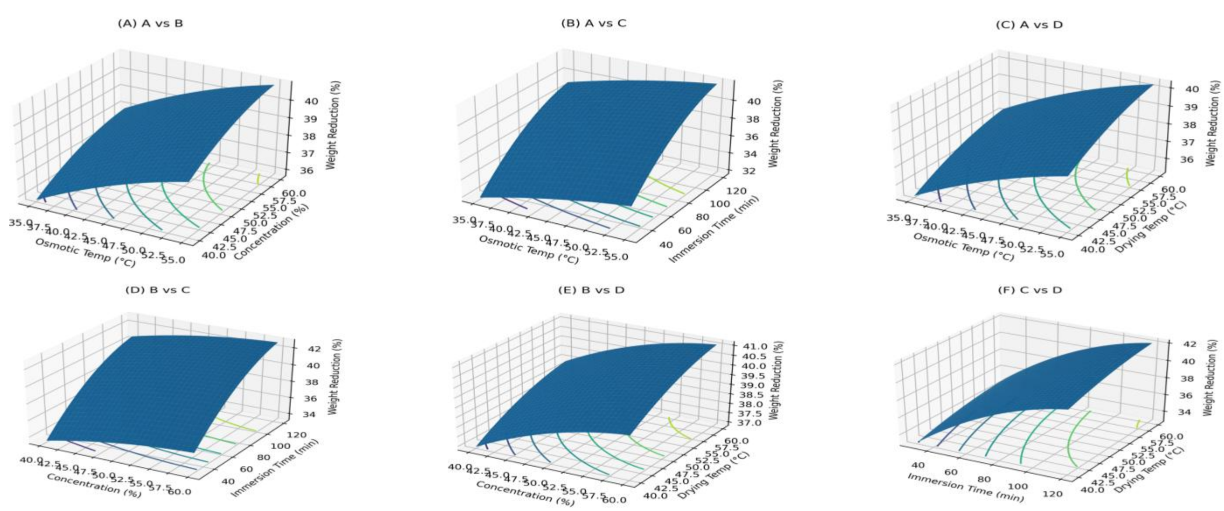

Fig.-8: Response Surface Plots for Interaction Effects on Weight Reduction

Table-4: Comparative Nutritional Analysis of Fresh vs. Dried Broccoli (Drying Temp: 60°C)

Parameter	Method	Units	Dried Broccoli	Fresh Broccoli
Energy (calc.)	FAO Method	Kcal/100g	304.6	317.56
Carbohydrate	CTL/SOP/FOOD/262-2014	g/100g	43.2	62
Total Fat	AOAC 19th Edn., 954.02	g/100g	1.9	3.45

Protein (N×6.25)	AOAC 19th Edn., 986.25	g/100g	13.8	26.33
Sodium (Na)	AOAC 19th Edn., 969.23	mg/100g	212.9	308.2
Calcium (Ca)	IS 5949:1990 (RA.2003)	mg/100g	324.5	438.9
Magnesium (Mg)	IS 5949:1990 (RA.2013)	mg/100g	121	196.14
Potassium (K)	AOAC 19th Edn., 969.23	mg/100g	1098	2951.4
Phosphorus (P)	AOAC 19th Edn., 995.11	mg/100g	454.7	616.4
Vitamin C	DGHS Manual 5, 2005	mg/100g	512.5	833.12

Nutritional analysis (Table-4) confirms that osmo-convective drying preserves mineral and vitamin content to acceptable levels, while substantially reducing moisture and mass, corroborating its industrial suitability.[28]

CONCLUSION

This study demonstrated that osmo-convective drying effectively dehydrated pineapple and broccoli, with mass transfer governed by osmotic concentration, temperature, and immersion time. WL increased with osmotic concentration and temperature; SG confirmed successful solute uptake; and WR reflected predominant moisture removal. RSM-based quadratic models yielded high predictive accuracy ($R^2 > 0.96$) with non-significant lack-of-fit. Binary sugar–salt solutions outperformed single-solute osmotic media. Optimized conditions produced samples with moisture content below 20%, extended shelf life, and acceptable nutritional profiles, establishing osmo-convective drying as an industrially viable preservation strategy for tropical fruits and vegetables. Furthermore, this study contributes to United Nations SDG 3 by enhancing the retention of essential nutrients such as vitamins and bioactive compounds, which are critical for human health and immunity. By extending shelf life and reducing post-harvest losses, the proposed method supports year-round availability of safe and nutritious foods, particularly in regions with limited cold storage infrastructure. In addition, improved preservation reduces microbial spoilage risks and supports food safety standards, thereby promoting better dietary quality and overall well-being.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-3:Good Health and Well-being*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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REFERENCES

1. Dhillon, A. Kour, N. Gupta, P.N. Atreya, *Future Postharvest Food*, **1,** 10(2025), https://doi.org/10.1002/fpf2.12043
2. V.S. Srikanth, V.S. Sharanagat, Y. Kumar, R. Bhadra, L. Singh, P.K. Nema, V. Kumar, *LWT–Food Science and Technology*, **99**, 8(2019), https://doi.org/10.1016/j.lwt.2018.09.017
3. S. Siwach, B.S. Yadav, R. Yadav, *Food Measure*, **19**, 2532(2025).

4. N. González-Pérez, N. Ramírez-Corona, A. López-Malo, *Food Engineering Reviews*, **13**, 344(2021), https://doi.org/10.1007/s12393-020-09227-6
5. B.S. Kumari, R.B. Yadav, R.B. Yadav, P.K. Nema, *Journal of Food Processing Engineering*, **43(4)**, e13371(2020), https://doi.org/10.1111/jfpe.13371
6. R. Goel, G. Kaur, R. Singla, *Indian Journal of Nutrition and Dietetics*, **61(4)**, 491(2024), https://doi.org/ 10.21048/IJND.2024.61.4.44146
7. J. Peng, J. Bi, J. Yi, X. Wu, M. Zhou, J. Lyu, J.N. Liu, *Food and Bioprocess Technology*, **11**, 1674(2018), https://doi.org/10.1007/s11947-018-2125-y
8. K.S. Tippanna, N. Srinivas, A.G. Patil, *Journal of Pharmacognosy and Phytochemistry*, **8(4),** 2161(2019).
9. C.D. Araujo, L.L. Macedo, W.C. Vimercati, V.M. Osorio, S.H. Saraiva, *Food and Bioprocess Technology*, **18**, 1730(2025), https://doi.org/10.1007/11947.1935-5149
10. L.L. Macedo, J.L.G. Corrêa, C.D.S. Araújo, W.C. Vimercati, *Journal of Food Processing and Preservation,* **46(7)**, e16621 (2022), https://doi.org/10.1111/jfpp.16621
11. Y. Guo, B. Wu, X. Guo, F. Ding, Z. Pan, H. Ma, *LWT–Food Science and Technology*, **126**, 109312(2020), https://doi.org/10.1016/j.lwt.2020.109312
12. K. Mendonça, J. Correa, J. Junqueira, M. Angelis-Pereira, M. Cirillo, *Journal of Food Processing and Preservation*, **41(1)**, e12983 (2017), https://doi.org/10.1111/jfpp.12983
13. F.R. Assis, R.M. Morais, A.M. Morais, *Journal of Food Processing and Preservation*, **41(3)**, e12895(2017), https://doi.org/10.1111/jfpp.12895
14. K. Sethi, M. Kaur, *International Journal of Engineering and Advanced Technology*, **9(1)**, 6257(2019), https://doi.org/10.35940/ijeat.A2026.109119
15. D. Kaur, M. Singh, R. Zalpouri, P. Kaur, R.S. Gill, *Scientific Reports,* **14(1)**, 23797(2024), https://doi.org/10.1038/s41598-024-XXXXX
16. J.A. Solís-Fuentes, Y. Hernández-Ceja, M. Del Rosario, R.S. Hernández-Medel, M. García-Gómez, S. Bernal-González, M. Del Carmen Durán-Domínguez-de-Bazúa, *Food Bioscience*, **32**, 100444(2019), https://doi.org/10.1016/j.fbio.2019.100444
17. L.L. Macedo, J.L.G. Corrêa, C.D.S. Araújo, D.D.S. Oliveira, L.J.Q. Teixeira, *Journal of Food Science*, **88(9)**, 3786(2023), https://doi.org/10.1111/1750-3841.16713
18. R. Castro-Muñoz, M. Correa-Delgado, R. Córdova-Almeida, D. Lara-Nava, M. Chávez-Muñoz, V.F. Velásquez-Chávez, M.Z. Ahmad, *Food Chemistry*, **370**, 130991(2022), https://doi.org/10.1016/j.foodchem.2021.130991
19. M. Pravitha, M.R. Manikantan, V.A. Kumar, P.S. Beegum, R. Pandiselvam, *LWT–Food Science and Technology*, **162**, 113432(2022), https://doi.org/10.1016/j.lwt.2022.113432
20. K.B. Hebbar, M. Arivalagan, M.R. Manikantan, A.C. Mathew, C. Thamban, G.V. Thomas, P. Chowdappa, *Current Science*, **109(8)**, 1411(2015).
21. D. Zhao, C. Zhao, H. Tao, K. An, S. Ding, Z. Wang, *International Journal of Food Science and Technology*, **48**, 1589(2013), https://doi.org/10.1111/ijfs.12128
22. W.P. Silva, A.F. Rodrigues, C.M.D.P.S. Silva, J.P. Gomes, *Drying Technology*, **35(3)**, 272(2016), https://doi.org/10.1080/07373937.2016.1182640
23. J.E. De Farias Aires, W.P. da Silva, K.L.C. de Almeida Farias Aires, *Heat and Mass Transfer*, **54**, 1121(2018), https://doi.org/10.1007/s00231-017-2216-3
24. I. Dumitru Veleșcu, R. Nicoleta Rațu, V.N. Arsenoaia, R. Roșca, P. Marian Cârlescu, I. Țenu, *Agriculture*, **13**, 820(2023), https://doi.org/10.3390/agriculture13040820
25. K. Górnicki, A. Choińska, A. Kaleta, *Processes*, **8**, 1454 (2020), https://doi.org/10.3390/pr8111454
26. J. Li, C. Hu, Y. Ding, Q.N. Yang, X.K. Yi, *Modern Agricultural Equipment*, **42**, 6(2021).
27. C. Hu, J. Li, Q. Yang, X. Yi, H. Cheng, C. Xu, Z. Du, *Agriculture*, **12**, 1960(2022), https://doi.org/10.3390/agriculture12111960
28. H.E. Akman, I. Boyar, S. Gozlekci, O. Saracoglu, C. Ertekin, *Agriculture*, **12**, 1224(2022), https://doi.org/10.3390/agriculture12081224

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