LWT - Food Science and Technology 154 (2022) 112750

Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

Efficacy of Ohmic Vacuum Concentration for orange juice concentrates and their physicochemical properties under different voltage gradients

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ARTICLE INFO

Keywords:
Concentration
Evaporation
Ohmic
Vacuum
Orange

ABSTRACT

The efficacy of ohmic vacuum concentration (OVC) was evaluated for the production of value-added orange juice concentrate under different voltage gradients. OVC enables the evaporation of moisture in fruit juice at low temperatures under a vacuum. An OVC system was customized using an ohmic cell, vacuum chamber, vacuum pump, and pressure regulator. During OVC treatment, orange juice extract was ohmically heated to 66 °C using different voltage gradients (15, 20, 25, and 30 V/cm) under 27 kPa vacuum. The highest concentration of OVC was 22 min, producing 2 kg water/kg dry solid orange concentrate. However, it took 40 min to produce the same concentration using ohmic atmospheric concentration (OAC) treatment. OVC minimized the depolymerization of pectin at lower concentrations and produced a thicker orange concentrate than that by OAC. OVC also enabled a slower concentration time in which the orange concentrate was exposed to less thermal abuse. OVC did not induce discoloration or degradation of vitamin C content because the juice extract was concentrated at low temperatures for a short time. This study showed the potential of OVC to produce value-added fruit juice concentrates.

1. Introduction

Orange juice is the most widely consumed juice in the world, accounting for 41.7% of the total juice consumption market in 2015 (Adnan, Mushtaq, & Islam, 2018). Orange juice is known to contain a variety of nutrients, including carotenoids, vitamin C, and phytochemicals, which can prevent non-communicable diseases, such as neurological disorders, cardiometabolic diseases, and several cancers (Castello et al., 2020; Stinco, Fernández-Vázquez, Heredia, Meléndez-Martínez, & Vicario, 2013). However, orange juice is primarily produced in countries where citrus is grown, thus the mass and volume of the juice must be reduced before it is shipped elsewhere (Berk, 2016). Therefore, juice extracts are often concentrated to increase their shelf life, reduce microbial growth, as well as save transportation cost and storage space (Sabanci & Icier, 2020). In the production of fruit concentrates, moisture removal is generally conducted using vacuum evaporation. However, vacuum evaporation is a time-consuming process because the conductive and convective heat transfer is slow under a vacuum.

Alternative technology is needed to expedite moisture removal in juice extracts and better preserve their beneficial attributes. In this study, the ohmic vacuum concentration (OVC) process was evaluated for the rapid evaporation of moisture from orange extracts. During OVC, moisture is evaporated through ohmic heating of the juice extract at a lower boiling point of water under vacuum. In ohmic heating, an electric current is passed through the food from electrodes at both ends of the equipment, and the electrical energy is converted to heat depending on the internal energy generated (Icier, Yildiz, Sabanci, Cevik, & Cokgezme, 2017; Jha et al., 2011; Soisungwan, Khampakool, You, & Park, 2020). Ohmic heating has the advantages of rapid and uniform heating, which are commonly used for pasteurization, thawing, and cooking (Cappato et al., 2017; Jo & Park, 2019). Furthermore, because OVC is performed under a vacuum, the heat loss of the internal energy generation is minimized. Ohmic heating showed promising efficacy in the retention of bioactive compounds. In a study by Vikram, Ramesh, and Prapulla (2005), ohmic heating showed the highest vitamin C retention after several thermal processes, including microwave heating, infrared heating, and conventional heating, where the D-value of ohmic heated ascorbic acid was 95.96 min at 50 °C; however, conventional heating showed it as 65.67 min at the same temperature. The authors explained

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Abbreviations: OAC, Ohmic Atmospheric Concentration; OVC, Ohmic Vacuum Concentration.

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https://doi.org/10.1016/j.lwt.2021.112750
Received 4 July 2021; Received in revised form 28 October 2021; Accepted 31 October 2021

that a shorter lag time of ohmic heating resulted in lesser degradation of vitamin C. Recently, Negri Rodríguez et al. (2021) reported that there was a greater color preference ($p < 0.05$) and a higher level of sensory attributes of OVC-treated concentrates than those of concentrates treated using conventional heating. Ohmic heating showed a promising effect on ascorbic acid retention at higher voltage gradients, which reduced thermal abuse, and there was no detrimental effect of the provided voltage gradients (Doan, Lai, Le, & Le, 2021).

Previous studies have shown that botanical extracts are ohmically heated for evaporation under a vacuum (Cokgezme, Sabanci, Cevik, Yildiz, & Icier, 2017; Fadavi, Yousefi, Darvishi, & Mirsaeedghazi, 2018; Icier et al., 2017; Sabanci & Icier, 2017; Sabanci & Icier, 2020.) However, limited information is available on the physicochemical properties of botanical extracts, such as viscosity, turbidity, color, and nutritional content, influenced by the voltage gradients of OVC treatment. This study hypothesized that the voltage gradient will have a significant effect on the qualities of fruit concentrates because thermal abuse can be minimized with a rapid concentration time. The purpose of this study was to evaluate the effect of different voltage gradients on the physicochemical properties of orange extracts in OVC treatments. OVC for the rapid production of high-quality orange concentrates was analyzed based on the concentration times and desirable attributes.

2. Materials and methods

2.1. Sample preparation

A sample of navel oranges (*Citrus sinensis*) was purchased from a local market (Guri Market, Guri-si, Gyeonggi-do, Korea). The oranges were peeled and squeezed using a juice extractor (HR1895/74, 250 Watts, BR 125, Philips Electronics Ltd.). Squeezed orange extracts were filtered through a mesh (test sieve, 1.0 mm, #18). The initial moisture content of the orange extracts was estimated as 7.87 kg water/kg dry solid via oven drying at 105 °C for 24 h. The extracts were then packaged into a polyethylene pouch (200 g per pouch), frozen, and stored at −60 °C until use. The extracts were thawed by immersion in water at 15 °C before OAC and OVC treatment.

2.2. Ohmic vacuum concentration system

Fig. 1 shows a custom-developed OVC system in our laboratory. The primary components of the OVC system consisted of an ohmic cell, titanium electrodes, variable AC power supply (HCS-2SD50; Hanchang Trans, Busan, Korea), a cylindrical stainless steel vacuum chamber (Ø 290 × 400 mm), a digital balance (CB-3000, A&D Co., Ltd., Seoul, Korea), a cold trap condenser at −105 °C (HC31110, GYROGEN Co., Ltd, Daejeon, Korea), a vacuum pump (EWS 50, Geunpoong Power Tool Inc., Seoul, Korea), pressure regulator (IRV20-LC10GN, SMC, Tokyo, Japan), and a proportional-integral-derivative (PID) controller (ITC-100VH, INK BIRD, Shenzhen, China). The vacuum chamber was made of stainless steel (316 grade) to ensure mechanical integrity at high temperatures under a vacuum. The top closure was made of a thick acrylic plate to ensure electrical insulation of the thermocouple, electrical power supply wire, and RS-232 data cable. A rectangular ohmic cell was custom-made using Teflon (80 mm × 80 mm × 250 mm). Titanium electrodes were fixed at both ends of the ohmic cell. The customized ohmic cell was placed on a digital balance to measure the weight reduction during the concentration process. The pressure regulator was connected to a vacuum pump to maintain an appropriate vacuum level (27 kPa). A K-type thermocouple with a needle sheath was installed at the center of the ohmic cell. A variable AC power supply provided voltage gradients of 15, 20, 25, and 30 V/cm. The target ohmic concentration temperature was controlled using the on/off function of the PID controller with a resolution of ±0.5 °C. The temperature, voltage, and current data were documented in a data acquisition (DAQ) system (34970A, Keysight, Santa Clara, CA, USA) and were utilized for process control.

2.3. Ohmic vacuum concentration and ohmic atmospheric concentration

The orange juice extract (200 g) was transferred to an ohmic cell. In this study, k-type thermocouples with a mineral-insulated stainless needle sheath (KMQSS-062U-12, Omega Engineering, Stamford, CT, USA) were used for temperature monitoring and process control. This enabled stable temperature monitoring under an alternating voltage gradient because mineral insulation minimized electrical noise. In a previous study of ohmic heating (Zell, Lyng, Morgan, & Cronin, 2009), a stainless-steel needle sheath thermocouple showed a stable temperature reading as well as a rapid response. Thermocouple were fixed to the ohmic cell at the geometric center of filled extracts depending on the final concentration of 2 and 4 kg water/dry solid. The experimental design for measuring the final concentration was determined based on a review article (Salehi, 2020), which investigated the rheological behavior of various fruit concentrates. In that review article, most fruit concentrates had a total solid content of 20–50°Brix. In this study, the target concentrations of orange juice samples were 20 and 40°Brix, which corresponded to a final moisture content of 2 and 4 kg water/kg

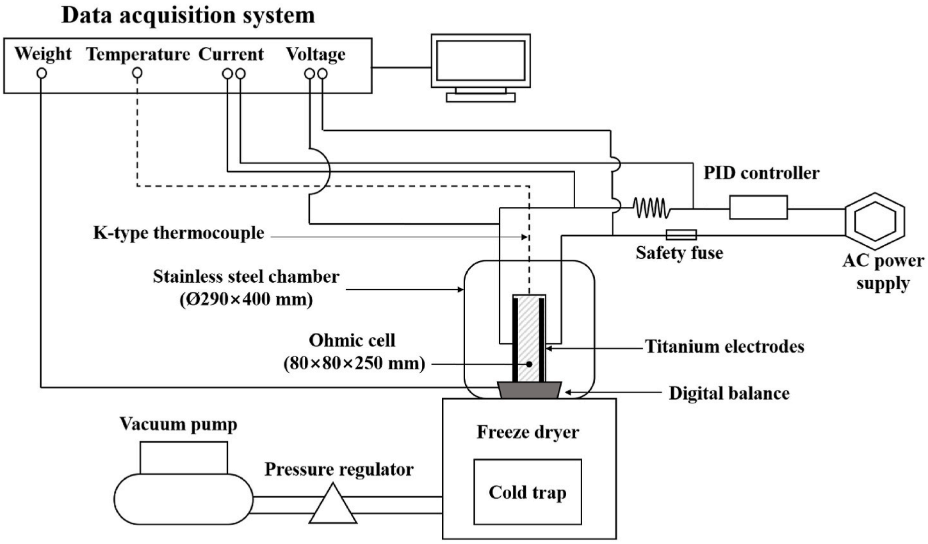


Fig. 1. Schematic diagram of lab-scale ohmic vacuum concentration (OVC) system.

dry solid, respectively. In the OVC treatment, the orange extract was ohmically heated to a concentration temperature of 66 °C under a vacuum of 27 kPa and different voltage gradients (15, 20, 25, and 30 V/cm). Subsequently, the orange extract was concentrated from an initial moisture content of 7.87 kg water/kg dry solid to a final moisture content of 2 and 4 kg water/kg dry solid. The concentration temperature of OVC was determined by considering the boiling point elevation of the orange concentrate. In this study, it was assumed that the boiling point of orange concentrate increased from 67 °C at 4 kg water/kg dry solid to 69 °C at 2 kg water/kg dry based on the work of Gabas, Sobral, Cardona-Alzate, Telis, and Telis-Romero (2008). Therefore, the resolution of the PID controller was set to ±3 °C at a target temperature of 66 °C.

In OAC, the samples were ohmically heated to 100 °C at atmospheric pressure (101.325 kPa) and different voltage gradients (15, 20, 25, and 30 V/cm). After all treatments, the concentrated orange extracts were chilled in ice water for 30 min. The experimental design and sequence of OAC and OVC are provided as a flow chart in Fig. 2.

2.4. Quality attributes

2.4.1. Viscosity

Viscosity was measured using a rotational viscometer (DV2T, AMETEK Brookfield, Middleboro, MA, USA). The orange concentrate (50 mL) was placed in a stainless steel tube (diameter: 29 mm, length: 129 mm). Spindle numbers 61 and 62 were selected, which maintained a constant torque of 50% during viscosity measurement at 5 °C.

2.4.2. Turbidity

Turbidity was measured using a portable turbidity meter (TUB-430, GOnDo Electronic Co. Ltd, Taipei, Taiwan) and expressed as nephelometric turbidity units (NTU). Ten milliliters of concentrate was placed in a glass vial, and its turbidity was measured at 90° scattered light. The turbidity meter was calibrated using distilled water prior to the measurement.

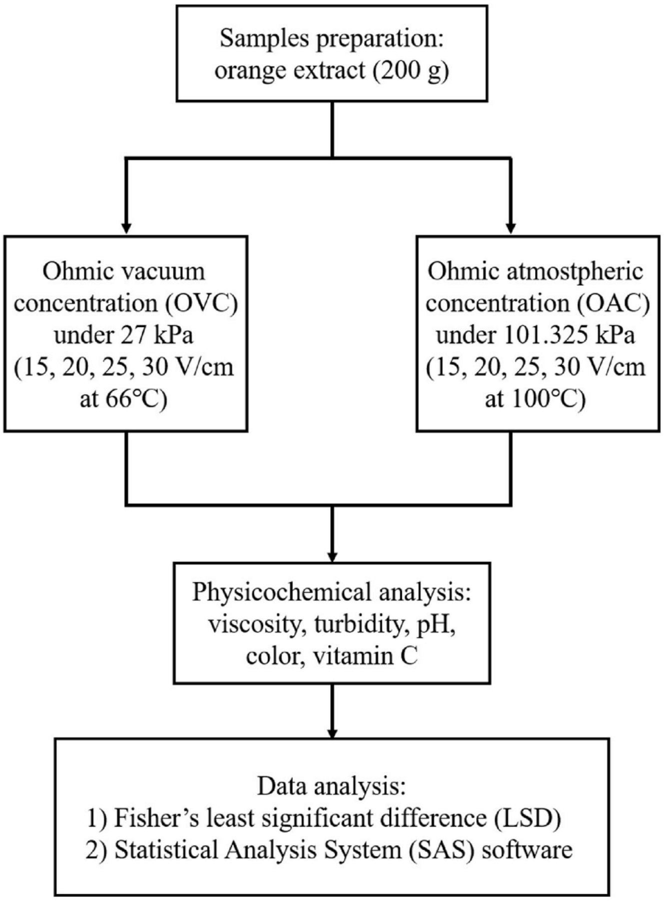


Fig. 2. Flow chart of The experimental design and sequence of OAC and OVC.

2.4.3. pH

A glass electrode pH meter (ORION STAR A211, Thermo Scientific, Waltham, MA, USA) was used to analyze the changes in the pH of the orange concentrate. The concentrated solution (25 mL) was transferred to a conical tube. pH was measured at a constant temperature of 5 °C. The pH meter was periodically calibrated using standard buffer solutions at pH 4.0, 7.0, and 10.0.

2.4.4. Color

A hand-held colorimeter (CR-10, Konica Minolta Sensing Inc., Sakai, Osaka, Japan) was used for the color measurements. Orange concentrates (20 mL) were poured into Petri dishes. They were placed on a sheet of white paper to measure brightness (L^*), redness (a^*), and yellowness (b^*). The total color difference (ΔE) was calculated to estimate the overall color change compared to that of the orange extract before concentration using Equation (1) below.

$$\Delta E = \sqrt{(L^* - L^*{}_0)^2 + (a^* - a^*{}_0)^2 + (b^* - b^*{}_0)^2} \tag{1}$$

2.4.5. Vitamin C content analysis

Vitamin C content analysis was performed as previously described (Leong & Oey, 2012; Mohamed, Fekry, Attia, Ibrahim, & Azab, 2020). One gram of the sample was weighed and dispersed into 1 g of 10% metaphosphoric acid. The mixture was homogenized in 5% metaphosphoric acid, and then brought up to 100 mL. The mixture was centrifuged, and the supernatant was immediately transferred to an autosampler for high-performance liquid chromatography (HPLC, Agilent 1200 system, Santa Clara, CA, USA). The HPLC analysis conditions consisted of a mobile phase of 0.05 M KH_2PO_4 and Acetonitrile (80:20), flow rate of 0.7 mL/min, injection volume of 10 μL, and detection at 254 nm using a UV detector (Agilent 1200 DAD, Santa Clara, CA, USA. Separation was conducted in an AQ-C18 column (4.6 × 250 mm, 5 μm), and the column oven temperature was 25 °C.

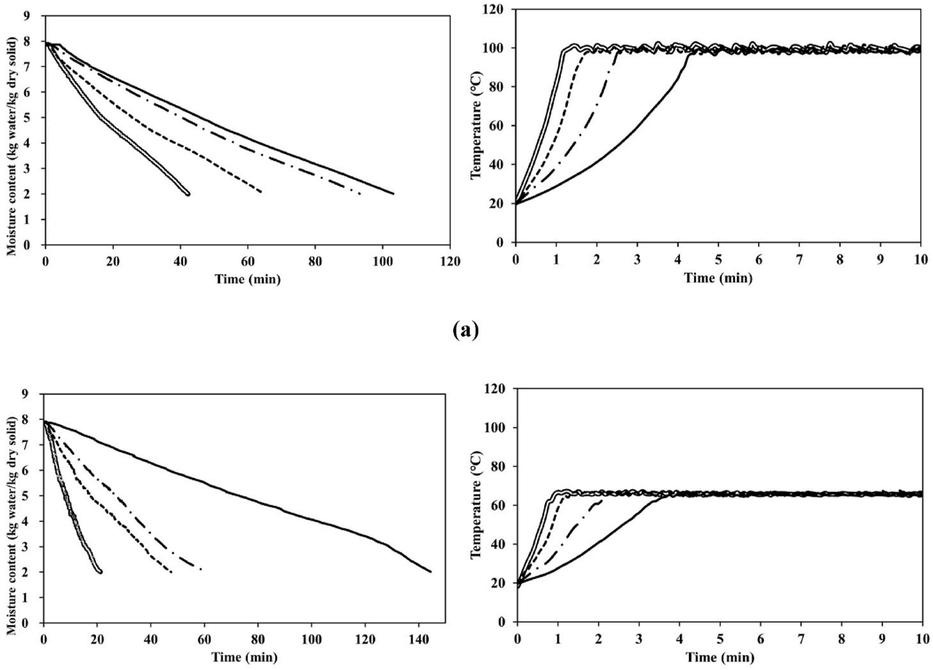
2.5. Statistical analysis

The OAC and OVC treatments were performed in triplicate. Analysis of variance (ANOVA) was performed to determine the statistical significance among treatments. Fisher's least significant difference (LSD) was conducted at a 95% confidence interval using the Statistical Analysis System (SAS) software (version 9.1.3, SAS Inst. Inc., Cary, NC, USA).

3. Results and discussion

3.1. Temperature profiles and moisture content

Fig. 3 shows the dry basis moisture content and temperature profiles of the orange concentrates during the OAC and OVC treatments. Table 1 summarizes the OAC and OVC concentrations under different voltage gradients. In this study, the final concentrations were 4 and 2 kg water/kg of dry solids. In both OAC and OVC treatments, the voltage gradient strength had a significant effect on the concentration time, and the stronger voltage gradient reduced the concentration time. For example, in the OAC treatment of the concentrate at 2 kg water/kg dry solid, a voltage gradient of 15 V/cm required a concentration time of 98.33 ± 4.21 min, as presented in Table 1. When the voltage gradient during OAC was increased to 30 V/cm, the concentration time was reduced to 40.86 ± 6.53 min. The internal energy generation rate of ohmic heating was calculated by multiplying the square of the voltage gradient (V/cm)



(a)

(b)

Fig. 3. Dry basis moisture content and temperature profiles of orange concentrate during (a) OAC and (b) OVC (15 V/cm: ——, 20 V/cm: — · —, 25 V/cm: - - - -, 30 V/cm: ═══).

Table 1
Comparison of concentration time between ohmic atmospheric concentration (OAC) and ohmic vacuum concentration (OVC).

Final concentration (kg water/ kg dry solid)	Voltage gradients (V/cm)	Concentration time (min)	
		OAC	OVC
4	**15**	76.5 ± 1.1^{b}	95.4 ± 7.1^{a}
	20	56.5 ± 1.2^{c}	39.8 ± 1.1^{d}
	25	34.8 ± 3.0^{d}	23.7 ± 2.9^{e}
	30	25.1 ± 2.6^{e}	15.0 ± 1.9^{f}
2	**15**	98.3 ± 4.2^{B}	140.7 ± 18.8^{A}
	20	92.8 ± 5.0^{B}	62.9 ± 3.3^{C}
	25	63.4 ± 2.7^{C}	46.9 ± 1.8^{D}
	30	40.4 ± 6.5^{D}	22.0 ± 1.6^{E}

$^{a\text{-}f}$Means(±Standard deviation) with a different letter in the 4 kg water/kg dry solid are significantly different at $P < 0.05$.
$^{A-E}$Means(±Standard deviation) with a different letter in the 2 kg water/kg dry solid are significantly different at $P < 0.05$.

by the electrical conductivity (S/m) (Jo & Park, 2019; Li & Zhang, 2010). Therefore, higher voltage gradients in the OVC will save the concentration time with more internal energy generation. Moisture was evaporated at a lower temperature of 66 °C during OVC compared to 100 °C during OAC because the boiling point of water decreases under a vacuum. OVC treatment reduced the concentration time compared to OAC treatment, except for the voltage gradient of 15 V/cm. For example, during OAC treatment, the voltage gradient of 30 V/cm required a concentration time of 40.9 ± 6.5 min; OVC reduced the concentration time down to 22.00 ± 1.6 min at the same voltage gradient. Rapid moisture evaporation during OVC reduces the boiling point of water and minimizes heat loss under vacuum conditions. Under OVC treatment with a voltage gradient of 30 V/cm, a temperature come-up time of ~60 s to reach 66 °C was required (Fig. 3 b-right). OAC treatment took a temperature come-up time of ~80 s–100 °C. Therefore, the OVC treatment enabled rapid heating to the concentration temperature because heat loss was minimized under the vacuum. In addition, the OVC treatment required less energy input for moisture evaporation at lower boiling temperatures. The required amount of heat energy to boil the liquid decreases, and subsequently, the heating time a decreases when the boiling point of the liquid decreases under vacuum (Darvish, Mohammadi, Fadavi, & Saba, 2019; Fadavi et al., 2018). In this study, a voltage gradient of 15 V/cm showed a significantly longer concentration time of 140.7 ± 18.8 min in OVC compared to 98.3 ± 4.2 min in OAC ($P < 0.05$). This is an exceptional result compared to the other tested voltage gradient strengths (20, 25, and 30 V/cm). When the temperature of the orange extracts slowly increased at a low electric field during OVC, heat loss was more significant than internal energy generation because ambient air in the vacuum chamber was continuously moved to the cold trap. A similar result was found in a previous study that compared the mean heating rate between vacuum and atmospheric conditions and showed that there was no significant difference in the mean heating rate when a low voltage gradient was used during OVC (Darvishi, Mohammadi, Fadavi, Saba, & Behroozi-Khazaei, 2019). This study demonstrates the potential of OVC for rapid concentration of liquids.

3.2. Viscosity

Table 2 compares the viscosity of orange concentrates at final concentrations of 4 and 2 kg water/kg dry solids after treatment via OAC and OVC. The orange extract showed a viscosity of 36.5 ± 2.3 mPa s, which increased after both OAC and OVC treatment. The concentrate with a final concentration of 2 kg water/kg dry solids had significantly higher viscosity than the concentrate with 4 kg water/kg dry solids, which had a 5- to 8-fold difference ($P < 0.05$). In both the OAC and OVC

Table 2

Ohmic atmospheric concentration (OAC) and ohmic vacuum concentration (OVC) treated quality attributes (viscosity, turbidity and pH) of orange concentrates.

Final concentration (kg water/kg dry solid)	Voltage gradients (V/cm)	Viscosity (mPa•s)		Turbidity (NTU)		pH	
		OAC	OVC	OAC	OVC	OAC	OVC
4	15	48.3 ± 2.5^{h}	512.8 ± 206.5^{cd}	261.0 ± 0.0^{h}	267.3 ± 0.6^{cd}	3.55 ± 0.04^{abc}	3.53 ± 0.01^{abc}
	20	35.8 ± 1.5^{a}	1454.7 ± 18.5^{a}	270.3 ± 0.6^{a}	270.0 ± 1.0^{a}	3.12 ± 0.18^{e}	3.21 ± 0.03^{de}
	25	41.1 ± 3.2^{bc}	2487.0 ± 154.9^{ab}	268.0 ± 1.0^{bc}	269.7 ± 0.6^{ab}	3.35 ± 0.12^{cd}	3.72 ± 0.20^{a}
	30	37.0 ± 2.0^{gh}	3048.0 ± 86.5^{h}	262.7 ± 1.2^{gh}	262.0 ± 0.0^{h}	3.71 ± 0.13^{a}	3.59 ± 0.16^{ab}
2	15	222.9 ± 18.8^{gh}	4424.3 ± 734.0^{fg}	262.3 ± 0.6^{gh}	264.0 ± 1.7^{fg}	3.65 ± 0.01^{ab}	3.46 ± 0.14^{bc}
	20	228.4 ± 25.7^{ef}	5838.0 ± 332.0^{de}	264.7 ± 0.6^{ef}	266.0 ± 2.6^{de}	3.59 ± 0.09^{ab}	3.67 ± 0.07^{ab}
	25	410.4 ± 41.7^{ef}	15290.0 ± 154.0^{cd}	265.0 ± 1.7^{ef}	267.0 ± 0.0^{cd}	3.65 ± 0.25^{ab}	3.46 ± 0.13^{bc}
	30	883.4 ± 5.5^{cd}	30080.0 ± 997.4^{ef}	267.7 ± 0.6^{cd}	265.0 ± 0.0^{ef}	3.57 ± 0.12^{ab}	3.54 ± 0.12^{abc}

$^{a\text{-}h}$Means(±Standard deviation) with a different letter in the each quality are significantly different at $P < 0.05$.

treatments, a stronger voltage gradient resulted in a higher viscosity of the orange concentrate. For example, the viscosity of the OVC-treated orange concentrates was 5838.0 ± 332.0 and 30080.0 ± 997.4 mPa s at 20 and 30 V/cm, respectively. In this study, a stronger voltage gradient enabled the rapid evaporation of moisture during the OAC and OVC treatments. There was be less pectin depolymerization when the concentration process was rapidly conducted; thus, OVC orange concentrate had a higher viscosity than that of OAC. Lesser thermal treatment resulted in reduced cell wall depolymerization and thicker fruit juice concentrates, which have higher efflux viscosity (Ramakrishna, Deng, Ding, Handa, & Ozminkowski Jr. 2003; Takada & Nelson, 1983).

All OVC-treated orange juices had higher viscosities than the OAC-treated juices. Although there are limited previous studies on the viscosity changes of fruit concentrates as influenced by a combination of vacuum and ohmic heating, it was hypothesized that a rapid concentration process at a lower boiling point minimizes the thermal degradation of physicochemical components such as pectin and fructose. This would result in the increased viscosity of OVC orange concentrates (Krokida, Maroulis, & Saravacos, 2001). This study showed the potential of OVC to produce thicker fruit concentrates that are preferred by consumers.

3.3. Turbidity and pH

The turbidity of OAC- and OVC-treated orange concentrates, expressed as NTU values, are compared in Table 2. The turbidity of the orange extract before concentration was 265 NTU. Turbidity of OAC and OVC orange concentrate ranged from 261 to 270 NTU; however, there were no significant differences among treatments. In this study, the turbidity of the orange concentrate was not influenced by the evaporation temperature or voltage gradient strength. In general, the increased turbidity of fruit concentrates is attributed to the high phenolic content of the extracts (Norouzi, Fadavi, & Darvishi, 2021; Oksuz, Tacer-Caba, Nilufer-Erdil, & Boyacioglu, 2019; Okur, Baltacıoğlu, Ağçam, Baltacıoğlu, & Alpas, 2019). Oranges have a low total phenolic content of 337 mg/100 g compared to that of other fruits (Wu et al., 2004). The minimized turbidity change in ohmic heating can be attributed to the deceleration of some biochemical processes, such as browning, under vacuum conditions (Fadavi et al., 2018). In this study, both OAC and OVC treatments did not induce significant changes in turbidity in orange concentrates.

The pH of the orange extract before the concentration was 3.74. Those of OAC- and OVC-treated orange concentrates ranged from 3.12 to 3.72 (Table 2); however, they were not influenced by the treatment conditions. The pH of orange juice did not change after microwave and conventional heating at 89–96 °C (Villamiel, Castillo, Martin, & Corzo, 1998). Park, Ha, and Kang (2017) also reported that the pH of ohmic pasteurized apple juice was 3.60, which was similar to the value (3.54) of the control sample. Orange extract is a highly acidic product; thus, its pH cannot be easily altered via thermal treatment. In this study, OVC treatment showed no detrimental effects on the turbidity and pH of orange juice concentrates.

3.4. Vitamin C content

Table 3 presents the vitamin C content of orange concentrates after different OAC and OVC treatments. The initial vitamin C content of the control sample was 51.2 mg/100 g. The vitamin C content of both OAC- and OVC-treated samples was relatively higher than that of the control sample with moisture evaporation. The vitamin C content of the OVC-treated concentrates was significantly higher than that of the OAC-treated concentrates at both 4 and 2 kg water/kg dry solid concentrations ($P < 0.05$). For example, OAC treatment at a voltage gradient of 15 V/cm showed a vitamin C content of 118.9 ± 0.0 mg/100 g in the 2 kg water/kg dry solid whereas it significantly increased to 145.6 ± 2.3 mg/100 g in the OVC-treated orange concentrate at a voltage gradient of 15 V/cm. In the comparison between 2 kg water/kg dry solid and control

Table 3

Ohmic atmospheric concentration (OAC) and ohmic vacuum concentration (OVC) nutritional attributes (vitamin C) of orange concentrates.

Final concentration (kg water/kg dry solid)	Voltage gradients (V/cm)	Vitamin C (mg/100 g)	
		OAC	OVC
4	**15**	84.2 ± 0.3^{c}	93.4 ± 8.5^{ab}
	20	83.1 ± 1.2^{c}	91.9 ± 0.9^{b}
	25	88.2 ± 0.6^{bc}	92.1 ± 2.6^{b}
	30	100 ± 0.1^{a}	93.4 ± 1.2^{ab}
2	**15**	118.9 ± 0.0^{C}	145.6 ± 2.3^{B}
	20	128.9 ± 11.2^{C}	160.7 ± 10.6^{A}
	25	116.9 ± 3.4^{C}	156.5 ± 3.0^{AB}
	30	123.9 ± 1.2^{C}	147.4 ± 1.2^{B}

$^{a\text{-}}$cMeans(±Standard deviation) with a different letter in the 4 kg water/kg dry solid are significantly different at $P < 0.05$.

$^{A-C}$Means(±Standard deviation) with a different letter in the 2 kg water/kg dry solid are significantly different at $P < 0.05$.

samples, OAC and OVC treatment at 20 V/cm produced 152 and 214% higher vitamin C content than the control sample. As expected, the low evaporation temperature in the OVC (66 °C) minimized the degradation of vitamin C compared to the high evaporation temperature of OAC (100 °C). Temperatures of pasteurization (60–90 °C) and sterilization (>100 °C) processes can cause vitamin C degradation (Blasco, Esteve, Frigola, & Rodrigo, 2004; Castro, Teixeira, Salengke, Sastry, & Vicente, 2004; Hughes, 1985; Rojas & Gerschenson, 2001; Verbeyst, Bogaerts, Van der Plancken, Hendrickx, & Van Loey, 2013). In ohmic heating, vitamin C is more rapidly degraded at 97 °C, which is more than twice that at 60 °C. It is well known that vitamin C is easily degraded in the presence of oxygen. Dissolved oxygen in the solution significantly expedites vitamin C degradation during thermal processing (Herbig, Maingonnat, & Renard, 2017). In this study, OVC was conducted at a significantly lower temperature than the OAC. There should be less dissolved oxygen in the OVC orange concentrate than that of OAC due to vacuum conditions. Thus, both the low temperature and low amount of dissolved oxygen contribute to minimizing vitamin C degradation during OVC treatment. Previous studies have also reported that vitamin C is easily denatured by temperature rise and exposure to long periods of heat (lgwemmar, Koawole, & Imren, 2013; Vikram et al., 2005). Voltage gradient strength did not affect vitamin C content in either concentrate at 4 or 2 kg water/kg dry solids. This study showed the efficacy of OVC treatment in minimizing vitamin C degradation during fruit extract concentration.

3.5. Color

The changes in the color values of OAC- and OVC-treated orange concentrates are summarized in Table 4. Orange extract (control) showed 42.4 ± 1.1 in L^* value, 13.9 ± 3.0 in a^* value, and 45.0 ± 0.7 in b^* value. All color parameters (L^*, a^*, b^*) increased in the orange concentrates after both OAC and OVC treatments. The final concentration had a greater influence on the changes in color than the voltage gradient and subsequent concentration time (treatment condition, color).

The decrease in the L^* and b^* values indicated that the orange juices turned dark and their yellowness was reduced (Wibowo et al., 2015), whereas the increase in a^* values signified an increasing reddish tone, showing that the color considerably changed.

There was no difference in the L^* values between the OAC and OVC treatments at final concentrations of 4 and 2 kg water/kg dry solids. However, it significantly decreased in the concentrate of 2 kg water/kg dry solid when a lower voltage gradient was applied. For example, the L^* value of OAC-treated concentrate was 44.3 ± 0.7 at 30 V/cm and then it decreased to 39.0 ± 0.2 at 15 V/cm. The OAC concentration time was 98.3 min at a voltage gradient field of 15 V/cm, whereas it took 40.4 min at a voltage gradient of 30 V/cm. A rapid concentration at a high voltage gradient minimizes discoloration.

There was a significant difference in the a^* values between OAC- and OVC-treated orange concentrates ($P < 0.05$). The OAC-treated concentrates had higher a^* values for both 4 and 2 kg water/kg dry solids. The initial a^* value of the orange extract was 13.9 ± 3.0 before concentration. OVC produced a smaller change in *the* a^* value compared to that of OAC. This is attributed to rapid evaporation at lower temperatures during the OVC treatment. As mentioned above, increased a^* values indicated significant discoloration of orange juice.

There was no significant difference in the b^* values between the OAC- and OVC-treated orange concentrates at 4 kg water/kg dry solid. When the orange extracts were concentrated to 2 kg water/kg dry solid, OVC treatment gave higher b^* values than OAC at voltage gradient strengths of 15 and 20 V/cm; however, the magnitude of change was smaller than that of the other color parameters, L^* and a^*.

Regarding the ΔE values, the OAC treatment showed significantly higher discoloration than the OVC treatment at the tested voltage gradients ($P < 0.05$). OACs were exposed to higher temperature concentrations for a longer time than those of OVC. Wang, Guo, Ma, Zhao, and Zhang (2018) also reported that lower temperature ultra-high-temperature (UHT) pasteurization at 110 °C minimized the total discoloration (ΔE) of watermelon juice than higher temperature UHT pasteurization at 120 and 135 °C. In this study, it was also possible to discriminate the OVC treated orange concentrate from OAC treated samples in the visual observation. OVC treated orange concentrate had more similar colors to orange extract before concentration. Rapid concentration at low temperatures is desirable for retaining the original color of the orange extract.

During thermal processing, the colors of fruits and their juices are prone to deterioration, which causes a degradation in product quality and a decline in consumer acceptance (Li, Wang, Wu, Wan, & Yang, 2020). The color change of orange juice depends on the loss of carotenoid content during thermal processing (Lee & Coates, 2003). OVC treatment was performed at a lower evaporation temperature, thus minimizing color deterioration.

Table 4
Ohmic atmospheric concentration (OAC) and ohmic vacuum concentration (OVC) treated color of orange concentrates.

Final concentration (kg water/kg dry solid)	Voltage gradients (V/cm)	Color							
		L^*		a^*		b^*		ΔE	
		OAC	OVC	OAC	OVC	OAC	OVC	OAC	OVC
4	15	45.9 ± 2.0^{b}	47.8 ± 1.1^{a}	22.0 ± 1.1^{a}	20.4 ± 0.7^{ab}	55.1 ± 2.1^{b}	61.3 ± 0.1^{a}	13.5 ± 2.1^{b}	18.4 ± 0.4^{a}
	20	46.4 ± 0.9^{ab}	46.0 ± 1.1^{b}	18.5 ± 1.8^{bc}	16.8 ± .0.8^{cd}	53.7 ± 2.3^{bc}	54.2 ± 0.2^{bc}	10.7 ± 2.2^{bc}	10.4 ± 0.6^{c}
	25	46.1 ± 0.8^{b}	45.4 ± 0.7^{b}	17.6 ± 0.5^{c}	16.6 ± 0.9^{cd}	52.6 ± 2.5^{bc}	52.0 ± 0.9^{c}	9.3 ± 1.9^{c}	8.1 ± 1.3^{c}
	30	45.6 ± 1.5^{b}	46.0 ± 0.6^{b}	15.5 ± 1.9^{d}	15.3 ± 0.9^{d}	52.5 ± 1.1^{bc}	51.8 ± 1.6^{c}	8.5 ± 1.7^{c}	7.9 ± 1.6^{c}
2	15	39.0 ± 0.2^{F}	41.5 ± 0.9^{CDE}	23.0 ± 0.7^{BC}	18.8 ± 0.9^{DE}	50.1 ± 0.6^{A}	52.5 ± 2.1^{C}	11.0 ± 0.4^{BC}	9.1 ± 1.8^{C}
	20	40.7 ± 0.4^{D}	41.3 ± 2.6^{DE}	25.8 ± 0.8^{A}	18.0 ± 1.7^{E}	50.0 ± 0.4^{A}	53.6 ± 0.5^{B}	13.0 ± 0.5^{AB}	9.6 ± 1.0^{C}
	25	43.1 ± 1.0^{ABC}	42.5 ± 1.8^{BCD}	25.8 ± 2.0^{A}	20.6 ± 1.1^{CD}	52.5 ± 1.5^{A}	53.1 ± 1.0^{BC}	14.1 ± 2.4^{A}	10.6 ± 1.3^{BC}
	30	44.3 ± 0.7^{A}	43.7 ± 0.6^{AB}	25.2 ± 2.0^{AB}	18.4 ± 0.7^{DE}	53.8 ± 0.1^{A}	53.1 ± 0.9^{B}	14.5 ± 1.6^{A}	9.4 ± 0.4^{C}

$^{a\text{-}}$cMeans(±Standard deviation) with a different letter in the 4 kg water/kg dry solid are significantly different at $P < 0.05$.

$^{A-F}$Means(±Standard deviation) with a different letter in the 2 kg water/kg dry solid are significantly different at $P < 0.05$.

4. Conclusions

The custom-developed OVC system enabled the evaporation of moisture in the orange extract at a low boiling point of 66 °C under a vacuum. OVC treatment significantly reduced the concentration time of the orange extract with the synergy of ohmic heating, lowering its boiling point. OVC treatment produced a thicker orange concentrate than OAC treatment at the same concentration, which implied that OVC minimized pectin depolymerization and physicochemical changes in the raw materials. OVC treatment did not have detrimental effects on turbidity and pH measurements. In the color measurement, OVC showed less discoloration because the level of carotenoids did not change much at the low boiling point observed during OVC treatment. As expected, the OVC-treated orange concentrates had significantly higher vitamin C content than the OAC-treated concentrates. Although the OVC system in this study was a lab-scale unit, it is expected that a similar efficacy of OVC is feasible for industrial scale units. Ohmic heating is the principle of volumetric heating, regardless of the sample size and volume, because it does not depend on conductive and convective heat transfer. Once the voltage gradient of the OVC is appropriately raised, it should be practically applicable to industrial-scale systems. This study showed the practical advantages of OVC treatment of fruit juices including reduced concentration time, higher viscosity, minimized color change, and reduced vitamin C degradation.

CRediT authorship contribution statement

Jeong Hyeon Hwang: Methodology, Experiment, Data Analysis, Writing – original draft. **Ah Hyun Jung:** Experiment, Data Analysis, Writing-assistance. **Sung Hee Park:** Conceptualization, Methodology, Experiment, Data Analysis, Writing – original draft, preparation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the Research Program funded by the SeoulTech(Seoul National University of Science and Technology).

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