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Enrichment of starch-based extruded cereals with chokeberry (*Aronia melanocarpa*) pomace: Influence of processing conditions on techno-functional and sensory related properties, dietary fibre and polyphenol content as well as *in vitro* digestibility

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ABSTRACT

Aiming at providing prototypes for ready-to-eat texturised (RTE) cereal products with reduced glycaemic load, starch blends with chokeberry (*Aronia melanocarpa*) pomace powder (CPP) rich in dietary fibre (DF) and polyphenols (PP) were extruded using a co-rotating twin-screw extruder. The CPP ratios (25%, 50%) and processing conditions applied (barrel temperature 100 °C, screw speed 200, 400, 600, 800 min^{-1}, water content 13%, 23%) result in specific mechanical energies of 87–336 $Whkg^{-1}$ and material temperatures of 111–155 °C. Extrudates containing 25% CPP still offer acceptable techno-functional and sensory related physical properties, while higher CPP ratios result in decreased expansion and cell pore size of the slightly darker and softer extrudates. The *in vitro* glucose release of both extruded blends is reduced by 25% and 50%, respectively. The DF contents are unaffected. As expected, anthocyanins are degraded by about 70% in both blends while phenolic acids and flavonols are fully retained. All PP are already accessible during the stomach phase of an *in vitro* digestion and are not changed significantly in the intestinal phases. Overall, these data substantiate, that marketable texturised RTE extruded cereals may be developed based on the results presented and on further sensory analysis.

1. Introduction

Common breakfast cereals and snacks are highly-demanded ready-to-eat texturised (RTE) cereal products but also high glycaemic index food. RTE cereals mainly consist of starch and sugar, both easily digestible carbohydrates resulting in high blood glucose levels directly after consumption. There is strong evidence that several metabolic disorders, e.g. obesity, type 2 diabetes, and cardiovascular diseases are developed, beside other factors, due to a high intake of this kind of food (Fogelholm, Anderssen, Gunnarsdottir, & Lahti-Koski, 2012; Hauner et al., 2012; Liu, 2002). Therefore, the reformulation of food towards reduced sugar contents and glycaemic loads is actually requested by WHO and EU (World Health Organization, 2015). An increased consumption of dietary fibre (DF) is associated with beneficial nutritional and physiological effects, as several studies have shown (Anderson et al., 2009; FDA, 2018; Lovegrove et al., 2017; Stephen et al., 2017). The replacement of starch with dietary fibre (DF) may counteract the lack of health-promoting nutrients in such foods. DF are cell wall polysaccharides like cellulose, hemicellulose, pectin, and lignin, which in contrast to starch are non-degradable by human digestive enzymes (Prosky, 1999; Trowell, 1976).

Fruit and vegetable processing by-products have gained increasing attention as available, underutilised and sustainable DF sources (Rodríguez, Jiménez, Fernández-Bolaños, Guillén, & Heredia, 2006) that contain numerous further bioactive compounds such as polyphenols (PP) partly linked to DF (Fernandes et al., 2020; Nawirska & Kwaśniewska, 2005; Renard, Watrelot, & Le Bourvellec, 2017). Chokeberry (*Aronia melanocarpa*) pomace, by-product of juice production, provides high contents of total DF (TDF) and total PP (TPP) (up to 60 g/100 g dm and 5 g/100 g dm, respectively), and sorbitol (about 7 g/100 g dm), the latter a natural non-caloric sweetener (Kulling &

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Abbreviations

BA-G	bioaccessibility of glucose
BA-PP	bioaccessibility of polyphenols
CPP	chokeberry pomace powder
c_W	water content
DF	dietary fibre
dm	dry matter
IDF	insoluble dietary fibre
HMW-SDF	high molecular weight soluble dietary fibre
HPLC	high-performance liquid chromatography
LEI	longitudinal expansion index
LMW-SDF	low molecular weight soluble dietary fibre
n	screw speed
PP	polyphenols
RTE	ready to eat
SEI	sectional expansion index
SME	specific mechanical energy
T_B	barrel temperature
TDF	total dietary fibre
T_M	material temperature
TPP	total polyphenols
WAI	water absorption index
WSI	water solubility index.

Rawel, 2008; Rodriguez-Werner, Winterhalter, & Esatbeyoglu, 2019; Schmid, Steck, et al., 2020; Sójka, Kołodziejczyk, & Milala, 2013).

Texturised RTE cereals may be reformulated using dried and powdered fruit and vegetable by-products to partially replace starch (Camire, Chaovanalikit, Dougherty, & Briggs, 2002; Camire, Dougherty, & Briggs, 2007; Karkle, Alavi, & Dogan, 2012; Karkle, Keller, Dogan, & Alavi, 2012; O'Shea, Arendt, & Gallagher, 2014; Wang, Gu, & Ganjyal, 2019). However, during processing, the materials are exposed to thermomechanical stress, which can cause physical and chemical changes of DF and bioactive plant metabolites (Camire, Camire, & Krumhar, 1990; Cheftel, 1986; Singh, Gamlath, & Wakeling, 2007). Although, the DF profiles and contents of pure chokeberry and apple pomace remain almost unchanged under extrusion and extrusion-like conditions except for a shift from insoluble DF (IDF) to high molecular weight soluble DF (HMW-SDF) (Hwang, Choi, Kim, & Kim, 1998; Schmid, Steck, et al., 2020; Schmid et al., 2021; Schmid, Trabert, et al., 2020). While the bioaccessibility of PP remains almost unchanged (Camire et al., 2007; White, Howard, & Prior, 2010; Witczak et al., 2021), the PP contents decrease for both extrusion and extrusion-like conditions (Hirth, Preiß, Mayer-Miebach, & Schuchmann, 2015; Khanal, Howard, Brownmiller, & Prior, 2009; Schmid, Steck, et al., 2020; Schmid et al., 2021).

The knowledge on the stability of DF and bioactive compounds of the material is merely one basic prerequisite in order to enrich common texturised RTE cereals with DF. It is essential, to control the processing conditions to obtain the desired techno-functional and physical properties related to sensory characteristics, i.e. water solubility, water absorption, sectional and longitudinal expansion, hardness and colour. As expected from the knowledge of the adverse impact of DF on these characteristics (Leonard, Zhang, Ying, & Fang, 2020; Wang et al., 2019), extruded pure chokeberry pomace without the addition of starch or flour is less crispy and softer as compared to common RTE cereals (Schmid et al., 2021). Thus, here the effects of extrusion processing were investigated on a model system for texturised RTE cereals production consisting of blends of starch and a commercial chokeberry pomace powder (CPP) with a focus on the techno-functional and physical properties related to sensory characteristics of the extrudates. As a proof of concept for the reduction of the glycaemic load due to DF enrichment, the glucose release during *in vitro* digestion of the extrudates was evaluated, too. Furthermore, DF and PP stability and composition, as well as PP bioaccessibility during *in vitro* digestion were analysed.

2. Materials and methods

2.1. Materials and reagents

Chokeberry (*Aronia melanocarpa*) pomace powder (CPP) was purchased from Aronia Original Naturprodukte GmbH (Germany) exhibiting a moisture content of 3.5 ± 0.6%. Corn starch (C*gel) was provided by Cargill Ingredients (USA) (moisture content 10.2 ± 1.0%). Unless otherwise stated, chemicals and reagents of analytical purity grade were obtained from Merck KGaA (Germany). Enzymes used for DF analysis (amyloglucosidase, 36,000 U/g; α-amylase, 100,000 U/g; protease, 9000 U/g) were from Megazyme (Ireland) and other materials (Celite 545, Amberlite FPA53, Ambersep 200) from Rohm and Haas Europe (Germany). Porcine bile acids and enzymes for *in vitro* digestion (porcine pepsin, pancreatin) were supplied by Sigma Aldrich (Germany). Standards for PP quantification (cyanidin-3-O-glucoside, ≥96%; cyanidin chloride, ≥97%; 5-caffeoylquinic acid, ≥97%; quercetin-3-O-glucoside, ≥99%; quercetin dihydrate, ≥99%) were obtained from Carl Roth GmbH & Co. KG (Germany). Ultrapure water was used for all experiments.

2.2. Extrusion processing

Corn starch and blends with 25% and 50% (w/w) CPP (A0, B0, C0) were extruded; the latter prepared by mixing for 2 min using a ploughshare mixer (type FM 50; Lödige, Germany). A co-rotating twin-screw extruder (ZSK 26 Mc, Coperion, Germany) with length to diameter ratio (L/D) of 29 and a screw diameter of 25.5 mm was used for extrusion trials. The screw configuration included three reverse discs and fifteen kneading blocks (Koch, Emin, & Schuchmann, 2017).

The trials were run at a constant feed rate of 10 kgh^{-1}, while CPP (6, 8, 9 kgh^{-1}) was fed with a gravimetrically controlled feeder (DDW-DDSR40 from Brabender, Germany). Water (4, 2, 1 kgh^{-1}) was added by a piston-membrane pump (model KM 251, Alldos, Germany). The barrel temperatures (T_B) were set to 40 °C, 60 °C, 80 °C, 100 °C, 100 °C, 100 °C. The screw speed (n) was set at 200, 400, 600, and 800 min^{-1}. The extruded material left the extruder by passing a circular die of 3 mm diameter and 10 mm length. The pressure and material temperature (T_M) were measured at the die entrance. The dependent process parameter specific mechanical energy (SME, $Whkg^{-1}$) was calculated by the following equation (1):

$$SME = \frac{\frac{n}{n_{max}} \; x \; \frac{M_d - M_{d,\ unload}}{100}}{\dot{m}} \; x \; P_{max} \qquad (1)$$

where n and n_{max} are the actual and maximum n (1,800 min^{-1}). M_d and $M_{d,unload}$ are the actual and idle torque (%). P_{max} represents the maximum engine power (40 kW) and $\dot{m}$ the total mass flow (kgh^{-1}). Each trial was carried out twice. Samples were taken from the equilibrium state of the extrusion processing, equilibrated at 40 °C for 15 min, stored at −80 °C, and analysed as described. All experiments and analytical measurements performed are shown in Table 1.

2.3. Techno-functional properties and physical properties related to sensory characteristics

2.3.1. Expansion indices

The expansion of extrudates is described by the sectional expansion index (SEI) and the longitudinal expansion index (LEI) (equation (2)).

Table 1
Experiments performed: Materials, extrusion parameters (at constant temperature of barrels 4–6 of 100 °C) and analyses. CPP: chokeberry pomace powder, n: screw speed (min^{-1}); c_w: water content (%), SME: specific mechanical energy ($Whkg^{-1}$), T_M: material temperature (°C), DF: dietary fibre, PP: polyphenols, BA-G: bioaccessibility of glucose (g/100 g); BA-PP: bioaccessibility of polyphenols (mg/100 g), SEI: sectional expansion index, LEI: longitudinal expansion index, WSI: water solubility index, WAI: water absorption index, H: hardness (Nm^{-2}), Colour: L*a*b* colour values.

Sample	Material		Extrusion parameters			Analysis										
	%starch	%CPP	n	c_w	SME	T_M	DF	PP	BA-G	BA-PP	SEI	LEI	WSI	WAI	H	Colour
A0	100	0	–	–	–	–	A	–	NA	NA	NA	NA	A	A	NA	A
A1a	100	0	200	13	A	A	NA	NA	A	NA	A	A	A	A	A	A
A2a	100	0	400	13	A	A	A	NA	NA	NA	A	A	A	A	A	A
A2b	100	0	400	23	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A3a	100	0	600	13	NA	NA	NA	NA	A	NA	A	A	A	A	A	A
A4a	100	0	800	13	A	A	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
B0	75	25	–	–	–	–	NA	A	NA	NA	NA	NA	A	A	NA	A
B1a	75	25	200	13	A	A	NA	NA	NA	NA	A	A	A	A	A	A
B1b	75	25	200	23	A	A	NA	NA	NA	NA	A	A	A	A	A	A
B2a	75	25	400	13	A	A	A	A	NA	NA	A	A	A	A	A	A
B2b	75	25	400	23	A	A	NA	NA	NA	NA	A	A	A	A	A	A
B3a	75	25	600	13	A	A	NA	NA	NA	NA	A	A	A	A	A	A
B3b	75	25	600	23	A	A	NA	NA	NA	NA	A	A	A	A	A	A
B4a	75	25	800	13	A	A	NA	NA	NA	NA	A	A	A	A	A	A
B4b	75	25	800	23	A	A	NA	NA	NA	NA	A	A	A	A	A	A
C0	50	50	–	–	–	–	NA	A	NA	NA	NA	NA	A	A	NA	A
C1a	50	50	200	13	A	A	NA	NA	A	A	A	A	A	A	A	A
C2a	50	50	400	13	A	A	A	A	A	A	A	A	A	A	A	A
C2b	50	50	400	23	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
C3a	50	50	600	13	A	A	NA	NA	NA	NA	A	A	A	A	A	A
C4a	50	50	800	13	A	A	NA	NA	A	A	A	A	A	A	A	A
C4b	50	50	800	23	A	A	NA	NA	NA	NA	A	A	A	A	A	A

A: analysed, NA: not analysed.

$$SEI = \left(\frac{d_{ext}}{d_{die}}\right)^2 \quad (2)$$

The diameter of the extrudates d_{ext} was determined by calliper after 24 h. For all extrusion trials, the die diameter d_{die} was 3 mm.

For LEI, extrudates were taken manually for a period of 3 s. The length of the sample was measured and LEI was calculated according to equations (3)–(5)

$$LEI = \frac{v_{ext}}{v_{die}} \quad (3)$$

$$v_{ext} = \frac{l}{t} \quad (4)$$

$$v_{die} = \frac{\dot{m}}{A_{die}\, x \rho_{die}} \quad (5)$$

whereas v_{ext} is the measured velocity of the extrudates (ms^{-1}), which can be calculated by dividing the measured length l (m) of the extrudates by the time of sampling t (3 s). v_{die} is the velocity of the extrudates (ms^{-1}) at the die exit, which is calculated by dividing the total mass flow $\dot{m}$ (10 kgh^{-1}) by the die area A (7.07 m^2), and the density of matrix ρ_{die} (1,400 kgm^{-3}) (Millauer, Rosa, & Schär, 1993). SEI and LEI were measured 5 times each.

2.3.2. Hardness

A texture analyser (Z2.5 TS, ZwickRoell, Germany) with Kramer shear cell (one blade) was used for measuring texture. Testing parameters were pre-test speed of 0.1 $mmin^{-1}$, test speed of 0.01 $mmin^{-1}$, test distance 6 mm, pre-force of 0.2 N. All trials were performed at least 4 times.

2.3.3. Colour

L*a*b* values of ground, sieved and dried samples were measured three times by a spectral photometer (CM 700d, Konica Minolta, Japan).

2.3.4. Water solubility index and water absorption index

Starch, CPP-starch unprocessed blends and extrudates were milled (coffee mill M55, Petra Electric, Germany), sieved to particle sizes $0.071 < x < 0.14$ mm and dried at 40 °C at 8 mbar in vacuum dryer (VT 5042 EK, Heraeus, Germany). A modified method of Anderson (1982) was used to determine WSI and WAI. Therefore, 0.5 g of milled extruded sample was added to 19.5 g of demineralised water, vortexed for 1 min, shaken at 200 min^{-1} on an orbital shaker for 24 h at room temperature and finally centrifuged at 4,600×*g* for 50 min at 20 °C (Rotanta 460 R, Andreas Hettich GmbH & Co. KG, Germany). After separation of supernatants and precipitates, both were weighed wet and dried for 72 h at 80 °C. After equilibration to room temperature in a desiccator, samples were weighed again and WAI and WSI were calculated:

$$WAI = \frac{m_{water} - m_{wet\ supernatant}}{m_{initial\ sample\ weight}} \quad (6)$$

$$WSI = \frac{m_{dried\ supernatant}}{m_{initial\ sample\ weight}} \quad (7)$$

The trials were performed in triplicate.

2.4. Dietary fibre content

Extrudates (A2a, B2a, C2a) were ground and homogenised (10 g, each, by mortar and pestle, to a particle size <500 nm). Two aliquots of about 250 mg, each, of ground extrudates and corn starch (A0) were analysed twice and in triplicate, respectively, for DF contents according to the modified AOAC Official Method 2011.25 (AOAC, 2012; McCleary, Sloane, & Draga, 2015). In brief, non-resistant starch and proteins were hydrolysed enzymatically by a mixture of pancreatic α-amylase and amyloglucosidase, and by protease, subsequently added to the sample dispersed in buffer. Water insoluble DF (IDF) were separated by filtration and ethanol was added to the filtrate in order to precipitate alcohol insoluble high molecular weight water soluble DF (HMW-SDF), which again were separated by filtration. After several washing steps, both filtration residues were dried and quantitated gravimetrically after correction for any protein or ash in the precipitate. The filtrate containing low molecular weight water and alcohol soluble DF (LMW-SDF) was concentrated, deionised using ion-exchange resins and finally analysed by HPLC combined with a Refractive Index Detector (1100 series,

Agilent Technologies, Germany) using two size exclusion columns in series (Toyo TSKgel, G2500PWXl, 7.8 × 300 mm, Tosoh, Germany). Total DF (TDF) was determined as the sum of all 3 fractions. The DF contents of the unprocessed blends were calculated based on the measured DF content for CPP and the CPP content of the blend.

2.5. In vitro digestion

In vitro digestion of extrudates (A1a, A3a, C1a, C2a, C4a) was performed according to Gille, Trautmann, Posten, and Briviba (2015). Briefly, the gastric phase was simulated by adding porcine pepsin (in 0.1 N HCl) to 50 mg of sample to achieve the final concentration of 1,875 U/mL. The pH was adjusted to 2.2–2.4 and shaken for 1 h in a water bath (37 °C). The intestinal phase was initiated by adding porcine bile acid (9 mM) and pancreatin (85 U/mL trypsin activity). The pH was adjusted to 7.2–7.6. Afterwards, the samples were treated with nitrogen gas and shaken for 2 h in a water bath (37 °C). During digestion, samples were collected to analyse the glucose release and PP bioaccessibility (BA-PP).

2.6. Glucose release

2.6.1. Release of bioaccessible glucose during in vitro digestion

Glucose was measured after gastric and intestinal *in vitro* digestion by adding 1 mL of ethanol to 0.5 mL of each digest (Section 2.5.) which was then centrifuged (17,000×*g*, 20 °C, 10 min). The supernatants were filtered (MWCO 3 kDa, Carl Roth GmbH, Germany) and the filtrates were incubated for 1 h at 37 °C with amyloglucosidase (2.7 U/mL), filtered again and analysed on an HPLC system (LC 626 System, Waters Corporation, USA) equipped with a 717Plus autosampler. To separate the monosaccharides, a SUGAR KS-801 (300 × 8 mm) column (Shodex, Japan) was used (Lareo et al., 2013). Glucose was detected three times as described by Clement, Yong, and Brechet (1992) with the following modifications: mobile phase was 100% water, a flow rate of 0.8 mL/min, column temperature 50 °C, detector gain 1, detector temperature 35 °C.

2.6.2. Glucose contents in AOAC digests

The LMW-SDF fractions from corn starch (A0), blends with CPP (B0, C0) and extrudates (A2a, B2a, C2a) prepared according to AOAC 2011.25 (AOAC, 2012, p. 10) (Section 2.4) were used to analyse sugar contents twice using commercial enzyme test kits (R-Biopharm AG, Germany).

2.7. Polyphenols contents and bioaccessibility

Two aliquots (1 g), each, of CPP-starch blends (B0, C0) and extrudates (B2a, C2a) after homogenisation (as described in section 2.4) were suspended in 3% aqueous formic acid (5 mL). After rehydration (5 min, ice bath in the dark) and homogenisation (Ultra Turrax, IKA-Werke, Germany), PP were extracted (B0, C0 fivefold and B2a, C2a fourfold, respectively), into a mixture of 12% water, 3% formic acid, and 85% methanol (v/v/v). Anthocyanins, phenolic acids, flavonols were measured by HPLC-DAD (1100 series, Agilent Technologies, Germany) as described earlier (Mayer-Miebach et al., 2019); the total PP (TPP-HPLC) was calculated as the sum of these PP. In addition, the total polyphenols contents (TPP) were determined using the unspecific Folin-Ciocalteu test and quantified using catechin monohydrate as a standard compound (Singleton, Orthofer, & Lamuela-Raventos, 1999). Each sample was analysed in duplicate.

In vitro digested samples (Section 2.5) were centrifuged (17,000×*g*, 20 °C, 10 min), filtered (0.22 μm, Merck Millipore, Germany), adjusted to 20% (v/v) formic acid, and analysed six times by HPLC according to Marinelli, Padalino, Conte, Del Nobile, & Briviba, 2018. Total PP content was calculated as the sum of total anthocyanins, total flavonols and total phenolic acids.

2.8. Statistics

Data are presented as mean ± standard deviation (SD). ANOVA followed by Holm-Sidak test (DF content, PP content, functional properties, and texture) or Tukey-Kramer test (bioaccessibility of glucose, PP) was performed to determine statistical significance ($p < 0.05$) between groups.

3. Results and discussion

3.1. Process conditions and impact of dietary fibre content

The effect of extrusion processing on blends of corn starch with a dietary fibre (DF) rich juice processing by-product was investigated as a model for RTE extruded cereals. A commercial chokeberry pomace powder (CPP) was used as DF source and blends containing 25% and 50% CPP were evaluated. The resulting specific mechanical energy (SME) and material temperature (T_M) of extrusion trials with corn starch and blends with CPP ratios of 25% and 50% (A0, B0, C0) are shown in Fig. 1.

The SME increases for corn starch and both CPP blends with increasing screw speed (n). At constant water content (c_W), the SME is highest for pure starch. The addition of CPP results in a decrease in SME. This can be explained by the higher viscosity of plasticised starch as compared to the blends. Consistently, the SME measured for pure CPP at c_W 13% (145, 174, 195, 222 Whkg^{-1}) is the lowest at each n (Schmid et al., 2021). For 25% CPP an increase in c_W from 13 to 23% reduces the viscosity of the melt and thus leads to lower SME. The results are predominantly compared with those for apple pomace as both, chokeberry and apple, are botanical relatives (Robertson, Phipps, Rohrer, & Smith, 1991). A decrease of SME by addition of by-products to starch and flour as well as by an increase in c_W was also measured for apple (Karkle, Alavi, & Dogan, 2012).

Like SME, T_M increases with increasing n and decreasing c_W, due to viscous dissipation. The addition of CPP to starch has no impact on T_M. The T_M measured for pure CPP (136, 146, 152, 155 °C) is slightly higher at each n than for starch or blends (Schmid et al., 2021). Contrary to these results, a decrease of temperature was reported by increasing the amount of added apple pomace at c_W 17.5% (Karkle, Alavi, & Dogan, 2012).

3.2. Effect of extrusion processing on techno-functional properties and physical properties related to sensory characteristics

Table 2 presents the results of sectional (SEI) and longitudinal expansion (LEI), hardness (H), and colour (L*a*b*) as well as water solubility index (WSI) and water absorption index (WAI) of all CPP blends and their extrudates.

3.2.1. Expansion indices and texture

For both CPP blends, SEI decreases with increasing n, whereas LEI increases with n. An increase in CPP content also results in a decrease of SEI. Especially insoluble DF acts as an interference factor in the expansion (Witczak et al., 2021). However, LEI is only slightly affected by CPP content. The reduction of SEI with the addition of pomace was also observed for apple pomace and other fruit pomaces like blueberry and cranberry (Karkle, Alavi, & Dogan, 2012; Karkle, Keller, et al., 2012; O'Shea et al., 2014; Wang et al., 2019).

The addition of CPP reduces the size of pore cells in extrudates, as estimated visually from the cross-section photographs (Fig. 2), which comes along with lower SEI. If more than 25% CPP is added, no crunchy texture like those of highly accepted RTE extruded cereals can be produced. An increase in c_W to 23% causes also smaller, spherical pore cells, however, the effect diminishes with increasing CPP content. The decrease in pore size and the increase in cell wall thickness was also reported for apple pomace by other authors (Karkle, Keller, et al., 2012).

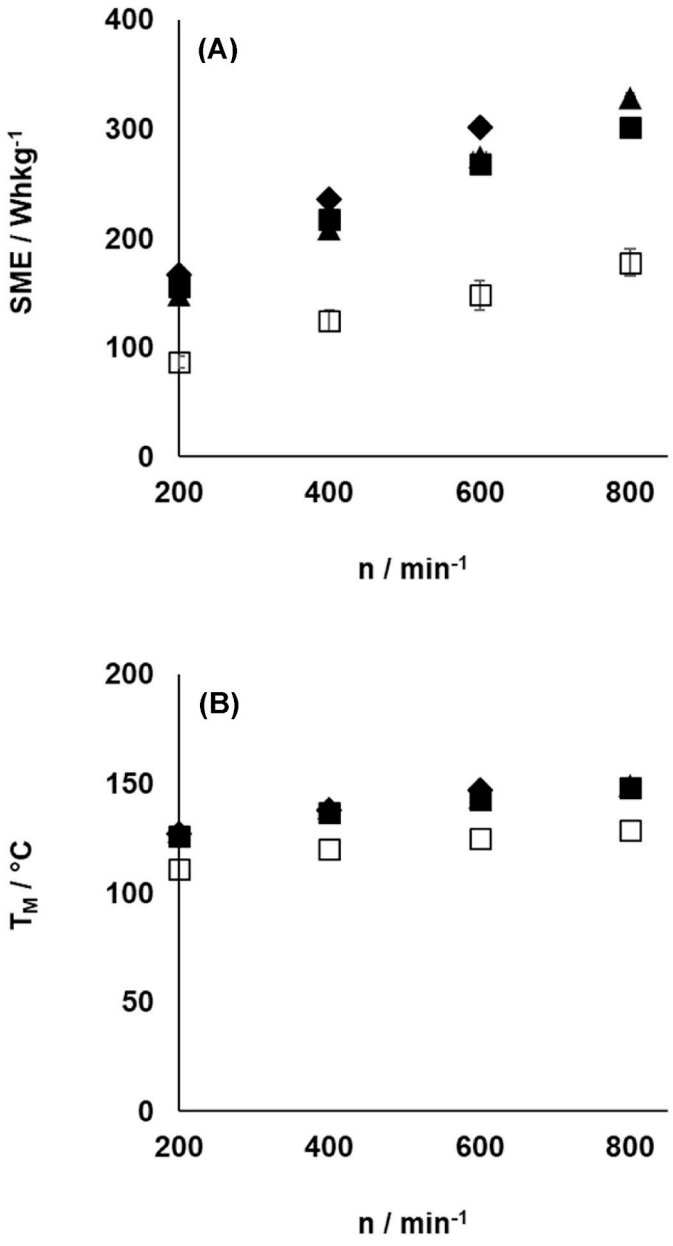

Fig. 1. Effect of screw speed (n), chokeberry pomace powder (CPP) and starch ratio and water content (c_w) on (A) specific mechanical energy (SME) and (B) material temperature (T_M) at 100 °C barrel temperature. ◆ CPP: 0%, c_W = 13% (A1a – A3a); ■ CPP: 25%, c_W = 13% (B1a – B4a); □ CPP: 25%, c_W = 23% (B1b – B4b); ▲ CPP: 50%, c_W = 13% (C1a – C4a).

The hardness of the extrudates is closely related to the expansion and porosity of extrudates and cell wall thickness (Karkle, Keller, et al., 2012). Hardness decreases with increasing starch content and n, and decreasing SEI, respectively. CPP does not work as a plasticiser and thus inhibits expansion and porous structure, as extrudates containing apple pomace do (O'Shea et al., 2014). Thus, an increase in CPP content results in smaller SEI and thus reduces hardness. Extrudates with high c_W of 23% are significantly harder than those with 13% c_W.

3.2.2. Colour

The purple colour (L*a*b*) of CPP blends is significantly affected by extrusion processing (Table 2). Non-extruded blends have much higher L* values than extrudates. Changing n causes an increase in all colour values. Water content is also an affecting parameter, the more water is added the darker the samples (Liu et al., 2019). Increasing the c_W results in lower L*, a*, and b* values. At the same extrusion conditions, an increase in CPP ratio from 25% to 50% provides a slightly darker, purplish colour (Fig. 2). Despite colour changes induced by extrusion processing, the appealing purple colour is preserved during extrusion processing.

3.2.3. Water solubility index and water absorption index

Starch without CPP addition is insoluble in water. During extrusion processing, the WSI of starch before extrusion (A0) increases up to 73.6% (A3a). The WSI of CPP can also be increased by extrusion processing (Schmid et al., 2021; Witczak, Stępień, Zięba, Gumul, & Witczak, 2020). The WSI of blends also increases with increasing n as they contain starch. An increase in c_W resulted in lower WSI values. An increase in WSI is observed with increasing n for both CPP contents of blends, which is higher than for starch und thus indicates solubilisation of the pomace as described for apple pomace (Hwang et al., 1998).

The WAI of starch before extrusion (A0) was 1.1 and increases to 4.8 (A1a) after extrusion. The blends with 25% and 50% CPP (B1a-B4a, C1a-C4a) have WAI values between 1.2 and 2.9 whether extruded or not at c_W 13%; a higher value was obtained at c_W 23% and 25% CPP (B1b). No correlation regarding the WAI of unprocessed and extruded chokeberry pomace blends were observed in other studies (Schmid et al., 2021; Witczak et al., 2021).

3.3. Dietary fibre content

The impact of extrusion processing on DF contents of corn starch and blends with CPP (A0, B0, C0) is given in Table 3. The corn starch used for all experiments contains traces of TDF (6.2 ± 2.8 g/100 g dm), probably representing resistant starch (Berry, 1986; Ring, Gee, Whittam, Orford, & Johnson, 1988). The TDF content of CPP is about 10-fold higher (57.8 ± 2.0 g/100 g dm), as described earlier (Schmid, Steck, et al., 2020). The initial DF contents of blends (B0, C0) were calculated based on the DF contents of both, CPP and corn starch. After extrusion processing in the SME range of 174–241 Whkg^{-1} typically used to produce texturised RTE extruded cereals resulting in T_M between 137 °C and 146 °C, no significant changes in the DF contents of starch (A2a), and blends with CPP (B2a, C2a) are observed as compared to the particular initial contents. The final contents of IDF as the main fraction of CPP DF within the extruded blends correspond to the DF ratios of CPP used for starch replacement. The same is true for TDF. However, the HMW-SDF contents of both blends do not differ significantly irrespective of extrusion processing. No significant difference between extruded corn starch and the blend containing 25% CPP is determined for this DF fraction. Likewise, the LMW-SDF contents of all materials examined do not differ significantly. These results are in accordance with the DF stability of CPP without starch after thermomechanical treatment, whether performed in a Closed Cavity Rheometer (Schmid, Steck, et al., 2020) or after extrusion processing (Schmid et al., 2021). Similar results were observed for other juice processing by-products incorporated in texturised RTE cereals. For apple pomace powder, which belongs to the same plant family as chokeberry presumably possessing comparable DF structures, the final contents of TDF, IDF, and HMW-SDF correspond to the replaced contents of starch and corn flour. The DF contents are only slightly affected by extrusion processing (Hwang et al., 1998; Karkle, Alavi, & Dogan, 2012; Stojceska, Ainsworth, Plunkett, & Ibanoğ;lu, 2010).

3.4. Glucose contents and release after extrusion processing

3.4.1. AOAC digest

As estimated using the digests prepared according to the modified AOAC Official Method 2011.25 (AOAC, 2012) (LMW-SDF fraction; section 2.4) glucose is released completely from corn starch before (A0) and after extrusion processing (A2a). The same is true for the blends with CPP (B0, B2a, C0, C2a) (Supporting information, Table S1). In contrast, extrusion processing at comparable SME reduces the initial

Table 2
Techno-functional and physical properties related to the sensory characteristics of starch and CPP-starch blends before (A0, B0, C0) and after extrusion processing. CPP: chokeberry pomace powder, SEI: sectional expansion index, LEI: longitudinal expansion index, H: hardness (Nm^{-2}), Colour: L* lightness, a* red/green value, b* blue/yellow value, WSI: water solubility index (%), WAI: water absorption index.

Sample	Material	Analysis[a]							
	% CPP	SEI	LEI	H	L*	a*	b*	WSI	WAI
A0	0	–	–	–	98.8 ± 0.3^{I}	-1.4 ± 0.0^{B}	5.0 ± 0.4^{H}	0.0 ± 0.0^{A}	1.1 ± 0.1^{A}
A1a	0	11.4 ± 1.9^{H}	0.5 ± 0.0^{A}	97 ± 32^{D}	95.0 ± 0.1^{H}	-2.9 ± 0.1^{A}	9.2 ± 0.5^{I}	65.4 ± 18.3^{FG}	4.8 ± 0.3^{F}
A2a	0	7.8 ± 0.3^{BG}	0.7 ± 0.0^{B}	46 ± 17^{C}	95.3 ± 0.1^{H}	-2.8 ± 0.1^{A}	9.6 ± 0.3^{I}	66.3 ± 3.5^{FG}	3.5 ± 0.9^{EF}
A3a	0	6.8 ± 0.6^{EFG}	1.0 ± 0.0^{D}	24 ± 9^{ABC}	95.6 ± 0.2^{H}	-2.6 ± 0.0^{A}	9.1 ± 0.5^{I}	73.6 ± 4.3^{G}	2.2 ± 0.3^{ABCDE}
B0	25	–	–	–	55.8 ± 1.5^{A}	10.8 ± 0.2^{C}	2.0 ± 0.2^{DE}	6.9 ± 0.1^{A}	1.8 ± 0.1^{ABCD}
B1a	25	8.4 ± 0.3^{B}	0.5 ± 0.0^{A}	29 ± 13^{ABC}	22.4 ± 0.4^{ABCD}	15.4 ± 0.1^{J}	1.4 ± 0.1^{CD}	56.9 ± 1.8^{DEF}	2.0 ± 0.3^{ABCD}
B1b	25	7.0 ± 0.9^{FG}	0.7 ± 0.1^{B}	18 ± 7^{ABC}	21.7 ± 0.2^{ABC}	12.8 ± 0.1^{E}	1.2 ± 0.0^{BC}	32.4 ± 0.3^{B}	4.5 ± 0.4^{F}
B2a	25	6.8 ± 0.4^{EFG}	0.9 ± 0.1^{C}	15 ± 3^{ABC}	23.6 ± 0.1^{D}	17.1 ± 0.1^{K}	1.9 ± 0.0^{DE}	62.9 ± 1.2^{EF}	1.3 ± 0.1^{ABC}
B2b	25	3.4 ± 0.1^{B}	1.0 ± 0.1^{D}	24 ± 11^{ABC}	21.1 ± 0.6^{AB}	14.3 ± 0.1^{G}	1.9 ± 0.1^{DE}	44.2 ± 2.2^{BCD}	2.9 ± 0.6^{D}
B3a	25	6.5 ± 0.6^{EF}	1.3 ± 0.0^{E}	6 ± 2^{A}	26.1 ± 0.3^{F}	18.1 ± 0.0^{L}	2.4 ± 0.0^{EF}	64.5 ± 4.0^{EFG}	1.2 ± 0.2^{AB}
B3b	25	1.9 ± 0.1^{A}	NA	23 ± 13^{ABC}	22.6 ± 0.1^{ACD}	14.6 ± 0.1^{GH}	1.4 ± 0.0^{CD}	50.8 ± 0.6^{CDE}	2.6 ± 0.5^{CDE}
B4a	25	5.7 ± 0.4^{DE}	1.7 ± 0.1^{G}	4 ± 0^{A}	26.9 ± 0.3^{F}	17.3 ± 0.1^{K}	3.2 ± 0.1^{G}	54.2 ± 4.7^{DEF}	2.2 ± 0.5^{ABCDE}
B4b	25	1.6 ± 0.3^{A}	NA	35 ± 12^{BC}	22.8 ± 0.2^{CD}	14.6 ± 0.1^{GH}	1.4 ± 0.1^{CD}	50.8 ± 1.5^{CDE}	2.7 ± 0.3^{DE}
C0	50	–	–	–	44.0 ± 0.3^{G}	14.9 ± 0.1^{HI}	2.8 ± 0.0^{FG}	11.1 ± 0.1^{A}	2.3 ± 0.1^{BCDE}
C1a	50	6.9 ± 0.5^{EFG}	0.6 ± 0.1^{B}	20 ± 8^{ABC}	21.1 ± 0.5^{B}	12.0 ± 0.1^{D}	0.8 ± 0.0^{AB}	38.2 ± 0.9^{BC}	2.1 ± 0.6^{ABCD}
C2a	50	4.9 ± 0.2^{CD}	1.1 ± 0.0^{D}	8 ± 3^{A}	23.8 ± 0.9^{DE}	13.4 ± 0.4^{F}	0.7 ± 0.1^{AB}	43.2 ± 1.1^{BCD}	2.7 ± 0.7^{DE}
C3a	50	4.1 ± 0.3^{BC}	1.5 ± 0.1^{F}	4 ± 1^{A}	23.7 ± 0.5^{DE}	13.6 ± 0.1^{F}	1.4 ± 0.1^{CD}	48.5 ± 1.6^{CD}	1.8 ± 0.2^{ABCD}
C4a	50	3.7 ± 0.3^{BC}	1.9 ± 0.1^{H}	3 ± 1^{A}	25.3 ± 0.8^{E}	15.0 ± 0.2^{I}	2.4 ± 0.1^{EF}	50.4 ± 0.3^{CDE}	1.7 ± 0.1^{ABCD}
C4b	50	1.9 ± 0.3^{A}	1.5 ± 0.1^{F}	9 ± 7^{AB}	22.1 ± 0.1^{ABC}	11.9 ± 0.1^{D}	0.5 ± 0.0^{A}	37.9 ± 0.4^{BC}	1.9 ± 0.1^{ABCD}

NA: not analysable.
[a] Means with different superscript capital letters within the same column differ significantly ($p < 0.05$).

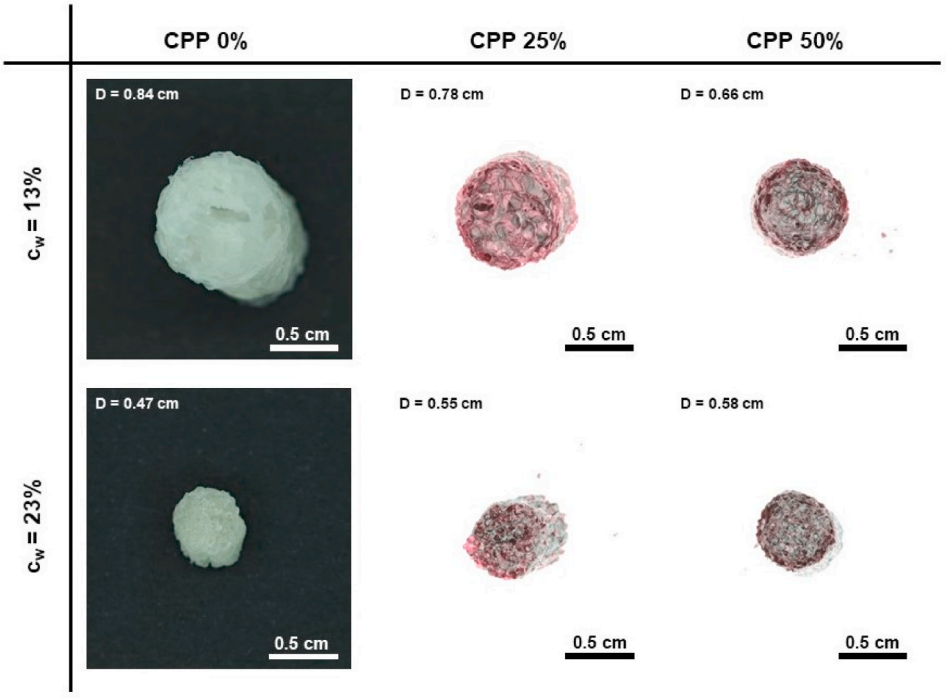

Fig. 2. Effect of chokeberry pomace powder (CPP) and starch ratio and water content (c_w) on the porosity of extrudates. All pictures at constant barrel temperature (100 °C) and screw speed (400 min^{-1}) (A2a, A2b, B2a, B2b, C2a, C2b).

glucose content of CPP by about 20% indicating the possible formation of Maillard glycation products (Cheftel, 1986; Singh et al., 2007). Altogether, with lower starch ratios of the blends, the glucose contents within LMW-SDF fractions are likewise reduced to about 75% and 50% as compared to the ratio of starch.

3.4.2. *Release of glucose during in vitro digestion*

Bioaccessibility data of glucose from selected extruded corn starch samples after *in vitro* digestion is given in Fig. 3. The extruded starch (A1a, A3a) show fast and nearly complete release of glucose from starch during the small intestine phase independent from the extrusion conditions at constant c_W (13%). *In vitro* digestion of differently extruded blends of corn starch with 50% CPP (C1a, C2a, C4a) show similar time dependence. But the release of bioaccessible glucose is about 2 times lower than that from the extruded starch. Similar to the extruded starch, the treatment parameters do not affect the amount and time course of the glucose release during *in vitro* digestion.

Table 3
Dietary fibre (DF) contents of corn starch and CPP-starch blends before (A0, B0, C0) and after extrusion processing (A2a, B2a, C2a) (g/100 g dm, mean ± SD, n = 2) at constant screw speed (400 min^{-1}) and water content (13%). CPP: chokeberry pomace powder, IDF: insoluble DF, HMW-SDF: high molecular weight soluble DF, LMW-SDF: low molecular weight soluble DF, TDF: total dietary fibre.

Sample	% CPP	IDF[a]	HMW-SDF[a]	LMW-SDF[a]	TDF[a]
A0	0	0.5 ± 1.1^{A}	1.6 ± 1.9^{A}	4.1 ± 1.6^{A}	6.2 ± 2.8^{A}
A2a	0	0^{A}	3.7 ± 0.5^{AB}	0.9 ± 0.3^{A}	4.5 ± 0.8^{A}
B0[b]	25	11.4 ± 0.9^{B}	4.1 ± 1.5^{AB}	3.7 ± 1.3^{A}	19.1 ± 2.1^{B}
B2a	25	11.7 ± 1.2^{B}	6.2 ± 1.2^{AB}	1.0 ± 0.3^{A}	18.9 ± 2.6^{B}
C0[b]	50	22.2 ± 0.9^{C}	6.6 ± 1.2^{AB}	3.3 ± 1.4^{A}	32.0 ± 1.7^{C}
C2a	50	22.8 ± 2.3^{C}	8.6 ± 1.5^{B}	2.2 ± 1.7^{A}	33.6 ± 2.1^{C}

[a] Means with different superscript capital letters within the same column differ significantly ($p < 0.05$).
[b] Calculated based on the measured DF contents for CCP and the CCP content in the blend.

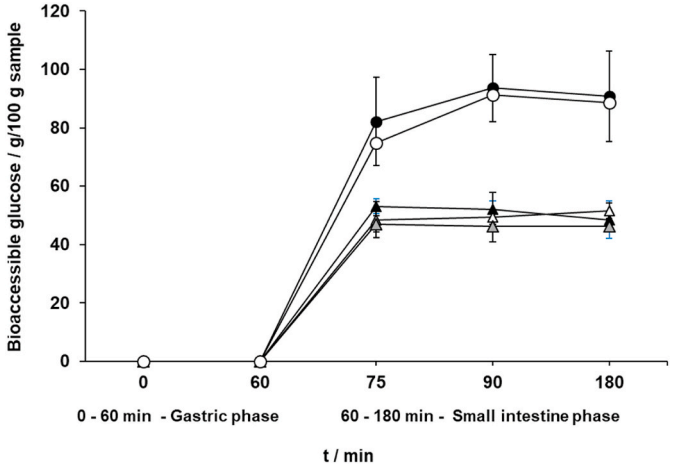

Fig. 3. Time (t) course of release of bioaccessible glucose during digestion of extrudates in an *in vitro* model (mean ± SD, n = 3). Extrudates: ● CPP: 0%, n = 200 min^{-1}, c_w = 13% (A1a); ○ CPP: 0%, n = 600 min^{-1}, c_w = 13% (A3a); ▲ CPP: 50%, n = 200 min^{-1}, c_w = 13% (C1a); △ CPP: 50%, n = 400 min^{-1}, c_w = 13% (C2a); ▲ CPP: 50%, w/w, n = 800 min^{-1}, c_w = 13% (C4a).

3.5. Polyphenol content and bioaccessibility

3.5.1. Effect of extrusion processing on polyphenol stability and composition

Polyphenols (PP) are known to be susceptible to oxidation and thermal treatment (Jackman, Yada, Tung, & Speers, 1987; Rodriguez-Amaya, 2019). It is to expect, therefore, that the preparation of corn starch and CPP blends using a ploughshare mixer at room temperature in the presence of atmospheric oxygen may induce PP oxidation. Compared to the calculated data, the contents of total polyphenols (TPP), anthocyanins, flavonols, and phenolic acids are not significantly affected during mixing (Table 4, Supporting information, Table S2-1, S2-2, S2-3). In order to describe the impact of extrusion processing on PP stability, the PP contents of extruded blends of CPP and corn starch were compared to the calculated data, therefore. Extrusion processing was performed at T_M within the typical range used to produce RTE extruded cereals between 137 °C and 146 °C. The results are given in Table 4.

The total anthocyanins contents decrease in both CPP-starch blends (25%, 50% CPP) by about 70% to final contents of 0.133 ± 0.032 g/100 g dm and 0.288 ± 0.054 g/100 g dm, respectively, (B2a, C2a) (Table 4). Similar effects are observed for cyanidin glycosides (Supporting information, Tables S2–1). In contrast, as described earlier, extrusion processing of CPP at comparable extrusion parameters resulted in a 75% total anthocyanins reduction with a remaining content of 0.43 ± 0.04 g/100 g dm (Schmid et al., 2021). In the presence of starch, the T_M during extrusion processing (137 °C and 139 °C, respectively) (Fig. 1B) is about 10 °C lower as compared to CPP with 146 °C, thus to some extent preventing thermal degradation of anthocyanins. The residual total anthocyanins contents after extrusion of CPP and the 50% blend with corn starch do not differ significantly (Table 4). The same is true for anthocyanin glycosides (Supporting Information, Tables S2–1). The degradation of total anthocyanins estimated here is in the same range as reported by other authors (Camire et al., 2007; Khanal et al., 2009; White et al., 2010) regarding extrusion processing of berry materials, e.g. blueberry, cranberry, raspberry, used as fruit powders, pomace, or combined at different ratios with starch. In a chokeberry extract added to a starchy matrix and extruded at SME 154 ± 13 and 219 ± 2 $Whkg^{-1}$, anthocyanins were retained by about 58% and 17%, respectively (Hirth et al., 2015). Total phenolic acids as well as 3- and 5-caffeoylquinic acid isomers are completely unaffected during extrusion processing irrespective of the corn starch ratio of the blends (B2a, C2a) (Table 4, Supporting information, Tables S2–2). The very minor isomer 4-caffeoylquinic acid remains unchanged during extrusion processing of the blends. This is in contrast to the increased content (by about 45%) of this isomer after extrusion processing of CPP probably due to isomerisation during thermal processing (Li et al., 2019). The starch content of the blends resulting in a lower T_M may protect from phenolic acid isomerisation. As determined for phenolic acids, the contents of total flavonols and quercetin glycosides in corn starch blends with CPP before and after extrusion processing do not differ significantly (Table 4, Supporting information, Tables S2–3). In contrast, cranberry flavonols contents are enhanced by 30%–34% due to extrusion processing in blends with starch (White et al., 2010). The total contents of PP as summarised from anthocyanins, phenolic acids, and flavonols contents (TPP-HPLC) are reduced by extrusion processing, while the measured TPP contents (Folin-Ciocalteu assay) are unaffected (Table 4). This may be on the one hand due to the unspecific Folin-Ciocalteu assay reducing not only phenolic compounds. On the other hand, a partly enhanced extractability of proanthocyanidins (Fernandes et al., 2020; Renard et al., 2017) as the main class of chokeberry TPP (Rodriguez-Werner et al., 2019; Sójka et al., 2013) may have induced this

Table 4
Polyphenols contents of corn starch and CPP-starch blends before (A0, B0, C0; as calculated and measured, respectively) and after extrusion processing (B2a, C2a) (g/100 g dm, mean ± SD, n = 2) at constant screw speed (400 min^{-1}) and water content (13%). TPP-HPLC: total polyphenols contents calculated as the sum of monomeric anthocyanins, phenolic acids and flavonols, TPP: total polyphenols contents analysed by the Folin-Ciocalteu test.

Sample	% CPP	Anthocyanins[a]	Phenolic acids[a]	Flavonols[a]	TPP-HPLC[a]	TPP[a]
B0[b]	25	0.450 ± 0.220^{C}	0.077 ± 0.007^{A}	0.046 ± 0.002^{A}	0.57 ± 0.03^{B}	0.79 ± 0.06^{A}
B0	25	0.361 ± 0.029^{BC}	0.067 ± 0.004^{A}	0.043 ± 0.003^{A}	0.47 ± 0.04^{B}	0.97 ± 0.04^{A}
B2a	25	0.133 ± 0.032^{A}	0.059 ± 0.004^{A}	0.039 ± 0.004^{A}	0.23 ± 0.02^{A}	1.04 ± 0.24^{A}
C0[b]	50	0.900 ± 0.045^{D}	0.153 ± 0.014^{B}	0.092 ± 0.003^{BC}	1.15 ± 0.06^{C}	1.59 ± 0.12^{B}
C0	50	0.853 ± 0.026^{D}	0.152 ± 0.003^{B}	0.104 ± 0.001^{C}	1.11 ± 0.02^{C}	2.30 ± 0.05^{B}
C2a	50	0.288 ± 0.054^{AB}	0.140 ± 0.003^{B}	0.088 ± 0.001^{B}	0.52 ± 0.05^{B}	2.96 ± 0.48^{B}

[a] Means with different superscript capital letters within the same column differ significantly ($p < 0.05$).
[b] Calculated based on the measured content for CCP and the CCP content in the blend.

effect, which was also observed in CPP (Schmid et al., 2021).

3.5.2. Polyphenol bioaccessibility

The *in vitro* digested starch extrudates (A1a, A3a) do not contain detectable polyphenols (PP). The time dependency of the bioaccessibility of PP (BA-PP) during *in vitro* digestion of the blends of corn starch and 50% CPP extruded at constant c_W (13%) and different n (C1a, C2a, C4a) are shown in Table 5.

Anthocyanins, phenolic acids, and flavonols as the most prominent PP detected are released in the bioaccessible form already during the stomach phase without significant changes during the gastric and the intestinal phases for the phenolic acids and the flavonols. For anthocyanins, the maximum release is observed directly after the gastric phase or 15 min after incubation in the intestinal phases. Longer incubation in the intestinal phase leads to a decrease in the concentrations of anthocyanins, apparently, due to the known instability of anthocyanins at the neutral pH (Fleschhut, Kratzer, Rechkemmer, & Kulling, 2006). The extrusion conditions have no or only minor effect on the bioaccessibility of phenolic acids and flavonols but significantly affect the bioaccessibility of anthocyanins. The highest bioaccessibility of anthocyanins is observed with the lowest n (200 min^{-1}). Increasing n to 400 and 800 min^{-1} leads to a significant decrease of bioaccessible anthocyanins by 1.5 and 7-fold, respectively, indicating that increased mechanical energy input (SME), causes a strong decrease in bioaccessible anthocyanins.

Table 5
Amount of bioaccessible polyphenols during *in vitro* digestion of blends of 50% corn starch and chokeberry pomace extruded at constant water content (13%) and different screw speeds (C1a, C2a, C4a).

Time/min, digestion phase[a]	C1a[b]	C2a[b]	C4a[b]
Anthocyanins (mg/100 g sample)			
0, G	626.7 ± 76.9^{C}	455.3 ± 23.0^{B}	111.0 ± 5.8^{A}
60, G	693.8 ± 118.7^{C}	474.0 ± 25.9^{B}	122.0 ± 11.6^{A}
75, SI	704.2 ± 75.3^{C}	449.6 ± 12.5^{B}	105.1 ± 11.9^{A}
90, SI	698.9 ± 69.3^{C}	454.0 ± 24.5^{B}	102.7 ± 10.7^{A}
180, SI	582.8 ± 61.4^{C}	386.9 ± 26.8^{B}	74.8 ± 5.5^{A}
Phenolic acids (mg/100 g sample)			
0, G	132.4 ± 12.9^{A}	$141.6 \pm 4,6^{A}$	136.2 ± 5.3^{A}
60, G	139.9 ± 20.6^{A}	150.7 ± 6.6^{A}	148.6 ± 10.4^{A}
75, SI	139.5 ± 15.0^{A}	137.7 ± 3.5^{A}	134.4 ± 11.5^{A}
90, SI	141.7 ± 14.1^{A}	140.6 ± 4.4^{A}	137.4 ± 9.6^{A}
180, SI	142.7 ± 14.7^{A}	143.4 ± 7.4^{A}	138.0 ± 7.6^{A}
Flavonols (mg/100 g sample)			
0, G	52.1 ± 6.0^{A}	$60.5 \pm 2,8^{B}$	$54,2 \pm 3,06^{AB}$
60, G	63.6 ± 11.5^{A}	$66.3 \pm 4,5^{A}$	62.9 ± 4.5^{A}
75, SI	67.1 ± 7.0^{B}	66.0 ± 2.1^{B}	57.7 ± 5.2^{A}
90, SI	68.4 ± 7.2^{B}	66.0 ± 3.6^{AB}	57.9 ± 5.0^{A}
180, SI	70.5 ± 8.5^{B}	68.2 ± 4.1^{B}	58.2 ± 4.4^{A}
Sum of polyphenols (mg/100 g sample)			
0, G	811.2 ± 94.6^{C}	657.4 ± 29.8^{B}	301.5 ± 13.5^{A}
60, G	897.2 ± 150.5^{C}	690.9 ± 36.2^{B}	333.5 ± 25.9^{A}
75, SI	910.8 ± 97.2^{C}	653.3 ± 17.5^{B}	297.2 ± 28.4^{A}
90, SI	909.0 ± 90.4^{C}	660.5 ± 32.3^{B}	298.1 ± 25.0^{A}
180, SI	795.9 ± 84.4^{C}	598.5 ± 38.0^{B}	271.0 ± 17.2^{A}

[a] 0–60 min - Gastric phase (G); 60–180 min – Small intestine phase (SI).
[b] Means with different superscript capital letters within the same row differ significantly ($p < 0.05$).

4. Conclusion

A dietary fibre (DF)- and polyphenols (PP)-rich commercial chokeberry pomace powder (CPP) was used to partially replace starch for making texturised ready-to-eat (RTE) extruded cereals prototypes. Extrudates containing 25% of CPP still offered acceptable techno-functional and sensory related characteristics. With increasing CPP content, the expansion and the cell pore size of extrudates decreased and the extrudates became slightly darker and softer. The *in vitro* glucose release from extruded starch-CPP blends was reduced as compared to that from pure starch, corresponding the extent of the reduction to the amount of corn starch replaced. Extrusion processing did not change DF contents nor its composition. Anthocyanins contents decreased linearly with increasing SME whereas phenolic acids and flavonols contents remained fully unaffected. All PP were accessible already during the stomach phase of an *in vitro* digestion and not further significantly changed in the intestinal phases. Only the bioaccessibility of anthocyanins, but not that of phenolic acids or flavonols, was affected by extrusion processing. Overall, our data proves that corn starch blends with up to 25% CPP provide DF- and PP-rich materials for the production of RTE extruded cereals with considerably reduced glucose release and bioaccessible PP. Marketable texturised RTE extruded cereals, e.g. crispy breakfast cereals and snacks, may be developed based on the results presented and on further sensory analysis.

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.

CRediT authorship contribution statement

Vera Schmid: Data curation, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Esther Mayer-Miebach:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Diana Behsnilian:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Karlis Briviba:** Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Heike P. Karbstein:** Conceptualization, Funding acquisition, Resources, Writing – review & editing. **M. Azad Emin:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2021.112610.

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