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MATHEMATICAL MODELING OF CONCENTRATIONS OF GRAPE, POMEGRANATE AND BLACK CARROT JUICES BY VARIOUS METHODS

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ABSTRACT

In the present study, grape, pomegranate and black carrot juices were concentrated to 65 °Brix (Bx) from initial concentrations of 15.93, 13.91 and 11.23 °Bx respectively. The concentration kinetics of the juices were investigated using a rotary vacuum evaporator at 80°C, a microwave vacuum evaporator at 180 W and 300 W and osmotic distillation (OD) at room temperature. Experimental data were compared according to three statistical parameters: the correlation coefficient (R^2), reduced chi-squared ($\chi 2$) value, and root mean-square error (RMSE), with values predicted by 13 models. Midilli model exhibited a better fit for the concentration kinetics ($R^2 \geq 0.9990$; $\chi^2 \leq 0.4588$; RMSE ≤ 0.5350) than the other models, in general. This model was followed by the logarithmic, Page and two-term exponential models. The logarithmic model exhibited slightly better fitting for the thermal concentration method than Midilli model. The lowest energy consumption (1.334-1.540 kWh) was determined for the OD technique.

Keywords: Juice concentration, mathematical modeling, microwave vacuum evaporation, osmotic distillation.

ÜZÜM, NAR VE KARA HAVUÇ SULARININ FARKLI YÖNTEMLERLE KONSANTRASYONUNUN MATEMATİKSEL MODELLENMESİ

ÖZ

Bu çalışmada başlangıç °Briks değerleri sırasıyla 15.93, 13.91 ve 11.23 olan üzüm, nar ve siyah havuç suları 65 °Briks değerine kadar konsantre edilmiştir. Meyve sularının konsantrasyon kinetik değerleri rotary vakum evoparatörde 80 °C'de, mikrodalga vakum evaporatörde 180 ve 300 W'da, ozmotik distilasyonda ise oda sıcaklığında çalışılarak belirlenmiştir. Elde edilen deneysel verilerin 13 farklı modele uygunluğu, korelasyon katsayısı (R^2), azaltılmış ki-kare ($\chi 2$) değeri ve hata kareler ortalamasının karekökü (RMSE) olmak üzere 3 istatistiksel parametreye göre karşılaştırılmıştır. Konsantrasyon kinetiği açısından Midilli modeli ($R^2 \geq 0.9990$; $\chi^2 \leq 0.4588$; RMSE ≤ 0.5350) diğer modellerden genel olarak daha uyumlu bulunmuş olup, bu modeli logaritmik, Page ve iki terimli eksponansiyel modelleri izlemiştir. Termal konsantrasyon yöntemi için logaritmik modelin Midilli modeline göre daha uyumlu olduğu görülmüştür. En düşük enerji tüketimi (1.334-1.540 kWh) ise ozmotik distilasyon tekniğinde belirlenmiştir.

Anahtar kelimeler: Meyve suyu konsantrasyonu, matematiksel modelleme, mikrodalga vakum evoparasyon, ozmotik distilasyon.

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INTRODUCTION

In the food industry, fruit juices are widely concentrated by thermal evaporation at high temperatures, to reduce storage, transport and packaging costs, and to achieve longer storage times. This process results in loss of fresh juice flavors, color degradation, reduction of nutritional value and formation of a cooked taste and of harmful compounds such as hydroxymethylfurfural (HMF) or furan compounds in the fruit juices. An additional drawback of thermal evaporation is the high energy cost, despite the use of energy-saving techniques. These disadvantages lead to a requirement for alternative methods (Jiao et al. 2004; Bánvölgyi et al. 2009; Dincer et al. 2016; Bozkir and Baysal 2017). Recently, vacuum microwave evaporation and osmotic distillation (OD) have been shown to be promising juice concentration methods for reducing energy costs and improving product quality.

Vacuum microwave evaporation provides quicker mass and energy transfer over a short time. It is known to be successful in concentrating many juice types, such as apple juice (Bozkir and Baysal 2017), pineapple juice (Assawarachan and Noomhorm 2008; 2011), black mulberry juice (Fazaeli et al. 2013a; Fazaeli et al. 2013b) and pomegranate juice (Yousefi et al. 2012). Microwave energy has the advantage of higher penetration into the material and preferential absorption by water molecules. Heat is generated within the food material by reorientation of the dipoles, which in turn causes water molecular friction and generates heat (Assawarachan and Noomhorm 2008; 2011).

On the other hand, osmotic distillation process is carried out at atmospheric pressure and room temperature. The osmotic distillation process involves the use of a microporous hydrophobic membrane to separate two circulating aqueous solutions at different solute concentrations. The difference between the two solute concentrations, i.e., the difference between the water activities, generates a vapor-pressure difference at the vapor–liquid interface, causing a vapor transfer from the dilute solution towards the stripping solution. This technique can be used to selectively extract the water from aqueous solutions at atmospheric pressure and room temperature, thus avoiding thermal degradation of the juice (Jiao et al. 2004; Bánvölgyi et al. 2009; Dincer et al. 2016).

Knowing the concentration characteristics of the concentrated samples is critical for equipment design, process optimization and product quality improvement. For this reason, the use of mathematical models is necessary for the control and optimization of the concentration process. In addition, the mathematical model descriptions are important for enabling performance improvements in the concentration process (Assawarachan and Noomhorm 2010).

Many researchers have used various mathematical models, (e.g., Lewis, Page, logarithmic, two-term, Midilli, etc.) to describe the drying process for different foods (Yaldýz and Ertekýn, 2001; Delgado et al. 2014; Demiray and Tulek 2014; Doymaz and Karasu, 2018; Karabacak et al. 2018). These models have also been used by a few researchers for the description of the concentration process for fruit juices (Assawarachan and Noomhorm, 2008; 2010; 2011; Goula et al. 2014; Bozkir and Baysal 2017).

To date, osmotic distillation and vacuum microwave concentration studies have mainly focused on operating conditions and their effects on the concentrates. There are also limited studies on mathematical modeling of the osmotic distillation and vacuum microwave concentrations of juices. However, to the best of our knowledge, there is no comparative study of mathematical modeling of osmotic distillation, thermal vacuum evaporation and microwave vacuum concentration for different juice types. Thus, the aim of the present study was to compare the mathematical models describing osmotic distillation, thermal vacuum concentration and microwave vacuum concentration for grape, pomegranate and black carrot juices.

MATERIALS AND METHODS

Sample Preparation

Commercial pasteurized clear grape and pomegranate juices (Dimes AS, Izmir, Turkey) were purchased from a local market in Antalya, Turkey. Black carrot juice concentrate was obtained from Meykon AS, Antalya, Turkey. Concentrated black carrot samples were diluted to the initial concentration of black carrot juice (≈ 11 °Bx) with deionized water prior to concentration. Then, the black carrot juice was pasteurized (at 85°C for 15 minutes (min.)) as described by Kırca et al. (2006).

Analyses

The °Brix value of the samples was measured using a refractometer (PAL-α ATAGO, Tokyo, Japan). Color analysis of the juice samples was carried out using a colorimeter (Chroma Meter CR-400, Konica Minolta Sensing, Inc., Osaka, Japan). Color parameters were expressed as L (darkness/whiteness), a (greenness/redness) and b (blueness/yellowness) on the Hunter scale. The instrument was standardized against a white tile where L = 95.24, a = -0.31 and b = 3.02. Turbidity was determined using a turbidimeter (Hach 2100N Turbidimeter, Loveland, CO) using a sample cell (95 mm high × 25 mm in diameter). The values read from the turbidimeter were expressed as nephelometric turbidity units (NTU) (Tajchakavit et al. 2001). The pH of the samples was measured with a pH meter (Orion 4-Star pH meter, Thermo Scientific, USA).

Concentration

Thermal evaporation of the juices (400 mL) was performed to 65 °Bx by rotary evaporator (IKA RV 10 rotary evaporator with HB 10 bath, Germany) at 75 rpm rotation speed and a pressure of 270 mbar in a water bath maintained at 80°C.

The microwave vacuum evaporation was performed using a programmable microwave oven (Samsung ME86V, 100-800W, 2450 MHz). An autoclavable glass bottle containing the juice sample (400 mL) was placed in the center of the microwave oven, which was connected to a vacuum pump (KNF Vacuum Pump N 022 AN.18, Germany) at a pressure of 270 mbar. Microwave (MW) studies were performed at 180 W and 300 W (10 s on and 20 s off) because these power settings do not cause undesirable results such as foaming and sample charring.

Osmotic distillation (OD) processes were performed as described by Dincer et al. (2016). Two laboratory-size hollow fiber membrane modules (MD 020 CP 2N, Microdyn, Germany) connected in series were used for osmotic distillation. Grape, pomegranate and black carrot juices (1,400 mL), at 15.93, 13.91 and 11.23 °Bx respectively, were pumped into the tube side. Brine solution (calcium chloride dihydrate at 65% w/w) was pumped into the shell side of the membrane. Both solutions were circulated in countercurrent mode using two peristaltic pumps (Heidolph PD 5006, Germany). The recycle flow rate was 20 L/hour (h) on both sides. The final grape, pomegranate and black carrot juice concentration of 65 °Bx was achieved in ≈ 560, 640 and 647 min. respectively. The initial weight of the brine solution was three times higher than that of the juice, in order to prevent significant dilution, which would decrease the driving force during the experiments. After osmotic distillation, the membrane module was cleaned as described.

MW 300W samples were taken at 10 min. intervals, thermal and MW 180W samples at 30 min. intervals and OD samples at 60 min. intervals and replaced after measurements were taken. All processes were performed in triplicate. The mean results were given.

Energy Consumption

Energy consumption during concentration of the samples was measured using an energy meter (PeakTech 9035, Germany).

Mathematical Model of Concentration

The 13 drying models given in Table 1 were used to describe the concentration kinetics of the juices. Parameters in all models were determined using SigmaPlot 11.0 (Systat Software Inc., USA). Evaluation of the models was assessed using the coefficient of determination (R^2), reduced chi-squared (χ^2) value and root mean-square error (RMSE). These three parameters were calculated

using the following equations (1-3), as reported by Assawarachan and Noomhorm (2011).

$$R^2 = 1 - \frac{Residual\ Soluble\ Solid}{(Corrected\ Residual\ Soluble\ Solid)} \quad (1)$$

$$\chi 2 = \frac{\Sigma(\Delta B_{exp,i} - \Delta B_{pred,i})^2}{N - n_p} \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta B_{exp,i} - \Delta B_{pred,i})^2} \quad (3)$$

where $\Delta B_{exp,i}$ and $\Delta B_{pred,i}$ are the experimentally observed and predicted concentration changes in terms of °Bx respectively. *N* is the number of observations and *n*p is the number of constants in the model.

Table 1. Mathematical models applied to concentration of juice.

Model name	Model equation	Reference
Lewis	$B\text{-}B_0 = \exp(-k.t)$	Goula et al. 2014
Henderson and Pabis	$B\text{-}B_0 = a.\exp(-k.t)$	Goula et al. 2014
Page	$B\text{-}B_0 = \exp(-kt^n)$	Goula et al. 2014
Two-term	$B\text{-}B_0 = a.\exp(-k_0.t) + b.\exp(-k_1.t)$	Delgado et al. 2014
Two-term exponential	$B\text{-}B_0 = a.\exp(-k.t) + (1-a).\exp(-k.a.t)$	Delgado et al. 2014
Logarithmic	$B\text{-}B_0 = a.\exp(-k.t) + c$	Delgado et al. 2014
Wang and Singh	$B\text{-}B_0 = 1 + a.t + b.t^2$	Goula et al. 2014
Modified Henderson and Pabis	$B\text{-}B_0 = a.\exp(-kt) + b.\exp(-g.t) + c.\exp(-ht)$	Delgado et al. 2014
Midilli	$B\text{-}B_0 = a.\exp(-kt^n) + b.t$	Midilli et al. 2002
Verma	$B\text{-}B_0 = a.\exp(-kt) + (1-a).\exp(-g.t)$	Swain et al. 2012
Diffusion approach	$B\text{-}B_0 = a.\exp(-kt) + (1-a).\exp(-k.b.t)$	Swain et al. 2012
Root of B-B_0	$B\text{-}B_0 = (n + k.t)^2$	Vega-Gálvez et al. 2008
Modified Page 2	$B\text{-}B_0 = \exp(-(kt)^n)$	Delgado et al. 2014

t: concentration time (min); B: soluble solid concentration of juice at any time (Brix), B_0: soluble solid concentration of juice at initial (Brix), k, a, b, c, g, h, n, k_0, k_1 are model constants.

RESULTS AND DISCUSSION

Physicochemical Properties of the Initial Juices

Some physicochemical properties of the juices are shown in Table 2. The °Brix and pH values of all samples ranged from 11.23-15.93 and 3.94-4.81 respectively. The highest turbidity value was recorded in pomegranate juice, at 24.88 NTU, while the lowest turbidity value was in black carrot juice at 0.64 NTU. The color parameters of the samples were found to be very close to one another. L, a and b values of the samples varied between 18.62-18.81, -0.05-2.31 and 1.55-2.43 respectively.

Table 2. Initial physicochemical properties of the juice samples.

	Grape juice	Pomegranate juice	Black carrot juice
Brix	15.93±0.04	13.91±0.04	11.23±0.04
pH	4.40±0.03	3.94±0.01	4.81±0.02
Turbidity (NTU)	12.99±0.03	24.88±0.15	0.64±0.02
Color			
L	18.81±0.01	18.63±0.11	18.62±0.07
a	2.31±0.04	1.69±0.09	-0.05±0.00
b	2.43±0.03	2.26±0.03	1.55±0.03

Results are means ± standard error.

Energy Consumption During Concentration Process

Minimizing energy consumption in the concentration of fruit juices is important in order to reduce the cost of the method used. Therefore, energy consumption during the concentration process is also shown in Table 3. In the OD method, 1400 mL of fruit juice was used to ensure sufficient sampling, while 400 mL samples were used in the other methods. Calculations for the comparison of energy consumption were carried out on a 1-L sample. The lowest energy consumption (1.334-1.540 kWh) was measured for the OD technique, for all juice types. In fact, it has previously been stated that the osmotic distillation process at moderate temperatures and pressures results in lower energy consumption than thermal methods (Cissé et al. 2011). The energy consumption for grape juice concentration via the thermal method was found to be 3.628 kWh, while that for pomegranate juice was 3.930 kWh and that for black carrot juice was 4.370 kWh. In addition, the energy consumed decreased as the microwave power increased from 180 W to 300 W, for all juice types.

Table 3. Concentration time and energy consumption of various concentration techniques applied to juices samples.

Sample	Concentration process	Initial sample volume (mL)	Concentration time (min)	Energy consumption (kW.h)/L
Grape juice (15.93 Bx)	Thermal	400	114.7	3.628
	MW 180 W	400	136.0	2.268
	MW 300 W	400	72.7	1.818
	OD	1400	560.0	1.334
Pomegranate juice (13.91 Bx)	Thermal	400	124.3	3.930
	MW 180 W	400	141.7	2.363
	MW 300 W	400	75.7	1.893
	OD	1400	640.0	1.524
Black carrot juice (11.23 Bx)	Thermal	400	138.2	4.370
	MW 180 W	400	148.0	2.468
	MW 300 W	400	80.0	2.000
	OD	1400	646.7	1.540

Concentration Changes During the Process

The concentration curves (time versus °Brix values) obtained using the various techniques (thermal, MW 180 W, MW 300 W and OD) for the grape, pomegranate and black carrot juice concentrates, are presented in Fig. 1, Fig. 2 and Fig. 3 respectively. The experimental data from all techniques show exponential-type concentration behavior in grape, pomegranate and black carrot juice. This is in agreement with the results reported in many studies on different materials (Assawarachan and Noomhorm, 2010; Onsekizoglu, 2013; Goula et al. 2014; Bozkir and Baysal, 2017). Grape, pomegranate and black carrot juice samples were concentrated to 65 °Bx by thermal methods for 114.7, 124.3 and 138.2 min. respectively. The same time ranking was also observed for the OD and MW methods. In addition, the concentration time decreased as the microwave power increased from 180 W to 300 W for all the juice types, as expected.

Modeling of Concentration Kinetics

The regression coefficients (R^2), reduced chi-squared (χ^2) values and root mean-square error (RMSE) values, calculated in order to observe the accuracy of the models, are presented in Tables 4, 5 and 6 for the grape, pomegranate and black carrot juice concentration processes respectively. The R^2 values of the models varied between 0.9156 and 0.9999 for grape juice, between 0.9600 and 0.9995 for pomegranate juice and between

0.9677 to 0.9997 for black carrot juice. The χ^2 and RMSE values of the models varied between 0.0351 and 33.1441 and between 0.1495 and 5.422 respectively. The higher R^2 and the lower χ^2 and RMSE values indicate better fitting of the model to the data. The kinetic parameters of the four best-fit models were estimated as shown in Tables 7, 8 and 9.

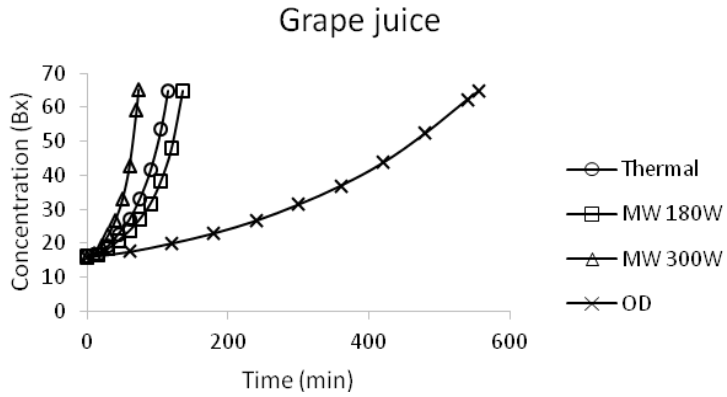

Fig. 1. The concentration curves for grape juice concentrated using the various techniques.

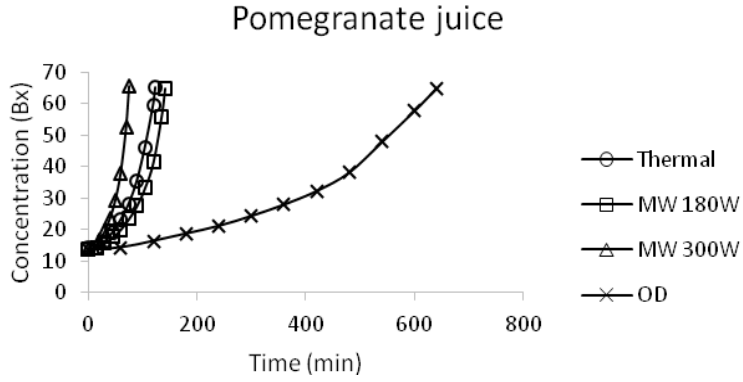

Fig. 2. The concentration curves for pomegranate juice concentrated using the various techniques.

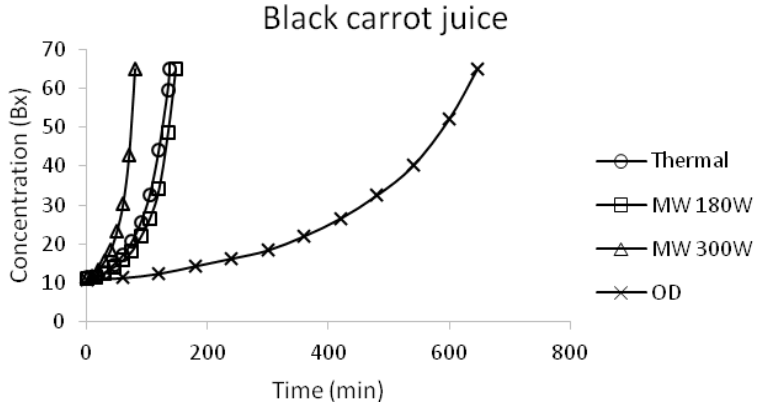

Fig. 3. The concentration curves for black carrot juice concentrated using the various techniques.

Table 4. Parameters of the kinetic models used to fit concentration data for grape juice concentrated by various concentration techniques.

Mathematical Model	Concentration method	R^2	χ^2	RMSE
Lewis	Thermal	0.9794	6.2082	2.3491
	MW 180W	0.9904	2.4211	1.4761
	MW 300W	0.9936	2.1815	1.3925
	OD	0.9156	26.5153	4.9097
Henderson and Pabis	Thermal	0.9943	1.9539	1.2327
	MW 180W	0.9969	0.8824	0.8402
	MW 300W	0.9980	0.7634	0.7705
	OD	0.9883	4.0902	1.8294
Page	Thermal	0.9978	0.7746	5.4220
	MW 180W	0.9980	0.5710	0.6759
	MW 300W	0.9990	0.4023	0.5594
	OD	0.9985	0.5233	0.6543
Two-term	Thermal	0.9943	2.7354	1.2327
	MW 180W	0.9969	1.1766	0.8402
	MW 300W	0.9980	1.0687	0.7705
	OD	0.9883	5.2589	1.8294
Two-term exponential	Thermal	0.9960	1.3928	1.0408
	MW 180W	0.9904	2.7238	1.4762
	MW 300W	0.9936	2.4932	1.3925
	OD	0.9983	0.5897	0.6946
Logarithmic	Thermal	0.9995	0.1923	0.3581
	MW 180W	0.9987	0.4067	0.5336
	MW 300W	0.9996	0.1910	0.3569
	OD	0.9998	0.0697	0.2252
Wang and Singh	Thermal	0.9941	2.0249	1.2550
	MW 180W	0.9837	4.6305	1.9247
	MW 300W	0.9892	4.1731	1.8016
	OD	0.9991	0.3246	0.5154
Modified Henderson and Pabis	Thermal	0.9943	4.5590	1.2327
	MW 180W	0.9969	1.7649	0.8402
	MW 300W	0.9989	1.0251	0.5846
	OD	0.9883	7.3624	1.8294
Midilli	Thermal	0.9993	0.3613	0.4480
	MW 180W	0.9993	0.2726	0.4045
	MW 300W	0.9997	0.1552	0.2936
	OD	0.9999	0.0351	0.1495
Verma	Thermal	0.9954	1.8438	1.1087
	MW 180W	0.9975	0.8251	0.7600
	MW 300W	0.9990	0.4427	0.5432
	OD	0.9917	3.2681	1.5417
Diffusion approach	Thermal	0.9794	8.2776	2.3491
	MW 180W	0.9904	3.1129	1.4761
	MW 300W	0.9936	2.9087	1.3925
	OD	0.9156	33.1441	4.9097
Root of B-B0	Thermal	0.9939	2.1021	1.2787
	MW 180W	0.9835	4.6807	1.9351
	MW 300W	0.9893	4.1340	1.7931
	OD	0.9990	0.3392	0.5268
Modified Page	Thermal	0.9794	7.0951	2.3491
	MW 180W	0.9904	2.7237	1.4761
	MW 300W	0.9936	2.4932	1.3925
	OD	0.9156	29.4614	4.9097

Table 5. Parameters of the kinetic models used to fit concentration data for pomegranate juice concentrated by various concentration techniques.

Mathematical Model	Concentration method	R^2	χ^2	RMSE
Lewis	Thermal	0.9844	5.5449	2.2339
	MW 180W	0.9969	0.9316	0.9203
	MW 300W	0.9963	1.2360	1.0482
	OD	0.9600	12.0568	3.3245
Henderson and Pabis	Thermal	0.9943	2.2999	1.3564
	MW 180W	0.9977	0.7940	0.8060
	MW 300W	0.9976	0.9220	0.8468
	OD	0.9935	2.1434	1.3365
Page	Thermal	0.9973	1.0881	0.9330
	MW 180W	0.9979	0.7141	0.7644
	MW 300W	0.9982	0.7018	0.7388
	OD	0.9982	0.6125	0.7144
Two-term	Thermal	0.9943	3.0666	1.3564
	MW 180W	0.9977	1.0209	0.8060
	MW 300W	0.9976	1.2908	0.8468
	OD	0.9935	2.6792	1.3365
Two-term exponential	Thermal	0.9962	1.5119	1.0998
	MW 180W	0.9978	0.7416	0.7790
	MW 300W	0.9980	0.7691	0.7734
	OD	0.9942	1.9375	1.2707
Logarithmic	Thermal	0.9995	0.2114	0.3847
	MW 180W	0.9985	0.5907	0.6554
	MW 300W	0.9992	0.3400	0.4761
	OD	0.9990	0.3585	0.5185
Wang and Singh	Thermal	0.9959	1.6332	1.1430
	MW 180W	0.9813	6.3386	2.2773
	MW 300W	0.9861	5.3008	2.0305
	OD	0.9939	2.0350	1.3022
Modified Henderson and Pabis	Thermal	0.9943	4.5998	1.3564
	MW 180W	0.9977	1.4293	0.8060
	MW 300W	0.9976	2.1514	0.8468
	OD	0.9935	3.5723	1.3365
Midilli	Thermal	0.9995	0.2408	0.3801
	MW 180W	0.9990	0.4497	0.5350
	MW 300W	0.9991	0.4588	0.5049
	OD	0.9991	0.3821	0.5047
Verma	Thermal	0.9949	2.3293	1.2769
	MW 180W	0.9978	0.8444	0.7836
	MW 300W	0.9978	0.9826	0.8094
	OD	0.9950	1.8506	1.1781
Diffusion approach	Thermal	0.9844	7.1291	2.2339
	MW 180W	0.9969	1.1644	0.9203
	MW 300W	0.9963	1.6480	1.0482
	OD	0.9600	14.7361	3.3245
Root of B-B0	Thermal	0.9959	1.6380	1.1447
	MW 180W	0.9820	6.0886	2.2319
	MW 300W	0.9864	5.1854	2.0083
	OD	0.9930	2.3319	1.3940
Modified Page	Thermal	0.9844	6.2380	2.2339
	MW 180W	0.9969	1.0351	0.9203
	MW 300W	0.9963	1.4126	1.0482
	OD	0.9600	13.2625	3.3245

Table 6. Parameters of the kinetic models used to fit concentration data for black carrot juice concentrated by various concentration techniques.

Mathematical Model	Concentration method	R^2	χ^2	RMSE
Lewis	Thermal	0.9980	0.7535	0.8277
	MW 180W	0.9960	1.2057	1.0470
	MW 300W	0.9976	0.7647	0.8245
	OD	0.9944	1.7088	1.2515
Henderson and Pabis	Thermal	0.9982	0.7719	0.7947
	MW 180W	0.9987	0.4399	0.5999
	MW 300W	0.9988	0.4455	0.5887
	OD	0.9979	0.7070	0.7676
Page	Thermal	0.9984	0.6665	0.7385
	MW 180W	0.9984	0.5453	0.6679
	MW 300W	0.9985	0.5441	0.6505
	OD	0.9987	0.4536	0.6148
Two-term	Thermal	0.9982	0.9924	0.7947
	MW 180W	0.9987	0.5656	0.5999
	MW 300W	0.9988	0.6237	0.5887
	OD	0.9979	0.8838	0.7676
Two-term exponential	Thermal	0.9985	0.6183	0.7113
	MW 180W	0.9983	0.5616	0.6778
	MW 300W	0.9985	0.5570	0.6582
	OD	0.9981	0.6423	0.7316
Logarithmic	Thermal	0.9997	0.1589	0.3400
	MW 180W	0.9989	0.4169	0.5507
	MW 300W	0.9992	0.3241	0.4648
	OD	0.9994	0.2431	0.4270
Wang and Singh	Thermal	0.9862	5.7769	2.1741
	MW 180W	0.9677	10.8922	2.9853
	MW 300W	0.9716	10.4286	2.8480
	OD	0.9839	5.4373	2.1286
Modified Henderson and Pabis	Thermal	0.9982	1.3893	0.7947
	MW 180W	0.9987	0.7918	0.5999
	MW 300W	0.9988	1.0395	0.5887
	OD	0.9979	1.1784	0.7676
Midilli	Thermal	0.9995	0.2662	0.4116
	MW 180W	0.9993	0.3217	0.4524
	MW 300W	0.9994	0.2843	0.3974
	OD	0.9995	0.2187	0.3819
Verma	Thermal	0.9982	0.8451	0.7840
	MW 180W	0.9985	0.5535	0.6345
	MW 300W	0.9976	1.0196	0.8245
	OD	0.9982	0.6831	0.7158
Diffusion approach	Thermal	0.9980	0.9419	0.8277
	MW 180W	0.9960	1.5072	1.0470
	MW 300W	0.9976	1.0196	0.8245
	OD	0.9944	2.0885	1.2515
Root of B-B0	Thermal	0.9867	5.6039	2.1413
	MW 180W	0.9687	10.5396	2.9365
	MW 300W	0.9718	0.9718	0.9718
	OD	0.9846	5.1969	2.0810
Modified Page	Thermal	0.9980	0.8372	0.8277
	MW 180W	0.9960	1.3397	1.0470
	MW 300W	0.9976	0.8740	0.8245
	OD	0.9944	1.8796	1.2515

Table 7. Kinetic parameters of selected models for grape juice concentrated by various concentration techniques.

Mathematical Model	Concentration method	Model constants				
		a	k	n	b	c
Midilli	Thermal	0.0159	-1.1821	0.3997	0.0618	
	MW 180W	0.0390	-0.3599	0.6009	0.0772	
	MW 300W	0.0320	-0.6736	0.5504	0.1276	
	OD	0.0003	-3.0816	0.2109	0.0217	
Logarithmic	Thermal	3.6320	-0.0233			-4.0064
	MW 180W	2.1864	-0.0231			-1.8918
	MW 300W	2.2203	-0.0431			-2.0341
	OD	9.2099	-0.0033			-9.5478
Page	Thermal		-0.1025	0.7667		
	MW 180W		-0.0591	0.8519		
	MW 300W		-0.1007	0.8528		
	OD		-0.0995	0.5806		
Two-term exponential	Thermal	1.2532	-0.0418			
	MW 180W	1.0000	-0.0288			
	MW 300W	1.0000	-0.0539			
	OD	-4.9996	0.0008			

Table 8. Kinetic parameters of selected models for pomegranate concentrated by various concentration techniques.

Mathematical Model	Concentration method	Model constants				
		a	k	n	b	c
Midilli	Thermal	0.0081	-1.7762	0.3292	0.0169	
	MW 180W	0.0578	-0.2244	0.6818	0.0648	
	MW 300W	0.0476	-0.5555	0.5801	0.0924	
	OD	0.00003185	-3.0661	0.2350	0.0212	
Logarithmic	Thermal	3.4807	-0.0222			-4.2504
	MW 180W	1.5498	-0.0247			-1.2589
	MW 300W	1.8339	-0.0444			-1.8946
	OD	4.6185	-0.0039			-4.6526
Page	Thermal		-0.0863	0.7920		
	MW 180W		-0.0376	0.9383		
	MW 300W		-0.0753	0.9144		
	OD		-0.0435	0.6978		
Two-term exponential	Thermal	-0.9930	0.0263			
	MW 180W	-0.2005	0.1317			
	MW 300W	1.2246	-0.0583			
	OD	1.2556	-0.0079			

Table 9. Kinetic parameters of selected models for black carrot juice concentrated by various concentration techniques.

Mathematical Model	Concentration method	Model constants				
		a	k	n	b	c
Midilli	Thermal	0.0320	-0.5512	0.5249	0.0327	
	MW 180W	0.0344	-0.2574	0.6674	0.0439	
	MW 300W	0.0540	-0.3426	0.6810	0.0775	
	OD	0.0450	-0.1563	0.5855	0.0133	
Logarithmic	Thermal	1.5950	-0.0256			-1.8504
	MW 180W	0.8302	-0.0282			-0.5209
	MW 300W	0.9887	-0.0500			-0.8054
	OD	1.9495	-0.0052			-1.7613
Page	Thermal		-0.0354	0.9580		
	MW 180W		-0.0164	1.0995		
	MW 300W		-0.0382	1.0601		
	OD		-0.0131	0.8835		
Two-term exponential	Thermal	1.2056	-0.0313			
	MW 180W	0.4890	-0.0311			
	MW 300W	0.5787	-0.0552			
	OD	1.2328	-0.0071			

The Midilli model exhibited the best fit for the concentration kinetics ($R^2 \geq 0.9990$; $\chi^2 \leq 0.4588$; RMSE $\leq$ 0.5350) in general, among the 13 models. Additionally, as seen from Figs 4-6, the Midilli model presented a successful prediction for the concentration characteristics of the grape, pomegranate and black carrot juices when the experimental concentration ratios were compared with those predicted by the model. This was followed by the logarithmic, Page and two-term exponential models. However, the logarithmic model exhibited better fitting for the thermal concentration method at 80°C than the Midilli model.

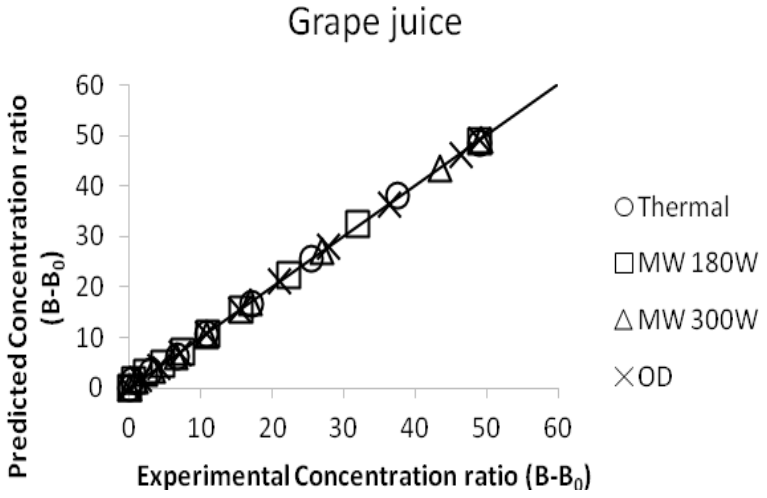

Fig. 4. Experimental and predicted values of total soluble solids concentration change in grape juice for the Midilli model, using various concentration techniques.

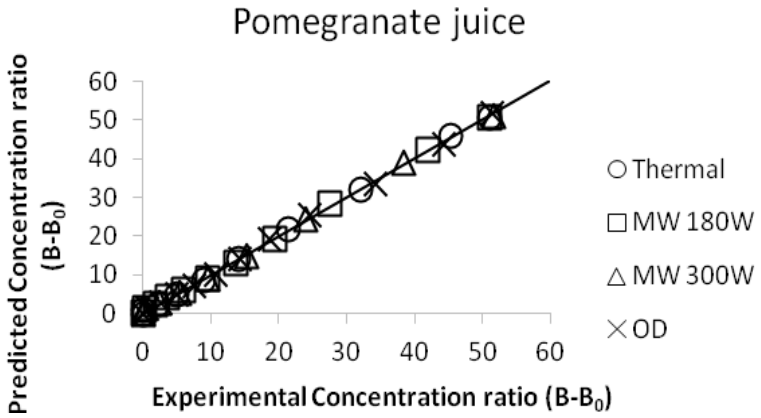

Fig. 5. Experimental and predicted values of total soluble solids concentration change in pomegranate juice for the Midilli model, using various concentration techniques.

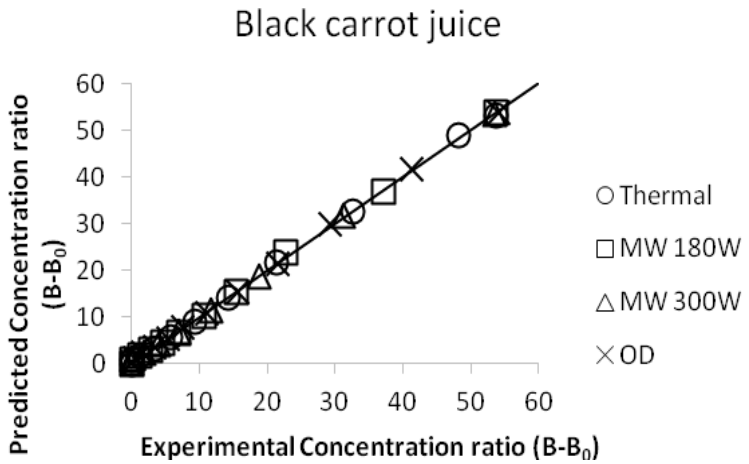

Fig. 6. Experimental and predicted values of total soluble solids concentration change in black carrot juice for the Midilli model, using various concentration techniques

Goula et al. (2014) reported that the logarithmic model was the best descriptive model for rotary vacuum evaporation of pomegranate juice, whereas Assawarachan and Noomhorm (2011) stated that the modified Page model gave better predictions for vacuum microwave concentration of pineapple juice. On the other hand, Yousefi et al. (2012) used a first-order reaction model to describe the concentration of pomegranate juice during microwave and conventional concentration processes. However, the authors did not test the Midilli model for describing the concentration process for the juice.

The *k*-value of the Midilli model varied between -3.0816 and -0.1563, whereas the *k*-value of the logarithmic model varied between -0.0500 and -0.0033 in the present study (Tables 7-9). On the other hand, the *k*-value of the logarithmic model varied between -0.120 and -0.0003 in pomegranate juice (Goula et al. 2014) and between 0.0422 and 0.0742 in pineapple juice (Assawarachan and Noomhorm, 2011).

The lowest R^2 value (91.56) among the established models was calculated for the grape juice samples that were concentrated using OD in the Lewis, modified Page and diffusion approach models. However, the fitting for these models is better in samples with lower initial Brix values (black carrot juice (11.23 °Bx) > pomegranate juice (13.91 °Bx) > grape juice (15.93 °Bx)) concentrated using OD.

In processes where liquid foods are concentrated by membranes, such as osmotic distillation, modeling studies have focused on the mass transfer flux in addition to the concentration level. The mass transfer flux of water can be estimated by Knudsen and molecular diffusion models (Romero et al. 2003; Valdés et al. 2009; Onsekizoglu Bagci, 2015). However, in this study, it was determined that using osmotic distillation, the concentration fits well with the selected models (Tables 1, 2 and 3).

CONCLUSION

In conclusion, it has been shown that the models used to calculate drying kinetics are quite compatible with the concentration process for various fruit juices. Midilli model exhibited a better fit for predicting concentration changes in grape, pomegranate and black carrot juice, than the other established models. Knowledge of modeling the concentration process for vacuum microwave and osmotic distillation processes may provide control and optimization of concentration processes in the industry. In addition, determination of the mathematical models may improve the efficiency of concentration processes. However, another important parameter is the quality of the product. Therefore, further studies should focus on comparing the quality parameters of juices concentrated using different methods, together with the mathematical modeling.

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