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Development and performance evaluation of a hybrid solar dryer using pumpkin fruit. Part 2. Analysis of the drying process and the operation of the equipment used

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This second part of our work presents the results of analyses of the process of drying pumpkin fruit slices at 50, 55, and 60 °C and slice thicknesses of 3, 5, and 7 mm. The dryer exhibited distinct heating phases under no-load and loaded conditions, with product load slowing the temperature rise. Drying temperature and slice thickness significantly affected drying rate and drying efficiency ($p<0.05$). The highest drying rate (12–14 kg/h) occurred within the first 2 hours, especially for 3 mm slices at 60 °C. The rate then declined to 2–3 kg/h between 2 and 5 hours and fell below 1 kg/h after 5 hours. Drying efficiency ranged from 42–58% at 50 °C, 47–72% at 55 °C, and increased markedly to 43–94% at 60 °C, with the 3 mm slices at 60 °C achieving the highest efficiency. Energy analysis showed a chamber efficiency of 32.2%. Product quality parameters, including shrinkage, rehydration ratio, proximate composition, microbial load, and colour, varied significantly with drying conditions. Economic analysis indicated a positive net benefit and a payback period of 1 year and 5 months. Overall, the hybrid dryer demonstrated high drying performance, improved energy use, acceptable product quality, and strong economic viability.

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1. Introduction

Drying is one of the most widely used preservation methods for fruits and vegetables because it lowers moisture content to levels that inhibit microbial activity, enzymatic reactions, and chemical degradation [1]. The effectiveness of the drying process is strongly influenced by drying temperature, slice thickness, and airflow, which govern heat and mass transfer dynamics during dehydration [2].

Studies have shown that reducing slice thickness significantly increases the drying rate by shortening

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the moisture diffusion pathway Doymaz [3], while optimized temperature selection enhances water removal without compromising nutritional quality [4]. Furthermore, thin-layer drying models have been shown to accurately explain drying behaviour when product geometry and operational parameters are well controlled [5]. These findings emphasize the need to investigate the combined effects of temperature and slice thickness when evaluating new drying systems.

In this study, a hybrid solar dryer integrating solar energy with a DC-powered heating unit was evaluated for drying pumpkin slices at three temperatures (50, 55, and 60 °C) and three slice thicknesses (3, 5, and 7 mm). The study aimed to analyse the temperature profile of the dryer under load and no-load conditions, assess drying rate and efficiency, and evaluate product quality factors including shrinkage, rehydration, proximate composition, microbial load, and colour attributes. An economic analysis was also conducted to determine the financial feasibility of the system. This work provides comprehensive insight into the technical and economic suitability of hybrid solar drying technology for pumpkin processing.

2. Material and methods

A detailed materials and methods section was discussed in the first part of the article [6].

3. Results and discussion

Temperature profile

Figure 1 represents the temperature profile in the hybrid cabinet dryer when evaluated with no load and with a load, respectively.

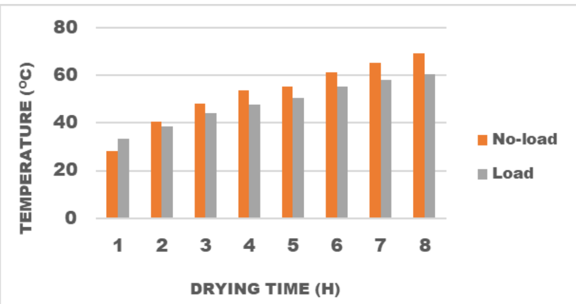


Fig. 1. Temperature profile in the hybrid cabinet dryer with no load and with a load.

The temperature rise during no-load testing was observed in two phases. In the first phase (0–4 h), the temperature increases relatively sharply from 28 °C to 52 °C, indicating that the system is heating up without product load. The distribution is more efficient and uniform due to no obstruction by the pumpkin slices. The temperature rises gradually from 52 °C to 68 °C in the second phase (4 –7 h), showing a steady-state behaviour where the system operates closer to its drying temperature setpoint.

But when loaded (pumpkin slices), the situation was slightly different. Although a similar two-phase drying behaviour can be seen, it was observed that the temperature in the first phase (0–4 h) increases from 31°C to 49 °C more slowly than in the no-load case. The presence of sliced pumpkin absorbs part of the heat, slowing the temperature rise. In the second phase (4 –7 h), a slower and more stable temperature rise from 49 °C to 60 °C was observed, exhibiting behaviour that is similar to achieving thermal equilibrium and an adiabatic process, which are characteristics of the food drying process [7]. The dryer was preheated and empty for 30 minutes before loading, which accounts for a slight increase in temperature at the beginning of drying when compared with unloaded testing.

Effect of drying temperature and pumpkin slice thickness on drying rate

The effects of drying temperature (50, 55, and 60 °C) and slice thickness (3, 5, and 7 mm) on drying rate were evaluated at a constant air velocity of 1.5 m/s. It was observed that both temperature and slice thickness had a significant effect on the drying rate of pumpkin ($p<0.05$). As shown in Figure 2, the drying rate was highest within the first 2 hours, ranging between 12–14 kg/h. At this stage, the 3 mm slices dried at 60 °C exhibited the fastest moisture removal, while the 7 mm slices dried at 50 °C recorded the slowest. Between 2–5 hours, the drying rate reduced suddenly to about 2–3 kg/h, but the influence of drying conditions was still significant ($p<0.05$), with higher temperatures and thinner slices maintaining higher rates of drying compared.

After 5 hours, the drying rate gradually declined below 1 kg/h, and by 10 hours, the differences among drying conditions became less distinct. However, the statistical analysis still showed that temperature and thickness significantly influenced the drying process ($p<0.05$). Beyond 10 hours, the drying rate approached zero across all treatments, indicating attainment of equilibrium moisture content. Moisture transfers due to drying occur due to capillary movement, molecular diffusion, thermal diffusion, pressure diffusion, and hydrodynamic flow [8]. Generally, the results show that drying pumpkin slices at higher temperatures and with reduced thickness not only accelerated drying but also significantly reduced the total drying time, making the process more efficient.

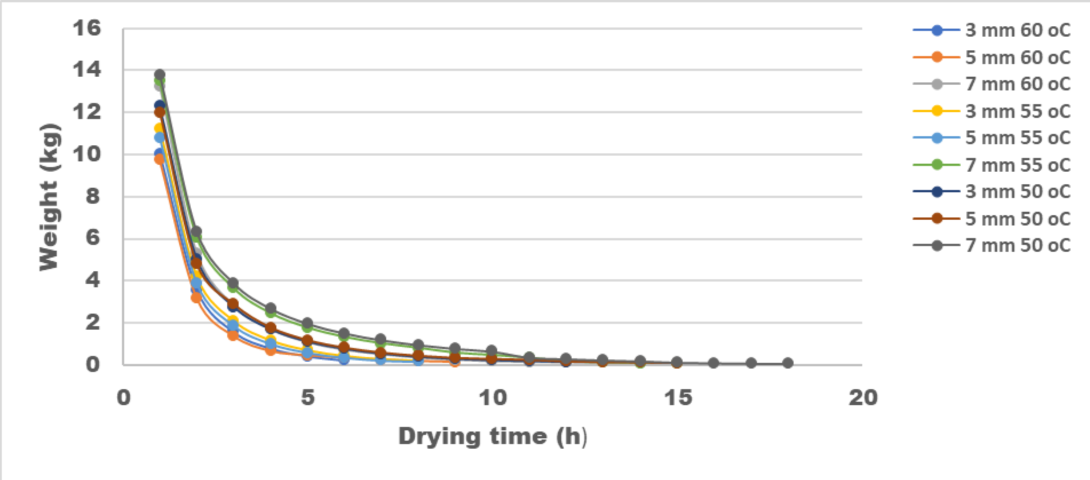


Fig. 2. Effect of temperature and slice thickness on drying rate of pumpkin

Effect of drying temperature and pumpkin slice thickness on drying efficiency

Drying performance across the tested conditions was conducted, and the result revealed significant differences in drying efficiency as influenced by both temperature and slice thickness. Figure 3 shows that drying temperature and slice thickness had a significant effect on the drying efficiency of pumpkin ($p<0.05$). At 50 °C, the drying efficiency was lowest across all slice thicknesses, with values of about 58%, 48%, and 42% for 3 mm, 5 mm, and 7 mm slices, respectively. Increasing the temperature to 55 °C significantly improved drying efficiency ($p<0.05$), particularly for thinner slices, where 3 mm samples achieved around 72% efficiency compared to 62% for 5 mm and 47% for 7 mm. This demonstrates that thinner slices responded better to moderate temperature increases, while thicker slices retained higher resistance to moisture removal.

At 60 °C, the differences among slice thicknesses became more pronounced. The 3 mm slices reached the highest drying efficiency of above 90%, which was significantly higher than both the 5 mm (64%) and 7 mm (43%) slices ($p<0.05$). These results indicate that while increasing drying temperature generally enhances drying efficiency, the magnitude of improvement depends strongly on slice thickness. Statistically, the interaction between temperature and thickness was significant ($p<0.05$), confirming that optimal drying efficiency can be achieved by combining higher temperatures with thinner slices.

These findings align with earlier research by Doymaz [9], who observed that reducing slice thickness significantly shortens drying time and increases drying rate in carrot slices. Similarly, Kidane et al. [10] reported that thin-layer drying models are most effective when the slice geometry is optimized for heat and mass transfer. Another study on mango slices by Kasse et al. [11] emphasized that both temperature and slice thickness significantly affect drying kinetics, with thinner slices consistently yielding higher drying efficiencies.

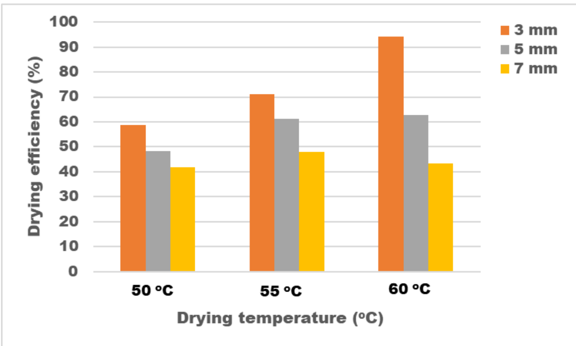


Fig. 3. Effect of temperature and pumpkin slice thickness on drying efficiency

Energy analysis

The drying chamber's energy efficiency, which shows the percentage of available energy that is efficiently used, was found to be 32.2%. The results of Cisni et al. [8] and Chinenye [12], who obtained exergy efficiency values ranging from 28.57% and 19.09-52%, respectively, are consistent with this conclusion. The amount of energy dissipated throughout the drying process in the hybrid cabinet dryer was demonstrated by the drying chamber's measured energy loss of 0.71 kJ.

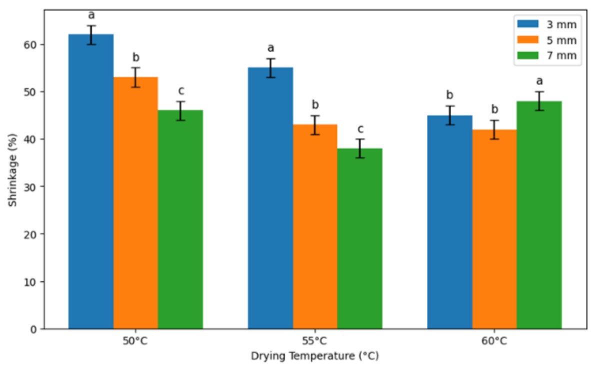
Effect of drying temperature on shrinkage and rehydration ratio

Figures 4 (a and b) present data on shrinkage (%) and rehydration ratio of pumpkin slices dried at three different temperatures (50°C, 55°C, and 60°C) and three slice thicknesses (3, 5, and 7 mm). The values are expressed as means ± standard deviation, and statistical significance is indicated using different lettered superscripts (values with the same letters are not significantly different at $p < 0.05$.

The results in Figure 4a show the influence of drying temperature and slice thickness on the shrinkage of pumpkin slices. Shrinkage decreased significantly ($p<0.05$) as slice thickness increased across all drying temperatures, with the 3 mm slices consistently exhibiting the lowest values. At 50°C, shrinkage was greatest, exceeding 60% for 3 mm slices, while 5 mm and 7 mm slices recorded significantly lower values of about 53% and 46%, respectively. This demonstrates that thinner slices are more prone to dimensional reduction due to their higher surface-area-to-volume ratio, which accelerates structural collapse during drying. As the drying temperature increased to 55 °C and 60 °C, shrinkage decreased significantly ($p<0.05$) for the thinner slices, with values dropping to 56% and 44%, respectively, for 3 mm slices. A similar trend was observed for the 5 mm slices, while the 7 mm slices showed a slight but significant ($p<0.05$) increase in shrinkage at 60 °C (47%), surpassing that of the 5 mm slices (42%). This indicates a temperature–thickness interaction effect, where thicker slices are more vulnerable to internal stress and structural collapse at elevated drying temperatures. It was generally observed that both drying temperature and slice thickness exert significant effects ($p<0.05$) on shrinkage, with moderate drying conditions (55 °C) minimizing shrinkage across all thicknesses. Seifu et al. [13] obtained a similar result where a gradual increase in shrinkage in drying onion as temperature increased from 50 °C to 90 °C. The result is also in agreement with the result reported by Abbasi et al. [14], where shrinkage increases as drying temperature increases from 60 to 90 °C.

Rehydration ratio is a quality parameter that reflects how well food material regains its initial form and indicates the extent of cell damage during drying [15]. It was observed that at 60 °C, rehydration capacity increased with increasing thickness from 3.69 (3 mm) to 4.44 (7 mm), as can be seen in Figure 4b. The rehydration ratios at 3 mm and 5 mm are not significantly different ($p>0.05$) but differ significantly ($p<0.05$) from 7 mm, while at 55 °C, the rehydration ratios at 5 mm and 7 mm are not significantly different ($p>0.05$) but are significantly different ($p<0.05$) from 3 mm. A similar trend was observed at 50 oC, where the rehydration ratios at 5 mm (4.46) and 7 mm (4.43) are not significantly different at ($p>0.05$) but are significantly different at ($p<0.05$) from 3 mm (4.49). The result obtained by Wang et al. [16] shows that the smaller the slice thickness, the higher the product rehydration performance, which is consistent with the results of this study. The result obtained by Srikanth et al. [17] also shows that the rehydration capacity increased with increasing drying temperature in a study on the drying and quality characteristics of yams. This could be because a thinner slice has a bigger specific surface area, which increases the likelihood of rehydration contact with water. This speeds up water absorption, which in turn increases the rehydration ratio [18, 19].

(a)



(b)

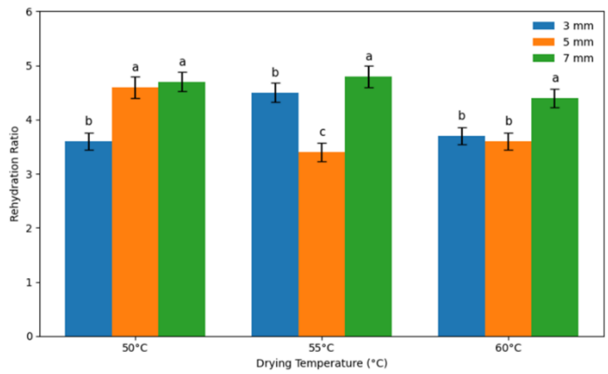


Fig. 4. Effect of drying temperature (50 °C, 55 °C, 60 °C) and slice thickness (3 mm, 5 mm, 7 mm) on shrinkage percentage and rehydration ratio of pumpkin slices

Quality of dried pumpkin slices

Effect of drying temperature and pumpkin slice thickness on nutritional content

The proximate composition of food reflects its basic nutritional value, which includes moisture, crude fibre, fat, ash, protein, and carbohydrate content. Table

1 presents the proximate composition (g/100 g) of fresh pumpkin and samples dried at 50, 55, and 60 °C.

The moisture content of pumpkin slices dried at 60 (9.38%), 55 (9.62%), and 50 °C (9.76%) was not significantly different from each other (p<0.05) except for the fresh sample, which is significantly different at (p>0.05). The moisture content of the fresh sample was found to be 89.74% and decreased significantly to 9.38, 9.62, and 9.76% after drying at 60, 55, and 50 °C. The moisture content of the dried samples decreased significantly as the drying temperature increased. Similar findings were made by [20], who found that drying aloe vera at 50, 60, 70, 80, and 90 °C significantly reduced its moisture content from 56.08% to 16.19%. Giang et al. [21] dried carrot peel powder at 50, 60, 70, and 80 °C and observed that the moisture content decreased from 8.67% to 6.18% with an increase in drying temperature, a similar result reported by Ihns et al. [22] in the drying of sweet potato flour. This outcome is in line with research by Limpaiboon et al. [23], which found that raising the drying temperature speeds up the process of removing water from vegetables, thereby increasing drying efficiency.

The result shows that crude fibre content increased significantly with temperature. The crude fibre for the fresh sample (1.75 g/100 g) and the samples dried at 60 °C (6.71 g/100 g), 55 °C (6.01 g/100 g), and 50 °C (5.08 g/100 g) were significantly different from each other (p<0.05). The observed increases could be attributed to the relative concentration of fibrous material following the loss of water. The studies done by Mota et al. [24] on onion show that the maximum crude fibre content of 6.10 ± 0.89 g/100 g was obtained at a low drying temperature of 40 °C. However, for sweet potato flour and olive-waste cake, [24] and [25] reported the highest crude fibre content of 5.95 g/100g and 24.31 ± 1.21 g/100g at 60 °C, respectively.

Fat content in the fresh sample was observed to be relatively low at 0.87 g/100 g. This value increased with an increase in drying temperature to 2.07, 2.06, and 2.12 g for drying at 50, 55, and 60 °C, respectively. The fat content for the fresh sample was significantly different (p<0.05) from the samples dried at 60 °C, 55 °C, and 50 °C, whereas the samples dried at 60 °C, 55 °C, and 50 °C were not significantly different from each other (p>0.05). The changes in fat content are primarily due to the concentration effect caused by moisture loss rather than a genuine increase in fat levels. Similar result of fat content was found in drying sweet potato flour and onion flour by Ihns et al. [22] and Mota et al. [24], who reported the minimum fat content values of 0.24 ± 0.08 g/100g and 0.59 g/100g, respectively, at 30 °C and 65 °C, respectively, and then increased as the temperature increased.

Ash content is an indicator of the total mineral content, and it was observed to vary at different drying temperatures. The Ash content dried at 50 and 55 °C is not significantly different (p>0.05) from each other, whereas the samples dried at 60 °C are significantly different (p<0.05). The Ash content increased as the temperature increased from the fresh sample value of 1.05 g/100g to 2.18, 2.23, and 3.01 g/100g for drying at 50, 55, and 60 °C, respectively. A maximum Ash content of 5.28 ± 0.35 g/100g dried at 40 °C was obtained by Ihns et al. [22], while Özkan Karabacak et al. [18] obtained a maximum ash value of 10.0 g/100g at 80 °C for carrot peel powder. At maximum temperature, the concentration of ash content was observed. This could be because insoluble forms of dietary fibre and ash are insoluble in water, and as the moisture content decreases due to drying, the density of ash and crude fibre rises per unit volume.

Protein content for the fresh sample and the samples dried at 50, 55, and 60 °C were observed to be significantly different from each other at (p<0.05). A noticeable increase in protein content as the drying temperature increased was observed from 2.03 g/100g in fresh samples to 10.77, 12.04, and 15.07 g/100g at 50, 55, and 60 °C, respectively. This trend is similar to observations by Garba et al. [26], who noted significant increases in protein content during pumpkin drying due to moisture loss and the concentration of solid matter. A similar result obtained by Limpaiboon et al. [23] also shows that the protein content of olive-waste cake increases with temperature.

In contrast to other components, carbohydrate content decreased with increasing temperature: 70.14 (50 °C), 68.04 (55 °C), and 63.71 g/100g (60 °C), compared to 4.56 g/100g in the fresh sample. The total carbohydrate for the fresh sample and the samples dried at 50, 55, and 60 °C were observed to be significantly different from each other (p<0.05). Although dehydration concentrates total solids, higher temperatures may promote thermal degradation of sugars and starches, leading to a slight decline in measurable carbohydrate content. Venkat et al. [27] confirmed that extended drying at elevated temperatures can break down simple sugars, reducing total carbohydrate values. Thus, lower drying temperatures may be more favourable for carbohydrate preservation.

Table 1. Proximate composition of fresh and dried pumpkin slices at various drying temperature

	Proximate Composition (g/100g)					
Treatment	**Moisture Content**	**Crude Fiber**	**Crude Fat**	**Ash**	**Crude Protein**	**Total Carbohydrate**
Fresh	89.74^{b}	1.75^{a}	0.87^{a}	1.05^{a}	2.03^{a}	4.56^{a}
60 °C	9.38^{a}	6.71^{d}	2.12^{b}	3.01^{c}	15.05^{d}	63.71^{b}
55 °C	9.62^{a}	6.01^{c}	2.06^{b}	2.23^{b}	12.04^{c}	68.04c
50 °C	9.76^{a}	5.08^{b}	2.07^{b}	2.18^{b}	10.77^{b}	70.14^{d}

Columns with similar subscripts are not significantly different ($p<0.05$).

Total plate count test (TPC)

A residual bacterial load of 2.28×10^5 CFU/g was achieved under drying conditions of approximately 55–60 °C using medium slice thickness (5–7 mm. This value is within the acceptable microbial limits for dried fruits and vegetables (10^3 and 10^6 CFU/g), depending on the intended use [28]. Nonetheless, it emphasizes how crucial hygienic procedures are throughout the processing to preserve the quality and safety of the final product. The bacterial load observed may reflect lapses in hygienic handling, post-drying contamination, or suboptimal drying conditions. Although the bacterial load remains within acceptable limits, it indicates the necessity for improved drying protocols and post-processing hygiene.

Effect of drying temperatures on colour parameters of dried pumpkin

Colour is an important quality factor in dried fruits and vegetables, influencing both consumer acceptance and perceived freshness. Table 2 shows the results of an evaluation of the impact of various drying temperatures (50, 55, and 60 °C) on the colour characteristics of pumpkin.

The L^* value defines the lightness of products; a value less than 50 indicates darkness, and a value higher than 50 describes lightness. The L^* values (50.90) for the fresh sample and 60 °C dried samples are not significantly different ($p>0.05$) but significantly different ($p<0.05$) from the L^* values recorded in 50 and 55 °C dried samples. The highest L^* value (52.34) was observed with the dried sample at 60 °C, whereas the least L^* value (39.38) was seen in the samples dried at 50 °C. Özkan Karabacak *et al.* [19] show that drying carrot peel powder at 50, 60, 70, and 80 °C results in a comparable rise in L^* values. Chinese jujube was dried at 50 °C, 60 °C, and 70 °C, and the L^* parameter dropped from 93.1 to 90.1in a study by Wang *et al.* [29]. The darker colour of dried goods is indicated by a drop in the L^* parameter's value. This indicates that fresh produce has a greater L^* rating for colour than dry produce.

The a^* value (36.46) for the fresh sample is similar ($p>0.05$) to the dried samples at 60 and 50 °C but significantly differs ($p<0.05$) from the a^* value recorded in 55 °C samples. The least a^* value (33.78) was observed with the dried sample at 50 °C, while the highest a^* value (40.90) was seen in the samples dried at 55 °C. Vega-Galvez *et al.* [30] found that when the drying temperature increased, the carrot's a^* parameter value increased from 28 to 36.5. However, for carrot peel powder by [18], when the drying temperature rises, the value of the a^* parameter falls from 25.7 to 19.4. With an increase in drying temperature, the value of the a^* parameter for Chinese jujube and sweet potato flour by Venkat *et al.* [27] and Mota *et al.* [24] rises from 0.2 to 1 and from 2.24 to 2.88, respectively. The redness of fruits and vegetables is indicated by the value of parameter a^*. From the obtained results, it was observed that when the drying temperature rises, the redness of the dried pumpkin only increases at 55 °C (40.90) and falls at 60 °C (33.99) and 50 °C (33.78).

The b^* value indicates the yellowness in fruits and vegetables. The b^* values (85.82) for the fresh sample and the dried samples at 60 °C (87.16) and 50 °C (84.17) are similar ($p>0.05$) but differ significantly ($p<0.05$) from the b^* values recorded in 55 °C (77.74) dried samples. The result obtained from CAC/RCP [27] for dried carrot shows an increase in b^* value with an increase in temperature. The b^* value rises from 13 to 22 as the drying temperature rises for Chinese jujube and sweet potato flour dried by Venkat *et al.* [27]. While the drop in b^* value, as seen at 55 °C (77.74) and 50 °C (84.17), may be the result of thermal degradation of yellow pigments, the increase in b^* value at 60 °C (87.16) may be the result of the development of a browning component linked to the non-enzymatic reaction.

The total colour change ΔE of the dried pumpkin slices increased with temperature. This was expected because the higher the drying temperature, the more colour deterioration took place in the dried pumpkin slices. The ΔE value for dried samples at 50 (4.64) and 55 °C (6.38) are not significantly different (p>0.05) but significantly different (p<0.05) from samples dried at 60 °C (13.72). A similar result was observed by Ihns *et al.* [22], the ΔE of Southern Red Apricot increased from 8.2 to 20.6 as the temperature increased from 60 to 100 °C, while that of Moorpark Apricot also increased from 17.0 to 35.1 under the same temperature conditions.

Chroma (*c*) reflects the colour vividness or dullness, and the results indicate that the chroma (*c*) values decreased with increasing temperature. However, the chroma (c) for fresh pumpkin (94.95) and the dried pumpkin slices at 50 °C (93.55) and 55 °C (90.70) were not significantly different from each other (p<0.05), while the sample dried at 60 °C (87.84) differed significantly (p>0.05). Ihns *et al.* [22] and Karabulut *et al.* [31] also observed that the chroma of non-sulphurated dried apricots decreased with increasing drying temperature.

As the drying temperature increased, the hue angle (h) values of the dried pumpkin slices decreased. The samples dried at 60 °C (62.25 °C) were significantly different from the fresh sample (p<0.05), but the samples dried at 50 °C (68.34 °C) and 55 °C (68.10 °C) were not substantially different from one another (p<0.05). The sample dried at 50 °C had the maximum hue angle (h) (68.34), whereas the sample dried at 60 °C had the lowest value (62.25). Similar findings were reported by Ihns et al. [22] and Karabulut et al. [31], who noted that as the drying temperature increased, the hue angle (h) values of non-sulfurated dried apricots decreased.

Table 2. Effect of drying temperatures on colour parameters of dried pumpkin

Samples	T (°C)	L^*	a^*	b^*	ΔE	c	h
Fresh	-	50.90^c	36.46^a	85.82^b	-	94.95^b	68.49^b
Dried	60	52.34^c	33.99^a	87.16^b	13.72^b	87.84^a	62.25^a
	55	46.29^b	40.90^b	77.74^a	6.38^a	90.70^{ab}	68.10^b
	50	39.38^a	33.78^a	84.17^b	4.64^a	93.55^b	68.34^b

Columns with similar subscripts are not significantly different (p<0.05).

Economic Analysis

In evaluating the economic viability of the developed hybrid cabinet dryer, some key financial performance indicators were computed, which include the Net Benefit, Benefit-Cost Ratio, Profitability Index, and the Payback Period. The result shows a positive net benefit of N157,400 (Naira). A benefit-cost ratio of 1.2 signifies that for every N1 invested, there will be a return of N1.20 (Naira), a 20% return on the capital invested, and a payback period of approximately 1 year 5 months.

Conclusion

The hybrid solar dryer demonstrated effective performance in drying pumpkin slices across the tested temperatures and slice thicknesses. The temperature profile confirmed stable heating behaviour, while drying rate and drying efficiency were significantly influenced by both drying temperature and slice thickness. Higher temperatures and thinner slices promoted faster moisture removal and improved overall drying efficiency. Energy analysis showed that the dryer utilized energy effectively, with an efficiency value comparable to previously reported ranges. Quality evaluation revealed that drying conditions affected shrinkage, rehydration ratio, proximate composition, microbial load, and colour characteristics of the dried product. Economic assessment further established the dryer's viability, showing a positive net return, a favourable benefit-cost ratio, and a short payback period. Overall, the hybrid solar dryer provides a reliable, energy-efficient, and economically feasible solution for producing high-quality dried pumpkin slices.

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