Food and Bioprocess Technology (2025) 18:6726–6742
https://doi.org/10.1007/s11947-025-03862-1

RESEARCH

The Impact of Hot Air Drying and Vacuum Drying on Oat Pulp Quality

Minh Son Le[1] · **Christian Hermansen**[2] · **Quan V. Vuong**[1]

Received: 17 December 2024 / Accepted: 22 April 2025 / Published online: 30 April 2025

Abstract
Oat pulp, a by-product of oat milk production, is highly nutritious but prone to spoilage due to its high moisture content (over 60%), suggesting effective drying for preservation and further utilisation. This study investigated the thin-layer drying kinetics of oat pulp using hot air drying (HAD) and vacuum drying (VD) at different temperatures (70 °C, 90 °C, 110 °C) and thicknesses (0.5 cm, 0.75 cm, 1 cm). Drying performance was evaluated based on drying rate, water activity, phenolic retention, antioxidant activity and energy consumption. Results indicated that higher temperatures and thinner layers increased drying rates and reduced drying times. Effective moisture diffusivity ranged from $5.49\times10^{-10}\pm2.64\times10^{-11}$ to $8.93\times10^{-9}\pm1.06\times10^{-10}$ m^2/s, with HAD exhibiting higher values than VD. Activation energy varied between 10.25 ± 1.67 and 23.76 ± 3.39 kJ/mol. The Henderson and Pabis model best describes oat pulp drying behaviours across tested conditions. Both HAD and VD at 90 °C and 110 °C reduced energy consumption, lowered water activity, and preserved more bioactive compounds compared to 70 °C. HAD was more energy efficient than VD while maintaining higher phenolic content and antioxidant properties. HAD at 110 °C for 2.5 h with a 1 cm thickness provided a balance of energy consumption, batch capacity, and bioactive retention. The dried oat pulp had 60% less weight and water activity of 0.33, ensuring microbiological stability and facilitating easier transport and storage. These findings provide valuable insights for optimizing oat pulp drying for further applications.

Keywords Oat waste · Oat milk · Oat pulp · Oat okara · Hot air drying · Vacuum drying · Waste valorisation

Introduction

Oat pulp, a solid by-product of oat milk and oat beverage production, is often relegated to animal feed, biogas production, (Oatly 2021) or landfill disposal (Helstad et al., 2023). Despite being treated as waste, oat pulp is nutritionally rich, containing 16–37% dietary fibre, 25–52% protein, and various phenolic compounds with high antioxidant capacity (Aiello et al., 2021; Bartkiene et al., 2021; Helstad et al., 2023; Wang et al., 2023). For every kilogram of oat milk produced, approximately 0.2–0.4 kg of oat pulp is generated (Deswal et al., 2014; Helstad et al., 2023; Röös et al., 2016; Yu et al., 2023), Given the global oat milk market, valued at nearly $3 billion (MarketsandMarkets™, 2023), with an average retail price of $5 per 64 oz (1.9 L), this translates to an annual production of 228 kilotons of oat pulp, projected to reach 500 kilotons by 2030 (Le et al., 2025). This escalating by-product volume presents significant waste management and sustainability challenges.

Repurposing oat pulp into human food applications offers a viable solution, supporting the circular bioeconomy and sustainable food production. Previous studies highlight its potential applications in high-fibre plant-based meat analogues, functional biscuits, bread, and fermented products (Bartkiene et al., 2021; Meanti et al., 2024; Wang et al., 2023; Zahari et al., 2023). However, short shelf-life is the major challenge for commercial applications due to its high moisture content which leads to rapid degradation (Helstad et al., 2023), therefore drying is a key strategy to reduce moisture and extend its shelf-life. Drying not only reduces water content but also increases biological stability and lowers handling, storage, and transportation costs by reducing material weight and volume (Kumar et al., 2012; Patrón-Vázquez et al., 2019).

✉ Quan V. Vuong
vanquan.vuong@newcastle.edu.au

[1] School of Environmental and Life Sciences, College of Engineering, Science and Environment, The University of Newcastle, Ourimbah, NSW 2258, Australia

[2] Singapore Institute of Food and Biotechnology Innovation (SIFBI), Agency for Science, Technology, and Research (A*STAR), 31 Biopolis Way, Nanos, Singapore 138669, Singapore

For high-volume food by-products like oat pulp, which are low-value yet high in moisture and dietary fibre, feasible drying methods such as hot air drying or vacuum drying present cost-effective, efficient, and scalable solutions (Davy & Vuong, 2021; Kieu Tran et al., 2020; Kumar et al., 2012). For instance, studies on soy okara demonstrated that drying at 100 °C using hot air or vacuum drying (309.8 mmHg) provides a faster drying time than freeze drying while retaining higher levels of phenolic compounds, antioxidant capacity, and soy saponins (Davy & Vuong, 2021). Hot air drying is a traditional method, simple and cost-effective but it can be energy-intensive compared to more advanced techniques like microwave drying (Martynenko & Vieira, 2023; Saifullah et al., 2019). It is also often associated with undesirable changes in sensory qualities and reduced rehydration ability in dried products (Lee & Zuo, 2013). In contrast, vacuum drying, conducted at reduced pressure, lowers the boiling point of water and eliminates oxygen, making it preferable for heat-sensitive products and compounds (Lee & Zuo, 2013). However, the effectiveness of each method depends heavily on the specific drying conditions and the nature of the sample being dried, which influence drying time, energy consumption, and product quality outcomes.

Drying is a complex process involving simultaneous heat and mass transfer (Onwude et al., 2016a, b). For food and by-products, thin-layer drying is a commonly used method (Onwude et al., 2016a, b), and thin-layer drying models serve as mathematical tools to simulate drying kinetics, predict moisture content changes over time, and optimise drying conditions (Onwude et al., 2016a, b; Zeng et al., 2024). The models, such as the Page, Newton (Lewis), Henderson and Pabis, Midilli et al., Logarithmic, and Two-Term models, have been widely applied in thin-layer drying (Onwude et al., 2016a, b). Optimizing the drying conditions for oat pulp requires integrating drying kinetics analysis with assessments of chemical properties, such as phenolic content and antioxidant capacity retention. This approach can help identify the optimal drying parameters, including time, temperature, and sample thickness (Davy & Vuong, 2021; Demiray et al., 2023).

While many studies have investigated the applications of dried oat pulp, there have been none exploring the effects of drying conditions on the starting material itself. This gap limits the understanding of the drying behaviour of oat pulp, its property changes during drying, and the determination of effective drying conditions to prevent excessive drying, which can negatively impact the quality of the final product. Therefore, this study aimed to investigate the drying kinetics of oat pulp and compare different drying temperatures and thicknesses using hot air drying (HAD) and vacuum drying (VD), focusing on physical properties, energy consumption, phenolic content retention, and antioxidant capacity. To the best of our knowledge, this is the first study to determine the antioxidant activity of fresh and dried oat pulp.

Materials and Methods

Materials

Fresh oat pulp was collected from Sanitarium, a commercial food company, in Warnervale NSW 2259, Australia, and immediately stored at −18 °C to minimise degradation until analysis. Before drying, the frozen pulp was thawed overnight at 5 °C. The initial moisture content of oat pulp was determined in triplicates by a moisture analyser (Shimadzu MOC63u, Kyoto, Japan).

Analytical grade chemicals from Sigma Aldrich (Castle Hill, Sydney, Australia) used for analysis included, gallic acid, Folin-Ciocalteu reagent, sodium carbonate (Na_2CO_3), Trolox, 2,4,6-tris(2pyridyl)-s-triazine (TPTZ), sodium acetate, iron (III) chloride ($FeCl_3$), hydrochloric acid (HCl), 2,2-Azino-bis(3-ethylbenzothiazoline-6-sulphoonic acid) diammonium salt (ABTS), potassium persulfate ($K_2S_2O_8$), 2,2-diphenyl-1-picrylhydrazil (DPPH), acetone, methanol.

Drying Experiment and Determination of Drying Kinetics

Fresh oat pulp was dried using freeze drying (FD, control), hot air drying (HAD), and vacuum drying (VAD). For FD, the pulp was spread evenly onto an aluminium tray (21 × 21 cm) to a thickness of 0.5 cm, frozen at −20 °C for 24 h before being lyophilized in a freeze dryer (VirTis Bench Top Pro SP Scientific, Warminster, Pennsylvania, U.S.A.) for 24 h.

For both HAD and VD, three thicknesses including 0.5 cm, 0.75 cm, and 1 cm were tested, and measured with a digital Vernier calliper. Drying for each thickness layer was done in triplicates, simultaneously at 70 °C, 90 °C, and 110 °C using HAD (Memmert UM400, Germany) with natural convection and VD (Memmert VO200, Germany), with vacuum pressure for VD set at 450 mmHg. Ovens were preheated to the desired drying temperature, and drying continued until the sample weight remained constant over three consecutive measurements, with weights recorded every 10 min. After drying, dried samples were ground, sieved through a 250 µm mesh, and stored at −18 °C for further analysis.

The moisture content at specific drying times was converted to a dimensionless moisture ratio (MR) using Eq. 1. The MR was then plotted against drying time to construct the drying kinetic curves (Kucuk et al., 2014)

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where M_t is the moisture content at time t on a dry weight basis (g, dwb), M_0 is the initial moisture content (g, dwb), and M_e is the equilibrium moisture content (g, dwb). At longer drying times, M_e becomes negligible compared to

M_t and M_0 so Eq. 1 was simplified to $MR = M_t/M_0$ (Chigbo et al., 2024).

The drying rate, which reflects the drying behaviour of oat pulp and the efficiency of the drying technique, was calculated using the following equation (Zeng et al., 2024):

$$Dryingrate = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (2)$$

Mathematical Modelling of Drying Characteristic

The drying kinetic curves were fitted to six commonly used thin-layer drying models (Table 1). The model constants for each model were determined using the nonlinear least squares method with the SOLVER tool in Microsoft Excel, based on the generalized reduced gradient method (Chigbo et al., 2024). The goodness of fit between the experimental and predicted data was assessed using three key parameters: the coefficient of determination (R^2), root mean square error (RMSE), and sum of squared errors (SSE), calculated using JMP Pro 17 software. The coefficient of determination (R^2) is the most critical parameter, indicating the quality of the fit, while RMSE evaluates prediction accuracy, and SSE represents the total variance between the experimental and predicted values. The most suitable model for describing the drying behaviour of oat pulp was identified by the highest R^2 and the lowest RMSE and SSE values.

Determination of Effective Moisture Diffusivity and Activation Energy

The effective moisture diffusivity (D_{eff}) was determined for a slab shape using Fick's second law of diffusion, which is expressed as follows (Crank, 1979):

$$MR = \frac{8}{\pi^2}\exp\left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (3)$$

Taking natural logarithm of both sides:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{4L^2} \quad (4)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), t is the drying time (min), and L is the half-thickness of the slab (m). The effective diffusivities were calculated from the slope ($-\frac{\pi^2 D_{eff} t}{4L^2}$) of the plot ln (MR) against drying time (t).

Activation energy (E_a) refers to the energy required to initiate the drying process and facilitate the movement of water molecules from the materials to the surrounding environment. The relationship between D_{eff} and temperature can be described by the Arrhenius equation (Onwude et al., 2016a, b):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

Taking natural logarithms on both sides:

$$\ln\left(D_{eff}\right) = \ln\left(D_0\right) - \frac{E_a}{R} * \frac{1}{T} \quad (6)$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a is the activation energy (J/mol), R is the gas constant (8.3145 J mol^{-1} K^{-1}), and T is the drying temperature (K). The activation energy was obtained from the slope ($-E_a/R$) of the plot of ln (D_{eff}) versus 1/T.

Determination of the Effects of Drying Conditions on Oat Pulp quality.

Physical Properties and Energy Consumption

Water activity (a_w) of the samples was measured in triplicate by an Aqualab Pawkit water activity meter (METER ®, Pullman, Washington, WA, USA).

Colour changes in the dried samples, compared to the fresh samples, were assessed using the CIE LAB colour space, which is commonly employed to describe food colour (Marković et al., 2013). *L*, a**, and *b** values were obtained using a handheld colourimeter (Konica Minolta

Table 1 Thin layer drying mathematical models tested for the hot air and vacuum drying of oat pulp

Model name	Model equation	References
Newton	$MR = exp(-kt)$	(El-Beltagy et al., 2007)
Page	$MR = exp(-kt^n)$	(Akoy, 2014)
Henderson and Pabis	$MR = a * exp(-kt)$	(Hashim et al., 2014)
Midilli et al	$MR = a * exp(-kt^n) + bt$	(Ayadi et al., 2014)
Logarithmic	$MR = a * exp(-kt) + b$	(Biswas et al., 2022)
Two-term	$MR = a * exp(-k_1 t) + b * exp(-k_2 t)$	(Popescu et al., 2023)

*MR – moisture ratio (dimensionless); k, k_1, k_2 – drying constants (s^{-1}); a, b, n – model constants (dimensionless); t – drying time (s)

CR-400/410, Osaka, Japan). These values were then used to calculate the following colour attributes:

Browning index (*BI*) (Oliveira et al., 2015):

$$BI = \frac{100(x - 0.31)}{0.17}, \quad (7)$$

where $x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 0.30121b^*}$

Total colour change (ΔE) (Zielinska & Markowski, 2012):

$$\Delta E = \sqrt{(\Delta L^2 + \Delta a^2 + \Delta b^2)} \quad (8)$$

Energy consumption (EC) for drying conditions was estimated following the method described by Saifullah et al. (2019). EC was calculated using the following equation:

$$EC(kWh) = \frac{D_{temp}}{M_{temp}} * MO * t \quad (9)$$

where D_{temp} is the current drying temperature (°C), M_{temp} is the maximum temperature of the oven (°C), MO is the maximum power of the oven (kW), and t is drying time (hours).

Determination of total phenolic content and antioxidant activity

To determine the total phenolic content and antioxidant capacity of fresh and dried oat pulp, the samples were extracted using 50% aqueous acetone (1:5 g/mL) with sonication at 35 °C and 150 W for 30 min (Soniclean, Pty Ltd., Thebarton, Australia). The mixtures were then centrifuged (Eppendorf 5804R, Australia) at 4,000 rpm for 30 min at 10 °C. The resulting supernatants were collected and immediately analysed for total phenolic content and antioxidant capacity.

Total phenolic contents (TPC) The total phenolic content (TPC) of each sample extract was determined using the Folin-Ciocalteu method, as described by Vuong et al. (2013), with gallic acid as the standard. Briefly, a 1 mL aliquot of the extract was combined with 5 mL 10% Folin-Ciocalteu reagent, vortexed, and left to stand in the dark for 8 min. Then, 4 mL 7.5% Na_2CO_3 solution was added and incubated in the dark for 1 h at room temperature. Absorbance was measured at 765 nm using a UV spectrophotometer (Cary 60 Bio, UV–Vis, Malaysia) in triplicate, and results were expressed as mg gallic acid equivalents per gram of dry sample (mg GAE/g dwb).

Ferric reducing antioxidant power (FRAP) FRAP assay was carried out as described by Vuong et al. (2013) with Trolox used as a standard. Briefly, a fresh FRAP solution was prepared by mixing 300 mM acetate buffer, 10 mM TPTZ in 40 mM HCl, and 20 mM $FeCl_3$ in a 10:1:1 ratio, and warmed to 37 °C. For the assay, 2.85 mL of FRAP solution was combined with 0.15 mL of the extract and incubated in the dark for 30 min at room temperature. Absorbance was measured at 593 nm in triplicates using a UV spectrophotometer (Cary 60 Bio, UV–Vis, Malaysia), with results expressed as mg Trolox equivalents per gram of dry sample on dwb (mg TE/g dwb).

ABTS scavenging capacity ABTS radical scavenging capacity was determined following the method of Vuong et al. (2013) using Trolox as a standard. A stock solution was prepared by mixing equal volumes of 7.4 mM ABTS and 2.6 mM potassium persulfate and incubating in the dark for 12–16 h at room temperature. The working solution was made by diluting 1 mL of the stock with 60 mL methanol to achieve an absorbance of 1.1 ± 0.02 at 734 nm. For the assay, 0.15 mL of sample extract was mixed with 2.85 mL of working solution and incubated for 2 h. Absorbance was measured at 734 nm using a UV–Vis spectrophotometer (Cary 60 Bio, UV–Vis, Malaysia). Results were expressed as mg Trolox equivalents per gram of sample on dwb (mg TE/g dwb).

DPPH scavenging capacity DPPH radical scavenging capacity was examined following the method of Vuong et al. (2013) using Trolox as a standard. A stock solution of 0.024 g DPPH in 100 mL methanol was prepared and stored at −20 °C. A working solution was made by diluting 10 mL of stock with 45 mL methanol to achieve an absorbance of 1.1 ± 0.02 units at 515 nm. For the assay, 0.15 mL of extract was mixed with 2.85 mL of working solution and incubated for 3 h. Absorbance was measured at 515 nm in triplicates using a UV–Vis spectrophotometer (Cary 60 Bio, UV–Vis, Malaysia). Results were expressed as mg Trolox equivalents per gram of sample on dwb (mg TE/g dwb).

Statistical Analysis

All results were measured in triplicates and are presented as means ± standard deviations (SD). One-way analysis of variance (ANOVA) and all pairs Tukey HSD were used to statistically compare the means using JMP PRO 17 statistic software version 17.0, with a significance level at $p < 0.05$.

Results and Discussion

Effect of Temperature and Layer Thickness on Drying Rate and Time

The effect of different drying temperatures and layer thicknesses on oat pulp was analysed, with Figs. 1a-b showing moisture content changes over time and Figs. 1c-d illustrating drying rates during HAD and VD. The results show that increasing the drying temperature from 70 °C to 110 °C or

decreasing the layer thickness from 1 cm to 0.5 cm significantly reduced drying time for both drying methods (Fig. 1a-b). For instance, at 0.5 cm thickness, drying oat pulp with HAD at 110 °C reduced the time to reach constant weight from 210 to 110 min (70 °C) (Fig. 1a). Similarly, reducing the thickness from 1 cm to 0.5 cm at 70 °C using HAD shortened the drying time from 300 to 210 min (Fig. 1a). Both HAD and VD exhibited a similar trend that is drying rate increased with higher temperature and thinner layers (Figs. 1c-d); however, the drying rate of HAD 70 °C, 90 °C, and 110 °C was higher than VD across all thicknesses (Fig. 1c-d). Faster drying times and drying rates at high drying temperatures can be explained by the increased moisture diffusion from the interior to the surface and the moisture absorption capacity of the surrounding air, which has lower humidity. This creates a larger moisture gradient between the sample and ambient air, reducing drying time (Zeng et al., 2024). Thinner layers also facilitate quicker evaporation by reducing the distance water must travel (Chigbo et al., 2024). With VD, increasing temperature raises the vapour pressure inside the sample, creating a larger vapour pressure gradient between the sample and the drying chamber, which speeds up the drying process (Mitra et al., 2011). Similar trends were observed in previous studies (Davy & Vuong, 2021; Vu et al., 2022; Zeng et al., 2024). It should be noted that VD took longer than HAD at the same temperature or thickness (Fig. 1a-b, 1c-d). For example, at 110 °C with 1 cm thickness, VD required 180 min to reach constant weight, whereas HAD took only 150 min (Fig. 1a-b). This difference is attributed to moisture accumulation in the VD drying chamber is removed slower by the vacuum system, while the HAD natural convection system allows for more efficient moisture removal (Saifullah et al., 2019). Similar findings have been reported in previous studies on lemon pomace (Papoutsis et al., 2017), lemon myrtle leaves (Saifullah et al., 2019), and kumquats (Ozcan-Sinir et al., 2018).

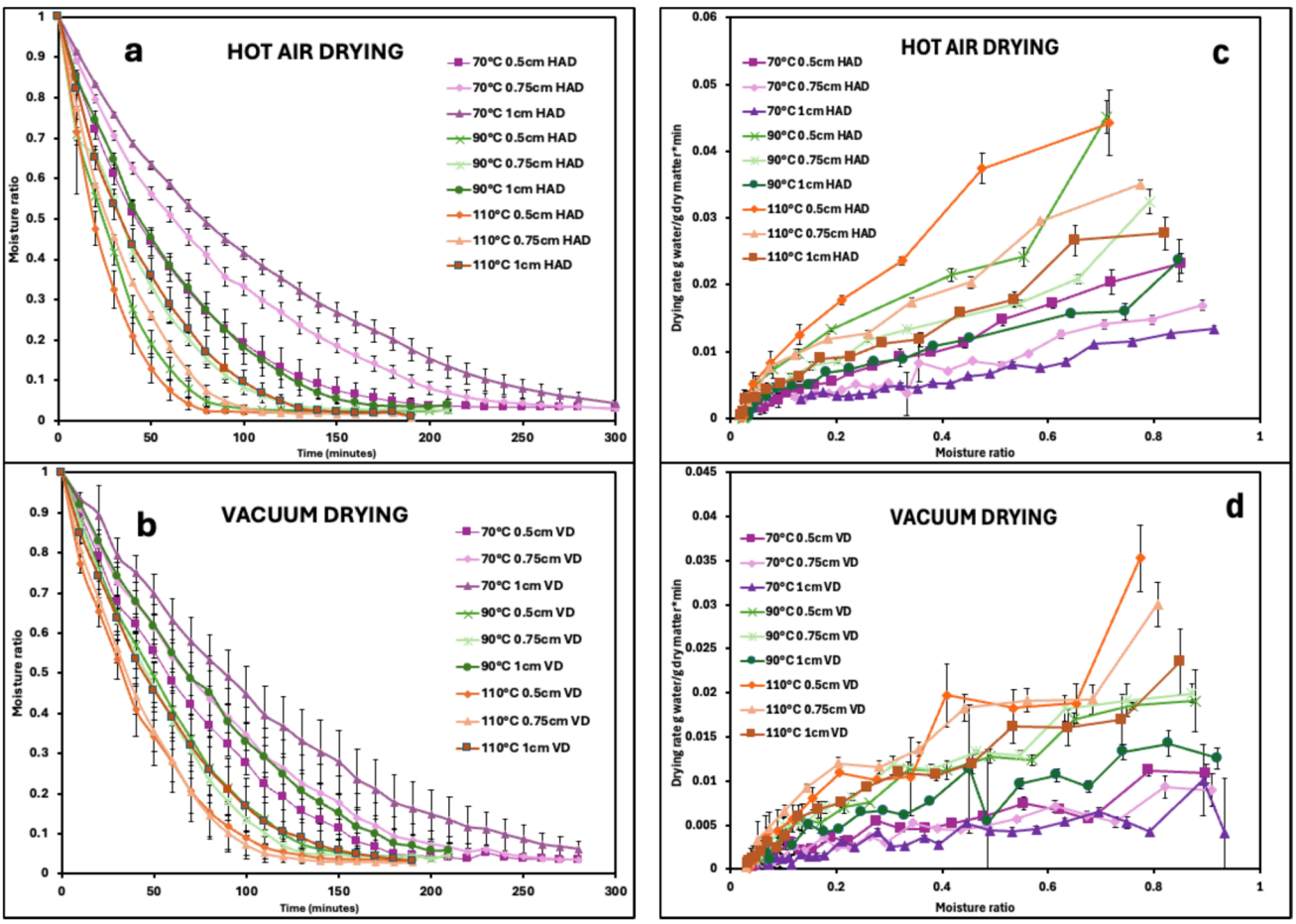

Fig. 1 The effect of drying temperature and layer thickness on moisture ratio vs drying time for hot air (HAD) (Fig. 1a) and vacuum drying (VD) (Fig. 1b); The effect of drying temperature and layer thickness on drying rate vs moisture for hot air (HAD) (Fig. 1c) and vacuum drying (VD) (Fig. 1d). Data are shown as mean ± standard deviation ($n = 3$)

Changes in Physical Properties of Oat Pulp Under Different Drying Conditions

The effect of different drying conditions on the physical properties of oat pulp, including moisture content, water activity, and colour is shown in Table 2. Fresh oat pulp had a high moisture content (60.96 ± 0.12%) and water activity (0.97 ± 0.00), whereas dried samples ranged from 3.34 ± 1.21% to 8.59 ± 1.45% moisture content, representing a 57%—60% weight reduction. Most dried oat pulp samples had a_w below 0.6, with FD oat pulp exhibiting the lowest (0.21 ± 0.03) and HAD at 70 °C for 5 h with a 1 cm thickness showing the highest (0.67 ± 0.05). This is beneficial for oat milk producers, as dried oat pulp is easier to transport over long distances without incurring additional costs for extra packaging or higher fuel consumption due to heavier loads. Additionally, reduced collection frequency and the elimination of cold storage further lower operational costs, as a_w below 0.6 indicates a lower risk of microbial and enzymatic spoilage (Chien Hwa Chong et al. 2023; Perera, 2005; Rahman, 2009). However, both HAD and VD oat pulp dried at 70 °C with a thickness of 1 cm had a_w values above 0.6, significantly higher than samples obtained at higher drying temperatures ($p < 0.05$). Similar patterns have been observed in prior studies, which found that increasing drying temperatures led to lower a_w values, likely due to improved water vapour migration at higher temperatures (Hawaree et al., 2009; Kalsi et al., 2023). This suggests that drying at 90 °C and 110 °C is more effective at reducing water activity, particularly for thicker samples. At 110 °C, the a_w values of both HAD and VD oat pulp (0.33 ± 0.06 and 0.35 ± 0.04, respectively) were comparable to that of the FD sample (0.21 ± 0.03).

Colour plays an important role in the acceptability of food products (Perera, 2005), and the colour of oat pulp was measured through L^* (lightness/darkness), a^* (red/green), and b^* (yellow/blue), as well as total colour change (ΔE) and the browning index (BI), as shown in Table 2. The results revealed significant effects of drying conditions on oat pulp lightness ($p < 0.05$). Dried oat pulp obtained from HAD, VD, and FD was lighter (higher L^* values) than fresh oat pulp ($p < 0.05$). The b^* values indicated that HAD and VD had a minor effect

Table 2 Moisture content, water activity, and colour attributes of oat pulp sample

Samples	Time (hours)	Moisture content (%)	Water activity	L^*	a^*	b^*	ΔE	Browning index
Fresh		60.96 ± 0.12^{a}	0.97 ± 0.00^{a}	58.4 ± 0.5^{c}	6.80 ± 0.20^{a}	21.93 ± 0.40^{b}	-	54.7 ± 1.9^{a}
Freeze dried	24	5.21 ± 0.02^{b}	0.21 ± 0.03^{j}	76.8 ± 0.3^{a}	5.20 ± 0.10^{b}	19.97 ± 0.15^{c}	18.5 ± 0.3^{a}	34.6 ± 0.5^{c}
70 °C 0.5 cm HAD	3.5	5.84 ± 4.67^{b}	0.52 ± 0.02^{cdefg}	67.4 ± 0.6^{b}	7.50 ± 0.17^{a}	24.27 ± 0.21^{a}	9.30 ± 0.6^{b}	52.0 ± 0.9^{ab}
90 °C 0.5 cm HAD	2.3	4.63 ± 0.53^{b}	0.46 ± 0.03^{defgh}	69.5 ± 0.8^{b}	7.37 ± 0.15^{a}	24.33 ± 0.21^{a}	11.3 ± 0.8^{b}	50.1 ± 1.3^{ab}
110 °C 0.5 cm HAD	1.8	3.34 ± 1.21^{b}	0.41 ± 0.02^{ghi}	68.9 ± 0.8^{b}	7.57 ± 0.15^{a}	25.23 ± 0.32^{a}	11.0 ± 0.7^{b}	52.9 ± 1.4^{ab}
70 °C 0.75 cm HAD	4.3	4.53 ± 2.52^{b}	0.56 ± 0.04^{bcd}	70.2 ± 0.6^{b}	6.90 ± 0.36^{a}	24.03 ± 0.45^{a}	11.9 ± 0.5^{b}	48.4 ± 1.8^{ab}
90 °C 0.75 cm HAD	2.8	4.20 ± 2.17^{b}	0.48 ± 0.02^{cdefg}	69.5 ± 0.6^{b}	7.17 ± 0.42^{a}	24.23 ± 0.50^{a}	11.4 ± 0.5^{b}	49.7 ± 2.0^{ab}
110 °C 0.75 cm HAD	2.2	2.94 ± 1.05^{b}	0.34 ± 0.03^{hi}	69.6 ± 0.2^{b}	7.37 ± 0.06^{a}	24.90 ± 0.10^{a}	11.6 ± 0.2^{b}	51.2 ± 0.2^{ab}
70 °C 1 cm HAD	5.0	5.15 ± 1.28^{b}	0.67 ± 0.05^{b}	70.0 ± 1.5^{b}	7.13 ± 0.38^{a}	24.63 ± 0.55^{a}	11.9 ± 1.4^{b}	50.1 ± 2.9^{ab}
90 °C 1 cm HAD	3.2	4.55 ± 0.93^{b}	0.53 ± 0.02^{cdef}	68.9 ± 1.9^{b}	7.40 ± 0.50^{a}	25.07 ± 0.85^{a}	11.0 ± 1.5^{b}	52.4 ± 4.1^{ab}
110 °C 1 cm HAD	2.5	3.88 ± 0.72^{b}	0.33 ± 0.06^{i}	70.1 ± 0.2^{b}	7.03 ± 0.06^{a}	25.07 ± 0.23^{a}	12.1 ± 0.2^{b}	50.8 ± 0.4^{ab}
70 °C 0.5 cm VD	3.7	5.36 ± 1.35^{b}	0.48 ± 0.04^{defg}	68.6 ± 1.5^{b}	7.53 ± 0.23^{a}	24.57 ± 0.06^{a}	10.6 ± 1.4^{b}	51.6 ± 1.7^{ab}
90 °C 0.5 cm VD	2.7	6.54 ± 3.19^{b}	0.43 ± 0.02^{efghi}	68.9 ± 0.9^{b}	7.57 ± 0.15^{a}	24.70 ± 0.17^{a}	10.8 ± 0.8^{b}	51.7 ± 1.3^{ab}
110 °C 0.5 cm VD	2.5	5.53 ± 0.78^{b}	0.41 ± 0.02^{ghi}	69.8 ± 0.6^{b}	7.37 ± 0.15^{a}	24.80 ± 0.36^{a}	11.8 ± 0.5^{b}	50.8 ± 1.4^{ab}
70 °C 0.75 cm VD	4.3	5.33 ± 4.88^{b}	0.60 ± 0.07^{bc}	69.3 ± 1.0^{b}	7.27 ± 0.21^{a}	24.67 ± 0.31^{a}	11.3 ± 0.8^{b}	50.9 ± 1.7^{ab}
90 °C 0.75 cm VD	3.0	5.80 ± 2.33^{b}	0.41 ± 0.01^{fghi}	69.5 ± 0.6^{b}	7.43 ± 0.15^{a}	24.43 ± 0.21^{a}	11.4 ± 0.6^{b}	50.4 ± 1.1^{ab}
110 °C 0.75 cm VD	2.7	4.74 ± 2.34^{b}	0.44 ± 0.07^{efghi}	69.8 ± 0.6^{b}	7.43 ± 0.15^{a}	24.70 ± 0.17^{a}	11.7 ± 0.5^{b}	50.7 ± 1.0^{ab}
70 °C 1 cm VD	4.7	8.04 ± 3.51^{b}	0.66 ± 0.06^{b}	70.1 ± 1.6^{b}	7.00 ± 0.50^{a}	24.20 ± 0.95^{a}	12.0 ± 1.4^{b}	49.0 ± 3.9^{ab}
90 °C 1 cm VD	3.3	8.59 ± 1.45^{b}	0.55 ± 0.03^{bcde}	69.4 ± 2.7^{b}	7.17 ± 0.64^{a}	24.60 ± 1.13^{a}	11.4 ± 2.2^{b}	50.8 ± 5.7^{ab}
110 °C 1 cm VD	3.0	5.33 ± 1.69^{b}	0.35 ± 0.04^{hi}	70.5 ± 0.7^{b}	6.80 ± 0.17^{a}	23.80 ± 0.17^{a}	12.2 ± 0.7^{b}	47.6 ± 1.1^{b}

*Data are shown as mean ± standard deviation (n = 3). Data in the same column sharing the same letters are not significantly different ($p < 0.05$)

on yellowness, with values ranging from 19.97 ± 0.15 to 25.23 ± 0.32, higher than those of FD and fresh samples. The a^* values, representing redness, showed no significant difference between fresh, HAD, and VD samples, except for FD, which had a lower a^* value ($p < 0.05$). FD oat pulp had the lowest a^* value (5.20 ± 0.10), while HAD and VD ranged from 6.80 ± 0.17 to 7.57 ± 0.15. The increase in L^* values of HAD and VD oat pulp might be due to high drying temperatures, similar to findings in Ganpu Tea infusions (Zhou et al., 2023). The decrease in a^* and increase in L^* values for FD oat pulp are likely due to pigment degradation from low pressure during drying (Jakubczyk & Jaskulska, 2021; Nowak & Jakubczyk, 2020). L^*, a^*, and b^* values of HAD and VD oat pulp are comparable with previous studies on dried brewer's spent grain, which was dried under various conditions at temperatures between 70 °C and 105 °C (Gomez-Delgado et al., 2023; Naibaho & Korzeniowska, 2021; Shih et al., 2020). Dried brewer's spent grains have been partially used to replace wheat flour in the formulation of functional muffins, which were more favourably received by consumers due to the improved colour (Shih et al., 2020). This suggests that HAD and VD can produce dried oat pulp that can be potentially used to replace wheat flour in bakery products such as bread and biscuits, for improving the nutritional quality while maintaining sensory attributes. However, the link between the changes in colour and the sensory acceptability of oat pulp could be further explored in food formulations. The variations in the colour of oat pulp resulting from different drying conditions are also reflected in the total colour change (ΔE). ΔE was highest for FD oat pulp (18.5 ± 0.3), indicating a significant colour shift from fresh pulp ($p < 0.05$). In contrast, HAD and VD samples exhibited lower ΔE values (9.30 ± 0.6 to 12.1 ± 0.2), with no significant variation across temperatures and thicknesses ($p > 0.05$). The differences in ΔE between thermal drying (HAD and VD) and FD oat pulp may be due to the distinct drying mechanisms and the low vacuum pressure during FD that cause oat pulp to undergo different physical, microstructure, and pigment changes. During the thermal drying process, browning occurs due to Maillard reactions or oxidative processes that darken the colour, as seen in the browning index (BI) (Kieu Tran et al., 2020). FD sample had the lowest BI (34.6 ± 0.5), likely due to the absence of heat and oxygen during drying, which prevents Maillard reactions (Akcicek et al., 2023). In contrast, HAD and VD samples had BI values similar to fresh oat pulp (47.6 ± 1.1 to 52.9 ± 1.4), indicating minimal browning.

Changes in Phytochemical Compounds and Antioxidant Capacity of Oat Pulp Under Different Drying Conditions

The quality of HAD and VD oat pulp was evaluated based on TPC and antioxidant capacity, as shown in Fig. 2. Drying significantly reduced TPC compared to fresh oat pulp ($p < 0.05$), with both HAD and VD samples having lower TPC than the FD sample ($p < 0.05$). The thickness of the oat pulp layer had minimal impact on TPC at 110 °C both HAD and VD, but at 70 °C and 90 °C, thicker samples experienced greater TPC loss. The highest TPC was observed at 110 °C for both HAD (0.60 ± 0.02 mg GAE/g dwb) and VD (0.58 ± 0.00 to 0.61 ± 0.02 mg GAE/g dwb), with no significant difference between the two methods ($p > 0.05$). These results align with previous studies (Davy & Vuong, 2021; Patrón-Vázquez et al., 2019). Notably, VD at 70 °C and 90 °C outperformed HAD at the same temperatures, particularly VD at 70 °C with 0.5 cm and 0.75 cm thickness, where TPC levels were similar to 110 °C HAD. Thicker samples when applied HAD and VD had lower TPC, likely due to prolonged drying times and exposure to heat and oxygen, leading to greater degradation of phenolic and other bioactive compounds (Abano et al., 2014; Adam et al., 2000). VD at 70 °C and 90 °C preserved more TPC, even though with longer drying time, was likely offset by the low-oxygen environment and lower temperature, which minimized oxidation of phenolic compounds (Ozcan-Sinir et al., 2018). However, VD under these conditions may not ensure microbiological stability during storage, especially at 0.75 cm and 1 cm thickness, which exhibited a water activity of 0.6 or higher (Chien Hwa Chong et al. 2023; Perera, 2005; Rahman, 2009). Thus, it is recommended that 110 °C is an effective drying temperature for both HAD and VD to preserve TPC while maintaining a low water activity and moisture content.

In terms of antioxidant properties, drying conditions significantly affected the FRAP, DPPH, and ABTS scavenging capacities ($p < 0.05$), but did not follow the same trend as TPC. Thickness and temperature significantly impacted the FRAP and DPPH scavenging capacities for both HAD and VD at 70 °C and 90 °C, as well as for VD at 110 °C. However, the effect was less pronounced at 110 °C with HAD. The effect on ABTS capacity was less noticeable in both HAD and VD. Increased thickness led to a decrease in FRAP and DPPH across all temperatures for both HAD and VD and vice versa when increased temperature. When subjected to HAD and VD at 110 °C across all thicknesses, dried oat pulp exhibited the highest FRAP (1.76 ± 0.05–2.20 ± 0.02 mM TE/g dwb), DPPH (1.52 ± 0.05–1.79 ± 0.09 mM TE/g dwb), and ABTS (4.14 ± 0.06–4.37 ± 0.07 mM TE/g dwb) capacities. FRAP and DPPH values of 110 °C HAD and VD samples were higher than those of FD samples, except for FRAP values of VD at 110 °C with a thickness of 1 cm. The mechanism of the two antioxidant assays are different, FRAP utilises electron transfer, while DPPH measures radical scavenging capacity (Jaganjac et al., 2021). The differences in FRAP and DPPH values suggest that antioxidant activity arises not only from phenolics but also bioactive compounds, such as Maillard products, that formed due to

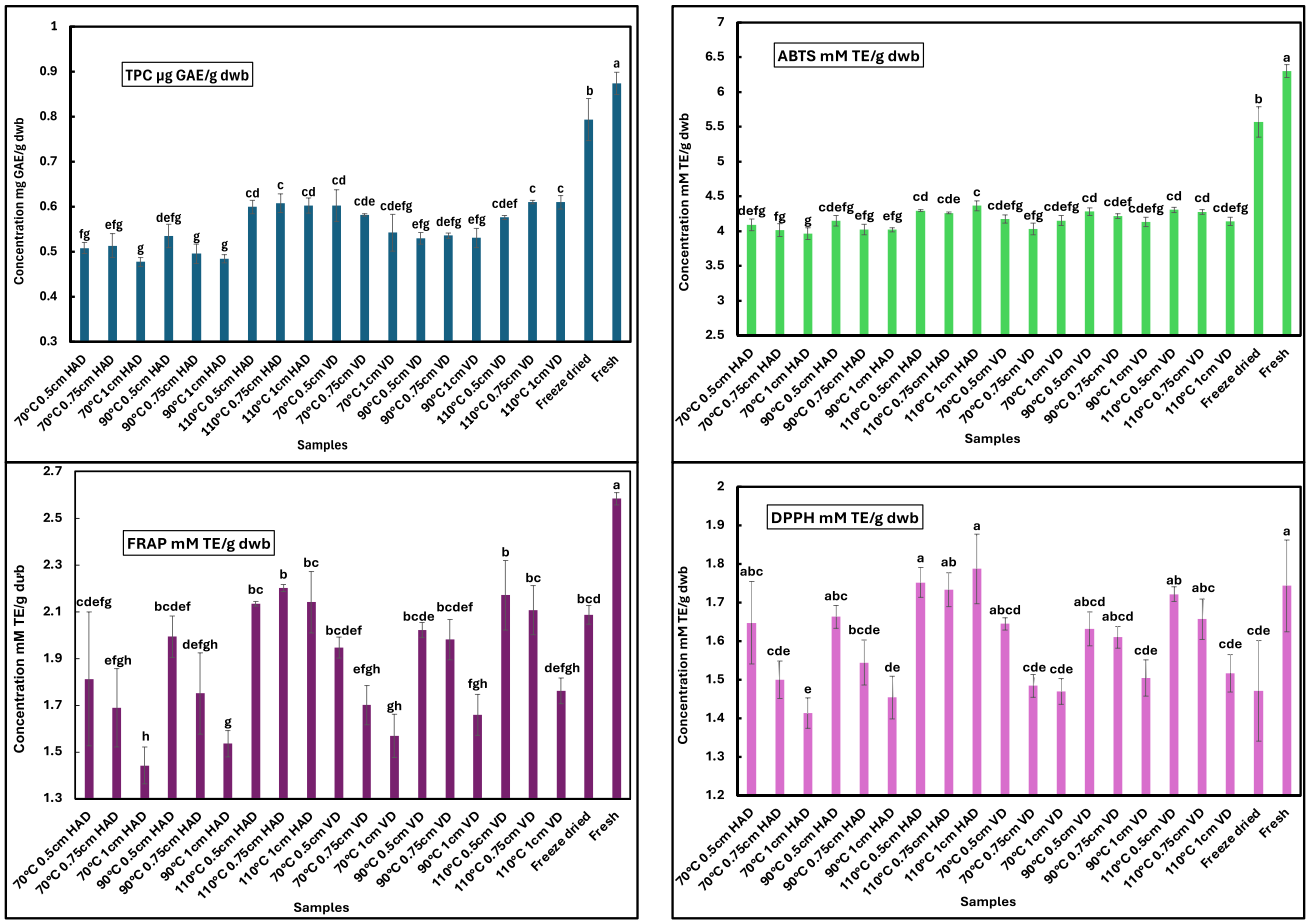

Fig. 2 TPC, FRAP, DPPH, and ABTS antioxidant capacity of oat pulp samples from each drying condition. Data are shown as mean ± standard deviation ($n = 3$). Data in the same column sharing the same letters are not significantly different ($p < 0.05$)

the presence of high heat and oxygen. Similar findings have been reported, with heat treatment likely promoting the formation of partially oxidized polyphenols and Maillard products, such as melanoidins, which enhance antioxidant capacity when drying at high temperatures (Balzarini et al., 2018; Nurkhoeriyati et al., 2021).

Energy Consumption at Different Drying Conditions

Energy consumption is a crucial factor in determining the most suitable drying conditions for oat pulp, as it is closely linked to both drying time and production costs. Figure 3 illustrates the effects of different drying conditions on energy consumption. Higher temperatures used less energy for drying at the same thickness, and vice versa for thicker layers when using HAD. The lowest energy consumption was found when applied HAD at 110 °C across all thicknesses (1.38–1.88 kWh). Based on energy consumption, along with the results for TPC and antioxidant capacity, it is recommended that HAD at 110 °C for 1.8 h with a 1 cm thickness is most effective for retaining TPC and antioxidant properties while improving production efficiency. This method is preferable for scalability in commercial production due to its simplicity, lower costs, and fewer requirements for specialized equipment (Bai et al., 2023; Onwude et al., 2016a, 2016b). However, despite its simplicity, HAD remains one of the most energy-intensive thermal drying methods (Martynenko & Vieira, 2023), which is a concern for the food industry striving to cut energy costs amid declining fossil fuel resources and increasing environmental pressures. To address this, hybrid drying techniques, such as combining HAD with microwave or infrared drying, or pre-treating samples with ultrasound, have been proposed. These methods have been shown to reduce energy consumption by at least 50% while significantly speeding up the drying process and minimizing the negative effects of prolonged thermal exposure and oxidation (Abbaspour-Gilandeh et al., 2020; Martynenko & Vieira, 2023). Future studies should explore more advanced drying technologies to optimize energy efficiency and broaden the use of oat pulp in high-value applications.

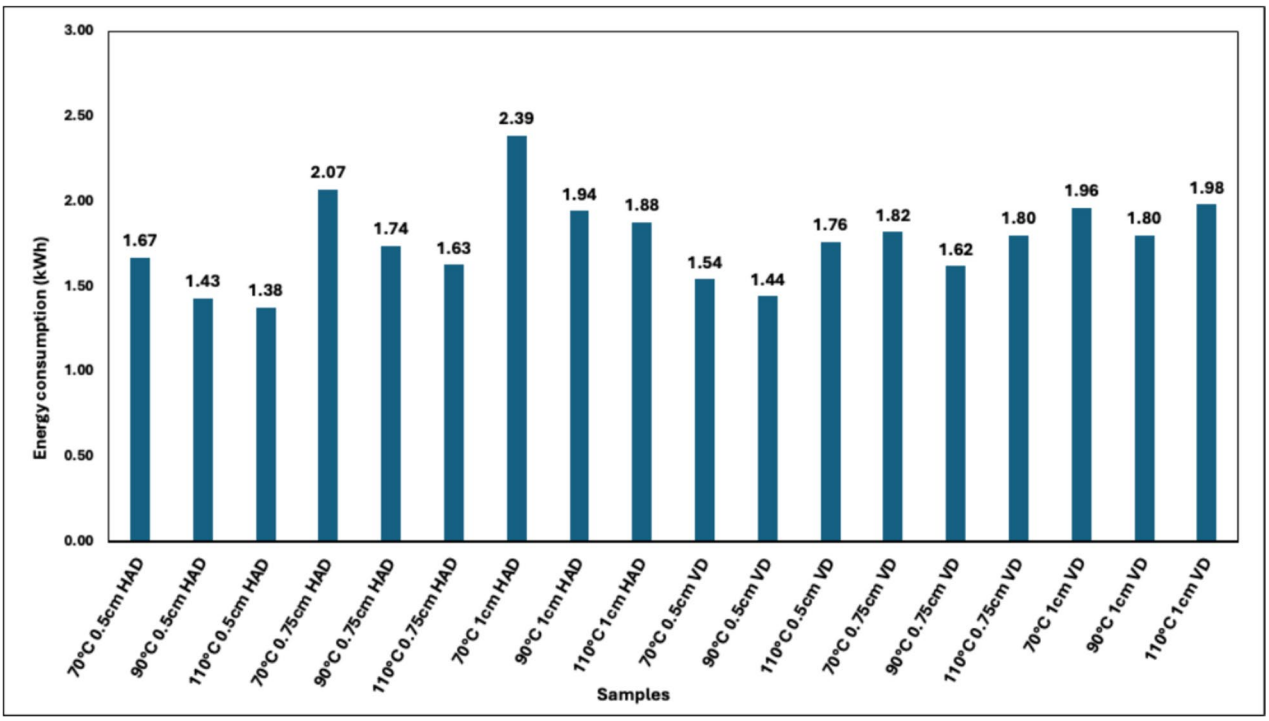

Fig. 3 Energy consumption (kWh) of all drying conditions

Fitting of Mathematic Thin Layer Drying Models

The fitting of six thin-layer drying models was assessed using the coefficient of determination (R^2), sum of square error (SSE), and root mean square error (RMSE), with the corresponding constants and coefficients provided in Table 3. Overall, all models exhibited high R^2 values, ranging from 0.9964 to 0.9988, indicating that the models effectively described the drying behaviour of oat pulp. However, the Henderson and Pabis model provided the best fit for most drying conditions, including HAD at 90 °C, 110 °C, and VD at 70 °C, 90 °C, and 110 °C, across all layer thicknesses, due to its highest R^2 values and lowest RMSE and SSE (Table 3, Fig. 4a-f). The exception was HAD 70 °C with a thickness of 0.5 cm, where the Midilli et al. model was found to be the most suitable. These findings are in agreement with previous studies, which have shown the Henderson and Pabis model and Midilli model to be the best at describing the drying behaviour of various plant materials under different conditions (Chigbo et al., 2024; Das Purkayastha et al., 2013). Further analysis in Table 3 shows that the drying constant (k) of the Henderson and Pabis model increased with temperature for samples of the same thickness for both HAD and VD. For example, when applied HAD to a layer of oat pulp of 0.75 cm, the drying constants for temperatures of 70 °C, 90 °C, and 110 °C were 0.6610, 1.1330, and 1.7316, respectively. This trend is attributed to the effect of temperature on moisture diffusivity. As temperature increases, it enhances the diffusion of water from the interior to the surface of the sample and increases the moisture absorption capacity of the surrounding air, which has lower humidity. This creates a larger moisture gradient between the inside and outside of the sample, reducing drying time. This is also reflected in the steeper slopes of the drying curves at higher temperatures (Figs. 1A-B), which indicate higher drying rates (Figs. 1C-D).

Effective Moisture Diffusivity and Activation Energy

Effective moisture diffusivity (D_{eff}) characterises various moisture transport mechanisms during food drying, including capillary flow, surface diffusion, and liquid diffusion, and is strongly influenced by drying temperature (Onwude et al., 2016a, b). The D_{eff} values in this study ranged from $5.49 \times 10^{-10} \pm 2.64 \times 10^{-11}$ m^2/s to $8.93 \times 10^{-9} \pm 1.06 \times 10^{-10}$ m^2/s for HAD, and from $5.78 \times 10^{-10} \pm 10^{-10}$ m^2/s to $3.22 \times 10^{-9} \pm 10^{-9}$ m^2/s for VD, falling within the typical range observed for dried biological materials (Onwude et al., 2016a, b). D_{eff} increased with higher drying temperatures and thicker sample layers. For instance, at 110 °C under vacuum pressure, D_{eff} values for 0.5 cm, 0.75 cm, and 1 cm layers were $8.40 \times 10^{-10} \pm 4.13 \times 10^{-11}$ m^2/s, $2.05 \times 10^{-9} \pm 5.14 \times 10^{-11}$ m^2/s, and $3.22 \times 10^{-9} \pm 1.13 \times 10^{-11}$ m^2/s, respectively. Likewise, for VD 1 cm of oat pulp, D_{eff} increased from $1.73 \times 10^{-9} \pm$

Table 3 Statistical analysis of thin layer drying models of oat pulp under hot air drying and vacuum drying. R2 coefficient of determination, RMSE root mean square error, SSE sum square error

Drying conditions		70 °C/(2.5–4.2 h)				90 °C/(1.2–2.3 h)				110 °C/(1.0–1.8 h)			
Model	Thickness (cm)	Model constant	R^2	RMSE	SSE	Model constant	R^2	RMSE	SSE	Model constant	R^2	RMSE	SSE
Newton	0.5	k = 0.9869	0.9987	0.0099	0.0027	k = 0.9869	0.9951	0.0192	0.0074	k = 2.3075	0.9964	0.0167	0.0050
	0.75	k = 0.6870	0.9986	0.0107	0.0032	k = 1.3692	0.9920	0.0257	0.0132	k = 1.6851	0.9969	0.0160	0.0046
	1	k = 0.5470	0.9977	0.0132	0.0049	k = 0.9967	0.9974	0.0149	0.0044	k = 1.3044	0.9981	0.0128	0.0029
Page	0.5	k = 0.9873 n = 0.9986	0.9987	0.0099	0.0028	k = 0.9873 n = 0.9986	0.9962	0.0171	0.0058	k = 2.4714 n = 1.1085	0.9986	0.0104	0.0020
	0.75	k = 0.6762 n = 1.0276	0.9986	0.0107	0.0032	k = 1.3693 n = 1.0016	0.9922	0.0257	0.0132	k = 1.7386 n = 1.1068	0.9984	0.0120	0.0026
	1	k = 0.5309 n = 1.0400	0.9979	0.0130	0.0048	k = 0.9754 n = 1.1056	0.9987	0.0110	0.0024	k = 1.3082 n = 1.0832	0.9987	0.0111	0.0022
Henderson and Pabis	0.5	k = 0.9909 n = 0.9951 a = 1.0229	0.9987	0.0099	0.0027	k = 0.9909 n = 0.9951 a = 1.0229	0.9962	0.0170	0.0058	k = 2.4719 n = 1.1070 a = 1.0011	0.9987	0.0104	0.0020
	0.75	k = 0.6610 n = 1.0449 a = 0.9878	0.9987	0.0104	0.0030	k = 1.3330 n = 1.0423 a = 0.9705	0.9923	0.0249	0.0124	k = 1.7316 n = 1.1163 a = 0.9932	0.9984	0.0119	0.0025
	1	k = 0.5099 n = 1.0682 a = 0.9823	0.9981	0.0123	0.0042	k = 0.9584 n = 1.1256 a = 0.9870	0.9988	0.0106	0.0022	k = 1.2972 n = 1.0954 a = 0.9912	0.9987	0.0108	0.0021
Two term	0.5	a = 0.5006 b = 0.5006 k_1 = 0.9882 k_2 = 0.9882	0.9986	0.0098	0.0027	a = 0.5006 b = 0.5006 k_1 = 0.9882 k_2 = 0.9882	0.9952	0.0191	0.0073	a = 0.5095 b = 0.5095 k_1 = 0.9882 k_2 = 0.9882	0.9966	0.0163	0.0048
	0.75	a = 0.5020 b = 0.5020 k_1 = 0.6897 k_2 = 0.6897	0.9985	0.0110	0.0034	a = 0.4912 b = 0.4912 k_1 = 1.3458 k_2 = 1.3458	0.9921	0.0252	0.0127	a = 0.5102 b = 0.5102 k_1 = 1.7173 k_2 = 1.7173	0.9968	0.0166	0.0050
	1	a = 0.5031 b = 0.5031 k_1 = 0.5505 k_2 = 0.5505	0.9976	0.0137	0.0053	a = 0.5123 b = 0.5123 k_1 = 1.0205 k_2 = 1.0205	0.9969	0.0166	0.0055	a = 0.5090 b = 0.5090 k_1 = 1.3268 k_2 = 1.3268	0.9978	0.0141	0.0036
Midilli and others	0.5	k = 1.0166 a = 1.0082 b = 0.0031	0.9993	0.0075	0.0016	k = 1.0166 a = 1.0082 b = 0.0031	0.9961	0.0171	0.0058	k = 2.3885 a = 1.0221 b = 0.0046	0.9973	0.0145	0.0038
	0.75	k = 0.6897 a = 1.0039 b = 0	0.9985	0.0110	0.0034	k = 1.3483 a = 0.9828 b = 0.0003	0.9921	0.0251	0.0126	k = 1.7173 a = 1.0205 b = 0	0.9968	0.0166	0.0050
	1	k = 0.5505 a = 1.0061 b = 0	0.9976	0.0137	0.0053	k = 1.0205 a = 1.0247 b = 0	0.9969	0.0166	0.0055	k = 1.3268 a = 1.0180 b = 0	0.9978	0.0141	0.0036

Table 3 (continued)

Drying conditions		70 °C/(2.5–4.2 h)				90 °C/(1.2–2.3 h)				110 °C/(1.0–1.8 h)			
Model	Thickness (cm)	Model constant	R^2	RMSE	SSE	Model constant	R^2	RMSE	SSE	Model constant	R^2	RMSE	SSE
Logarithmic	0.5	k = 1.0295 a = 0.9967 c = 0.0119	0.9991	0.0084	0.0020	k = 1.0295 a = 0.9967 c = 0.0119	0.9955	0.0184	0.0068	k = 2.4104 a = 1.0140 c = 0.0082	0.9968	0.0157	0.0045
	0.75	k = 0.6897 a = 1.0039 c = 0	0.9985	0.0110	0.0034	k = 1.3458 a = 0.9824 c = 0	0.9921	0.0252	0.0127	k = 1.7173 a = 1.0205 c = 0	0.9968	0.0166	0.0050
	1	k = 0.5505 a = 1.0061 c = 0	0.9976	0.0137	0.0053	k = 1.0205 a = 1.0247 c = 0	0.9969	0.0166	0.0055	k = 1.3268 a = 1.0180 c = 0	0.9978	0.0141	0.0036
Drying conditions		70 °C VD/(3.7–4.7 h)				90 °C VD/(2.7–3.3 h)				110 °C VD/(2.5–3.0 h)			
Model	Thickness (cm)	Model constant	R^2	RMSE	SSE	Model constant	R^2	RMSE	SSE	Model constant	R^2	RMSE	SSE
Newton	0.5	k = 0.9869	0.9955	0.0200	0.0098	k = 0.9869	0.9937	0.0232	0.0107	k = 2.3075	0.9974	0.0150	0.0041
	0.75	k = 0.6870	0.9964	0.0173	0.0084	k = 1.3692	0.9914	0.0270	0.0145	k = 1.6851	0.9969	0.0160	0.0046
	1	k = 0.5470	0.9963	0.0167	0.0075	k = 0.9967	0.9930	0.0234	0.0110	k = 1.3044	0.9974	0.0151	0.0041
Page	0.5	k = 0.9873 n = 0.9986	0.9987	0.0099	0.0028	k = 0.9873 n = 0.9986	0.9962	0.0171	0.0058	k = 2.4714 n = 1.1085	0.9986	0.0104	0.0020
	0.75	k = 0.6762 n = 1.0276	0.9986	0.0107	0.0032	k = 1.3693 n = 1.0016	0.9922	0.0257	0.0132	k = 1.7386 n = 1.1068	0.9984	0.0120	0.0026
	1	k = 0.5309 n = 1.0400	0.9979	0.0130	0.0048	k = 0.9754 n = 1.1056	0.9987	0.0110	0.0024	k = 1.3082 n = 1.0832	0.9987	0.0111	0.0022
Henderson and Pabis	0.5	k = 0.9909 n = 0.9951 a = 1.0229	0.9987	0.0099	0.0027	k = 0.9909 n = 0.9951 a = 1.0229	0.9962	0.0170	0.0058	k = 2.4719 n = 1.1070 a = 1.0011	0.9987	0.0104	0.0020
	0.75	k = 0.6610 n = 1.0449 a = 0.9878	0.9987	0.0104	0.0030	k = 1.3330 n = 1.0423 a = 0.9705	0.9923	0.0249	0.0124	k = 1.7316 n = 1.1163 a = 0.9932	0.9984	0.0119	0.0025
	1	k = 0.5099 n = 1.0682 a = 0.9823	0.9981	0.0123	0.0042	k = 0.9584 n = 1.1256 a = 0.9870	0.9988	0.0106	0.0022	k = 1.2972 n = 1.0954 a = 0.9912	0.9987	0.0108	0.0021

Table 3 (continued)

Drying conditions		70 °C/(2.5–4.2 h)				90 °C/(1.2–2.3 h)				110 °C/(1.0–1.8 h)			
Model	Thickness (cm)	Model constant	R^2	RMSE	SSE	Model constant	R^2	RMSE	SSE	Model constant	R^2	RMSE	SSE
Two term	0.5	a = 0.5006 b = 0.5006 k_1 = 0.9882 k_2 = 0.9882	0.9959	0.0204	0.0116	a = 0.5006 b = 0.5006 k_1 = 0.9882 k_2 = 0.9882	0.9928	0.0259	0.0135	a = 0.5095 b = 0.5095 k_1 = 0.9882 k_2 = 0.9882	0.9974	0.0150	0.0041
	0.75	a = 0.5020 b = 0.5020 k_1 = 0.6897 k_2 = 0.6897	0.9954	0.0198	0.0109	a = 0.4912 b = 0.4912 k_1 = 1.3458 k_2 = 1.3458	0.9907	0.0294	0.0173	a = 0.5102 b = 0.5102 k_1 = 1.7173 k_2 = 1.7173	0.9941	0.0231	0.0096
	1	a = 0.5031 b = 0.5031 k_1 = 0.5505 k_2 = 0.5505	0.9946	0.0212	0.0122	a = 0.5123 b = 0.5123 k_1 = 1.0205 k_2 = 1.0205	0.9906	0.0289	0.0167	a = 0.5090 b = 0.5090 k_1 = 1.3268 k_2 = 1.3268	0.9967	0.0174	0.0054
Midilli and others	0.5	k = 1.0166 a = 1.0082 b = 0.0031	0.9993	0.0075	0.0016	k = 1.0166 a = 1.0082 b = 0.0031	0.9928	0.0259	0.0135	k = 2.3886 a = 1.0221 b = 0.0046	0.9974	0.0149	0.0040
	0.75	k = 0.6897 a = 1.0039 b = 0	0.9954	0.0198	0.0109	k = 1.3483 a = 0.9828 b = 0.0003	0.9907	0.0294	0.0173	k = 1.7173 a = 1.0205 b = 0	0.9941	0.0231	0.0096
	1	k = 0.5505 a = 1.0061 b = 0	0.9946	0.0212	0.0122	k = 1.0205 a = 1.0247 b = 0	0.9906	0.0289	0.0167	k = 1.3268 a = 1.0180 b = 0	0.9967	0.0174	0.0054
Logarithmic	0.5	k = 1.0295 a = 0.9967 c = 0.0119	0.9959	0.0204	0.1159	k = 1.0295 a = 0.9967 c = 0.0119	0.9928	0.0259	0.0135	k = 2.4104 a = 1.0140 c = 0.0082	0.9974	0.0150	0.0041
	0.75	k = 0.6897 a = 1.0039 c = 0	0.9955	0.0196	0.0103	k = 1.3458 a = 0.9824 c = 0	0.9907	0.0294	0.0173	k = 1.7173 a = 1.0205 c = 0	0.9941	0.0231	0.0096
	1	k = 0.5505 a = 1.0061 c = 0	0.9946	0.0212	0.0122	k = 1.0205 a = 1.0247 c = 0	0.9906	0.0289	0.0167	k = 1.3268 a = 1.0180 c = 0	0.9967	0.0174	0.0054

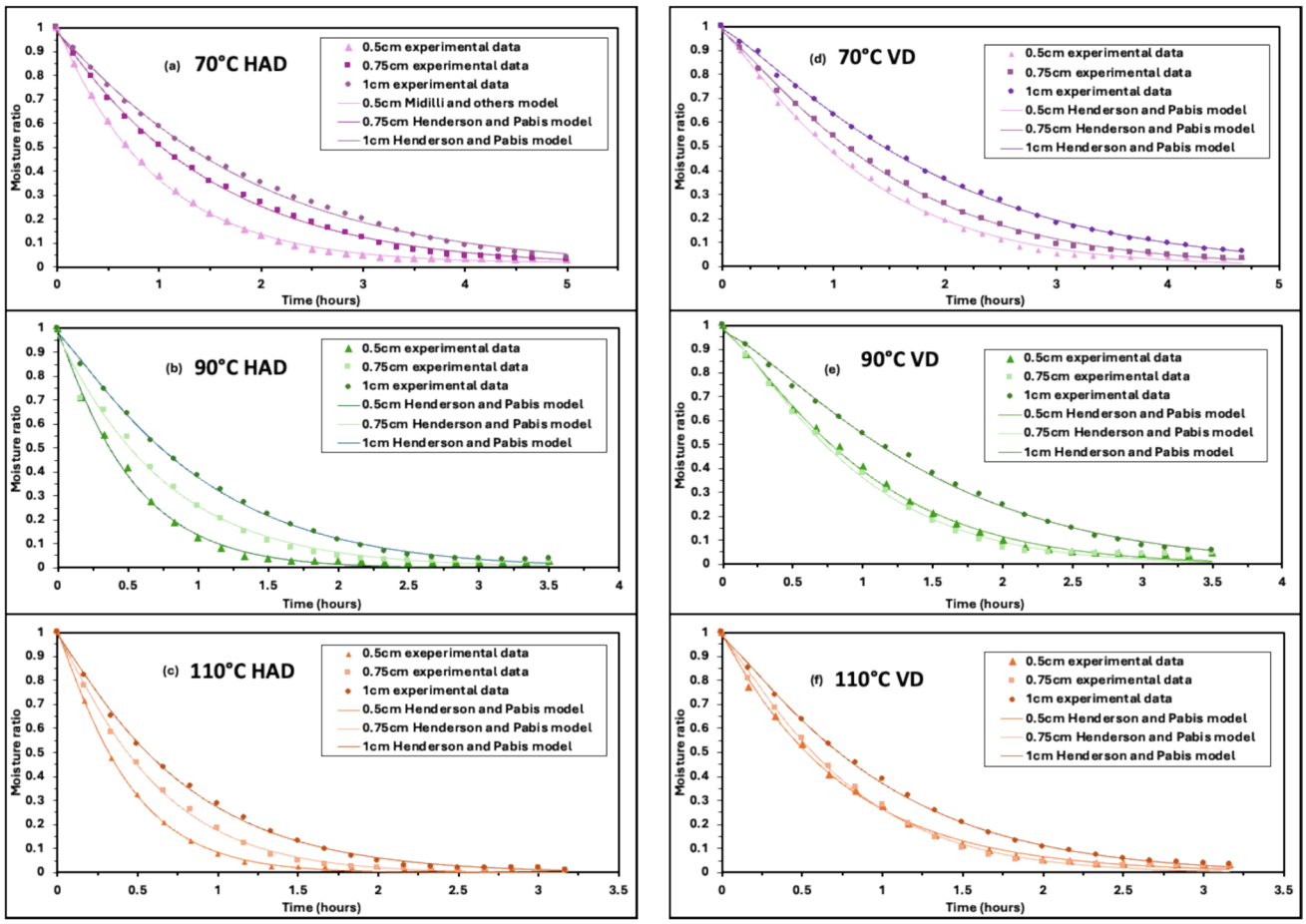

Fig. 4 Experimental and predicted drying data with the best-fitting model at different drying temperatures under hot air drying (**a-c**) and vacuum drying (**d-f**)

Table 4 Activation energy and effective moisture diffusivity of dried oat pulp

	Thickness (cm)	Temperature	Time (minutes)	E_a (kJ/mol)	D_{eff} (m^2/s)
Hot air drying	0.5	70 °C	210	13.41 ± 2.31	$5.49 \times 10^{-10} \pm 2.64 \times 10^{-11}$
		90 °C	140		$7.62 \times 10^{-10} \pm 8.70 \times 10^{-11}$
		110 °C	110		$8.93 \times 10^{-9} \pm 1.06 \times 10^{-10}$
	0.75	70 °C	260	19.51 ± 2.04	$1.19 \times 10^{-9} \pm 8.36 \times 10^{-12}$
		90 °C	170		$1.84 \times 10^{-9} \pm 4.83 \times 10^{-11}$
		110 °C	130		$2.42 \times 10^{-9} \pm 7.09 \times 10^{-11}$
	1	70 °C	300	23.76 ± 3.39	$1.75 \times 10^{-9} \pm 8.42 \times 10^{-12}$
		90 °C	190		$3.08 \times 10^{-9} \pm 2.51 \times 10^{-11}$
		110 °C	150		$4.16 \times 10^{-9} \pm 3.20 \times 10^{-11}$
Vacuum drying	0.5	70 °C	220	10.25 ± 1.67	$5.78 \times 10^{-10} \pm 2.32 \times 10^{-11}$
		90 °C	160		$7.43 \times 10^{-10} \pm 3.27 \times 10^{-11}$
		110 °C	150		$8.40 \times 10^{-10} \pm 4.13 \times 10^{-11}$
	0.75	70 °C	260	13.69 ± 1.50	$1.24 \times 10^{-9} \pm 8.90 \times 10^{-12}$
		90 °C	180		$1.69 \times 10^{-9} \pm 4.51 \times 10^{-11}$
		110 °C	160		$2.05 \times 10^{-9} \pm 5.14 \times 10^{-11}$
	1	70 °C	280	16.94 ± 0.58	$1.73 \times 10^{-9} \pm 6.17 \times 10^{-12}$
		90 °C	200		$2.45 \times 10^{-9} \pm 1.73 \times 10^{-11}$
		110 °C	180		$3.22 \times 10^{-9} \pm 1.13 \times 10^{-11}$

6.17×10^{-12} m^2/s at 70 °C to $3.22 \times 10^{-9} \pm 1.13 \times 10^{-11}$ m^2/s at 110 °C (450 mmHg). This trend can be attributed to the higher drying temperatures and thicker layers elevating the internal vapour pressure of oat pulp, which enhances heat transfer and accelerates water molecule movement, improving moisture diffusion to the surface (Mugodo & Workneh, 2021). Similar findings have been reported in studies involving the drying of tea leaves (Zeng et al., 2024) and banana slices (Chigbo et al., 2024). In addition, D_{eff} values for HAD at 110 °C is higher than VD at the same temperature across all thicknesses. HAD oat pulp at 110 °C 0.5 cm is about 10 times higher than VD at the same temperature and thickness. This likely results from the differences in moisture removal mechanisms between the two drying methods. In HAD, moisture is removed more quickly due to natural convection, which maintains a higher moisture gradient between the sample and ambient air, facilitating faster moisture diffusion and a higher drying rate. In contrast, moisture is removed more slowly from a vacuum chamber in VD. However, at 70 °C and 90 °C across all thicknesses, the differences in D_{eff} between the two methods are minimal.

The activation energy (E_a) represents the energy required to initiate moisture diffusion during drying and reflects the sensitivity of D_{eff} to temperature changes (Ambawat et al., 2022; Erbay & Icier, 2010). A higher E_a value indicates a greater sensitivity of D_{eff} to temperature variations and more energy is required to start the drying process (Erbay & Icier, 2010). E_a values for both HAD and VD are presented in Table 4. E_a increased with sample thickness, ranging from 13.36 ± 2.31 to 23.76 ± 3.39 kJ/mol for HAD and from 10.25 ± 1.67 to 16.94 ± 0.58 kJ/mol for VD. These values align with previous studies on plant-based byproducts such as carrot pomace (approximately 23 kJ/mol) (Kumar et al., 2012) and berry and grape pomaces (18.69 to 48.22 kJ/mol) (Ross et al., 2020). The lower E_a for VD is due to drying at reduced pressure, which allows moisture to evaporate at a lower boiling point, requiring less energy to initiate moisture diffusion compared to HAD.

Conclusion

This study demonstrated that drying techniques, temperatures, and layer thicknesses significantly influenced the energy efficiency, bioactive quality, and physical properties of dried oat pulp. Higher temperatures and thinner layers accelerated the drying process, improving drying rates while reducing energy consumption. The Henderson and Pabis model was the most suitable for describing drying behaviour in most testing conditions. Both hot air drying (HAD) and vacuum drying (VD) produced oat pulp with lighter colour (higher L* values) and more intense yellowness (higher b* values) compared to fresh samples, with favourable browning indices, making the dried product suitable for bakery applications. Drying at 110 °C was particularly effective, preserving antioxidant properties— FRAP (1.76 ± 0.05–2.20 ± 0.02 mM TE/g dwb), DPPH (1.52 ± 0.05–1.79 ± 0.09 mM TE/g dwb) capacities approaching those of freeze-dried samples (2.09 ± 0.04 mM TE/g dwb and 1.47 ± 0.13 mM TE/g dwb for FRAP and DPPH, respectively)—while minimizing energy usage. Among the tested conditions, HAD at 110 °C for 2.5 h with a 1 cm thickness offers a good balance between energy consumption (1.88 kWh) and browning index (50.8 ± 0.4). This drying condition produced oat pulp with low water activity (0.33 ± 0.06) for microbiological stability and high antioxidant capacity that are promising for potential food applications. Future studies are recommended to focus on scaling up the conditions for HAD or applying HAD and hybrid drying for further improved energy consumption and sample quality. Consumer acceptability of the sensory qualities of dried oat pulp also needs further investigation, especially in food applications such as bakery products.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11947-025-03862-1.

Acknowledgements Author ML wishes to acknowledge the support of supervisor Q Vuong and the University of Newcastle via Research Training Program (RTP) Scholarship and co-supervisor Christian Hermansen and Agency for Science, Technology and Research (A*STAR) via A*GA-A*STAR Research Attachment Programme.

Author Contribution MSL contributed on conceptualisation, methodology, investigation, formal analysis, writing—original draft. CH contributed on conceptualisation, formal analysis, writing—review and editing. QVV contributed on conceptualisation, methodology, formal analysis, writing—review and editing.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. This research received no specific grant. However, the author ML received a PhD scholarship from the University of Newcastle and Agency for Science, Technology and Research, Singapore.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

References

Abano, E. E., Ma, H., & Qu, W. (2014). Optimization of Drying Conditions for Quality Dried Tomato Slices Using Response Surface Methodology. *Journal of Food Processing and Preservation, 38*(3), 996–1009. https://doi.org/10.1111/jfpp.12056

Abbaspour-Gilandeh, Y., Kaveh, M., & Aziz, M. (2020). Ultrasonic-Microwave and Infrared Assisted Convective Drying of Carrot: Drying Kinetic. *Quality and Energy Consumption. Applied Sciences, 10*(18), 6309. https://doi.org/10.3390/app10186309

Adam, E., Mühlbauer, W., Esper, A., Wolf, W., & Spiess, W. (2000). Quality changes of onion (Allium CepaL.) as affected by the drying process. *Food/Nahrung, 44*(1), 32–37. https://doi.org/10.1002/(SICI)1521-3803(20000101)44:1%3c32::AID-FOOD32%3e3.0.CO;2-F

Aiello, G., Li, Y., Xu, R., Boschin, G., Juodeikiene, G., & Arnoldi, A. (2021). Composition of the Protein Ingredients from Insoluble Oat Byproducts Treated with Food-Grade Enzymes, Such as Amylase, Cellulose/Xylanase, and Protease. *Foods, 10*(11), 2695. https://doi.org/10.3390/foods10112695

Akcicek, A., Avci, E., Tekin-Cakmak, Z. H., Kasapoglu, M. Z., Sagdic, O., & Karasu, S. (2023). Influence of Different Drying Techniques on the Drying Kinetics, Total Bioactive Compounds, Anthocyanin Profile, Color, and Microstructural Properties of Blueberry Fruit. *ACS Omega, 8*(44), 41603–41611. https://doi.org/10.1021/acsomega.3c05749

Akoy, E. (2014). Experimental characterization and modeling of thin-layer drying of mango slices. *International Food Research Journal, 21*, 1911–1917. https://doi.org/10.5555/20143326010

Ambawat, S., Sharma, A., & Saini, R. K. (2022). Mathematical Modeling of Thin Layer Drying Kinetics and Moisture Diffusivity Study of Pretreated Moringa oleifera Leaves Using Fluidized Bed Dryer. *Processes, 10*(11), 2464. https://doi.org/10.3390/pr10112464

Ayadi, M., Mabrouk, S. B., Zouari, I., & Bellagi, A. (2014). Kinetic study of the convective drying of spearmint. *Journal of the Saudi Society of Agricultural Sciences, 13*(1), 1–7. https://doi.org/10.1016/j.jssas.2013.04.004

Bai, T., Wan, Q., Liu, X., Ke, R., Xie, Y., Zhang, T., et al. (2023). Drying kinetics and attributes of fructus aurantii processed by hot air thin-layer drying at different temperatures. *Heliyon*, *9*(5). https://doi.org/10.1016/j.heliyon.2023.e15554

Balzarini, M. F., Reinheimer, M. A., Ciappini, M. C., & Scenna, N. J. (2018). Comparative study of hot air and vacuum drying on the drying kinetics and physicochemical properties of chicory roots. *Journal of Food Science and Technology, 55*(10), 4067–4078. https://doi.org/10.1007/s13197-018-3333-5

Bartkiene, E., Bartkevics, V., Pugajeva, I., Borisova, A., Zokaityte, E., Lele, V., et al. (2021). The Quality of Wheat Bread With Ultrasonicated and Fermented By-Products From Plant Drinks Production. *Frontiers in Microbiology, 12*, 652548. https://doi.org/10.3389/fmicb.2021.652548

Biswas, R., Hossain, M. A., & Zzaman, W. (2022). Thin layer modeling of drying kinetics, rehydration kinetics and color changes of osmotic pre-treated pineapple (Ananas comosus) slices during drying: Development of a mechanistic model for mass transfer. *Innovative Food Science & Emerging Technologies, 80*, 103094. https://doi.org/10.1016/j.ifset.2022.103094

Chien Hwa Chong, M. K. D., Wahi, R., Choo, C. M., Chew, S. J. (2023). 1. Introduction to Drying and Valorisation of Food Processing Waste. In *Drying and Valorisation of Food Processing Waste*. 1–18: CRC Press. https://www.routledge.com/Drying-and-Valorisation-of-Food-Processing-Waste/Chong-Wahi-Choo-Chew-Dassanayake/p/book/9781032320878

Chigbo, K. S., Linus-Chibuezeh, A., Moufunanya, U. F., Adindu-Linus, C. O., Adepoju, F. O., Eke, A. B., & Okechukwu, Q. N. (2024). Mathematical modeling of the effects of thickness and temperature on thin-layer drying kinetics of oven-dried cooking bananas (Musa spp., sub. grp. ABB) slices. *Food Production, Processing and Nutrition*, *6*(1), 51. https://doi.org/10.1186/s43014-024-00233-9

Crank, J. (1979). *The Mathematics of Diffusion*. Clarendon Press.

Das Purkayastha, M., Nath, A., Deka, B. C., & Mahanta, C. L. (2013). Thin layer drying of tomato slices. *Journal of Food Science and Technology, 50*(4), 642–653. https://doi.org/10.1007/s13197-011-0397-x

Davy, P., & Vuong, Q. V. (2021). The fate of phenolics, soysaponins, major isoflavones and antioxidant activity in soy milk by-product during conventional drying process. *Future Foods, 4*, 100084. https://doi.org/10.1016/j.fufo.2021.100084

Demiray, E., Yazar, J. G., Aktok, Ö., Çulluk, B., Çalışkan Koç, G., & Pandiselvam, R. (2023). The Effect of Drying Temperature and Thickness on the Drying Kinetic, Antioxidant Activity, Phenolic Compounds, and Color Values of Apple Slices. *Journal of Food Quality, 2023*(1), 7426793. https://doi.org/10.1155/2023/7426793

Deswal, A., Deora, N. S., & Mishra, H. N. (2014). Optimization of Enzymatic Production Process of Oat Milk Using Response Surface Methodology. *Food and Bioprocess Technology, 7*(2), 610–618. https://doi.org/10.1007/s11947-013-1144-2

El-Beltagy, A., Gamea, G. R., & Essa, A. H. A. (2007). Solar drying characteristics of strawberry. *Journal of Food Engineering, 78*(2), 456–464. https://doi.org/10.1016/j.jfoodeng.2005.10.015

Erbay, Z., & Icier, F. (2010). A Review of Thin Layer Drying of Foods: Theory, Modeling, and Experimental Results. *Critical Reviews in Food Science and Nutrition, 50*(5), 441–464. https://doi.org/10.1080/10408390802437063

Gomez-Delgado, E., Medina-Jaramillo, C., & López-Córdoba, A. (2023). Analysis of drying kinetic of brewer´s spent grains: effect of the temperature on the physical properties and the content of bioactive compounds. *Vitae*, *30*(2). https://doi.org/10.17533/udea.vitae.v30n2a351025

Hashim, N., Daniel, O., & Rahaman, E. (2014). A Preliminary Study: Kinetic Model of Drying Process of Pumpkins (Cucurbita Moschata) in a Convective Hot Air Dryer. *Agriculture and Agricultural Science Procedia, 2*, 345–352. https://doi.org/10.1016/j.aaspro.2014.11.048

Hawaree, N., Chiewchan, N., & Devahastin, S. (2009). Effects of Drying Temperature and Surface Characteristics of Vegetable on the Survival of Salmonella. *Journal of Food Science, 74*(1), E16–E22. https://doi.org/10.1111/j.1750-3841.2008.01010.x

Helstad, A., Marefati, A., Ahlström, C., Rayner, M., Purhagen, J., & Östbring, K. (2023). High-Pressure Pasteurization of Oat Okara. *Foods, 12*(22), 4070. https://doi.org/10.3390/foods12224070

Jaganjac, M., Sredoja Tisma, V., & Zarkovic, N. (2021). Short Overview of Some Assays for the Measurement of Antioxidant Activity of Natural Products and Their Relevance in Dermatology. *Molecules, 26*(17), 5301. https://doi.org/10.3390/molecules26175301

Jakubczyk, E., & Jaskulska, A. (2021). The Effect of Freeze-Drying on the Properties of Polish Vegetable Soups. *Applied Sciences, 11*(2), 654. https://doi.org/10.3390/app11020654

Kalsi, B. S., Singh, S., Alam, M. S., & Sidhu, G. K. (2023). Comparison of ANN and ANFIS modeling for predicting drying kinetics of Stevia rebaudiana leaves in a hot-air dryer and characterization

of dried powder. *International Journal of Food Properties, 26*(2), 3356–3375. https://doi.org/10.1080/10942912.2023.2283380

Kieu Tran, T. M., Kirkman, T., Nguyen, M., & Van Vuong, Q. (2020). Effects of drying on physical properties, phenolic compounds and antioxidant capacity of Robusta wet coffee pulp (Coffea canephora). *Heliyon, 6*(7), e04498. https://doi.org/10.1016/j.heliyon.2020.e04498

Kucuk, H., Midilli, A., Kilic, A., & Dincer, I. (2014). A Review on Thin-Layer Drying-Curve Equations. *Drying Technology, 32*(7), 757–773. https://doi.org/10.1080/07373937.2013.873047

Kumar, N., Sarkar, B. C., & Sharma, H. K. (2012). Mathematical modelling of thin layer hot air drying of carrot pomace. *Journal of Food Science and Technology, 49*(1), 33–41. https://doi.org/10.1007/s13197-011-0266-7

Le, M. S., Hermansen, C., & Vuong, Q. V. (2025). Oat Milk By-Product: A Review of Nutrition, Processing and Applications of Oat Pulp. *Food Reviews International*, 1–38. https://doi.org/10.1080/87559129.2025.2450263

Lee, J. H., & Zuo, L. (2013). Mathematical modeling on vacuum drying of Zizyphus jujuba Miller slices. *Journal of Food Science and Technology, 50*(1), 115–121. https://doi.org/10.1007/s13197-011-0312-5

MarketsandMarkets™. (2023). Dairy Alternatives Market Size, Revenue, Trends - 2027. *MarketsandMarkets*. https://www.marketsandmarkets.com/Market-Reports/dairy-alternative-plant-milk-beverages-market-677.html. Accessed 8 April 2023

Marković, I., Ilic, J., Markovic, D., Simonovic, V. D., & Kosanic, N. (2013). Color measurement of food products using CIE L*a*b* and RGB color space. *Journal of Hygienic Engineering and Design*. https://www.semanticscholar.org/paper/Color-measurement-of-food-products-using-CIE-L*a*b*-Markovi%C4%87-Ilic/1cee1344b571346987bb03df4622a603c1691899. Accessed 1 September 2024

Martynenko, A. A., & Vieira, G. N. A. (2023). Sustainability of drying technologies: System analysis. *Sustainable Food Technology, 1*(5), 629–640. https://doi.org/10.1039/D3FB00080J

Meanti, F., Mussio, C., Rocchetti, G., Rebecchi, A., Lucini, L., & Morelli, L. (2024). Oat Okara Fermentation: New Insights into the Microbiological and Metabolomic Characterization. *Fermentation, 10*(11), 545. https://doi.org/10.3390/fermentation10110545

Mitra, J., Shrivastava, S. L., & Rao, P. S. (2011). Process optimisation of vacuum drying of onion slices. *Czech Journal of Food Sciences, 29*(6), 586–594. https://doi.org/10.17221/162/2010-CJFS

Mugodo, K., & Workneh, T. S. (2021). The kinetics of thin-layer drying and modelling for mango slices and the influence of differing hot-air drying methods on quality. *Heliyon*, *7*(6). https://doi.org/10.1016/j.heliyon.2021.e07182

Naibaho, J., & Korzeniowska, M. (2021). The variability of physicochemical properties of brewery spent grain from 8 different breweries. *Heliyon*, *7*(3). https://doi.org/10.1016/j.heliyon.2021.e06583

Nowak, D., & Jakubczyk, E. (2020). The Freeze-Drying of Foods—The Characteristic of the Process Course and the Effect of Its Parameters on the Physical Properties of Food Materials. *Foods, 9*(10), 1488. https://doi.org/10.3390/foods9101488

Nurkhoeriyati, T., Kulig, B., Sturm, B., & Hensel, O. (2021). The Effect of Pre-Drying Treatment and Drying Conditions on Quality and Energy Consumption of Hot Air-Dried Celeriac Slices: Optimisation. *Foods, 10*(8), 1758. https://doi.org/10.3390/foods10081758

Oatly AB. (2021). Oatly and Our Fiber Residues. *OatlyFans*. https://community.oatly.com/conversations/news-and-views/oatly-and-our-fiber-residues/6318b759eb08200ed8a11f96. Accessed 14 July 2023

Oliveira, S. M., Ramos, I. N., Brandão, T. R. S., & Silva, C. L. M. (2015). Effect of Air-Drying Temperature on the Quality and Bioactive Characteristics of Dried Galega Kale (Brassica oleracea L. var. Acephala). *Journal of Food Processing and Preservation, 39*(6), 2485–2496. https://doi.org/10.1111/jfpp.12498

Onwude, D. I., Hashim, N., & Chen, G. (2016a). Recent advances of novel thermal combined hot air drying of agricultural crops. *Trends in Food Science & Technology, 57*, 132–145. https://doi.org/10.1016/j.tifs.2016.09.012

Onwude, D. I., Hashim, N., Janius, R. B., Nawi, N. M., & Abdan, K. (2016b). Modeling the Thin-Layer Drying of Fruits and Vegetables: A Review: Thin-layer models of fruits and vegetables. *Comprehensive Reviews in Food Science and Food Safety, 15*(3), 599–618. https://doi.org/10.1111/1541-4337.12196

Ozcan-Sinir, G., Ozkan-Karabacak, A., Tamer, C. E., & Copur, O. U. (2018). The effect of hot air, vacuum and microwave drying on drying characteristics, rehydration capacity, color, total phenolic content and antioxidant capacity of Kumquat (*Citrus japonica*). *Food Science and Technology, 39*, 475–484. https://doi.org/10.1590/fst.34417

Papoutsis, K., Pristijono, P., Golding, J. B., Stathopoulos, C. E., Bowyer, M. C., Scarlett, C. J., & Vuong, Q. V. (2017). Effect of vacuum-drying, hot air-drying and freeze-drying on polyphenols and antioxidant capacity of lemon (Citrus limon) pomace aqueous extracts. *International Journal of Food Science & Technology, 52*(4), 880–887. https://doi.org/10.1111/ijfs.13351

Patrón-Vázquez, J., Baas-Dzul, L., Medina-Torres, N., Ayora-Talavera, T., Sánchez-Contreras, Á., García-Cruz, U., & Pacheco, N. (2019). The Effect of Drying Temperature on the Phenolic Content and Functional Behavior of Flours Obtained from Lemon Wastes. *Agronomy, 9*(9), 474. https://doi.org/10.3390/agronomy9090474

Perera, C. O. (2005). Selected Quality Attributes of Dried Foods. *Drying Technology, 23*(4), 717–730. https://doi.org/10.1081/DRT-200054180

Popescu, M., Iancu, P., Plesu, V., Bildea, C. S., & Manolache, F. A. (2023). Mathematical Modeling of Thin-Layer Drying Kinetics of Tomato Peels: Influence of Drying Temperature on the Energy Requirements and Extracts Quality. *Foods, 12*(20), 3883. https://doi.org/10.3390/foods12203883

Rahman, M. S. (2009). Food Stability Beyond Water Activity and Glass Transtion: Macro-Micro Region Concept in the State Diagram. *International Journal of Food Properties, 12*(4), 726–740. https://doi.org/10.1080/10942910802628107

Röös, E., Patel, M., & Spångberg, J. (2016). Producing oat drink or cow's milk on a Swedish farm — Environmental impacts considering the service of grazing, the opportunity cost of land and the demand for beef and protein. *Agricultural Systems, 142*, 23–32. https://doi.org/10.1016/j.agsy.2015.11.002

Ross, K. A., DeLury, N., Fukumoto, L., & Diarra, M. S. (2020). Dried berry pomace as a source of high value-added bioproduct: Drying kinetics and bioactive quality indices. *International Journal of Food Properties, 23*(1), 2123–2143. https://doi.org/10.1080/10942912.2020.1847144

Saifullah, M., McCullum, R., McCluskey, A., & Vuong, Q. (2019). Effects of different drying methods on extractable phenolic compounds and antioxidant properties from lemon myrtle dried leaves. *Heliyon, 5*(12), e03044. https://doi.org/10.1016/j.heliyon.2019.e03044

Shih, Y.-T., Wang, W., Hasenbeck, A., Stone, D., & Zhao, Y. (2020). Investigation of physicochemical, nutritional, and sensory qualities of muffins incorporated with dried brewer's spent grain flours as a source of dietary fiber and protein. *Journal of Food Science, 85*(11), 3943–3953. https://doi.org/10.1111/1750-3841.15483

Vu, N. D., Tran, N. T. Y., Le, T. D., Phan, N. T. M., Doan, P. L. A., Huynh, L. B., & Dao, P. T. (2022). Kinetic Model of Moisture Loss and Polyphenol Degradation during Heat Pump Drying of Soursop Fruit (Annona muricata L.). *Processes, 10*(10), 2082. https://doi.org/10.3390/pr10102082

Vuong, Q. V., Hirun, S., Roach, P. D., Bowyer, M. C., Phillips, P. A., & Scarlett, C. J. (2013). Effect of extraction conditions on total phenolic compounds and antioxidant activities of Carica papaya leaf aqueous extracts. *Journal of Herbal Medicine, 3*(3), 104–111. https://doi.org/10.1016/j.hermed.2013.04.004

Wang, A., Zhu, Y., Zou, L., Zhao, G., & Wu, J. (2023). Development of protein-enriched biscuit based on oat-milk byproduct fortified with chickpea flour. *LWT - Food Science and Technology*, *177*. https://doi.org/10.1016/j.lwt.2023.114594

Yu, Y., Li, X., Zhang, J., Li, X., Wang, J., & Sun, B. (2023). Oat milk analogue versus traditional milk: Comprehensive evaluation of scientific evidence for processing techniques and health effects. *Food Chemistry: X, 19*, 100859. https://doi.org/10.1016/j.fochx.2023.100859

Zahari, I., Purhagen, J. K., Rayner, M., Ahlström, C., Helstad, A., Landers, M., et al. (2023). Extrusion of high-moisture meat analogues from hempseed protein concentrate and oat fibre residue. *Journal of Food Engineering, 354*, 111567. https://doi.org/10.1016/j.jfoodeng.2023.111567

Zeng, Z., Han, C., Wang, Q., Yuan, H., Zhang, X., & Li, B. (2024). Analysis of drying characteristic, effective moisture diffusivity and energy, exergy and environment performance indicators during thin layer drying of tea in a convective-hot air dryer. *Frontiers in Sustainable Food Systems*, *8*. https://doi.org/10.3389/fsufs.2024.1371696

Zhou, J., Zhang, X., Liu, W., Zhang, Q., & Wu, L. (2023). Effect of different drying methods on color difference, microorganisms and volatile metabolites profiles of Ganpu Tea. *Food Bioscience, 56*, 103314. https://doi.org/10.1016/j.fbio.2023.103314

Zielinska, M., & Markowski, M. (2012). Color Characteristics of Carrots: Effect of Drying and Rehydration. *International Journal of Food Properties, 15*(2), 450–466. https://doi.org/10.1080/10942912.2010.489209