Effects of extrusion with CO₂ injection on physical and antioxidant properties of cornmeal-based extrudates with carrot powder

Sasimaporn Samard¹ · Sasathorn Singkhornart^{1,2} · Gi-Hyung Ryu¹

Received: 2 April 2017 / Revised: 7 June 2017 / Accepted: 21 June 2017 / Published online: 25 October 2017
© The Korean Society of Food Science and Technology and Springer Science+Business Media B.V. 2017

Abstract Carrot powder and cornmeal were extruded at ratios of 0:100, 10:90, and 20:80 with and without CO₂ injection at die temperatures of 80, 100, and 120 °C. The effects of the composition of the extrudate, die temperature, and CO₂ injection on physicochemical and antioxidant properties of extruded products were studied. The results showed that die temperature had a significant effect on expansion ratio (ER), specific length, piece density, color, water absorption index (WAI), and water solubility index (WSI) ($p < 0.05$). The injection of CO₂ significantly affected the ER, WAI, WSI, lightness, redness, microstructure, total phenolic content, and the 2,2-diphenyl-1-picrylhydrazyl radical-scavenging activity of extrudates ($p < 0.05$). Increasing the proportion of carrot powder in extrudates resulted in better antioxidant properties and higher levels of crude ash, crude fat, crude protein, and redness; however, it resulted in lower WAI, lightness, and yellowness ($p < 0.05$). The study demonstrated that extrusion with CO₂ injection and addition of carrot powder may improve the nutritional quality and structure-forming ability of extrudates.

Keywords Carrot powder · Extrusion · CO₂ injection · Physicochemical property · Antioxidant activity

Introduction

Extrusion cooking has been used to manufacture various types of snack foods in many shapes and a variety of textures [1]. The two main factors that influence the characteristics of extrudate are: raw material characteristics and extrusion process variables [2]. It is well known that injection of CO₂ into an extruder barrel can improve the structure of expanded extrudates [1–3], but only a few studies have been undertaken using CO₂ injection to improve the antioxidant properties of extrudates. Wang and Ryu [3] presented that antioxidant properties of extruded corn grits mixed with 30% corn fiber at 120 °C with CO₂ injection were more stable than those without CO₂ injection, whereas antioxidant properties of extrudates at other temperatures (90 and 105 °C) with and without CO₂ injection did not show a significant difference. Thin et al. [4] found that the TPC and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical-scavenging activity of extruded sorghum at 80 °C with CO₂ injection were higher than those without CO₂ injection; however, there was no significant effect of CO₂ injection on antioxidant properties of extruded oats and millet. Therefore, it was evident that antioxidant properties of extrudates from previous studies did not show a clear result when CO₂ was injected.

Extrusion cooking of corn and oat meal has been successfully commercialized, especially in the production of breakfast cereals. These products are rich in carbohydrates but low in vitamins, carotenoids, dietary fibers, and antioxidants. The consumption of carrot and its related products has increased steadily because there is higher consumer demand for nutritious snacks with enhanced bioactive compounds. Carrot is a vitaminized food product with dietary fiber. Carrots are unique roots rich in ascorbic acid, carotenoids, natural antioxidants, and anticancer

✉ Gi-Hyung Ryu
ghryu@kongju.ac.kr

¹ Department of Food Science and Technology, Kongju National University, Kongju, Chungnam 32439, Korea

² Department of Food Technology and Nutrition, Rajamangala University of Technology Krungthep, Bangkok 10120, Thailand

components [5]. Therefore, carrot powder was chosen for this research to increase content of carotenoids, dietary fibers, vitamins, phenolic compounds, and antioxidants in extruded products.

Several studies have used extrusion cooking for developing food with health-promoting characteristics such as antioxidant activity [6, 7]. The incorporation of dehydrated carrot powder in ready-to-eat snacks was reported to be promising [8]. Özer et al. [6] encouraged the utilization of carrot powder in the formulation of snack foods due to its high content of carotenoids. Mridula et al. [9] revealed that the extruded beetroot and carrot powders had relatively high protein and fiber contents. In the recent years, the incorporation of up to 3.25% of carrot pomace powder into ready-to-eat expanded products was suggested by Alam et al. [10]. Kalyani et al. [11] reported that the addition of carrot powder in maize-based extruded snacks increased piece density (PD) but decreased the expansion ratio (ER) and brightness. Although several researches persuaded the utilization of carrot powder for producing extrudates, no study used carrot powder mixed with cornmeal in the extrusion with CO₂ injection.

The purpose of this work was to investigate the effects of extrusion conditions such as die temperature (80, 100, and 120 °C) and CO₂ injection on the physicochemical and antioxidant properties of extruded cornmeal with varying levels of carrot powder (0, 10, and 20%).

Materials and methods

Materials

Carrot powder was purchased from Garunara Co. (Seoul, Korea). Cornmeal was purchased from Dongilgrain Co. (Gyeonggi, Korea). Three levels of carrot powder/corn meal mixtures were formulated. The carrot powder was mixed with corn meal in the ratios of 0:100, 10:90, and 20:80 (w/w).

Chemicals

Folin–Ciocalteu reagent, sodium carbonate (Na₂CO₃), DPPH, sodium hydroxide (NaOH), and boric acid were purchased from Sigma Chemical Co. (St. Louis, MO, USA). Other chemicals and solvents were the highest commercial grade and were used without further purification.

Extrusion process

A co-rotating intermeshing twin-screw extruder (Incheon Machinery Co., Incheon, Korea) with a diameter of 32 mm and a length of 768 mm (L:D = 24:1) was used. The screw

configuration of the extruder was shown in Fig. 1. The extrusion was carried out at 150 rpm screw speed, 100 g/min feed rate, and 3 mm die diameter. The CO₂ was injected in the barrel at 150 mL/min. The moisture content of the material was adjusted to 35% before extrusion processing. The die temperatures were set at 80, 100, and 120 °C. The extrudate was dried directly in an oven at 50 °C for 8 h, and the dried samples were stored in polyethylene bags at room temperature and used for measurement of physical properties (ER, density, and mechanical properties). The dried extrudates were ground to powder using a stainless steel mixer (FM-909T, Hanil Electrical Co., Korea) and then passed through a 30 mesh sieve (pore size: 400 µm US Standard Sieve Series) and stored at 4 °C until measurements were taken. The specific mechanical energy (SME) input (kJ/kg) was calculated as described by Edou-Ondo et al. [1] using the following equation:

$$SME = \frac{E^v - E^0}{Fr}$$

where E = electric current after material is fed (amperes, A); E⁰ = initial electric current (amperes, A); E^v = the voltage applied to the armature of the motor (volt, V), and F^r = the feed rate supplied to the extruder (kg/s).

Chemical properties

The moisture, crude fat, crude protein, and ash contents of both raw material and extrudates were determined according to the standard methods of the AOAC [12]. The reducing sugar was measured using the colorimetric method with 3,5-dinitrosalicylic acid (DNS) reagent. Glucose solution was used as a standard [13]. All experiments were performed in triplicate.

Physical properties

Expansion ratio (ER) and specific length (SL)

Radial expansion was determined by measuring the extrudate diameter using a digital caliper (IP67, Mitutoyo Co., Japan). The ER was measured as the diameter of extrudates divided by the diameter of the die exit (3 mm). Each assay was the mean of 10 repetitions. The SL of the extrudates was obtained as the length divided by the equivalent weight of extrudates. 10 replicates of extrudates were randomly selected.

Piece density (PD)

PD was determined after the extrudates were cut into pieces of approximately 2 cm length via a modified millet seed displacement method. The millets were poured into a

Fig. 1 Screw configuration for the extrusion process (model THK 3)

125 mL tube up till about one-fourth of the tube height. Then, the extrudates (approximately 2 g) were weighed and placed into the tube. The millets were then added to fill the tube, and the excess millet was scraped out. The tube containing extrudates and millet was weighed. Measurements were performed in triplicate for each sample.

$$\rho_e = \frac{M}{M + M_0 - M_1} \times \rho_m$$

ρ_e : PD of extrudate (g/cm³); ρ_m : PD of millet (g/cm³); M: Mass of extrudates (g); M_0 : Mass of millet in tube (g); M_1 : Mass of extrudate and millet in tube (g).

Color

Color measurements were performed on ground samples using a Minolta colorimeter (Minolta CR-300, Osaka, Japan) as lightness (*L*), redness (*a*), and yellowness (*b*). The *L* value ranged from black (0) to white (100), the *a* value ranged from greenness (−80) to redness (+100), and the *b* value ranged from blueness (−70) to yellowness (+70). For each sample, three measurements were taken and averaged.

WAI and WSI

The WAI was determined by a modification of the method used by Anderson et al. [14]; briefly, 1.5 g of ground extrudate was mixed in 25 mL of distilled water for 30 min at 30 °C, followed by centrifugation at 3000×g for 20 min.

The supernatant was dried in an oven at 130 °C for 2 h. The WAI calculated as the increase in weight of the sediment (gel) formed after decanting the supernatant. For the WSI, the supernatant from the WAI determination was transferred carefully into an evaporating dish. The supernatant was dried to constant weight in the oven.

$$WAI = \frac{\text{Weight of wet sediment (g)}}{\text{Weight of dried sediment (g)}}$$

$$WSI(\%) = \frac{[\text{Weight of dish} + \text{dried supernatant (g)}] - \text{Weight of dish (g)}}{\text{Weight of dry sample (g)}} \times 100$$

Mechanical properties

The apparent elastic modulus (E_{app}) and breaking strength (BS) of the extrudates were determined using a rheometer (Compac-100 II, Sun Scientific Co., Tokyo, Japan) equipped with a 2-kg load cell [15]. The crosshead speed was set at 60 mm/min. The results were the average of 10 measurements.

Microstructure

The microstructure of extrudates was obtained by field emission scanning electron microscopy (MIRA III LMH, Tescan Co., Cranberry Township, PA) with an accelerating voltage of 25 kV. The extrudates were sputter-coated with gold–palladium alloy. The magnification ranged from ×35 to ×77.

Antioxidant properties

Extraction

The ground extrudate (5 g) was extracted with 20 mL of ethanol 95% at room temperature for 3 h. The supernatant was filtered through a Whatman No. 1 filter paper and then transferred into a sample vial for measurement of TPC, total flavonoid content (TFC), and DPPH radicle scavenging activity.

TPC

The TPC was determined according to the Folin–Ciocalteu colorimetric method [16]. The reaction mixture containing 20 μ L of ethanol extracts was mixed with 100 μ L of the freshly prepared, tenfold diluted Folin–Ciocalteu reagent and a 1.58 mL of distilled water. After 3 min, 0.3 mL of 20% Na_2CO_3 was added. The solution was incubated in the dark at room temperature for 2 h. The absorbance at 765 nm was measured by a UV–vis spectrophotometer (Libra S35 UV/Vis-spectrophotometer, Biochrom Ltd., Cambridge, UK). Gallic acid was used as the standard, and results were calculated as gallic acid equivalents (mg GAE/100 g dry weight of sample). The assay was carried out in triplicate.

TFC

The TFC was measured as described by Woisky and Salatino [17]. The extracts (0.5 mL) were mixed with 0.1 mL of 10% aluminum nitrate. Further, 0.1 mL of 1 M potassium acetate and 4.3 mL of 95% ethanol were added. After incubation at room temperature for 40 min, the absorbance of the mixture was read at 415 nm. Quercetin was used as the standard, and the results were reported as mg quercetin equivalents per 100 g of dry sample. Samples were assayed in triplicate.

DPPH radical-scavenging activity

Radical-scavenging activity of extracts was estimated using the stable radical DPPH as proposed Brand-Williams et al. [18] with a slight modification. 1000 mL of the extract was quickly added to 2 mL of a 0.1 mM DPPH solution. The mixtures were shaken and held for 60 min at room temperature in the dark, and the absorbance was measured at 517 nm. The 80% ethanol was used as a control. The DPPH radical-scavenging activity was calculated according to the following equation:

$$\text{Scavenging activity(\%)} = \frac{[A_{\text{control}} - A_{\text{sample}}]}{A_{\text{control}}} \times 100$$

where A_{control} is the absorbance of the control and A_{sample} is the absorbance of the sample.

Statistical analysis

All data were analyzed using statistical analysis system (SAS) program, version 9.1 (SAS Institute Inc., Cary, N.C., U.S.A.). One-way analysis of variance (ANOVA) was used to analyze the data. A significant difference among means of treatments was observed by Duncan's range test, and the statistical significance was defined as $p < 0.05$.

Results and discussion

Proximate composition

The amount of crude ash, crude fat, and crude protein in the extrudates increased with increasing carrot powder levels, whereas the moisture content decreased (Table 1). The extruded cornmeal with 20% carrot powder had significantly higher crude ash, crude fat, and crude protein contents than the extruded cornmeal with 10 and 0% carrot powder. There was no significant effect of die temperature and CO_2 injection on crude ash, crude fat, and crude protein, except for extruded cornmeal with 20% carrot powder with CO_2 injection, which had higher crude fat than the one extruded without CO_2 injection. The cornmeal-based extrudates with carrot powder contained significantly higher amounts of crude ash, crude fat, and crude protein compared to raw cornmeal 100%, whereas the moisture content was significantly lower than that of raw cornmeal 100% ($p < 0.05$).

All extrudates had significantly lower reducing sugar content than the raw carrot powder 100% ($p < 0.05$). There was no significant difference in reducing sugar content between raw cornmeal 100% and extruded cornmeal without carrot powder. The highest reducing sugar content (60.38 mg/g) was observed in extruded cornmeal mixed with 20% carrot powder at a die temperature of 80 °C and with CO_2 injection. The combinations of cornmeal with carrot powders resulted in increasing reducing sugar content; however, it decreased as the temperature increased. Singkhornart et al. [19] reported that during the extrusion process, the reducing sugar generally decreases due to a browning reaction (Maillard reaction) as the reducing sugar reacts with amino acids.

SME input

The SME input of extrudates under different extrusion conditions is shown in Table 2. The maximum SME input

Table 1 Proximate composition of extruded corn meal-carrot products

Materials	Barrel temperature (°C)	CO ₂ injection	Composition (%)				Reducing sugar (mg/g)
			Moisture	Ash	Fat	Protein	
Extruded cornmeal with 0% carrot powder	80	Without CO ₂	9.92 ^{ef}	0.57 ^g	0.16 ^{ij}	6.50 ^d	3.70 ^g
	100		10.95 ^{ab}	0.49 ^{hg}	0.15 ^{ij}	5.97 ^e	4.15 ^g
	120		10.52 ^{bcd}	0.45 ^h	0.14 ^{ij}	6.23 ^{de}	6.61 ^g
	80	CO ₂ (150 mL/min)	10.18 ^{def}	0.51 ^{hg}	0.15 ^{ij}	6.40 ^d	3.53 ^g
	100		10.26 ^{cdef}	0.47 ^{hg}	0.14 ^{ij}	6.36 ^{de}	4.14 ^g
	120		10.95 ^{ab}	0.49 ^{hg}	0.10 ^j	6.21 ^{de}	6.33 ^g
Extruded cornmeal with 10% carrot powder	80	Without CO ₂	8.74 ^g	0.90 ^f	0.33 ^{fgh}	6.98 ^c	27.34 ^d
	100		10.38 ^{cde}	0.88 ^f	0.28 ^{gh}	7.15 ^c	20.26 ^{ef}
	120		5.66 ⁱ	0.89 ^f	0.33 ^{fgh}	6.90 ^c	18.71 ^f
	80	CO ₂ (150 mL/min)	10.00 ^{ef}	1.02 ^e	0.43 ^f	6.91 ^c	25.96 ^d
	100		9.77 ^f	0.97 ^{ef}	0.36 ^{fg}	7.18 ^c	22.43 ^{def}
	120		11.37 ^a	0.98 ^{ef}	0.41 ^f	7.13 ^c	21.04 ^{ef}
Extruded cornmeal with 20% carrot powder	80	Without CO ₂	5.83 ⁱ	1.42 ^{cd}	0.65 ^e	8.36 ^b	54.92 ^b
	100		8.36 ^g	1.33 ^d	0.77 ^d	8.44 ^b	42.77 ^c
	120		5.50 ⁱ	1.44 ^c	0.58 ^e	8.34 ^b	39.06 ^c
	80	CO ₂ (150 mL/min)	5.83 ⁱ	1.59 ^b	1.12 ^c	8.35 ^b	60.38 ^b
	100		6.57 ^h	1.50 ^{bc}	1.03 ^c	8.46 ^b	44.41 ^c
	120		6.95 ^h	1.52 ^{bc}	1.12 ^c	8.44 ^b	42.24 ^c
Raw cornmeal 100%	—	—	10.76 ^{bc}	0.44 ^h	1.78 ^b	4.84 ^f	1.15 ^g
Raw carrot powder 100%	—	—	4.07 ^j	4.20 ^a	3.09 ^a	11.68 ^a	474.07 ^a

Values with in the same column with different letters are significantly different at $p < 0.05$

(153.87 kJ/kg) was obtained through viscous dissipation at 80 °C die temperature and CO₂ injection by extruded cornmeal without carrot powder, whereas the minimum SME input (39.80 kJ/kg) was obtained through viscous dissipation at 120 °C die temperature by extruded cornmeal with 20% carrot powder without CO₂ injection. The SME input of extruded cornmeal without carrot powder decreased with increasing die temperature, whereas extruded cornmeal with 10% carrot powder decreased when die temperature increased from 80 to 100 °C ($p < 0.05$). As reported by Guha et al. [20], high temperatures are usually associated with a decrease in the melt viscosity inside the extruder, which in turn reduces the energy input of the extruder. The increase of the carrot proportion of extrudates from 0 to 10% led to a decrease in SME input at 80 and 100 °C die temperature. The low SME input was due to reduced dough viscosity in the extruder barrel [21]. The SME input was increased by CO₂ injection at 80 °C die temperature for 100% extruded cornmeal and for cornmeal with 10% carrot powder, whereas extruded cornmeal with 20% carrot powder at 80 and 100 °C die temperature did not show a significant difference in the SME input. The injection of CO₂ gives a more viscous melt requiring a higher torque, which increases SME input [1].

Physical properties

ER and SL

Expansion of the extrudate is closely linked to the size, number, and distribution of air cells within the material [22]. The ER of the extrudate without CO₂ injection was significantly increased with increasing die temperature, whereas the ER of the extrudate with CO₂ injection increased with increasing die temperature from 80 to 100 °C ($p < 0.05$) (Table 2). The ER increased with increasing die temperature may be due to gelatinization of starch at high temperatures. In contrast, it is expected that if the melt temperature is further decreased, expansion would actually decrease because lowering the melt temperature leads to an increase in melt viscosity, which would reduce expansion [22]. The increasing carrot powder tended to decrease the ER. The melt viscosity decreased with decreasing starch content when carrot powder was added to cornmeal. Hence, the high protein and fiber content of the extrudates may result in a low melt viscosity, which could be attributed to low expansion and high PD.

The SL of the extrudates correlates their length with their weight as an expression of axial expansion. The highest

Table 2 Physical and mechanical properties of extruded corn meal-carrot products

Materials	Barrel temperature (°C)	CO ₂ injection	SME input (kJ/kg)	Physical properties		Mechanical properties		Color		WAI (g/g)	WSI (%)
				Expansion ratio	Specific length (m/kg)	Piece density (g/cm ³)	Elastic modulus (N/m ²)	Breaking strength (N/m ²)	L		
Extruded cornmeal with 0% carrot powder	80	Without CO ₂	145.07 ^b	0.98 ⁱ	115.20 ^d	0.99 ^{ab}	1.70E+09 ^a	1.83E+06 ^a	80.74 ^{cd}	36.06 ^j	3.76 ^j
	100		101.66 ^c	1.41 ^g	63.84 ^j	0.85 ^{cde}	7.83E+08 ^b	7.95E+05 ^c	78.39 ^g	44.78 ^a	3.77 ^d
	120		52.89 ^f	2.19 ^a	89.43 ^h	0.32 ⁱ	1.36E+08 ^d	6.14E+05 ^{cde}	81.45 ^b	39.92 ^f	5.42 ^{ab}
Extruded cornmeal with 10% carrot powder	80	CO ₂ (150 mL/min)	153.87 ^a	1.12 ^j	114.88 ^d	0.97 ^{abc}	8.41E+08 ^b	1.13E+06 ^b	83.32 ^a	42.86 ^d	3.25 ^f
	100		61.12 ^e	1.85 ^c	76.97 ⁱ	0.79 ^{def}	2.55E+08 ^d	8.21E+05 ^c	80.51 ^d	43.03 ^c	4.74 ^c
	120		52.29 ^{fg}	1.32 ^h	89.85 ^h	1.05 ^a	3.62E+08 ^{cd}	1.32E+06 ^b	83.33 ^a	43.13 ^c	5.24 ^b
Extruded cornmeal with 20% carrot powder	80	Without CO ₂	59.97 ^e	0.98 ^{kl}	123.50 ^c	1.05 ^a	1.35E+09 ^a	7.36E+05 ^{cd}	79.60 ^e	34.21 ^k	2.78 ^g
	100		47.74 ^h	1.66 ^e	76.66 ⁱ	0.71 ^{fg}	4.72E+08 ^{bcd}	6.81E+05 ^{cde}	77.32 ^h	39.11 ^g	3.59 ^d
	120		49.35 ^{fgh}	1.90 ^b	90.29 ^{hg}	0.57 ^h	1.61E+08 ^d	3.26E+05 ^f	76.80 ⁱ	33.94 ^l	3.22 ^f
Extruded cornmeal with 0% carrot powder	80	CO ₂ (150 mL/min)	98.05 ^d	1.01 ^{kl}	135.15 ^b	1.04 ^a	8.41E+08 ^b	6.88E+05 ^{cde}	80.68 ^{cd}	36.81 ⁱ	3.09 ^f
	100		49.22 ^{fgh}	1.56 ^f	92.67 ^g	0.75 ^{efg}	3.62E+08 ^{cd}	5.09E+05 ^{def}	79.72 ^e	40.86 ^e	4.53 ^c
	120		48.71 ^{gh}	1.36 ^h	87.27 ^h	0.89 ^{bcd}	4.81E+08 ^{bcd}	7.97E+05 ^c	81.45 ^b	43.46 ^b	5.49 ^a
Extruded cornmeal with 20% carrot powder	80	Without CO ₂	48.53 ^{gh}	0.97 ^l	126.85 ^c	1.05 ^a	6.74E+08 ^{bc}	7.60E+05 ^c	79.25 ^f	30.38 ^o	2.81 ^g
	100		47.33 ^h	1.25 ⁱ	80.45 ⁱ	0.77 ^{def}	7.69E+08 ^{bc}	7.90E+05 ^c	76.12 ^j	33.63 ^m	3.11 ^f
	120		39.80 ⁱ	1.78 ^d	99.28 ^f	0.63 ^{gh}	3.61E+08 ^{cd}	3.62E+05 ^f	73.84 ^k	32.13 ⁿ	2.76 ^g
Extruded cornmeal with 0% carrot powder	80	CO ₂ (150 mL/min)	46.97 ^h	1.03 ^k	157.79 ^a	0.95 ^{abc}	4.68E+08 ^{bcd}	3.71E+05 ^f	80.97 ^c	30.13 ^p	2.53 ^h
	100		48.56 ^{gh}	1.24 ⁱ	100.07 ^f	0.77 ^{def}	5.45E+08 ^{bcd}	1.19E+06 ^b	78.36 ^g	36.15 ^j	3.49 ^e
	120		49.43 ^{fgh}	1.21 ⁱ	109.36 ^e	0.89 ^{bcd}	2.16E+08 ^d	4.79E+05 ^{ef}	76.07 ^j	37.66 ^h	3.47 ^e

Values with in the same column with different letters are significantly different at $p < 0.05$

value of SL (157.79 m/kg) was obtained in extruded cornmeal with 20% carrot powder with CO₂ injection at a die temperature of 80 °C (Table 2). Die temperature has been found to be the main factor affecting the SL of extrudates. The SL of all extrudates sharply decreased with increasing die temperature from 80 to 100 °C; however, it slightly increased when die temperature increased up to 120 °C ($p < 0.05$). Only the SL of extruded cornmeal with 10% carrot powder with CO₂ injection was reduced significantly when die temperature increased from 100 to 120 °C ($p < 0.05$). The result indicated that the extrudates expanded in the radial direction with increasing die temperature. The increased SL denoted higher expansion in the axial direction. Launay and Lish [23] have reported that lower melt viscosity increased SL, whereas higher melt elasticity leads to higher cross-sectional expansion. In addition, the increase of carrot powder ratio increases the SL of CO₂ injected extrudates. It showed that the extrudates expanded in the axial direction with the addition of carrot powder.

PD

The effect of extrusion variables on the PD of extrudates was shown in Table 2. PD, which considers expansion in all directions, ranged from 0.32 to 1.05 g/cm³ in this study. The PD of all extruded products decreased with increasing die temperatures. Low density (a desirable characteristic of expanded products) was obtained at high die temperatures [2]. At a die temperature of 120 °C, the PD of extrudates with CO₂ injection was higher than that without CO₂ injection, whereas the effect of CO₂ injection was not significant on the PD of extrudates at die temperatures of 80 and 100 °C. Altan et al. [22] reported that the higher PD values and lower ER of extrudates might be because of the lower levels of gelatinization of starch and also because of molecular degradation of starch. There was no difference in PD between extruded cornmeal with 0, 10, and 20% carrot powder, except at 120 °C die temperature without CO₂, where the PD increased with increasing carrot powder content ($p < 0.05$).

Color

Analysis of variance indicated that the effect of carrot powder content, die temperature, and CO₂ injection on extrudate color was significant ($p < 0.05$) (Table 2). The increase of carrot powder ratio significantly affected the brightness, redness, and yellowness of extrudates in each formulation ($p < 0.05$). The extruded cornmeal with 20% carrot powder without CO₂ injection at a die temperature 120 °C showed the highest redness and the lowest brightness. The addition of carrot powder increased redness significantly but decreased brightness and yellowness of all

extrudates ($p < 0.05$). Mridula [24] reported that different levels of carrot powder affected the color of biscuit samples because of the typical orange-like color of the carrot powder. In addition, an increase in die temperature from 80 to 100 °C significantly decreased the brightness of all extrudates ($p < 0.05$), whereas the reverse was observed for yellowness. The reduction in brightness with increasing temperature may have resulted from the occurrence of browning reactions such as Maillard reactions and caramelization [22]. Higher brightness was obtained from extrudates with CO₂ injection, whereas no CO₂ injection expressed lower brightness ($p < 0.05$). It is possible that CO₂ may give rise to a decrease in pH causing inhibition of the Maillard reaction, leading to the higher brightness of extrudates with CO₂ injection [19]. The injection of CO₂ also significantly affected the redness as it showed lower value than the extrudates without CO₂ injection.

WAI and WSI

The WAI of the extrudates varied from 2.53 to 5.49 g/g (Table 2). The WAI increased with increasing die temperature from 80 to 100 °C ($p < 0.05$); however, the WAI did not show a clear trend when die temperature increased up to 120 °C. The WAI mostly increased by adding CO₂ to extrudates. Further, the increase of carrot powder ratio at die temperatures of 100 and 120 °C without CO₂ injection resulted in a decrease in the WAI of extrudates. Thin et al. [4] found that the WAI of extruded millet was increased by the increase of barrel temperature. The amount of water absorbed by the ground extrudate has been used as an indirect estimation of the porosity of the material [25]. As the porosity of the extrudate material increases, the WAI would also increase [26].

The WSI of extrudates was significantly ($p < 0.05$) affected by die temperature, CO₂ injection, and addition of carrot powder (Table 2). The WSI decreased when die temperature increased from 80 to 100 °C, which may be attributed to the reduction in macro-molecular degradation, whereas the WSI increased with the increase in die temperature from 100 to 120 °C due to dextrinization and melting. The combination of cornmeal with carrot powders resulted in significantly increased WSI ($p < 0.05$), especially for the extruded cornmeal mixed with 20% carrot powder at a die temperature of 80 °C with CO₂ injection being the highest, which had a WSI of 18.29% (Table 2). The injection of CO₂ to extruded cornmeal with 10 and 20% carrot powder had higher WSI than the one extruded without CO₂ injection.

Mechanical properties

The observation for E_{app} and BS with different combinations of the process parameters is presented in Table 2. The BS of

the extrudates with CO₂ injection ranged from 3.26E+05 to 1.83E+06 N/m². Die temperature had a significant effect on the BS and E_{app} of extrudates ($p < 0.05$). The BS of extruded cornmeal without carrot powder decreased as die temperature increased from 80 to 100 °C. E_{app} of cornmeal-based extrudates with 0 and 10% carrot powder decreased with increasing die temperature from 80 to 100 °C, whereas die temperature and CO₂ injection had no significant influence on E_{app} of extruded cornmeal with 20% carrot powder. E_{app} depends on the intrinsic rigidity and the longitudinal expansion of the expanded matrix. This study found that cornmeal-based extrudates with 0 and 10% carrot powder became brittle when extrusion was performed at high die temperature (120 °C). It was reported by previous studies that mechanical properties had a correlation with PD and ER. Singhornart et al. [2] reported that the BS and PD of extruded whole wheat with CO₂ injection decreased but the ER increased. Similar to this study, the BS and PD of extruded cornmeal with carrot powder without CO₂ injection decreased at 100 and 120 °C but ER increased.

Microstructure

The alternations of cellular structures of the extruded cornmeal-based extrudates with carrot powder were observed via SEM microphotographs. The magnification ranged from $\times 35$ to $\times 77$. Figure 2 shows the structure of extrudates with varying carrot powder ratios with and without CO₂ injection. At low die temperature (80 and 100 °C), an internal structure of the extruded cornmeal without carrot powder had some fracture in extrudates without CO₂ injection, whereas the extrudates with CO₂ injection did not show the fracture. Cross sections of the extrudates with CO₂ injection showed more uniform distribution of enclosed air cells with thin cell walls at a die temperature of 100 °C compared with those of the extrudates without CO₂ injection. The reduction of interfacial tension with CO₂ injection causes more rapid and homogeneous nucleation, and thus creates a finer pore structure [27]. When carrot powder content was increased from 10 to 20%, size of the air cells reduced and more rigid structures were formed. Similar results have been observed by Lazou and Krokida [28]; the number of air cells in extruded corn decreased and more rigid structures formed when lentil content was increased. Expansion of air cells and the number of air cells in extruded cornmeal with 20% carrot powder with CO₂ injection decreased at die temperatures of 80 and 120 °C. The decrease in bubble size with increasing carrot powder was probably due to the addition of increasing amounts of fiber and protein to the blend, which may have affected the melt viscosity, and thus a denser product with smaller air cell diameters was formulated. Stojceska et al. [29] found a high correlation between mean cell area to the expansion in high-fiber extrudates, indicating that the higher

level of fiber lowered the expansion of products, giving a structure containing more number of small cell. Besides, Kannadhasan and Muthumarapan [21] described that protein is found to have a negative impact on the expansion of extrudates. Furthermore, when the die temperature increased from 80 to 100 °C, air cell size of the extrudates increased and the air cell density decreased. Singhornart et al. [19] reported that the rise in the die temperature increases the degree of superheating of water in the extruder.

Antioxidant properties

TPC

The Folin–Ciocalteu assay was used for determination of TPC in this study, and results were expressed as gallic acid equivalents. The TPC of extrudates was significantly lower than the raw materials, and it decreased ($p < 0.05$) with increasing die temperature (Table 3). These results are in good agreement with those previously reported by Thin et al. [4] and Bisharat et al. [7] for extruded cereals (sorghum, barley, oats, and millet) and extruded broccoli, respectively. The reduction in the TPC may be attributed to either the decomposition of phenolic compounds under the high extrusion temperature or to the alteration of molecular structure of phenolic compounds that may lead to reduction in the chemical reactivity of phenolic compounds [8]. In all extrudates, the highest TPC was observed in extruded cornmeal made from 80:20 cornmeal/carrot powder mixtures with CO₂ injection at 80 °C die temperature. The TPC of the extrudates increased when carrot powder ratio was increased ($p < 0.05$). TPC values of the CO₂-injected extrudates were significantly higher than those of non CO₂-injected extrudates ($p < 0.05$). CO₂ gas has been demonstrated to increase the extraction of polyphenolic compounds [30]. This result indicated that CO₂ injection could have a major impact on antioxidant capacities of extrudates.

TFC

The cornmeal-based extrudates with carrot powder had significantly lower TFC than raw carrot powder 100% ($p < 0.05$). The TFC varied with carrot powder levels and ranged from 3.15 to 17.33 mg/100 g as quercetin equivalents (Table 3). After extrusion, a significant decrease in the TFC was observed when the die temperature increased ($p < 0.05$). The decrease in TFC may be attributed to the thermal destruction of flavonoids. Although TFC was increased with CO₂ injection, this increase was not significant for extruded cornmeal with 10% carrot powder. Increasing concentration of flavonoid content with increasing CO₂ concentration was observed in *Betula pendula* [31] and strawberry [32]. TFC of extrudates

Fig. 2 Scanning electron micrographs of extruded cornmeal with 0% (A), 10% (B), and 20% (C) carrot powder by without (X) and with (Y) CO₂ injection

tended to increase with increasing carrot powder. The result indicated that higher carrot powder levels in extrudates led to higher TFC.

DPPH-radical-scavenging activities

The DPPH radical-scavenging activity of extruded cornmeal with carrot powder decreased after extrusion and it decreased ($p < 0.05$) with the increasing die temperature (Table 3). The extruded cornmeal with 20% carrot powder

and CO₂ injection at 80 °C had the strongest radical-scavenging activity compared with the other extrudates. Again, a statistically significant difference ($p < 0.05$) between the DPPH radical-scavenging activities in extrudates with and without CO₂ injection was observed. The DPPH radical-scavenging activity in extrudates with CO₂ injection was higher than that in extrudates without CO₂ injection at die temperatures of 80 and 100 °C. These results can also be explained by the fact that the CO₂ increased the extraction of polyphenols [8]. However, CO₂

Table 3 TPC, TFC, and DPPH-radical-scavenging activity of extruded corn meal-carrot products

Materials	Barrel temperature (°C)	CO ₂ injection	Total phenolic (mg GAE/100 g)	Total flavonoid (mg QE/100 g)	DPPH (%)
Extruded cornmeal with 0% carrot powder	80	Without CO ₂	9.54 ^{ijk}	4.58 ^f	9.83 ^h
	100		7.32 ^l	3.86 ^{hi}	8.55 ⁱ
	120		6.73 ^l	3.15 ^j	4.99 ^k
	80	CO ₂ (150 mL/min)	11.47 ^{gh}	4.75 ^e	15.44 ^{cd}
	100		10.06 ^{ij}	4.11 ^g	11.87 ^{fg}
	120		8.8 ^{jk}	3.29 ^j	4.89 ^k
Extruded cornmeal with 10% carrot powder	80	Without CO ₂	11.47 ^{gh}	4.87 ^{cde}	12.26 ^f
	100		9.84 ^{ijk}	3.98 ^{hg}	11.12 ^g
	120		8.58 ^k	3.19 ^j	6.41 ^j
	80	CO ₂ (150 mL/min)	14.35 ^{de}	5.01 ^c	16.39 ^e
	100		12.36 ^{gf}	4.04 ^g	15.72 ^{cd}
	120		10.28 ^{hi}	3.29 ^j	6.37 ^j
Extruded cornmeal with 20% carrot powder	80	Without CO ₂	13.69 ^{ef}	5.30 ^b	14.96 ^d
	100		12.51 ^{gf}	4.59 ^f	12.59 ^{ef}
	120		10.58 ^{hi}	3.78 ⁱ	8.65 ⁱ
	80	CO ₂ (150 mL/min)	16.73 ^c	5.31 ^b	18.43 ^b
	100		15.17 ^d	4.80 ^{de}	16.39 ^e
	120		13.02 ^f	4.00 ^{hg}	13.35 ^e
Raw cornmeal 100%	–	–	32.95 ^b	4.93 ^{dc}	17.95 ^b
Raw carrot powder 100%	–	–	95.17 ^a	17.33 ^a	83.99 ^a

Values within the same column with different letters are significantly different at $p < 0.05$

injection in extruded cornmeal mixed with 0 and 10% carrot powder at 120 °C die temperature did not significantly affect the DPPH radical-scavenging activity.

Change in extrusion conditions, die temperature (80, 100, and 120 °C) and CO₂ injection (150 mL/min), affected physicochemical and antioxidant properties of the extruded cornmeal with varying levels of carrot powder (0, 10, and 20%). Die temperature has been found to be the main factor affecting the physical properties of all extruded products. In addition, it was conclusive that CO₂ injection used in the present study could enhance antioxidant properties, some physical properties (ER, WAI, WSI, brightness, and redness), and the microstructure of extrudates. TPC and DPPH radical-scavenging activities of the extruded products with CO₂ injection were higher than those of extruded products without CO₂ injection. The incorporation of carrot powder can be used to increase contents of phenolic compounds, antioxidants, crude ash, crude fat, and crude protein of extruded products. The extruded cornmeal with 20% carrot powder with CO₂ injection at 80 °C die temperature had the highest radical-scavenging TPC and TFC compared with the other extrudates. This study suggests that extrusion with CO₂ injection and incorporation of carrot powder have the potential to

enhance the nutritional quality and structure-forming ability of the extrudate.

Acknowledgements This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012-0004577).

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

References

1. Edou-Ondo S, Gu BJ, Kim YS, Ryu GH. Effects of feed moisture and barrel temperature on physical and pasting properties of cassava starch extrudate. *Korean J. Food Preserv.* 18: 271–278 (2011)
2. Singkhornart S, Edou-ondo S, Ryu GH. Influence of germination and extrusion with CO₂ injection on physicochemical properties of wheat extrudates. *Food Chem.* 143: 122–131 (2014)
3. Wang YY, Ryu GH. Physical properties of extruded corngrits with corn fibre by CO₂ injection extrusion. *J. Food Eng.* 116: 14–20 (2013)
4. Thin T, Myat L, Ryu GH. The effect of CO₂ injection and barrel temperatures on the physiochemical and antioxidant properties of extruded cereal. *Prev. Nutr. Food Sci.* 21(3): 271–280 (2016)

5. Raeesul H, Kamlesh P. Nutritional and processing aspects of carrot (*Daucus carota*). South Asian J. Food Technol. Environ. 1(1): 1–14 (2015)
6. Özer EA, Herken EN, Güzel S, Ainsworth P, İbanoğlu Ş. Effect of extrusion process on the antioxidant activity and total phenolics in a nutritious snack food. Int. J. Food Sci. Technol. 41: 289–293 (2006)
7. Bisharat GI, Lazou AE, Panagiotou NM, Krokida MK, Maroulis ZB. Antioxidant potential and quality characteristics of vegetable-enriched corn-based extruded snacks. J. Food Sci. Technol. 52(7): 3986–4000 (2015)
8. Sharma P, Gujral HS, Singh B. Antioxidant activity of barley as affected by extrusion cooking. Food Chem. 131: 1406–1413 (2012)
9. Mridula D, Jain R, Singh KK. Effect of storage on quality of fortified Bengal gram *sattu*. J. Food Sci. Technol. 47(1): 119–123 (2010)
10. Alam MS, Pathania S, Sharma A. Optimization of the extrusion process of development of high fibre soybean-rice ready-to-eat snacks using carrot pomace and cauliflower trimmings. LWT-Food Sci. Technol. 74: 135–144 (2016)
11. Kalyani G, Samuel DVK. Effect of addition of carrot powder on physical properties of maize based extruded snack. J. Life Sci. 13: 0973–1431 (2016)
12. AOAC. Official Method of Analysis of AOAC Intl. 15th ed. Method 69. Association of Official Analytical Chemists, Washington, DC, USA (1990)
13. Miller GL. Use of dinitrosalicylic acid reagent for determination of reducing sugar. Anal. Chem. 31: 426–428 (1959)
14. Anderson RA, Conway HF, Pfeifer VF, Griffin EL. Gelatinization of corn grits by roll and extrusion cooking. Cereal Sci. Today 14: 4–12 (1969)
15. Ryu GH, Ng PKW. Effect of selected process on expansion and mechanical properties on wheat flour and cornmeal extrudates. Starch/Stärke 53: 147–154 (2001)
16. Singleton VL, Orthofer R, Lamela-Raventos RM. Analysis of total phenols and other oxidation substrates and antioxidant means of Folin-Ciocalteu reagent. Methods Enzymol 299: 152–178 (1999)
17. Woisky R, Salatino A. Analysis of propolis: Some parameters and procedures for chemical quality control. J. Agric. Res. 37: 99–105 (1998)
18. Brand-Williams W, Cuvelier ME, Berset C. Use of a free radical method to evaluate antioxidant activity. LWT-Food Sci. and Technol. 28: 25–30 (1995)
19. Singkhornart S, Gu BJ, Ryu GH. Physicochemical properties of extruded germinated wheat and barley as modified by CO₂ injection and difference extrusion conditions. Int. J. Food Sci. Tech. 48(2): 290–299 (2013)
20. Guha M, Ali SZ, Bhattacharya S. Twin-screw extrusion of rice flour without a die: Effect of barrel temperature and screw speed on extrusion and extrudate characteristics. J. Food Eng. 32: 251–267 (1997)
21. Kannadhason S, Muthumarapan K. Effect of starch sources and protein content on extruded aquaculture feed containing DDGS. Food Bioprocess. Tech. 4: 282–294 (2011)
22. Altan A, McCarthy KL, Maskan M. Evaluation of snack foods from barley- tomato pomace blends by extrusion processing. J. Food Eng. 84: 231–242 (2008)
23. Launay B, Lish JM. Twin-screw extrusion cooking of starches: flow behavior of starch pastes, expansion and mechanical properties of extrudates. J. Food Eng. 2: 259–280 (1983)
24. Mridula D. Physico-chemical and sensory characteristics of β -carotene rich defatted soy fortified biscuits. Afr. J. Food Sci. 5(5): 305–312 (2011)
25. Colonna P, Tayeb J, Mercier C. Extrusion cooking of starch and starchy products. In C Mercier, P Linko, JM Harper. ed. Extrusion Cooking, American Association of Cereal Chemists International, St. Paul, MN, USA. pp. 247–320 (1989)
26. Rayas-Duarte P, Majewska K, Doetkott C. Effect of extrusion process parameters on the quality of buckwheat flour mixes. Cereal Chem. 75: 338–345 (1998)
27. Sauceau M, Fages J, Common A, Nikitine C, Rodier E. New challenges in polymer foaming: A review of extrusion process assisted by supercritical carbon dioxide. Prog. Polym. Sci. 36: 749–766 (2011)
28. Lazou A, Krokida M. Structural and textural characterization of corn-lentil extruded snacks. J. Food Eng. 100: 392–408 (2010)
29. Stojceska V, Ainsworth P, Plunkett A, İbanoğlu S, İbanoğlu Ş. Cauliflower by-products as a new source of dietary fibre, antioxidants and proteins in cereal based ready-to-eat expanded snacks. J. Food Eng. 87: 554–563 (2008)
30. Arlorio M, Coisson JD, Travaglia F, Miglio G, Lombardi G, Martelli A. Antioxidant and biological activity of phenolic pigments from Theobroma cacao hulls extracted with supercritical CO₂. Food Res. Inter. 38: 1009–1014 (2005)
31. Lavola A, Julkunen TR. The effect of elevated carbon dioxide and fertilization on primary and secondary metabolites in *Betula pendula* (Roth). Oecologia 99: 315–321 (1994)
32. Wang YSH, Bunce AJ, Maas LJ. Elevated carbon dioxide increases contents of antioxidant compounds in field-grown strawberries. J. Agric. Food Chem. 51: 4315–4320 (2003)