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Air-impingement jet drying at high temperature and air velocity enhanced the dehydration efficiency, quercetin content, and antiradical properties of fig slices

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Abstract

Drying is an effective method for preserving figs. Air-impingement jet drying (AIJD) and hot-air drying (HAD) were applied to investigate the effect of drying methods on the drying kinetics, polyphenol constituents, and antiradical properties of fig slices. Results showed that AIJD was more effective than HAD in decreasing drying time and protecting the 1,1-diphenyl-2-picrylhydrazyl (DPPH·) scavenging activity of the fig slices. Additionally, AIJD was used to dry the fig slices at different temperatures (40, 50, 60, 70, and 80°C) and air velocities (6, 7, and 8 m/s). The drying rates (DR) and effective moisture diffusivities (D_{eff}) of the fig slices increased with the AIJD drying temperature. The AIJD drying activation energy (E_a) of the fig slices determined by the Arrhenius equation was 21.66 kJ/mol. The Page model was used to describe and predict the dehydration behaviour of the fig slices during AIJD. UHPLC-QqQ-MS/MS analysis identified seven phenolic acids and nine flavonoids in the dried fig slices, with quinic acid, rutin, and chlorogenic acid being the primary polyphenols. AIJD at 80°C and 8 m/s induced the highest 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) ($ABTS^{\cdot+}$) scavenging activity and quercetin content in the fig slices than the other treatments.

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Introduction

Figs (*Ficus carica* L.) are from part of the Moraceae family, and cultivated worldwide for consumption in both its fresh and dried forms (Russo *et al.*, 2014). Figs are an excellent sources of polyphenols, minerals, vitamins, and dietary fibres while exhibiting antioxidant activity, providing cardiovascular protection, and inhibiting tumour proliferation (Veberic *et al.*, 2008). However, fresh figs are exceedingly sensitive to microbial spoilage (post-harvest life of 7 - 10 d) even under cold storage conditions (Doymaz, 2005). Therefore, an effective method is necessary to preserve fresh figs which are typically preserved in dried or canned form (Doymaz, 2005).

Drying refers to either traditional or industrial process for removing moisture from agricultural products, inhibiting microbial spoilage, and minimising chemical reactions (Huang *et al.*, 2017). Currently, figs can be dried using various techniques including sun drying, pulsed vacuum osmotic dehydration, hot-air drying (HAD), microwave drying, and foam mat drying (Doymaz, 2005; Şahin and Öztürk, 2016; Varhan *et al.*, 2019).

Air-impingement jet drying (AIJD) is an effective drying technology that uses high-speed gas to impinge the surface of the sample, enhancing the heat transfer rate, and decreasing the drying time (Qiu *et al.*, 2018). Previous studies suggested that the heat transfer coefficient of AIJD is about five times higher than when using cross-circulation dryers (Seyedein *et al.*, 1995). In addition, AIJD fruits and vegetables displayed higher levels of vitamin C and polyphenols, as well as stronger antioxidant activity, and decreased browning than those exposed to HAD (Li *et al.*, 2016; Huang *et al.*, 2017). Therefore, AIJD may be a promising drying technology for the rapid drying of figs with high polyphenolic contents.

A novel drying method must exhibit characteristics such as high efficiency, low cost, exceptional product quality, operational safety, low environmental impact, and improved energy efficiency (Mujumdar and Law, 2010). Drying kinetics is a valuable tool for assessing drying efficiency, and widely applied to present the

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combined macro- and microscopic mechanisms for mass and heat transfer during processing. Moreover, drying kinetics can be affected by drying techniques, drying parameters, material attributes, and various other factors (Pei *et al.*, 2014). Thin-layer drying models have been developed to facilitate calculations for optimising the drying process, designing and constructing new drying systems, describing the drying behaviour, and eventually minimising the total energy requirements (Onwude *et al.*, 2016). However, thus far, no studies are available regarding the thin-layer drying models of figs exposed to AIJD in different drying conditions, including drying temperature and velocity.

Polyphenols are vital phytochemicals found in figs that can improve the overall fruit quality by enhancing and standardising the production process, as well as via specific genetic selection programs and plant breeding (Russo *et al.*, 2014). The polyphenols in figs display strong antioxidant activity which helps scavenge harmful free radicals (Pande and Akoh, 2010). Previous studies suggested a significant difference in the polyphenol constituents and contents between fresh and dried figs (Vallejo *et al.*, 2012). To the best of our knowledge, the effect of AIJD on the antioxidant activity and polyphenols in figs has not yet been examined.

The present work thus aimed to investigate the feasibility of AIJD during the drying process of figs. The difference between the impact of AIJD and HAD on figs was examined, as well as the effect of AIJD on the drying kinetics, total phenolic content (TPC), and antiradical properties. Moreover, the monomeric polyphenol compounds were measured using UHPLC-QqQ-MS/MS.

Materials and methods

Raw materials

Figs were purchased from a vegetable market in the Fuling District, Chongqing City, China, and cut into approximately 5 mm slices. The moisture content of the fresh figs was 81.5 ± 1.2% (wet mass, W.M.), which was determined via oven drying at 105°C until a constant weight was reached (Marey and Shoughy, 2016).

Standard polyphenol (purity > 95%) chemicals were purchased from Shanghai Yuanye Bio-Technology Co., Ltd. (Shanghai, China). Formic acid and methanol (chromatographic grade) were purchased from Adamas Reagent, Ltd. (Shanghai, China). Ultrapure water was purchased from Hangzhou Wahaha Group Co., Ltd. (Hangzhou, China), while 1,1-diphenyl-2-picrylhydrazyl (DPPH·) and 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid ($ABTS^{\cdot+}$) were purchased from Beijing Solarbio Science and Technology Co., Ltd. (Beijing, China). Other reagents were of analytical grade unless otherwise stated.

Drying treatment

Following the methods described in previous studies (Şahin and Öztürk, 2016; Varhan *et al.*, 2019), the fig slices were subjected to HAD at a temperature of 60°C and an air velocity of 0.3 m/s. Then, 250 g of the fig slices were placed in a single layer on a mesh tray in the hot-air dryer (101A-1, Shanghai Pudong Rongfeng Scientific Instrument Co., Ltd., Shanghai, China). The samples were dried at 40, 50, 60, 70, and 80°C, respectively, at an air velocity of 8 m/s, in an air-impingement jet dryer manufactured by a fruit and vegetable processing technology laboratory at the Yangtze Normal University, according to a previously established design (Li *et al.*, 2016). In addition, the fig slices were subjected to AIJD at 60°C at air velocities of 6 and 7 m/s, respectively. During the drying process, the fig slices (250 g) were placed separately in a stainless-steel wire box in the air-impingement jet dryer to avoid the samples from blown away. All drying treatments were terminated when the decrease in weight was below 0.005 g over 30 min. The dried fig slices were packed into polyethylene bags, and stored at -20°C.

Extraction of polyphenols

The dried fig slices (3 g) and 10 mL of 80% ethanol were added to a centrifuge tube, and ground using a dynamoelectric homogeniser at 10,000 rpm (FSH-2A, Changzhou Jintan Liangyou Instrument Co. Ltd., Changzhou, China), after which, the mixture was centrifuged at 1,500 *g* for 10 min. The supernatant was collected to determine the TPC, total flavonoid content (TFC), antioxidant activity, and monomeric polyphenol levels.

Determination of TPC

The TPC was determined using the Folin-Ciocalteu method with some modifications (Singleton *et al.*, 1999). Briefly, 50 μL of polyphenol extract was added to 96-well plates, and combined with Folin-Ciocalteu reagent (10 μL). After 6 min incubation in the dark, 450 μL of 7% Na_2CO_3 and deionised water (80 μL) was added. The mixture was left to stand for 30 min, after which the absorbance was measured at 760 nm using a microplate reader (PT-3502C, Beijing Putian Xinqiao Technology Co. Ltd., Beijing, China). The TPC was expressed as milligram of gallic acid equivalent (GE) per gram of dry matter (mg GE/g DM).

Determination of TFC

The TFC was determined following a method described by Matyuschenko and Stepanova (2003) with some modifications. Here, 10 μL of polyphenol extract was blended with 5% $NaNO_2$ (10 μL). After 6 min incubation, it was then combined with 10% $AlNO_3$ (10 μL), 4% NaOH (100 μL), and 60% ethanol (60 μL). The mixture was then incubated for 15 min, after which, the absorbance was measured at 510 nm. The TFC was expressed as milligram of rutin equivalent (RE) per gram of dry matter (mg RE/g DM).

Assessing antiradical properties

The antiradical properties of the polyphenol extracts were assessed based on the DPPH· and $ABTS^{\cdot+}$ scavenging activities (Li *et al.*, 2020a; 2020b). The DPPH· scavenging activity was assessed following a previously modified method (Blois, 1958), while the $ABTS^{\cdot+}$ scavenging activity was measured following the method reported by Re *et al.* (1999).

The determination of monomeric polyphenols

The monomeric polyphenols in the dried fig polyphenol extract were determined using UHPLC-QqQ-MS/MS (Li *et al.*, 2019). Briefly, the extract was injected in a ZORBAX Eclipse Plus C_{18} column (100 × 2.1 mm i.d., 1.8 μm; Agilent, Waldbronn, Germany). The ion pairs were detected using triple quadruple mass spectrometry (6460C, Agilent, Waldbronn, Germany) in negative ion mode (electrospray ionisation source, ESI). The mobile phase consisted of 0.1% aqueous formic acid (A) and 0.1% methanol formic acid (B). The flow rate was 0.2 mL/min, while the linear gradient included 20 - 20% B (0 - 0.5 min) and 20 - 80% A (0.5 - 15.0 min). The dynamic multiple reaction monitoring (MRM) model was used to acquire the data.

Calculations

The moisture ratio (MR) was calculated using Eq. 1 (Li *et al.*, 2016):

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

where, M_0, M_t, and M_e = initial moisture content (%), moisture content at any time (%), and equilibrium moisture content (%), respectively.

The drying rate (DR) was calculated using Eq. 2 (Li *et al.*, 2020a):

$$DR = \frac{M_{t1} - M_{t2}}{t_1 - t_2} \quad \text{(Eq. 2)}$$

where, M_{t1} and M_{t2} = moisture content of the fig slices at time t_1 and t_2, respectively.

Fick's second law of diffusion equation (Eq. 3) describes the drying characteristics of fruits and vegetables during the falling rate period. The effective moisture diffusivity (D_{eff}), m^2/s, was calculated using the simplified diffusion equation (Eq. 4).

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\left\{\begin{array}{c} \exp\left(-\frac{\pi^2 D_{eff}}{L^2}t\right) + \frac{1}{9}\exp\left(-\frac{9\pi^2 D_{eff}}{L^2}t\right) + \frac{1}{25}\exp\left(-\frac{25\pi^2 D_{eff}}{L^2}t\right) + \cdots \\ + \frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2 D_{eff}}{L^2}t\right] (n \in N, N \to +\infty) \end{array}\right\} \quad \text{(Eq. 3)}$$

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

where, t and L = drying time (s) and slice thickness (mm) of the figs, respectively.

Arrhenius' law provides valuable information regarding kinetics (van Boekel, 2008), and an Arrhenius-type equation (Eq. 5) was used to calculate the activation energy (E_a), kJ/mol (van Boekel, 2008):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad \text{(Eq. 5)}$$

where, R = ideal gas constant (8.314 J/mol·K), T = drying temperature (°C), and D_0 = pre-exponential factor (m^2/s) of the Arrhenius equation.

Statistical analysis

The MR, DR, TPC, TFC, and monomeric polyphenol content results were expressed as mean ± SD of triplicates (*n* = 3). Principal component analysis (PCA) and sparse partial least squares (sPLS) analysis were performed using mixOmics (version 6.10.2), which is an *R* package. The thin-layer drying models were fitted using SPSS (20.0, IBM), while the statistical assessment of the analysis of variance (ANOVA and Tukey's multiple comparison *post-hoc* test) was conducted using GraphPad Software Prism (8.0). Differences were considered significant at $p < 0.05$.

The thin-layer drying models were selected based on three statistical parameters, namely R^2, χ^2, and root mean square error (RMSE) (Falade and Solademi, 2010). These parameters were calculated using Eqs. 6, 7, and 8, respectively.

$$R^2 = 1-\frac{\sum_1^N (MR_{exp,i}-MR_{pre,i})^2}{\sum_1^N (\overline{MR}_{exp}-MR_{pre,i})^2} \quad \text{(Eq. 6)}$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i}-MR_{pre,i})^2}{N-n} \quad \text{(Eq. 7)}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^N (MR_{pre,i}-MR_{exp,i})^2\right]^{\frac{1}{2}} \quad \text{(Eq. 8)}$$

where, MR_{exp}, MR_{pre}, and $\overline{MR}_{exp}$ = experimental, predicted, and average MRs, respectively, while N and n = observed value and constant, respectively, in the thin-layer drying model equation.

Results and discussion

The different effects of HAD and AIJD on the drying kinetics, polyphenol content, and antioxidant activity of the fig slices

The fig slices were dried at 60°C using HAD and AIJD, revealing the different effects of these drying technologies on the drying kinetics, polyphenolic contents, and antioxidant activity. Figure 1A shows that the time required to decrease the moisture in the fig slices to equilibrium content using AIJD and HAD were 570 and 700 min, respectively. The initial DR of AIJD increased by 292.8% when compared with HAD, thus suggesting that the mass and heat transfer rates of AIJD were higher than HAD while drying the fig slices (Figure 1B). Similar results were evident in AIJD- and HAD-dried onion and kiwifruit (Li *et al.*, 2015; Huang *et al.*, 2017). These results could be ascribed to the air velocity of AIJD (8 m/s) being about 27 times higher than HAD (0.3 m/s) in the present work. Air impinging on the product surface at a high velocity decreased the drying boundary layers to increase the heat and mass transfer efficiency (Li *et al.*, 2015). Therefore, as far as drying efficiency is concerned, AIJD was more effective than HAD in drying the fig slices.

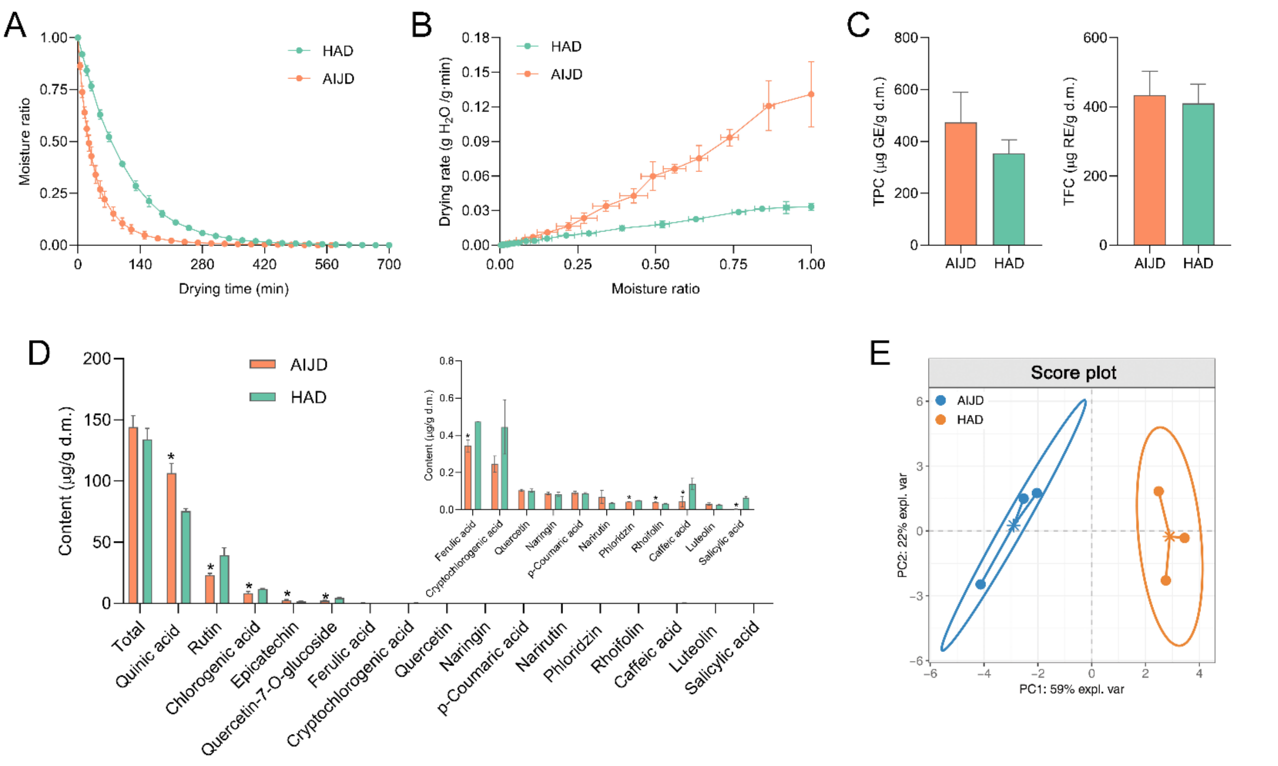

Figure 1. The effect of AIJD and HAD on MR **(A)**, DR **(B)**, TPC and TFC **(C)**, monomeric polyphenol content **(D)**, and polyphenol profile **(E)** (PCA score plot) of red radishes at 60°C. $^*p < 0.05$, relative to hot-air-dried fig slices.

Figure 1C indicates that although the TPC and TFC in the AIJD-treated fig slices were slightly higher than in the HAD-treated fig slices, no significant differences were observed. Moreover, the AIJD-dried fig slices exhibited stronger DPPH· scavenging activity than those subjected to HAD. This could be attributed to the fact that the variety and content of the monomeric polyphenols in the AIJD-dried fig slices differed significantly from those exposed to HAD. A similar result was apparent regarding AIJD- and HAD-dried kiwifruit slices (Huang *et al.*, 2017). However, no differences were evident between the ABTS$^{\cdot+}$ scavenging activity of the AIJD- and HAD-treated fig slices. The monomeric polyphenols in the fig slices were analysed using UHPLC-QqQ-MS/MS to determine the differences in the DPPH· scavenging activity. The results revealed 16 polyphenolic compounds in the fig slices, including seven phenolic acids and nine flavonoids (Figure 1D). Similar to the results reported by Russo *et al.* (2014), the present work also found rutin, chlorogenic acid, and epicatechin as the primary polyphenols in the fig slices (Figure 1D), while quinic acid was identified as the main polyphenol. These findings expanded on previous research regarding polyphenols in fresh and dried figs (Veberic *et al.*, 2008; Vallejo *et al.*, 2012; Russo *et al.*, 2014). In addition, the quinic acid and epicatechin contents in the AIJD-dried fig slices was significantly higher than the samples subjected to HAD. However, the HAD-dried samples displayed higher rutin, chlorogenic acid, and quercetin-7-*O*-glucoside levels than those exposed to AIJD (Figure 1D). The PCA score plot suggested that the polyphenolic profile of the AIJD-dried fig slices was significantly different from those exposed to HAD (Figure 1E). Russo *et al.* (2014) and Vallejo *et al.* (2012) also found drying-induced differences in the polyphenolic profiles of figs, which could cause imparity in antioxidant activity. Consequently, AIJD seemed superior to HAD for drying fig slices due to higher quinic acid content, and stronger DPPH· scavenging activity.

Drying characteristics of the fig slices during AIJD

Figures 2A - 2D show that the drying time and DR of the fig slices were affected by the drying temperature and air velocity during AIJD, thus indicating that the drying temperature effect was more significant than the air velocity (Figures 2A - 2D). Furthermore, the drying time decreased while the DR increased in conjunction with an elevated drying temperature. These findings corresponded with those reported by Xiao *et al.* (2010) regarding the drying process of Monukka seedless grapes using AIJD. Figures 2B and 2D show that the DR curves exhibited no constant rate period. Therefore, the AIJD process of fig slices only occurred during a falling rate period, corresponding with the AIJD processes of onions (Li *et al.*, 2015), kiwifruit (Li *et al.*, 2016), and Monukka seedless grapes (Xiao *et al.*, 2010). This result may be attributed to the fact that the moisture evaporation rate on the surface of the fig slices exceeded the moisture diffusion on the interior of the fruits during AIJD. Notably, the drying behaviour of agricultural products during the falling rate period can be expressed via Fick's diffusion equation (Wang *et al.*, 2007; Falade and Solademi, 2010). Accordingly, the D_{eff} value was calculated, representing the degree of dehydration difficulty during the drying process. The D_{eff} values for the fig slices in various AIJD conditions were between 7.05×10^{-10} and 1.01×10^{-9} m^2/s. Previous studies indicated that the D_{eff} for figs ranged from 2.75×10^{-10} to 655.5×10^{-10} m^2/s (Şahin and Öztürk, 2016). In addition, the D_{eff} value of the AIJD fig slices increased with increasing drying temperature corresponding with the results from previous research (Xiao *et al.*, 2010; Li *et al.*, 2015). The E_a indicates the required energy necessary to transfer moisture from the interior to the exterior of a drying sample (Xiao *et al.*, 2010). In the present work, the E_a was calculated by the slope of the natural logarithm function of D_{eff} ($\ln D_{eff}$) and Kelvin temperature. Results showed that the E_a value of the AIJD fig slices was 21.66 kJ/mol, which was lower than the E_a value (30.81 - 48.47 kJ/mol) of the figs exposed to thin-layer drying (Şahin and Öztürk, 2016). This implied that AIJD expended less energy than thin-layer drying during the drying process of figs.

Thin-layer drying models for AIJD fig slices

Although the theoretical, semi-theoretical, and empirical models can be employed to describe fruit and vegetable drying, the most widely applied categories involve semi-theoretical and empirical models (Onwude *et al.*, 2016). Consequently, four semi-theoretical (Newton, Page, Modified Page, and Modified Midilli) and two empirical (Wang and Singh, and Peleg) thin-layer drying models were used to fit the drying curves for the fig slices during AIJD

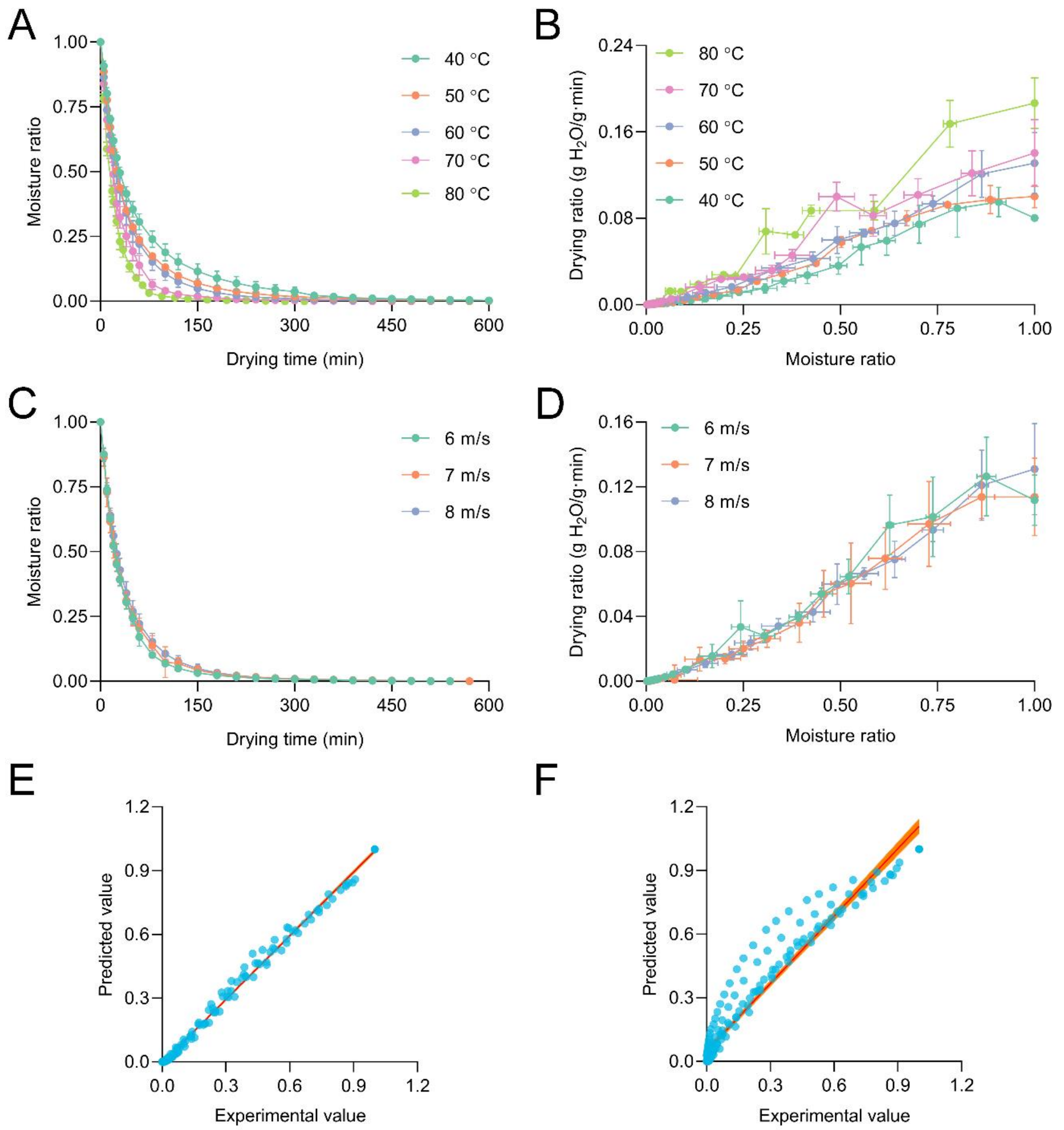

Figure 2. The effect of AIJD drying temperature and air velocity on the MR **(A & C)** and DR **(B & D)** of fig slices. Verification of the predictive ability of the Page model **(E)** and the Modified Page model **(F)**.

(Table 1). Table 1 shows that the Page and Modified Page models exhibited the highest R^2 (0.9948 - 0.9994), as well as the lowest χ^2 (0.0001 - 0.0004) and RMSE (0.0072 - 0.0210) for all the models. Although these two models showed the same R^2, χ^2, and RMSE values, they displayed different model constants. Therefore, their predictive ability for the water desorption of the fig slices during AIJD was further verified by creating predictive equations based on the model constants. Next, the present work compared the experimental and corresponding predicated MRs, which were calculated using predictive Eq. 9 for the Page model, and predictive Eq. 10 for the Modified Page model. Figures 2E and 2F indicate that the predicated MRs from the Page model (R^2 = 0.9958) displayed higher experimental MR consistency than the Modified Page model (R^2 = 0.9384). However, previous reports suggested that the Modified Page model was the most suitable in describing the drying behaviour of onions (Li *et al.*, 2015), kiwifruit (Huang *et al.*, 2017), and Hami melons (Zhang *et al.* 2011) during AIJD. These findings can be attributed to the differences in organisational structure and chemical components of the various fruits and vegetables. Additionally, the two-term exponential model and the logarithmic model yielded the best predictions regarding the drying behaviour of figs during tunnel-drying (Babalis *et al.*, 2006) and single-

Table 1. Thin-layer models applied to fit air-impingement jet drying curves of figs slices.

Type of model	Model and equation	Parameter	Air-impingement jet drying (Temperature (°C), air velocity (m/s))						
			40, 8	**50, 8**	**60, 8**	**70, 8**	**80, 8**	**60, 7**	**60, 6**
Semi theoretical	Newton MR = exp(-kt)	a	0.022	0.025	0.027	0.036	0.048	0.029	0.030
		R^2	0.9879	0.9936	0.9962	0.9984	0.9985	0.9959	0.9981
		χ^2	0.0011	0.0006	0.0004	0.0001	0.0001	0.0004	0.0002
		RMSE	0.0337	0.0245	0.0187	0.0122	0.0113	0.0196	0.0131
	Page MR = $\exp(-kt^n)$	k	0.047	0.041	0.043	0.041	0.059	0.046	0.037
		n	0.791	0.859	0.865	0.953	0.929	0.871	0.942
		R^2	0.9948	0.9964	0.9992	0.9987	0.9994	0.9985	0.9986
		χ^2	0.0004	0.0003	0.0001	0.0001	0.0001	0.0001	0.0001
		RMSE	0.0210	0.0178	0.0082	0.0109	0.0072	0.0115	0.0112
	Modified Page MR = $\exp[-(kt)^n]$	k	0.021	0.024	0.026	0.036	0.048	0.029	0.030
		n	0.791	0.859	0.865	0.953	0.929	0.871	0.942
		R^2	0.9948	0.9964	0.9993	0.9987	0.9994	0.9985	0.9986
		χ^2	0.0004	0.0003	0.0001	0.0001	0.0001	0.0001	0.0001
		RMSE	0.0210	0.0178	0.0082	0.0109	0.0072	0.0115	0.0112
	Modified Midilli and other MR = aexp(-kt)+b	a	0.951	0.969	0.962	0.990	0.981	0.967	0.989
		b	0.022	0.019	0.013	0.007	0.007	0.013	0.010
		k	0.022	0.026	0.027	0.036	0.048	0.0294	0.031
		R^2	0.9911	0.9958	0.9978	0.9986	0.9989	0.9972	0.9987
		χ^2	0.0008	0.0004	0.0002	0.0001	0.0001	0.0002	0.0001
		RMSE	0.0274	0.0191	0.0140	0.0109	0.0093	0.0155	0.0107
Empirical	Wang and Singh MR = $1+at+bt^2$	a	-0.005	-0.006	-0.007	-0.009	-0.014	-0.007	-0.007
		b	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		R^2	0.7065	0.6930	0.7057	0.6524	0.6450	0.6771	0.6781
		χ^2	0.0566	0.0605	0.0587	0.0721	0.0689	0.0654	0.0654
		RMSE	0.2379	0.2459	0.2380	0.2685	0.2625	0.2557	0.2557
	Peleg MR = 1-t/(a+bt)	a	29.309	26.030	24.181	18.028	13.038	21.863	21.577
		b	0.943	0.938	0.929	0.927	0.918	0.934	0.928
		R^2	0.9954	0.9919	0.9925	0.9831	0.9842	0.9911	0.9856
		χ^2	0.0004	0.0007	0.0006	0.0014	0.0012	0.0007	0.0012
		RMSE	0.0194	0.0258	0.0248	0.0372	0.0347	0.0270	0.0348

MR = moisture ratio; t = drying time; a, b, k, and n = thin-layer model constants.

layer drying (Xanthopoulos *et al.*, 2007), respectively.

Page model:

$$MR = \exp[-(0.00024T+0.0039V+0.00075)\times t^{(0.0037T-0.025+0.86)}] \quad \text{(Eq. 9)}$$

Modified Page model:

$$MR = \exp\{-[(0.00065T+0.00076V-0.014)\times t]^{(0.0037T-0.025+0.86)}\} \quad \text{(Eq. 10)}$$

AIJD modified the polyphenol content and antioxidant activity of the fig slices

Phenolic compounds are primarily responsible for the positive health benefits of figs (Russo *et al.*, 2014). However, the TPC and TFC in the fig slices were affected by AIJD (Figures 3A and 3B). Although the fig slices dried at 60°C and 8 m/s AIJD exhibited the highest TPC, they also displayed the lowest TFC, known for playing a prominent polyphenolic role of all the AIJD samples (Nayak *et* *al*., 2015). The results further revealed that the TFC of the fig slices was modified without altering the TPC during the AIJD process (Figures 3A and 3B), while similar results were found during the air-drying and vacuum-drying of lemons (Papoutsis *et al*., 2017). This could be ascribed to the fact that the changes in different monomeric polyphenols during AIJD varied, and that these polyphenols displayed different levels of detection sensitivity during TFC and TPC analyses. Therefore, the effect of AIJD on the health value of fig slices based on the TPC and TFC could not be confirmed. Further analysis of the antiradical properties showed that when exposed to various conditions, and AIJD did not cause significant differences in the DPPH· scavenging activity of the dried fig slices (Figure 3C). However, the ABTS$^{·+}$ scavenging activity increased with increasing temperature, while decreasing with increasing AIJD air velocity (Figure 3D). The fig slices dried at 80°C and 8 m/s exhibited the highest ABTS$^{·+}$ scavenging activity of all the samples (Figure 3D). Therefore, a high TPC and TFC did not necessarily translate to significant antiradical properties. This can be ascribed to the fact that individual polyphenols with different molecular structures display different antiradical qualities (Moure *et al*., 2001). Consequently, it was speculated that the fig slices exposed to AIJD at 80°C and 8 m/s displayed more specific polyphenolic content and substantial antiradical properties.

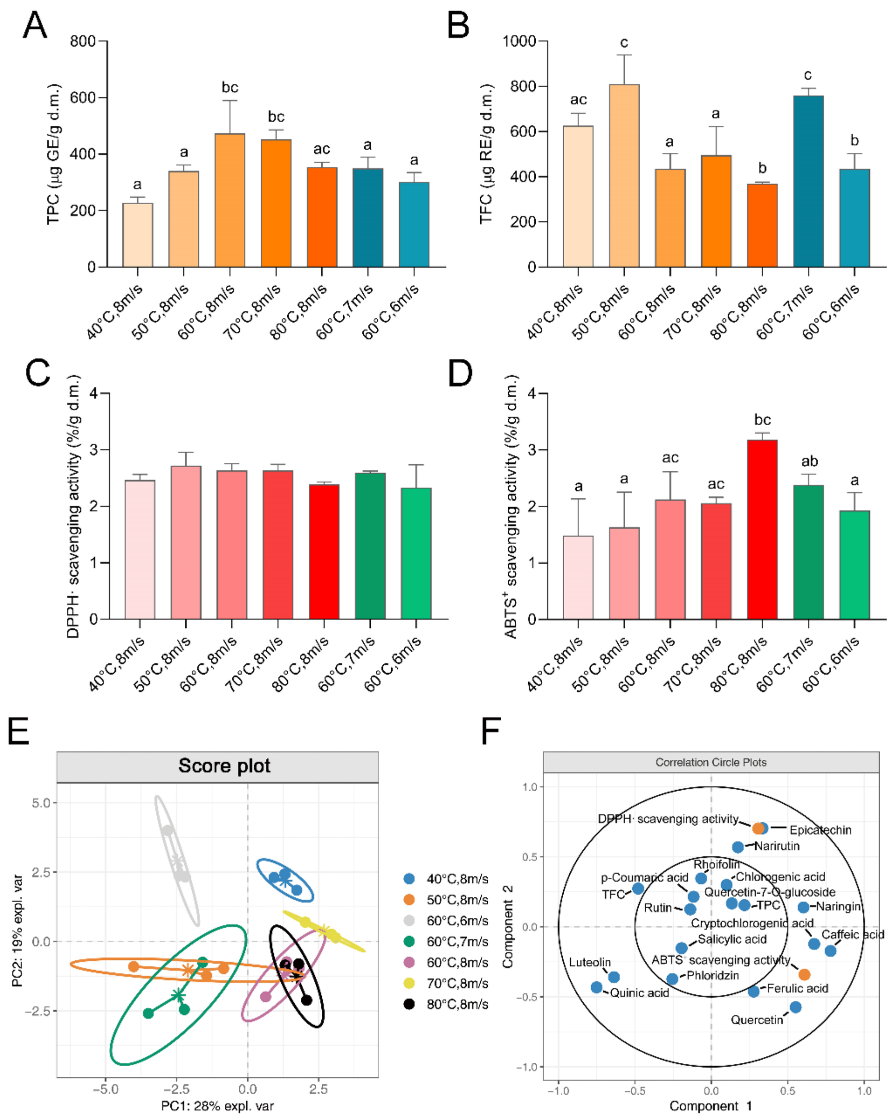

Figure 3. The effect of AIJD on the polyphenol and activities of fig slices. TPC **(A)**, TFC **(B)**, DPPH·scavenging activity **(C)**, ABTS$^{·+}$ scavenging activity **(D)**, the PCA score plot for the polyphenol compounds **(E)**, and the correlation circle plot of the sPLS of the polyphenols and antiradical properties **(F)**. Means with different lowercase letters denote significant differences between the treatments (p < 0.05).

Table 2. Monomeric polyphenol compounds in air-impingement jet dried fig fruit slices.

Polyphenol (μg/g d.m.)	Air-impingement jet drying						
	40°C, 8 m/s	**50°C, 8 m/s**	**60°C, 8 m/s**	**70°C, 8 m/s**	**80°C, 8 m/s**	**60°C, 7 m/s**	**60°C, 6 m/s**
Phenolic acid							
Quinic acid	121.89 ± 26.59^{ab}	104.56 ± 4.19^{b}	106.63 ± 7.76^{b}	113.06 ± 3.33^{ab}	100.25 ± 1.47^{b}	87.81 ± 3.97^{b}	155.73 ± 31.87^{a}
Chlorogenic acid	6.36 ± 0.54^{ab}	12.83 ± 0.39^{e}	8.47 ± 1.32^{bc}	5.56 ± 1.04^{a}	8.87 ± 0.89^{cd}	11.05 ± 0.91^{de}	10.86 ± 0.58^{cde}
Salicylic acid	0.11 ± 0.12^{a}	0.02 ± 0.01^{a}	0.00 ± 0.00^{a}	0.08 ± 0.02^{a}	0.04 ± 0.00^{a}	0.03 ± 0.00^{a}	0.03 ± 0.01^{a}
Cryptochlorogenic acid	0.15 ± 0.09^{a}	0.30 ± 0.10^{a}	0.25 ± 0.04^{a}	0.17 ± 0.05^{a}	0.44 ± 0.25^{a}	0.34 ± 0.21^{a}	0.15 ± 0.01^{a}
Caffeic acid	0.07 ± 0.01^{ab}	0.1 ± 0.04^{abc}	0.04 ± 0.03^{a}	0.12 ± 0.05^{abc}	0.15 ± 0.03^{bc}	0.18 ± 0.05^{c}	0.05 ± 0.02^{a}
p-Coumaric acid	0.06 ± 0.02^{a}	0.33 ± 0.19^{c}	0.09 ± 0.01^{ab}	0.10 ± 0.01^{ab}	0.08 ± 0.00^{ab}	0.19 ± 0.04^{abc}	0.29 ± 0.01^{bc}
Ferulic acid	0.84 ± 0.06^{de}	0.49 ± 0.09^{ab}	0.34 ± 0.03^{a}	0.95 ± 0.07^{e}	0.76 ± 0.07^{cd}	1.01 ± 0.06^{e}	0.63 ± 0.03^{bc}
Flavonoid							
Rutin	41.73 ± 10.39^{abc}	56.94 ± 15.71^{bc}	23.07 ± 1.59^{a}	15.05 ± 0.83^{a}	31.37 ± 4.37^{ab}	69.45 ± 19.32^{c}	70.16 ± 3.46^{bc}
Quercetin-7-*O*-glucoside	3.03 ± 0.74^{ab}	4.39 ± 1.45^{bc}	2.22 ± 0.20^{ab}	1.77 ± 0.10^{a}	2.87 ± 0.47^{ab}	6.37 ± 1.55^{c}	4.66 ± 0.52^{bc}
Naringin	0.05 ± 0.01^{a}	0.13 ± 0.07^{a}	0.09 ± 0.01^{a}	0.13 ± 0.01^{a}	0.11 ± 0.02^{a}	0.12 ± 0.01^{a}	0.06 ± 0.02^{a}
Narirutin	0.02 ± 0.00^{ab}	0.07 ± 0.00^{c}	0.07 ± 0.03^{c}	0.01 ± 0.00^{a}	0.03 ± 0.01^{ab}	0.08 ± 0.01^{c}	0.05 ± 0.00^{b}
Phloridzin	0.04 ± 0.01^{a}	0.05 ± 0.01^{a}	0.04 ± 0.00^{a}	0.05 ± 0.01^{a}	0.05 ± 0.00^{a}	0.1 ± 0.09^{a}	0.11 ± 0.12^{a}
Rhoifolin	0.05 ± 0.01^{b}	0.04 ± 0.01^{ab}	0.04 ± 0.00^{ab}	0.04 ± 0.01^{ab}	0.02 ± 0.00^{a}	0.07 ± 0.01^{c}	0.05 ± 0.00^{b}
Epicatechin	0.36 ± 0.05^{a}	1.54 ± 0.51^{b}	2.8 ± 0.29^{c}	0.44 ± 0.12^{a}	0.71 ± 0.14^{a}	1.88 ± 0.3^{b}	0.5 ± 0.39^{a}
Quercetin	0.09 ± 0.00^{a}	0.16 ± 0.04^{bc}	0.1 ± 0.01^{ab}	0.23 ± 0.02^{cd}	0.25 ± 0.03^{d}	0.2 ± 0.03^{cd}	0.19 ± 0.00^{cd}
Luteolin	0.08 ± 0.01^{bc}	0.05 ± 0.02^{ab}	0.03 ± 0.01^{a}	0.1 ± 0.03^{c}	0.04 ± 0.00^{ab}	0.06 ± 0.01^{abc}	0.34 ± 0.01^{d}
Total	174.95 ± 27.16^{a}	182 ± 19.44^{a}	144.29 ± 9.05^{a}	137.84 ± 2.76^{a}	146.03 ± 6.12^{a}	178.94 ± 24.28^{a}	243.85 ± 28.42^{b}

Moreover, to reveal the differences between the monomeric polyphenol compounds in the dried fig slices, UHPLC-QQQ-MS/MS was used for polyphenolic quantification. The PCA score plot showed that the polyphenolic constituents in the fig slices subjected to AIJD at 40°C and 8 m/s, and at 60°C and 6 m/s differed significantly from the other samples (Figure 3E). Additionally, the polyphenolic constituents in the fig slices exposed to AIJD at 50°C and 8 m/s were similar to those dried at 60°C and 7 m/s, while the samples dried at 60°C and 8 m/s were analogous to 80°C and 8 m/s (Figure 3E). These results indicated that a high AIJD temperature decreased the drying time and polyphenolic degradation. In addition, the characteristics of the thermal and mass transfer of fig slices during AIJD at a low temperature and high air velocity may be similar to that at a high temperature and low air velocity. These findings corresponded with previous reports regarding the drying process of Hongjv peel and red radishes using HAD (Li *et al.*, 2020a; 2020b).

The correlation circle plots showed that the $ABTS^{\cdot+}$ scavenging activity, quercetin, ferulic acid, caffeic acid, and cryptochlorogenic acid were clustered together, thus suggesting a positive correlation between the scavenging activity of $ABTS^{\cdot+}$ and the content of these compounds in the dried fig slices (Figure 3F). Quercetin represents one of the most prominent antioxidants in food such as vegetables, fruit, tea, and wine, as well as countless food supplements, and is claimed to exert beneficial health effects (Boots *et al.*, 2008). The quercetin content in the dried fig slices assessed in the present work increased by 178% with increasing AIJD drying temperature from 40 to 80°C, while displaying an increase of 100% as the AIJD air velocity decreased from 8 to 6 m/s (Table 2). The present work revealed that polyphenols in a binding state in fruits could be released to increase the biological accessibility during the drying process (Li *et al.*, 2019). Additionally, AIJD induced flavonoid glycoside degradation to produce flavonoid aglycone (Li *et al.*, 2020c). However, no differences were observed in the quercetin-7-*O*-glucoside content at altered drying temperatures and air velocities (Table 2). Consequently, AIJD increased the quercetin content in the fig slices due to the uncoupling of quercetin in a binding state. Furthermore, quercetin was only found in the fig leaves (8.4 ± 2.0 mg/100 g fresh weight) and not in the pulp, seeds, peel, and fruits (Pande and Akoh, 2010). However, AIJD did not induce the same variations in the remaining content of other polyphenols when exposed to different AIJD temperatures and air velocities (Table 2). These results indicated that the fig slices should be dried using AIJD at 80°C and 8 m/s due to the high $ABTS^{\cdot+}$ scavenging activity and quercetin content at this level.

Conclusion

The present work demonstrated that AIJD could be more effective in decreasing drying time and protecting the antiradical properties of the fig slices than HAD. The Page model was ideal for describing and predicting the dehydration behaviour of the fig slices during AIJD. Moreover, drying the fig slices at 80°C and 8 m/s denoted the optimal AIJD conditions for decreasing the drying time while increasing the $ABTS^{\cdot+}$ scavenging activity and quercetin content. These results indicated that AIJD could be a novel and promising technology that can be applied for drying fig slices.

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