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AUTHORS: Delić, J., Ikonić, P., Jokanović, M., Peulić, T., Ikonić, B., Banjac, V., Stojkov, V., Vidosavljević, S., Hadnađev, M.

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Sustainable snack products: Impact of protein- and fiber-rich ingredients addition on nutritive, textural, physical, pasting and color properties of extrudates

Jovana Delić[a], [b], *, Predrag Ikonić[b], Marija Jokanović[a], Tatjana Peulić[b], Bojana Ikonić[a], Vojislav Banjac[b], Strahinja Vidosavljević[b], Viktor Stojkov[b], Miroslav Hadnađev[b]

[a] University of Novi Sad, Faculty of Technology Novi Sad, Bulevar cara Lazara 1, 21000 Novi Sad, Serbia
[b] University of Novi Sad, Institute of Food Technology, Bulevar cara Lazara 1, 21000 Novi Sad, Serbia

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ABSTRACT

The objective of this study was to explore the feasibility of incorporating mechanically deboned poultry meat (MDPM) and brewers spent grain (BSG) to corn based extruded snack products. The addition of protein- and fiber-rich ingredients creates nutritionally fortified snack product, however with lower quality of physical and textural characteristics and altered color. Therefore, the impacts of different MDPM (from 4 to 12%) and BSG (from 10 to 30%) concentrations and varying screw speeds (500, 700, 900 rpm) on physico-chemical properties of extruded snack products were investigated. Through optimization, with defined desired nutritional and physical characteristics and within the investigated range of input variables (MDPM, BSG and screw speed), the optimal product was defined. The optimized snack formulation contained 4% MDPM and 14.8% BSG, and it was produced at 900 rpm screw speed. Furthermore, the analysed parameters of the optimal snack demonstrated good agreement with the predicted values, indicating successful optimization.

1. Introduction

Last few decades the prevalence of common diseases such as obesity, diabetes and cardiovascular diseases is rising, thus a healthy diet is becoming increasingly important and widely implemented in order to rise life expectancy and quality (Blüher, 2019; Galmiche, Déchelotte, Lambert, & Tavolacci, 2019). Due to demand derived from the previous statement and increasing cost of healthcare, food industry has been trying to satisfy consumers' requests by developing a different types of functional food (Duttaroy, 2019). Contemporary consumers are looking for the sensory-acceptable food enriched with nutritive or functional ingredients, such as dietary fibers, proteins, grassmicronutrients, polyphenols, etc. (Schlinkert, Gillebaart, Benjamins, Poelman, & de Ridder, 2020). Extruded snack food is widely consumed and represents perfect base for development of different types of functional products. The term “snack food” usually implies to energy-dense, nutrient-poor foods high in sodium, sugar, and/or fat, consumed by both children and adults (Younginer et al., 2016). For example, in United States around 27% of daily energy intake of children is coming from snacks, and as regards adults snacks contribute 23% of daily energy intake (Hess, Jonnalagadda, & Slavin, 2016); while in the UK, 90% of households frequently eat crisps and crisp-like snacks as a part of lunch (Grasso, 2020). Kant and Graubard (2015) showed that during the last 40 years, energy intake from main meals has been decreasing, while the energy from snacking has been increasing, and around a quarter of energy has been brought in between the meals. Among emerging adults (ages 18–24 years) from Australia the highest influence on food choice, except the taste, had the convenience (availability), cost and nutrition/health value of the food product; hence, authors concluded that development of “ready availability of tasty and nutritious foods at a low cost” should be in focus (Hebden, Chan, Louie, Rangan, & Allman-Farinelli, 2015). Therefore, extruded low nutritional quality cereal-based abundantly consumed snacks products are presenting a great area for development of novel healthy functional snack products.

The quality of extruded snack products has been widely influenced by their expansion ratio, bulk density, microstructure as well as textural properties such as breaking force and crispness (Philipp, Oey, Silcock, Beck, & Buckow, 2017; Tas & Shah, 2021). Therefore, texture and phys-

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Abbreviations: MDPM, Mechanically deboned poultry meat; BSG, Brewer spent grain

* Corresponding author at: University of Novi Sad, Institute of Food Technology, Bulevar cara Lazara 1, 21000 Novi Sad, Serbia.
E-mail address: jovana.delic@fins.uns.ac.rs (J. Delić).

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ical characteristics are critical parameters regarding the consumer acceptability of snack products. Addition of protein- and fiber-rich ingredients to starchy extruded snack products has a negative influence on these textural and physical characteristics. It has been demonstrated that an increase of protein and dietary fiber content, lower the expansion rate and increase bulk density (Basilio-Atencio, Condezo-Hoyos, & Repo-Carrasco-Valencia, 2020; Beck et al., 2018; Philipp et al., 2017; Téllez-Morales, Herman-Lara, Gómez-Aldapa, & Rodríguez-Miranda, 2020). Physical and textural properties of extruded snack products are also influenced by different production conditions. Some authors showed that screw speed is the process parameter that has the most significant influence on these properties (Neder-Suárez et al., 2021). Rising of the screw speed has a positive effect, i.e. increased expansion and decreased hardness of snack product (Félix-Medina et al., 2020; Neder-Suárez et al., 2021; Philipp, Emin, Buckow, Silcock, & Oey, 2018). Hence the creation of nutritionally valuable extruded snack product with desirable texture is a challenge for many food processors.

Improvement in the nutritional quality of extruded snacks could be achieved by inclusion of different plant materials (Basilio-Atencio et al., 2020; Oliveira, Alencar, & Steel, 2018; Philipp et al., 2018), or animal products (Cakmak, Altinel, Kumcuoglu, Kisla, & Tavman, 2016; Lee, Min, Kim, & Lee, 2003; Yadav, Anand, Navnidhi, & Singh, 2014) and insects (Azzollini, Derossi, Fogliano, Lakemond, & Severini, 2018; Borges, da Costa, Trombete, & Câmara, 2022; Jorge Iñaki et al., 2022) or even some species of microalgae (Lucas, de Morais, Santos, & Costa, 2018). Some waste co-products form food industry represent nutritionally valuable materials that are underestimated and remain as an unexploited waste. In order to reduce waste and improve planet ecosystem, different utilization of these materials should be enforced. Brewer's spent grain (BSG) is nutritionally valuable by-product of the brewing industry. It is a lingo-cellulosic material rich in protein (20%) and fiber (70%) (Mussatto, 2014). Mechanically deboned poultry meat (MDPM) is a low-cost turkey and/or chicken product, produced by mechanical separation of a bone and attached skeletal muscle (Pereira et al., 2011). In the presented work, these two ingredients has been incorporated in the extruded snack products as a rich sources of proteins, antioxidants, dietary fibers, minerals and essential fatty acids. BSG has been selected as one of the ingredients, due to its nutritional quality and also due to its disposal problem and need for a new valorisation approach, while MDPM as an animal product is fulfilling nutrient base with all essential amino acids. Hence, the aim of this study was to investigate influence of different BSG and MDPM share and different screw speed on nutritional, physical, textural and pasting parameters of obtained extrudates.

2. Materials and methods

2.1. Raw materials

The raw materials used in the production of extruded snack products were cornmeal, MDPM, BSG and table salt. Cornmeal (protein 6.5%, fat 0.59%, ash 0.31%, carbohydrates 79.6%, starch 74.3%, dietary fibers 5.73%) was purchased from Mirotin Tisa (Savino selo, Serbia). MDPM (protein 15.8%, fat 14.98%, ash 0.95%, carbohydrates 0.1%, starch 0%; dietary fibers 0%) was bought from DB Rodić (Titel, Serbia). BSG was supplied by 3beer craft brewery (Novi Sad, Serbia) and further dried in convection dryerD-018, Solaris + (Dryer d.o.o., Belgrade, Serbia) to meet the target moisture level around 5.0%. After drying, BSG was finely milled in a hammer mill (type 2.2, ABC Inženjering, Serbia) equipped with a 1 mm sieve giving the final product of the following chemical composition: protein 19.1%, fat 5.58%, ash 4.38%, carbohydrates 65.94%, starch 13.18%, dietary fibers 45.59%. Table salt was purchased from a local store.

2.2. Experimental design

A three-level-three-factor Box-Behnken experimental design was employed to study effect of screw speed and feed composition on physical and textural parameters (bulk density, expansion index, extrudates' length, hardness, firmness, crispiness). MDPM content (X1), BSG share (X2) and screw speed (X3) were the independent variables selected to be in this experimental design. Table 1 presents Box-Behnken design matrix with coded and actual values of each factor.

2.3. Sample preparation and extrusion process

Eleven selected blends were prepared following experimental design (Table 1) by mixing cornmeal, MDPM, BSG and salt (0.5% in each mixture) in appropriate ratios in bowl cutter SMZ 20/82 (Alexanderwerk, Germany) until homogenous mixtures were obtained. The moisture content of each blend was targeted to 18% by adding required content of water directly in bowl cutter during mixing. The moisture content of 18% was chosen since it was highest moisture content between mixtures.

The extrusion process was conducted using a co-rotating twin-screw extruder (model BTSK30, Buhler, Uzwil, Switzerland) with specially designed screw configuration for directly expanded products (Kojić et al., 2018) of L/D ratio 28:1. The screw configuration was kept constant throughout the experiments. The extruder barrel consisted of seven sections with a total barrel length of 880 mm. The extruder was equipped with two tempering tools (Regloplas P140 smart, Regloplas, St. Gallen, Switzerland) for controlling temperature of sections 2–4 (set at 100 °C) and sections 6–7 (set at 120 °C). The extruder was operated at a constant feed rate of 50 kg/h and screw speed was varied at three levels: 500, 700 and 900 rpm. A die with an aperture diameter of 4 mm and total opening surface of 12.56 mm^2 was used throughout. The final length of the extrudates was acquired by cutting product after exiting the die using assembly of six knives rotating with a constant speed of 350 rpm. After the extrusion, samples were dried for half an hour at the room temperature, sealed in paper and plastic bags and stored at ambient temperature (20 °C) until further analysis.

2.4. Proximate analysis

Protein, fat, moisture, ash, starch and crude fiber analysis of cornmeal, BSG and extrudates were performed using the Official Methods of Analysis (AOAC, 2019). Protein, fat, moisture and ash content of MDPM were examined using ISO methods: SRPS ISO 937, 1992; SRPS

Table 1
Experimental design for extrusion experiments with coded and actual variable levels.

Sample	Process variables		
	X1 MDPM (%)	X2 BSG (%)	X3 Screw speed (rpm)
1	4 (−1)	10 (−1)	700 (0)
2	12 (+1)	10 (−1)	700 (0)
3	4 (−1)	30 (+1)	700 (0)
4	12 (+1)	30 (+1)	700 (0)
5	4 (−1)	20 (0)	500 (−1)
6	12 (+1)	20 (0)	500 (−1)
7	4 (−1)	20 (0)	900 (+1)
8	12 (+1)	20 (0)	900 (+1)
9	8 (0)	10 (−1)	500 (−1)
10	8 (0)	30 (+1)	500 (−1)
11	8 (0)	10 (−1)	900 (+1)
12	8 (0)	30 (+1)	900 (+1)
13	8 (0)	20 (0)	700 (0)
14	8 (0)	20 (0)	700 (0)
15	8 (0)	20 (0)	700 (0)

ISO 1444, 1998; SRPS ISO 1442, 1997; SRPS ISO 936, 1999, respectively. Carbohydrate content was calculated subtracting protein, fat, moisture and ash content of 100, following instructions given by Food and Agriculture Organization of the United Nations (Food and Agriculture Organisation of the United Nations (FAO), 2003).

2.5. Physical properties

The diameter and the length of the extrudates were measured using a calliper (MIB Messzeuge GmbH, Spangenberg, Germany). Lateral expansion (LE, %) was calculated using the Eq. 1, where d_e was diameter of extrudates and d_d was the diameter of die hole (4 mm). All measurements were repeated 10 times.

$$LE = \frac{d_e - d_d}{d_d} * 100\ (\%) \tag{1}$$

Bulk density (BD) of extruded snacks was determined in triplicates using bulk density tester (Tonindustrie, West und Goslar, Germany).

2.6. Textural properties

Textural properties (hardness, firmness and crispiness) were investigated using a TA.XT2 Texture Analyser (Texture Technologies Corp., Scarsdale, NY/Stable MicroSystems, Godalming UK) equipped with 250 kg load cell. Hardness and firmness of the extrudates were measured in 15 probes according to methods described in the work of Paula and Conti-Silva (2014), i.e. Compression test and Cut test using Warner-Bratzler V-shaped cutting blade, respectively. Following instructions of Oliveira, Schmiele, and Steel (2017), crispiness has been determined, using 5-blade Kramer shear cell. Measurements were done in 5 repetitions.

2.7. Scanning electron microscopy (SEM)

Extrudates were cut in the radial direction to 3–4 mm thick pieces and placed on SEM stub using double sided adhesive tape. The microstructure was examined with a scanning electron microscope (TM3030, Hitachi, Tokyo, Japan) implementing acceleration voltage of 5 kV. The different magnification was used depending on the lateral expansion of the extrudates.

2.8. Pasting properties

Modular Advanced Rheometer System-MARS (HAAKE™, Thermo Scientific™, Germany) equipped with measuring cup Z40 (43.4 mm diameter, 8 mm gap) and FL2B paddle-shaped rotor with 2 blades was used to determine the pasting properties of the investigated samples. The solvent trap Z40 DIN was used to prevent moisture evaporation during the measurement procedure. The examined samples were first ground into fine powder and mixed with 60 mL of distillate water in measuring cup Z40, thus 30% moisture (dry wt.) basis dispersions were achieved. Aqueous dispersion were equilibrated at 50 °C for 5 min, heated at the rate of 1.5 °C/min to 95 °C, held at 95 °C for 15 min, cooled to 50 °C at 1.5 °C/min and, lastly, held at 50 °C for 15 min. During the measurements a shear rate of 10 s-1 was applied, which corresponded to 95 rpm. The pasting properties were determined using plot of paste viscosity in Pas versus time. The obtained results included initial viscosity (IV), peak viscosity (PV), hot phase viscosity (HPV), trough viscosity (TV), breakdown viscosity (BDV) = PV- HPV, final viscosity (FV), setback (SBV) = FV-HPV and pasting temperature (PT) of the mixtures and extruded samples.

2.9. Color analysis

The color was analysed using the MINOLTA Chroma Meter CR-400 (Minolta Co., Ltd., Osaka Japan) applying D-65 lighting, a 2° standard observer angle and an 8-mm aperture in the measuring head. It was expressed by L* [black (0)/white (100)], a* [green($^{<}$0)/red($^{>}$0)] and b* [blue(($^{<}$0)/yellow($^{>}$0)] color parameters according to the CIELAB system of color measurement. The colorimeter was calibrated against a standard white tile before measurements. The samples were gridded to fine powder and each sample was analysed five times.

2.10. Data analysis and optimisation

In order to evaluate the effects of multiple input factors and their interactions on output variables, Response Surface Methodology (RSM) was used. A second-order polynomial regression model used in the response surface analysis was explained by Eq. 2,

$$Y = b_0 + \sum b_i X_i + \sum b_{ii} X_{ii}^2 + \sum \sum b_{ij} X_i X_j \tag{2}$$

where b_0 represents intercept (constant), b_i the linear, b_{ii} the quadratic and b_{ij} the interaction effect of the factors and Y represents response. 3-D response surface plots were generated from the developed models.

An analysis of variance (ANOVA) with 5% level of significance was performed. Tukey HSD (honest significant difference) test was used to calculate the differences between means using statistical package Statistica 14.0.0.15 (TIBCO Software Inc., USA).

The optimization was carried out in Design Expert 8.0.4 software (Stat-Ease, Inc., MN, USA) and aimed at finding the levels of independent variables MDPM content (4–12%), BSG share (10–30%) and screw speed (500–900 rpm) which would result in product with maximum expansion, length, crispiness, protein and fiber content, while maintaining minimum bulk density, hardness and firmness.

3. Results and discussion

3.1. Proximate analysis of extruded snack products

Protein, fat, fiber and ash contents of the extrudates were found in the range of 8.42–12.35%, 0.28–1.79%, 6.82–17.01% and 2.71–3.51%, respectively (Table 2). The highest protein, fat and ash content were determined in sample 4, which contained 12% of MDPM and 30% of BSG, while the sample 1 (4% MDPM and 10% BSG) had the lowest protein, fat and ash content. These results could be explained by composition of starting raw materials due to fact that the sample 4 contain the highest

Table 2

Proximate analysis of extruded snack products.

Run	Protein content (%)	Fat content (%)	Fiber content (%)	Ash content (%)
1	8.42 ± 0.76^{a}	0.28 ± 0.02^{a}	7.41 ± 1.01^{a}	2.71 ± 0.06^{a}
2	10.85 ± 0.03^{b,c,d,e}	0.73 ± 0.01^{b,h}	6.85 ± 0.56^{a}	2.98 ± 0.01^{b,e}
3	11.24 ± 0.40^{d,e}	1.05 ± 0.02^{c,d}	17.01 ± 0.95^{b}	3.57 ± 0.03^{c}
4	12.35 ± 0.03^{e}	1.79 ± 0.02^{e}	16.60 ± 0.55^{b}	3.85 ± 0.01^{d}
5	10.23 ± 0.89^{b,c,d}	0.68 ± 0.03^{b,f}	12.23 ± 1.78^{c}	3.13 ± 0.09^{e,f}
6	11.03 ± 0.72^{c,d,e}	1.23 ± 0.03^{d,g}	11.75 ± 1.81^{c}	3.31 ± 0.02^{f,g}
7	10.94 ± 0.88^{b,c,d}	0.89 ± 0.23^{c,h}	12.53 ± 1.01^{c}	3.15 ± 0.02^{e,f,g}
8	11.28 ± 1.46^{d,e}	1.25 ± 0.02^{g}	12.35 ± 0.77^{c}	3.33 ± 0.03^{g,h}
9	9.52 ± 0.06^{a,b,c}	0.50 ± 0.02^{f,i}	6.82 ± 0.59^{a}	2.86 ± 0.01^{a,b}
10	11.50 ± 0.05^{d,e}	1.41 ± 0.01^{g}	15.82 ± 0.93^{b,d}	3.51 ± 0.14^{c,h}
11	9.37 ± 0.04^{a,b}	0.44 ± 0.02^{a,i}	7.20 ± 0.88^{a}	2.88 ± 0.01^{a,b}
12	11.43 ± 0.20^{d,e}	1.28 ± 0.02^{g}	16.94 ± 0.64^{b}	3.51 ± 0.14^{c,h}
13	10.48 ± 0.18^{b,c,d}	0.98 ± 0.03^{c}	11.72 ± 0.20^{c}	3.22 ± 0.08^{f,g}
14	10.88 ± 0.72^{b,c,d,e}	0.91 ± 0.04^{h,c}	13.08 ± 0.54^{c,d}	3.23 ± 0.03^{f,g}
15	10.74 ± 0.72^{b,c,d,e}	1.06 ± 0.03^{c,d}	11.27 ± 0.63^{c}	3.22 ± 0.01^{f,g}

Values bearing the same letters within the same column are not significantly different from each other ($P < 0.05$).

and sample 1 the lowest amounts of MDPM and BSG. MDPM and BSG are higher in protein, fat and ash share than corn meal, hence with increase of these materials in starting formulation, protein, fat and ash content rose. The lowest fiber content had samples 2 and 9, while extrudate 3 had the highest, due to highest incorporation of BSG and corn meal, while sample 2 was composed of lowest amount of these two fiber-rich materials. Varying the BSG content (10, 20, 30%) significantly increased amount of fiber in extrudates, as expected since 100 g of BSG used in this research had 45.59 g of dietary fiber. On the other hand, increse of MDPM (0% fiber material) share from 4 to 12% non significantlly lowered fiber content, since it substituted corn meal that only contained 5.73% of fiber, and furthermore the share of MDPM was lower than BSG's. All extrudates had over 6% of fiber content, hence fulfilling requirement to be labelled as "high fiber"food product. Moreover, due to fat content lower that 3%, samples could also carry "low fat"nutrition claims (EC (No) 1924/2006, 2023).

Screw speed did not have statistically significant influence on nutritional composition of obtain extrudates. Content of protein, fat, fiber and ash increased with higher screw speed, however the enhacement was not notable.

3.2. Physical properties

According to P of F values (P of F < 0.05), as well as non-significant lack of fit, the predicted responses (lateral expansion, BD, length, hardness, firmness and crispiness), based on regression coefficients obtained by the second-order polynomial equation, were significant and valid (Table 3). The high values of of R^2, in range of 0.91 to 0.99, suggested well correlation between the BSG, MDPM and screw speed, and physical and textural properties of extrudates. Coefficients of variation of examined responses were <10, indicating a high precision and a good reliability of the experimental values. The significant coefficients in each polynomial model, with $P < 0.05$, are marked with an asterisk.

The relationships between LE, length and BD of extrudates, and the process variables are shown in the three-dimensional response surface plots in Fig. 1 (A, B, C, respectively). The produced expanded snacks presented a lateral expansion ranging from 104.50 to 223.00%, length 9.99 to 16.27 mm and BD from 71.2 to 225.57 g/L.

Table 3
Regression coefficient and analysis of variance for physical and textural properties of extruded snack products.

Coefficient	Lateral expansion	Bulk density	Length	Hardness	Firmness	Crispiness
Intercept	112.08*	106.59*	6.59*	13.71*	67.45*	169.42*
b_1	4.31	4.74*	0.11	−2.36E-004	2.25	−5.01*
b_2	−6.86*	9.12*	−0.34	0.23*	2.70*	−6.19*
b_3	0.40*	−0.17*	0.01*	−0.015*	−0.04*	−0.01*
b_{12}	−0.10	0.04	2.19E-004	4.75E-003	−4.54E-003	0.11
b_{13}	−1.41E-003	7.95E-003	−9.34E-004	4.82E-004	4.68E-003	2.19E-004
b_{23}	−1.05E-003	−1.68E-003	−4.36E-004	1.43E-004	8.00E-004	−3.99E-003*
b_{11}	−0.13	−0.53	0.03	0.03	−0.32	0.10
b_{22}	0.08	−0.09*	0.01*	−6.63E-003	−0.06*	0.14*
b_{33}	−2.33E-004*	−2.09E-005	8.23E-006	6.02E-007	−6.29E-005	9.81E-005
P of F (model)	< 0.01	< 0.01	0.03	0.03	< 0.01	< 0.01
Lack of fit	0.29	0.50	0.15	0.60	0.33	0.05
R^2	0.99	0.99	0.92	0.91	0.97	0.99
CV (%)	4.10	4.63	7.70	9.08	6.96	4.71

b1 - MDPM content; b2 - BSG content; b3 - Screw speed;
CV - coefficient of variance.
* Significance ($P < 0.05$).

MDPM had no, or poorly notable, influence on lateral expansion of extrudates. A possible explanation for such behaviour may lie in the fact that MDPM has 15.8% of protein, and its addition in amount of 4 to 12% contribute only with 0.63 to 1.9% of protein, probably causing insufficient amount of protein to influence LE of extrudates. It can be noticed that LE of extrudates was mostly affected by BSG share. Increase in BSG content resulted in a lower LE rates, regardless of the MDPM content and screw speed. Based on previously published results (Félix-Medina et al., 2020; Neder-Suárez et al., 2021), it was expected that change in a screw speed, especially with a pace of 200 rpm (500–700–900) would have higher impact on expansion. However, obtained results showed that escalation of screw speed from 500 to 900 rpm led to an increase of about 20% in LE, at different MDPM and BSG levels.

Having in mind that speed of knife at the end of extruder was constant, length of extrudates could be observed as a measurement of longitudinal expansion. Increase in screw speed induced linear rise of their length, especially in samples with low MDPM and BSG shares. Increase of BSG from 10 to around 25% caused the drop of extrudates length, while further BSG addition had opposite impact, i.e. lead to increase in snacks' length. Increase of MDPM share show low influence on length of extrudates.

BD represents mass of extrudates in a given volume, hence more expanded products will have less magnitude of BD, meaning that bulk density and expansion are reciprocal parameters (Lisiecka, Wójtowicz, Mitrus, Oniszczuk, & Combrzyński, 2021; Menis-Henrique, Janzantti, Monteiro, & Conti-Silva, 2020). This observation is confirmed comparing LE and BD response surface plots, presented in Fig. 1. MDPM addition had slightly positive effect on BD, what was expected based on its influence on lateral and longitudinal expansion of snacks. BD also increased with increase of BSG share, what was in agreement with results presented by Ainsworth et al. (2007). Obtained results could be explained by chemical composition of BSG, since significant amount of proteins and fibers diminished expansion and increased BD, which was in accordance with earlier published results (Basilio-Atencio et al., 2020; Téllez-Morales et al., 2020). High dietary fiber and protein content affects the starch gelatinization, since, during the extrusion, dietary fiber and the globulins may bind water more tightly than the starch. Hence, loss of water at the die of extruder is disrupted, resulting in reduced extrudates expansion and increased bulk density (Chadha, Young, Otter, & Kam, 2021). Screw speed had negative effect on BD, similar to results published by Sandrin, Caon, Zibetti, and Francisco (2018), regardless MDPM and BSG content.

3.3. Textural properties

The impact of the process variables on textural properties (hardness, firmness and crispiness) is shown in the Fig. 2 (A, B, C, respectively). The values of hardness and firmness ranged from 5.82 to 10.76 kg and from 38.28 to 78.24 N, respectively, and it can be noticed that these two responses shown similar behaviour, within the examined range of input variables. However, it was important to investigate both parameters since hardness usually refers to force applied by molar teeth in order to break food and firmness refers to force applied by incisors (Paula & Conti-Silva, 2014). Considering both responses, the influence of MDPM is less pronounced, compared with the influence of BSG and screw speed. Having in mind that MDPM contain 0% of starch and 15.8% of protein it could be expected that its addition increases hardness and firmness. However, observed increase in hardness and firmness was not significant, probably due to small share of MDPM in mixtures. When BSG share was kept at constant level (20%), hardness and firmness showed opposite trend with MDPM change, at low (500 rpm) and high (900 rpm) screw speed. At low screw speed, increase of MDPM share caused decrease of hardness and firmness, which could be possibly explained by higher content of lipids that reduce breaking force of extrudate (Desrumaux, Bouvier, & Burri, 1999). Nevertheless,

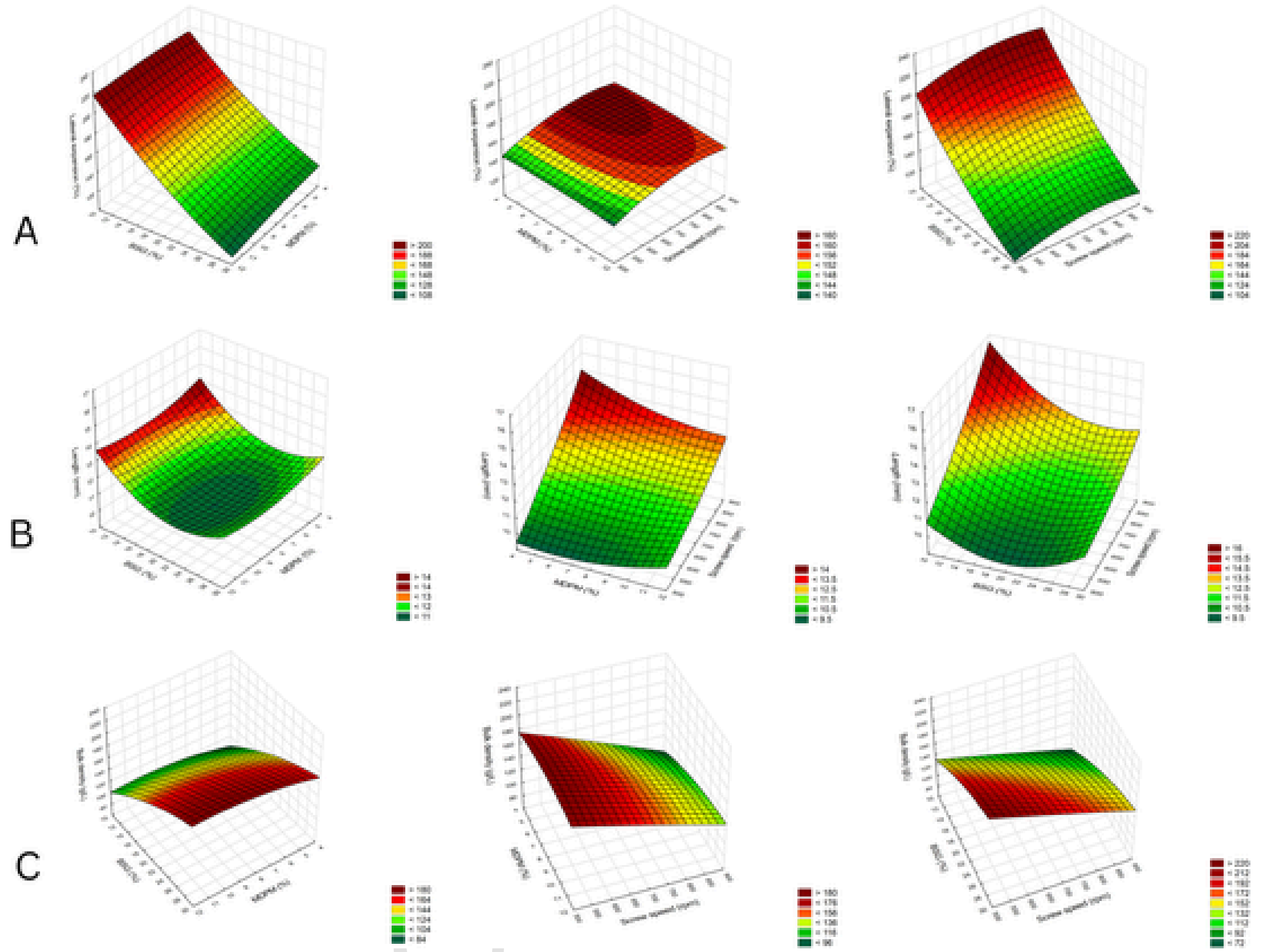

Fig. 1. Response surface plots for the effect of MDPM, BSG and screw speed on the expansion index(A), length (B) and bulk density(C).

at high screw speed expected increases of these two textural parameters were noticed. Other two independent variables (BSG and screw speed) had significant influence on hardness and firmness. Increase of BSG share promoted hardness and firmness. BSG is a fiber- and protein-rich material, thus its inclusion results in less expanded and more compact structure, leading to higher hardness values (Ačkar et al., 2018). According to results shown in Fig. 2A and B, the maximum values of hardness and firmness could be observed at 25% content of BSG approximately, following with slight decrease of hardness and firmness at higher values of BSG. These results are in direct correlation with length of extrudates which showed same trend. It could be explained by weakening of internal structure, due to rupture of cell walls caused by very high fiber content and formation of cells with damaged walls (Ferreira, 2011). Meanwhile, hardness and firmness were negatively influenced by screw speed, that was similar to results published by Stojceska, Ainsworth, Plunkett, and Ibanoğlu (2008) and Félix-Medina et al. (2020). The screw speed had more pronounced influence on both mentioned responses at low MDPM level comparing to addition of maximum value of MDPM in prepared mixtures.

The crispiness of obtained extrudates varied between 64.25 and 135.1. Response surface plots of crispiness were opposite to hardness' and firmness' ones. MDPM and screw speed at the high BSG content (30%) did not show any effect on crispiness of snacks, while at lower BSG content increase in MDPM share resulted in less crispy product, and increase in screw speed caused crispier product. These results could probably be explained by more pronounced influence of BSG share on crispiness, than the other two variables. Incorporation of BSG had negative effect on crispiness of extrudatess, esspecially noticeable at low MDPM levels and high screw speeds, which confirms suggestion that fibers and proteins often lead to less crispy products (Lobato, Anibal, Lazaretti, & Grossmann, 2011; Sharif, Rizvi, & Paraman, 2014). Furthermore, addition of BSG caused a decrease of starch content in the mixtures. Since the starch is material most responsible for snack puffing (Oliveira et al., 2017), less starch content in the mixtures results in higher hardness and lower crispiness (Ačkar et al., 2018). Crispiness of products containing 10% of BSG, was more influenced by screw speed elevation, comparing to influence of MDPM.

3.4. *Microscopic structure*

Scanning electron microscopy (SEM) was used to determine the internal cellular structures of the expanded extruded snacks. SEM images of some snacks produced, at different production conditions (mixture composition – MDPM, BSG contents and screw speeds), are shown in Fig. 3. Fig. 3 displays SEM images of five extruded samples' cross section, that differs by MDPM content (a and b), screw speed (c and d) and BSG share (d and e). More dense structure with smaller cells is the evidence of less product expansion and it is directly correlated with textural characteristics of the product. Fig. 3e reviles the least dense structure with the largest cells of extrudate, produced at the highest screw

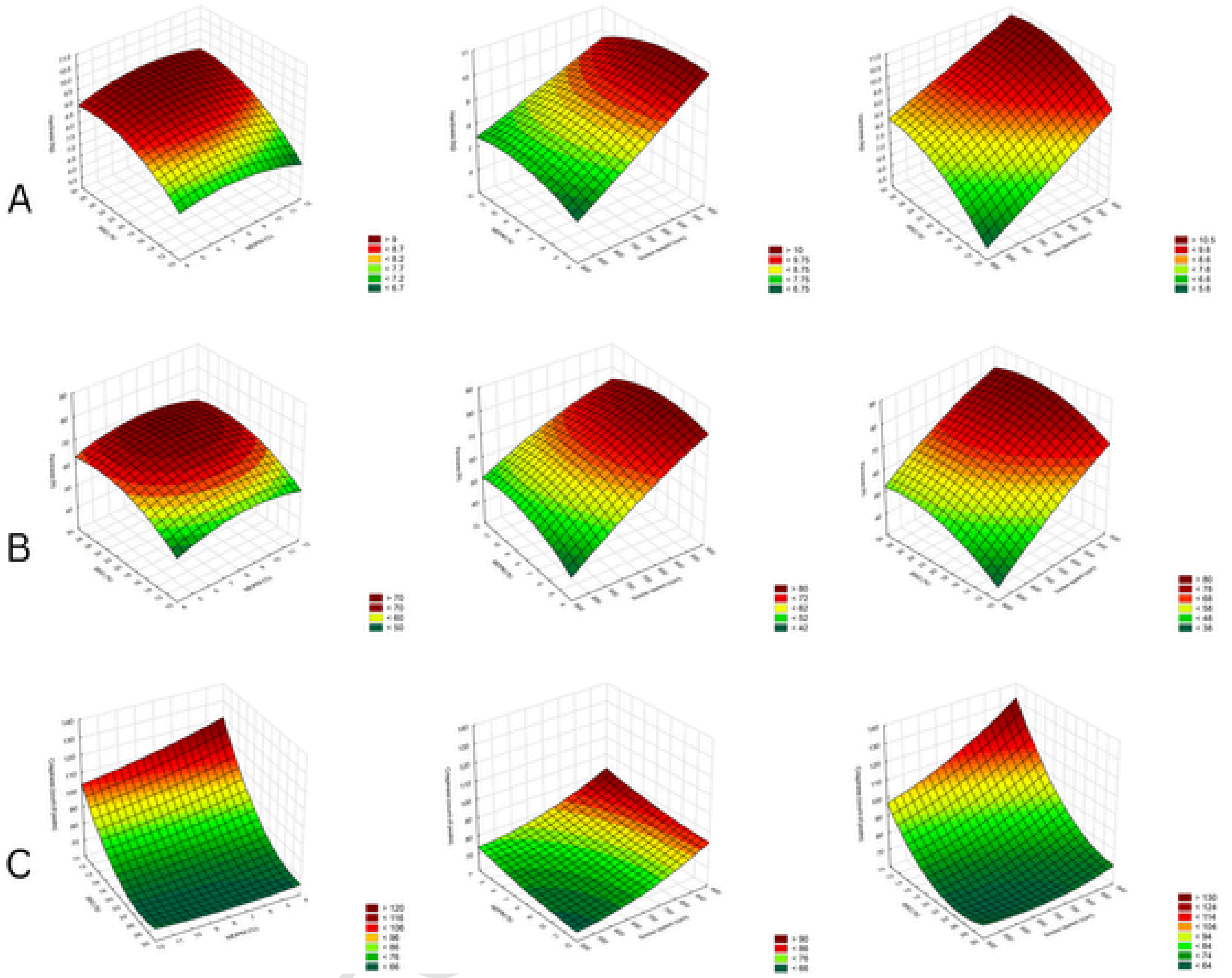

Fig. 2. Response surface plots for the effect of MDPM, BSG and screw speed on the hardness (A), firmness (B), crispiness (C).

speed and containing the lowest BSG content, which is in accordance with our previous results of physical and textural properties. Han, Tra Tran, Man Le, & V., 2018 reported that fibers, which content is high in BSG, cause reduction of cell size and increase the frequency of incomplete holes formed. Moreover, increase of BSG content provides increase of protein content in mixture, and this is associated with smaller and non-homogeneous cell size formations. Proteins assimilate part of the moisture content on the extrusion process, thus reduce starch hydration as well as gelatinization (Sumargo, Gulati, Weier, Clarke, & Rose, 2016). Compactness of extrudate decreases with the increase of screw speed, due to higher expansion. Therefore, the structure of extudate became softer and crispier. Furthermore, it can be seen that between the figures with highest and lowest MDPM share (Fig. 3 a and b) there is almost no difference in internal structure confirming results obtained by response surface plots that MDPM had no or slight impact on physical and structural characteristics of expanded snack products.

3.5. *Pasting properties*

The pasting properties are an important indicator of how different processing conditions will influence starch. Pasting properties of prepared starting mixtures are presented in Table 4. Obtained pasting curves of formulations followed the pattern of the conventional starch pasting curve (Fig. 4). Initial viscosity was not significantly different between mixtures. However, addition of MDPM and BSG significantly decreased values of PV, while incorporation of BSG significantly reduced also other pasting features (HFV, FV, hence BDV and SBV). The reduction could be attributed to starch depletion in the mixtures, since the higher share of starch mean higher pasting properties (Bhat, Wani, Hamdani, & Gani, 2019). Furthermore, it has been reported that pasting properties decrease with addition of insoluble fiber to mixture (Yadav, Rajan, Sharma, & Bawa, 2010). Hence, beside starch dilution, incorporation of BSG as a insoluble fiber-rich material has more prominent effect on pasting features than addition MDPM. PV values were higher than IV confirming presence of non-gelatinized starch in the mixtures. Viscosity of mixture increased with temperature due to cooking and gelatinization process.

The pasting temperature is the temperature at the beginning of gelatinization, i.e. the temperature when the viscosity starts to rise (Al-Attar, Ahmed, & Thomas, 2022). This parameter did not significantly differ between samples. At the end of heating phase there is a decline of viscosity reaching value of HPV indicating more stable pasta. Starting the cooling cycle the viscosity begins to increase as a consequence of starch retrogradation, a process in which disaggregated amylose and amylopectin chains in a gelatinized starch paste reassociate to form more ordered structures (Sandrin et al., 2018). At the end of cooling

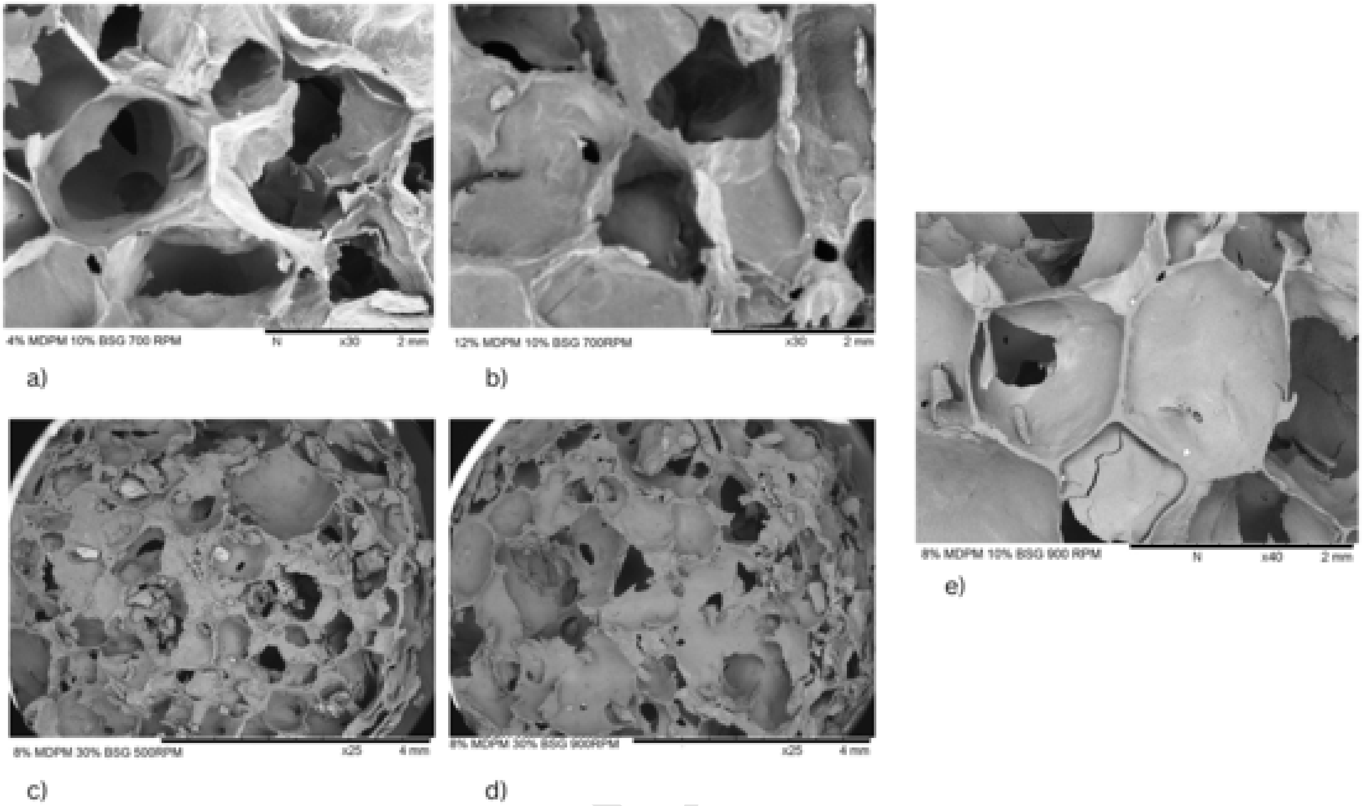

Fig. 3. Scanning electron microscopy images of samples.

Table 4
Pasting/Rheological properties of prepared mixtures.

Mixtures	IV (Pa*s)	PV (Pa*s)	PT (°C)	HPV (Pa*s)	BDV = PV- HPV (Pa*s)	FV (Pa*s)	SBV = FV-HPV (Pa*s)
4% MDPM - 10% BSG	0.09 ± 0.02^{a,b}	28.54 ± 0.77^{a}	76.61 ± 0.06^{a,b,d}	12.79 ± 0.52^{a}	15.75 ± 0.43^{a}	37.33 ± 0.65^{a}	22.69 ± 1.21^{a}
12%MDPM - 10% BSG	0.14 ± 0.04^{b}	23.13 ± 0.32^{b}	76.85 ± 0.05^{a,b,c}	10.45 ± 0.16^{b}	12.68 ± 0.43^{b}	35.48 ± 0.68^{b}	26.87 ± 0.50^{b}
4% MDPM - 30% BSG	0.08 ± 0.06^{a,b}	17.64 ± 0.39^{c}	76.71 ± 0.08^{a,b,d}	7.97 ± 0.31^{c,d,e}	9.67 ± 0.50^{c,d}	26.99 ± 0.23^{c}	19.02 ± 0.28^{c,f}
12% MDPM - 30% BSG	0.06 ± 0.01^{a,b}	14.24 ± 0.26^{d}	76.94 ± 0.06^{a,b,c}	7.03 ± 0.22^{d}	7.21 ± 0.09^{e}	22.49 ± 0.41^{d}	15.46 ± 0.56^{d}
4% MDPM - 20% BSG	0.05 ± 0.01^{a}	22.71 ± 0.69^{b}	76.51 ± 0.17^{a,d}	8.63 ± 0.25^{c,f}	14.08 ± 0.89^{b,f}	30.29 ± 0.17^{e}	21.66 ± 0.14^{b,e}
12% MDPM - 20% BSG	0.07 ± 0.01^{a,b}	17.70 ± 0.57^{c}	76.81 ± 0.08^{a,b,c}	8.37 ± 0.31^{c,e}	9.33 ± 0.56^{c}	31.29 ± 0.69^{e}	22.92 ± 0.61^{c}
8% MDPM - 10% BSG	0.05 ± 0.02^{a}	25.59 ± 1.29^{e}	76.33 ± 0.36^{d}	10.64 ± 0.80^{b}	14.94 ± 0.68^{a,f}	35.67 ± 0.45^{b}	25.03 ± 0.38^{a,e}
8% MDPM - 30% BSG	0.12 ± 0.01^{a,b}	15.04 ± 0.04^{d}	76.55 ± 0.09^{a,d}	7.53 ± 0.14^{d,e}	7.51 ± 0.10^{e}	24.99 ± 0.44^{f}	17.46 ± 0.30^{d}
8% MDPM - 20% BSG 1. mixture	0.07 ± 0.01^{a,b}	19.01 ± 0.20^{c,f}	77.20 ± 0.05^{c}	9.63 ± 0.16^{b,f,g}	9.38 ± 0.10^{c}	32.60 ± 0.14^{g}	22.97 ± 0.03^{c}
8% MDPM - 20% BSG 2. mixture	0.14 ± 0.03^{b}	19.40 ± 0.71^{c,f}	76.94 ± 0.13^{a,b,c}	9.85 ± 0.33^{b,g}	9.56 ± 0.41^{c,d}	32.69 ± 0.03^{g}	22.84 ± 0.36^{c,f}
8% MDPM - 20% BSG 3. mixture	0.06 ± 0.00^{a}	19.73 ± 0.93^{f}	76.99 ± 0.18^{b,c}	8.84 ± 0.25^{c,f,g}	10.89 ± 0.68^{d}	28.74 ± 0.40^{h}	19.90 ± 0.23^{f}

Values bearing the same letters within the same column are not significantly different from each other ($P < 0.05$).

phase, final viscosity (FV) of all mixtures (24.99–37.33 Pas) was higher than PV (14.24–28.54 Pas), indicating the ability of the material to form a viscous paste. Higher FV means higher competence of gelatinized starch to reassociate (Clerici & El-Dash, 2008).

All extruded samples did not show the viscosity peak, rather the viscosity line showed trend of polynomial quadratic function. Raw starch pasting curves have low IV values, followed by high values of PV caused by swelling of granules of raw starch, and a relatively higher FV. The Fig. 4 display viscosity in time during set temperature regime of sample containing 4% MDPM and 10% BSG, extruded at 700 rpm. These results demonstrate that starch has been gelatinized during extrusion, since pasting plot of gelatinized starch are distinctive by lack of peak viscosity, viscosity declines between 50 and 95 °C and accelerating increase during cooling phase (da G C Do Nascimento, Carvalho, Takeiti, Freitas, & Ascheri, 2012). Another indicator of starch gelatinization in extruded samples are higher values of initial viscosity (IV) which were in range of 5.71–12.75 Pas, while IV of starting mixtures was from 0.05 to 0.14 Pas; consistent with the data reported by (Sandrin et al., 2018), confirming that starch has been gelatinized during the extrusion and hence it absorb water faster that untreated mixtures. FV of starting formulations (24.99–37.33 Pas) were higher than FV of extruded samples (3.38–6.23 Pas), demonstrating less degree of retrogradation in the extruded samples, due to mechanical and thermal damage of starch molecules.

3.6. Color analysis

Color is important parameters of snack quality and has high influence on possible purchase of it (Saldanha do Carmo et al., 2019). The results of extrudates' color parameters are presented in Table 5. The lightness (L^*) of samples was in the range of 59.68 ± 0.96–70.84 ± 0.91, and significantly decreased with increase of BSG share. BSG is brownish in color, hence it was expected that its addition will result in darker sample, confirming previously published results (Ačkar et al., 2018; Delić et al., 2020; Nocente, Taddei, Galassi, & Gazza, 2019;). The significant difference in lightness among samples

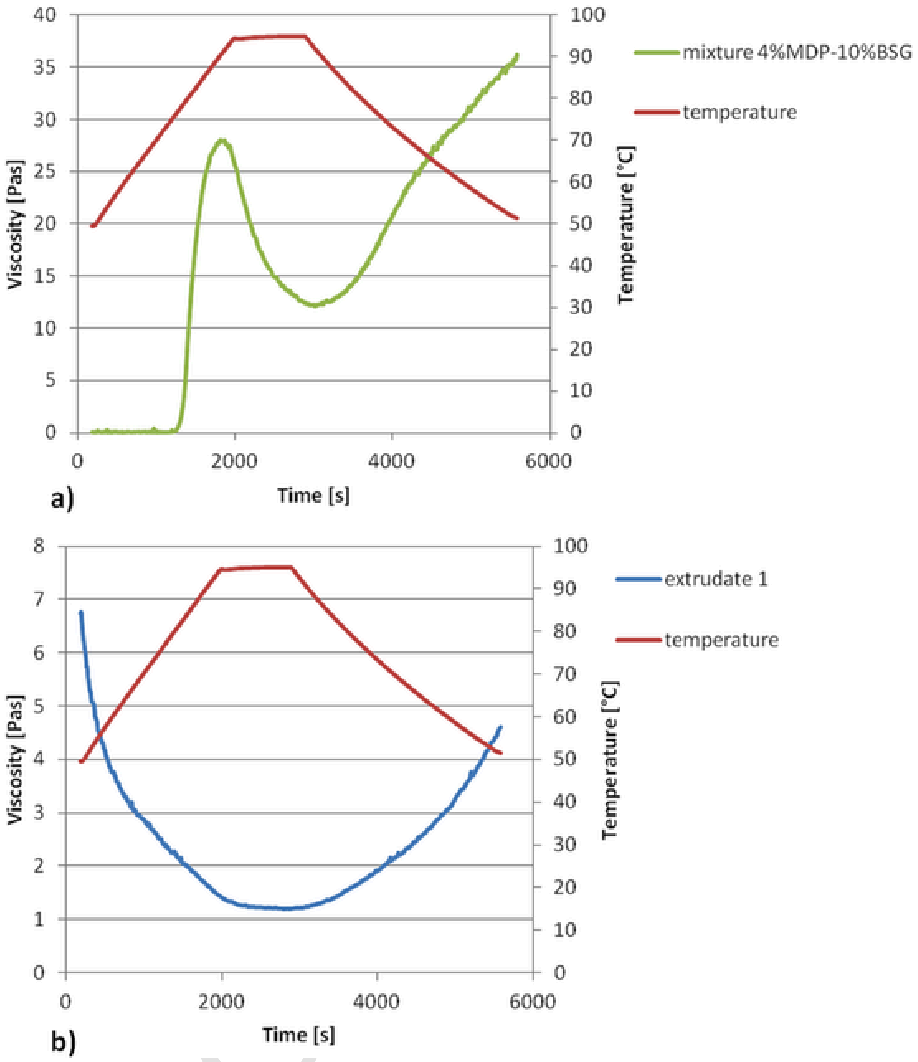

Fig. 4. Comparative viscosity profiles of unextruded mixture (a) and extrudate (b).

Table 5
Color parameters of samples.

Sample/Run	L^*	a^*	b^*
1	70.84 ± 0.91 ^{a}	1.63 ± 0.10 ^{a}	29.73 ± 0.55 ^{a}
2	70.33 ± 0.26 ^{a,b}	2.16 ± 0.13 ^{b}	28.86 ± 0.39 ^{b}
3	62.21 ± 0.52 ^{c}	4.92 ± 0.11 ^{c}	24.68 ± 0.26 ^{c,e}
4	60.36 ± 0.53 ^{d}	5.41 ± 0.12 ^{d}	23.91 ± 0.08 ^{d}
5	65.23 ± 0.61 ^{g}	3.82 ± 0.14 ^{i}	25.80 ± 0.30 ^{f,g,h}
6	62.26 ± 0.44 ^{c}	4.49 ± 0.12 ^{g}	25.44 ± 0.34 ^{f,h}
7	67.98 ± 0.30 ^{e}	3.49 ± 0.13 ^{h}	26.12 ± 0.26 ^{g}
8	64.40 ± 0.79 ^{f,g}	4.38 ± 0.15 ^{f,g}	25.25 ± 0.20 ^{e,h}
9	69.95 ± 0.36 ^{a,b}	2.09 ± 0.14 ^{b}	29.40 ± 0.46 ^{a,b}
10	60.17 ± 0.41 ^{d}	5.25 ± 0.05 ^{d}	24.18 ± 0.20 ^{c,d}
11	69.55 ± 0.62 ^{b}	1.95 ± 0.17 ^{b}	29.19 ± 0.29 ^{a,b}
12	59.68 ± 0.96 ^{d}	5.40 ± 0.05 ^{d}	24.41 ± 0.22 ^{c,d}
13	65.39 ± 0.57 ^{g}	3.98 ± 0.16 ^{e,i}	25.46 ± 0.26 ^{f,g,h}
14	64.99 ± 0.62 ^{g}	4.00 ± 0.20 ^{e,i}	25.44 ± 0.34 ^{f,g,h}
15	63.44 ± 0.26 ^{c,f}	4.18 ± 0.21 ^{e,f}	26.10 ± 0.16 ^{f,g}

Values bearing the same letters within the same column are not significantly different from each other ($P < 0.05$).

with different MDPM ration was evident in some samples; however it was less eminent than influence of BSG. Increase of screw speed led to significantly lighter samples between 6 and 8 and 5–7 extrudates, while the significant differences in lightness between 9 and 11 and 10–12 samples were not remarked. Higher values of screw speed results in smaller particles causing increase of specific surface area that permits more reflection of light (Hejna et al., 2021). Redness (a^*) and yellowness (b^*) of samples significantly altered with composition change, while screw speed did not show significant influence on these parameters. The a^* value of extrudates was in the range of 1.63–5.41, whereas the span of b^* value was 23.91–29.73. Increase of BSG and MDPM caused increase of samples' redness and decrease of yellowness, what was in accordance with results published by Ačkar et al., 2018; Delić et al., 2020; Lee et al., 2003; Nocente et al., 2019. Replacement of cornmeal with BSG and MDPM resulted in less yellow color, since corn contains carotenoids that confer yellow color to corn-based products (Oliveira & Rodriguez-Amaya, 2007). The lightest and yellowiest, and the least red extrudate, was sample 1, which contained the highest share of cornmeal.

3.7. Optimization

In order to optimize the mixture and screw speed for extrusion process by numerical optimization, importance coefficient was assigned to each of dependent parameter, based on preferred characteristics of optimal sample. Length, hardness, firmness and fiber content carried coefficient of importance of 3, expansion and bulk density 4, while 5 was designated to crispiness and protein content. Regarding the criteria used for the independent variables, the criteria “is in range” was used and importance of 3 for each parameter. The optimal mixture was containing 4% MDPM and 14.8% BSG extruded at 900 rpm, with predicted values of length (16.23 mm), expansion (187.02%), bulk density (71.20 g/L), hardness (5.92 kg), firmness (34.40 N), crispiness (114.24 peak counts), protein content (9.69%), fiber content (10.01%) having desirability value of 0.661. Experimental values of the optimized snack were: length (16.12 mm), expansion (187.00%), bulk density (86.44 g/L), hardness (6.5 kg), firmness (40.52 N), crispiness (112.2 peak counts), protein content (9.17%), fiber content (9.09%). The experimental values were exhibited to be in close conformity the predicted values.

4. Conclusion

In the present research influence of MDPM addition, BSG share and screw speed on nutritional, physical, textural, pasting and color properties of corn extrudates has been examined. Screw speed had no significant effect on chemical composition of extrudates. It has been shown that MDPM had no significant effect on either textural or physical parameters, what was further confirmed by extrudates' cross sections SEM images. Increase of screw speed had improved physical and textural characteristics of extruded samples. However, the most pronounce effect on nutritional, physical, textural, pasting and color properties of snack products had BSG. Addition of BSG caused decrease of lateral expansion and increase of BD, as a direct consequence of nutritional improvement (higher protein and fiber share) of obtained snack products. Furthermore, BSG incorporation significantly decreased lightness of extrudates. The viscosity analysis showed that in all extrudates starch was gelatinized.

Incorporation of BSG and MDPM into corn-base extruded snack products has a purpose to create nutritionally valuable product desirable to children and adults, which could contribute to promotion and facilitation of nutrient-dense and health-promoting diets. Optimum extrusion at 900 rpm of optimal mixture containing 4% MDPM and 14.8% BSG having desirability value of 0.661 could be utilized for developing of desirable functional snack product. Consumption of healthy food that promotes health and reduces risk of disease can decrease medical cost, thus it has also a socio-economic perspective.

Author statment

Conceived and designed experiments: J. Delić, P. Ikonić, M. Jokanović, B. Ikonić and T. Peulić. Performed extrusion process: V. Banjac, S. Vidosavljević, V. Stojkov, J. Delić and T. Peulić,. Performed analysis of physical, chemical, textural, rheological and color properties: J. Delić, M. Hadnađev and V. Stojkov. Preformed statistical analysis and interpretation of results: J. Delić, B. Ikonić. Wrote the manuscript: J. Delić, P. Ikonić, M. Jokanović, B. Ikonić, V. Banjac, M. Hadnađev.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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