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Effect of Coating on Physico-Chemical Characteristics of Puffed Wheat Grains

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Abstract. Durum wheat (*Triticum turgidum*) is used for the production of various ready-to-eat products such as breakfast cereals, puffed grains, and extruded products. Technological processes of grain processing and the addition of different ingredients cause changes in the physical and chemical properties of the product, which give puffed grains a unique porous structure and change their nutritional value. This study aimed to evaluate the effect of coating on the physico-chemical characteristics of puffed wheat grains depending on the coating material. The study revealed that the application of coating increased dry matter and thousand-kernel weight (TKW). Water activity decreased in puffed grain without coating (BZ), and puffed grain with whey powder (MC) compared to wheat grain. The reduction in the moisture content increased the crispiness of product. Application of coating led to a decrease in the hardness of both MC and puffed wheat grain with vanillin and sugar (BV). Applying additives to the product's surface led to a decrease in the water absorption index (WAI). The water solubility index (WSI) increased in the MC and BV samples. Samples BZ, BV and MC had higher L* (lightness) values than wheat grains because the puffing process expanded the cells, confirmed by scanning electron microscopy, and caused starch gelatinisation. The a* (redness) value of wheat was greater than that of BZ, BV and MC, which may be due to the partial removal of the outer layer of wheat grains. The milled samples of BZ, BV and MC were slightly darker, having lower L* values, compared to unprocessed wheat grain.
Key words: wheat, texture, microstructure, colour, water absorption index, water solubility index.

Introduction

Durum wheat (*Triticum turgidum*) is a staple food in the human diet. Wheat grains are rich in carbohydrates, proteins, vitamins, dietary fibre and minerals. Wheat is widely used in the production of bread, bakery and pasta. Durum wheat is also often used as the raw material for making ready-to-eat products. These products include breakfast cereals, puffed grains, and extruded products. Puffed grains are obtained from grains of corn, rice, wheat, etc. When puffed, together with heating, the pressure in the apparatus increases above atmospheric pressure, and after reaching such pressure, the pressure vessel is depressurised by opening the lid of the vessel, which causes expansion of the grains (Köprüalan *et al.*, 2021).

In the process of obtaining puffed grains, complex physical and chemical processes occur – proteins absorb moisture, swell and denature; starch grains absorb moisture, swell and gelatinise. Under the action of high temperature, amino acids and sugars undergo the Maillard reaction (van Hecke, Allaf, & Bouvier, 1998). These complex reactions give puffed products a unique porous structure, a pleasant mouthfeel, and alter functional properties of the grain (Li, Masatcioglu, & Koksel, 2019).

Unfortunately, such products have low nutritional value with a low content of biologically active compounds. There are various ways to enrich products. One way is to include ingredients possessing high nutritional value in the snack recipes. Such additives as basil, moringa, marjoram, thyme, mint, watercress, amaranth, fenugreek and defatted coconut flour have been used in cereal products (Vishwakarma *et al.*, 2022). For the enrichment of cereal product nutritional value, barberry fruits (Bakmohamadpo *et al.*, 2021),

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sesame seeds (Hashempour-Baltork *et al.*, 2018), whey protein (Fernandes *et al.*, 2016) and pumpkin (Promsakha na Sakon Nakhon *et al.*, 2018) have been included in product recipes. Among many flavourings, vanilla is considered the most popular and frequently used in the food industry. It is used to improve the taste and aroma of cakes, sweets, drinks, etc. (Ben Khemis *et al.*, 2023). Alcaire *et al.* (2017) have proven that vanilla aroma increases the intensity of the sweet taste of sugar several times, which makes it possible to reduce the sugar concentration in the product (Ben Khemis et al., 2023). In cheese production, about 80% of the volume of milk is discarded as whey and disposal of raw whey is a serious environmental pollution problem due to the high content of organic matter in its composition (Zandona, Blažić, & Režek Jambrak, 2021). Whey has a high nutritional value and biological activity (Panghal *et al*., 2018), therefore it may be used in new products.

The aim of this study was to evaluate the effect of coating on the physico-chemical characteristics of puffed wheat grains depending on the coating material.

Materials and Methods

Materials

Durum wheat (*Triticum turgidum*) grains, cleaned of impurities and scales, sunflower oil, powdered sugar, vanillin and whey powder were purchased from the Kyrgyz market.

Puffing

Durum wheat grain was cleaned of impurities, moistened with warm water (35–40 °C) to a moisture content of 14–14.5% and kept at this temperature for 14–16 h. Then, the grains were loaded into a preheated puffing gun B-35M (China) and the lid was closed hermetically. They were then heated for 15 min, raising the pressure in the apparatus to 1.0–1.2 MPa. The temperature in the device rose to 220–240 °C. When the lid is opened, grains expand due to the pressure difference inside the grain and the surrounding atmosphere.

Puffed wheat grains without coating (BZ) served as the raw material for the development of breakfast cereals – puffed wheat with vanillin and sugar (BV) and puffed wheat with whey powder (MC). To obtain BV, powdered sugar, sunflower oil and vanillin were used as coating materials; for MC, powdered sugar, sunflower oil, vanillin and whey powder were added (Konkubaeva, 2016). Refined and deodorised sunflower oil, finely ground white sugar with a mass fraction of moisture 0.2%, colourless vanillin crystals with a characteristic vanilla aroma and a moisture content of 1.0%, fine whey powder with a specific sweet taste and smell of whey were used. Whey powder may have colour from white to yellow. Mass fraction of moisture in whey powder was 2.7%. Mixing of the components was carried out in a drum mixer (China) for 4–5 minutes. The resulting products were packaged in the sealed pouches of metallised polypropylene (metPP), 30 g each. Samples were stored at ambient temperature (20 ± 2 °C) with relative air humidity not more than 70% until analysis within one week from production.

Dry matter

Dry matter (DM; n = 3) on raw and puffed grains was determined immediately after sample grinding, following the standard method 44-15A (AACC 44-15A, 2000).

Thousand kernel weight

The thousand kernel weight (TKW) was determined by weighting one thousand undamaged raw or puffed grains on the analytical balance Pioneer PX5202 (OHAUS Corporation, Switzerland). The results (n = 3) was expressed in grams.

Water activity

Water activity (a_w) of the samples was determined using a LabMaster-aw neo water activity meter (Novasina AG, Switzerland) at ambient temperature (21 ± 1 ºC). All experiments were carried out in triplicate.

Texture analysis

Texture analysis was carried out using TA.HD. Plus texture analyser (Stable Microsystems Ltd., UK) equipped with a cylindrical probe, with a diameter of 4.5 cm and a back-extrusion cell with an inner diameter and height of 5.0 and 7.0 cm, respectively. The cell was filled with 100 mL of puffed product and the sample was compressed to 50% of original height, as described by Smith and Hardacre (2011). The test was conducted at the following conditions: 1.0 mm s^{-1} pre-test speed; 5 mm s^{-1} test speed; 0.049 N trigger force; 1 kN load cell. Hardness value was considered as the maximum compression force and expressed in newtons (N). Crispiness was the number of positive peaks in the force versus time graph. A greater number of positive peaks indicated a greater number of fracture events, thus, a crisper puffed grain (Luo *et al.,* 2020). Data acquisition was performed using the Texture Exponent 32 software (Stable Microsystems Ltd., UK). Three replications for each sample were carried out.

Water absorption index (WAI) and water solubility index (WSI)

Ground sample (2.5 g) was suspended in 25 mL of water at ambient temperature (20 ± 2 °C) for 30 min, with intermediate shaking, and then centrifuged in a CM-6MT centrifuge (ELMI Ltd., Latvia) at 1660 × g for 15 min. The supernatant was poured into an evaporating dish of a known weight. The WSI is the weight of dry solids in the supernatant, whereas WAI

$$WAI = \frac{weight\ of\ sediment}{sample\ dry\ weight} \quad (1)$$

$$WSI = \left(\frac{weight\ of\ dry\ dish - weight\ of\ empty\ dish}{sample\ dry\ weight}\right) \times 10 \times 100 \quad (2)$$

$$\Delta E = \sqrt{(L^* - {L_0}^*)^2 + (a^* - {a_0}^*)^2 + (b^* - {b_0}^*)^2}, \quad (3)$$

where the subscript 0 indicates the initial colour values of wheat grain and ground wheat (ΔE_{wheat}) or puffed wheat without coating (ΔE_{BZ}) (Bajaj & Singhal, 2019).

is the weight of the sediment obtained after removal of the supernatant per unit weight of original dry solids.

Water absorption index (WAI) and water solubility index (WSI) of puffed wheat were calculated using equations 1–2, as per the method described by Janve & Singhal (2018)viz. calcium carbonate, calcium lysinate and tricalcium phosphate, at equivalent calcium concentration. The physiochemical properties, organoleptic acceptability and calcium bioaccessibility were studied for puffed rice extrudates before and after frying, and for noodles before and after cooking. Calcium fortification decreased the bulk density (from 0.224 to 0.126 g/cm3.

Colour

The colour of wheat and puffed wheat was measured using a ColorFlex EZ spectrophotometer (Hunter Lab., USA) in CIE L*a*b* coordinates. The colour components L* (luminosity), a* (red-green), b* (yellow-blue) were recorded to evaluate the impact of wheat grain processing and applied coating materials on grain colour. The measuring head was equipped with a 50 mm diameter viewing port and used the system of diffuse illumination with 10º viewing geometry, the illuminant was D65. The colorimeter was calibrated against a standard white title. For each sample, ten measurements were taken and averaged. The total colour change (ΔE) was calculated according to equation 3.

Microstructure evaluation by scanning electron microscope (SEM)

The micrographs of raw wheat, puffed grains and puffed grains with coating were taken using a Mira3 scanning electron microscope (SEM) by Tescan Orsay Holding, a.s. (Brno, Czech Republic). First, the test specimens were cut in the axial direction into two equal pieces using a blade for morphological analysis. Afterwards, the test specimens were mounted onto SEM pin stubs using double-sided adhesive carbon discs, and non-fixed material was blown by a gentle stream of N_2 and coated with a gold-palladium (80/20, respectively) 9 nm thick layer using a high vacuum spotter coater Leica EM ACE600 (Leica Microsystems, Wien, Austria). The raw wheat, puffed grains and puffed grains with coating were completed at three regions of the whole grain, cross-section and surface. The conditions were adjusted to operate under high vacuum mode utilising the Secondary Electron (SE) detector. The morphology of grains was analysed by increasing magnification up to 500× for precise dimension measurement operating at 8 kV acceleration voltage.

Statistical analysis

The experimental data of the wheat and puffed products were subjected to t-test by Microsoft Excel 2016 software. Significance of the differences among the values of all parameters were determined at $p \leq 0.05$.

Results and Discussion

The physical characteristics of raw wheat grains, puffed wheat grains, puffed wheat grains with vanillin and sugar, and puffed wheat grains with whey powder are presented in Table 1. The dry matter content of the puffed grains is higher compared to the raw grains (on average, dry matter increased from 90.9 ± 0.1 to 94.1 ± 0.2 g 100 g^{-1}). The application of coating resulted in an increase of dry matter compared to BZ (MV, 96.8 ± 0.1 and MC, 96.9 ± 0.1).

TKW of wheat grains is greater than TKW of BZ, as during the processing wheat grains underwent a partial loss of cell walls and moisture, the cells stretched and became bigger. This was observed because upon reaching the specified pressure in the puffing gun, the lid of the apparatus opens, the pressure in the chamber instantly drops, but high pressure remains in the grain. Due to the created pressure difference inside the grain and in the environment, air under high pressure in the pores of the grain explodes. The grain volume increases by 4–6 times, acquiring a porous structure. The use of ingredients such as vegetable oil, powdered sugar, vanillin, and whey powder resulted in an increase of TKW of the BV and MC.

Water activity a_w largely defines the storage potential of a particular product and this is an important critical control point for risk analysis as proposed by the HACCP concept. It has been

Table 1

Physico-chemical characteristics of puffed wheat grain in comparison to whole wheat grain

Variables	Wheat grain	BZ	BV	MC
Dry matter, g 100 g^{-1}	90.9 ± 0.1^{c}	94.1 ± 0.2^{b}	96.8 ± 0.1^{a}	96.9 ± 0.1^{a}
TKW, g	46.4 ± 1.1^{c}	34.3 ± 0.7^{d}	61.6 ± 0.5^{b}	92.1 ± 0.1^{a}
a_w	0.421 ± 0.001^{a}	0.157 ± 0.004^{b}	0.106 ± 0.014^{c}	0.159 ± 0.005^{b}
Crispiness	–	26 ± 6^{b}	50 ± 1^{a}	47 ± 3^{a}
Hardness, N	–	361 ± 42^{a}	295 ± 17^{b}	318 ± 51^{ab}
WAI, g g^{-1}	–	4.5 ± 0.2^{a}	2.9 ± 0.1^{b}	2.3 ± 0.1^{c}
WSI, g kg^{-1}	–	34.7 ± 1.3^{c}	52.7 ± 0.9^{b}	62.7 ± 1.3^{a}

Average (n = 3) ± SD. TKW – thousand kernel weight, WAI – water absorption index, WSI – water solubility index, BZ – puffed grain without coating, BV – puffed grain with vanillin and sugar, MC – puffed grain with whey powder. Crispiness, hardness, WAI, and WSI were not determined for wheat grain. Different letters in the same row indicate significant differences at $p \leq 0.05$.

reported that higher a_w in product tends to support microorganism proliferation. Bacteria usually require a_w that is higher or equal to 0.91, while 0.6 is sufficient for the growth of fungi. The results of this study imply that the highest a_w was observed in unprocessed wheat grain, corresponding to 0.421. In turn, puffed grains had lower a_w possibly because of the heat treatment and moisture loss from the grains. The water activity of BZ and MC was found to be the same, whereas BV was significantly lower.

Texture of puffed wheat grain

Texture and crispiness values for BZ and puffed wheat grains with vanillin and sugar (BV) and whey powder (MC) coatings are presented in Table 1. Analysis was not performed for wheat grains, as textural analysis is not applicable to objects with a hard texture (Costantini *et al*., 2021)mostly due to the prolonged soaking and cooking process they require. This problem could be solved by preparing legume-based ready-to-eat snacks. In this study, the effect of two different dies (circular and star-shaped, with cross-sections of 19.6 and 35.9 mm2, respectively. The use of various coating materials resulted in a significant increase in the crispness of BV and MC, which is an important quality indicator for puffed grains. This may also be the result of moisture absorption by the added components such as sugar, vanillin and whey powder. Considering the coated samples, the MC sample was less crisp than the BV sample. As confirmed by the findings *(*Román *et al.*, 2018), moisture content affects crispness and hardness, i.e. reducing the moisture content increases the crunchiness of the product. The introduction of coating led to a decrease in the hardness of BV and MC.

The application of coating to the surface of puffed wheat grains led to a decrease in WAI. This is due to the physical properties of added sugar, which dissolves in water contrary to starch and proteins present in grain, which binds water. The water solubility index increased in the BV and MC samples due to the ingredients used during the coating process. The water absorption index (WAI) measures the amount of water immobilised by air grains and the water solubility index (WSI) is the number of molecules dissolved in water *(*Mezreb *et al.*, 2003). A higher WAI indicates a product's ability to absorb more water due to increased porosity (Janve & Singhal, 2018)viz. calcium carbonate, calcium lysinate and tricalcium phosphate, at equivalent calcium concentration. The physiochemical properties, organoleptic acceptability and calcium bioaccessibility were studied for puffed rice extrudates before and after frying, and for noodles before and after cooking. Calcium fortification decreased the bulk density (from 0.224 to 0.126 g/cm^3.

Colour

Food colour is an important physical indicator as it is closely related to perception (Zhang *et al.*, 2023). Table 2 shows the L*, a*, b* colour components and total colour difference ΔE of raw whole grain of wheat (Wheat), puffed wheat (BZ), puffed wheat with vanillin and sugar (BV) and puffed wheat with whey powder (MC), as well as their ground forms. The L* value is of particular interest during the evaluation of L*, a*, and b* coordinates, as it gives insight into the process of browning that usually occurs due to enzymatic and non-enzymatic chemical reactions (Li, Masatcioglu, & Koksel, 2019).

Whole puffed grains without coating (BZ) and coated grains (MV, MC) had higher L* (lightness) values than wheat grains (Wheat) because the puffing process led to the formation of void spaces making grains look lighter. The a* (redness) value of whole

wheat grains was higher than the a* values of BZ, BV and MC. This may be due to the loss of outer layers (epicarp) of the wheat grains, which were partially removed in the process before the grains were puffed and also by pressure created in the puffing process. The outer layers of grains contain phenolic compounds responsible for red colour (Gunenc *et al.*, 2013). There was an increase in b* (yellowness) value in the BZ, BV and MC samples due to removal of bran fraction and exposing hyaline and aleurone fraction, which contains carotenoids (Huang *et al*., 2018).

In ground form, the puffed and coated puffed grain had a lower L* (lightness) value and higher a* (redness) and b* (yellowness) values compared to the raw whole grain (Wheat). In the coated sample BV, the L* (lightness) value was found to be the lowest compared to other grains. In turn, the values a* (redness) and b* (yellowness) in this sample were observed to be the highest. Whey powder gives the MS sample less red and yellow hues. In general, slight changes in L* (lightness) and a* (redness) of puffed grains compared to the original wheat indicate a less profound Maillard reaction and, therefore, smaller loss of amino acids during the explosion at high temperature (Singkhornart, Edou-Ondo, & Ryu, 2014).

Microstructure

Figure 1 shows images of Wheat (a, b, c), BZ (d, e, f), BV (g, h, i) and MC (j, k, l) microstructure. The assessment of morphological features in unprocessed wheat grain (Wheat) was conducted by SEM analysis (Figure 1 a, b, c). As seen, a nearly homogeneous epidermal layer with no obvious cracking or decomposition was observed in the unprocessed grain sample (Figure 1 c). The presence of starch fraction was distinguished in the starchy endosperm (Figure 1 b). Ellipse-shaped starch granules with a size of 20 µm take prevalence, making a strong carcass integrated into the matrix of starchy endosperm. A tightly attached aleurone layer partially filled with protein bodies can also be seen on micrograph.

The treatment of grains with high pressure during puffing has led to partial degradation of the epidermal layer of wheat, as depicted in Figure 1 f. No visible signs of starch are observed in starchy endosperm after puffing. The observation made in this study, supported by Huang *et al.* (2018), indicated the formation of dextrin and other soluble polysaccharides due to starch degradation. The disruption of high molecular-weight compounds and destruction of the tertiary and quaternary structure of the protein partially explain the relatively higher WAI observed in the previous experiment.

The technological processes of preparing wheat grains for puffing led to the absorption of moisture, the swelling of starch grains and proteins, and the formation of a colloidal solution of starch paste. Further heat treatment led to the expansion of the swollen proteins, as well as the simultaneous expansion of the starch paste. As a result, the endosperm became porous, the cells stretched, some ruptured (e). Charles, Kao, & Huang (2003) stated that wheat starch grains

Table 2

Colour of whole grains and ground grains

Colour components	Wheat	BZ	BV	MC
Whole grain				
L*	51.82 ± 0.71^{c}	59.9 ± 1.35^{b}	60.08 ± 1.49^{b}	63.43 ± 1.87^{a}
a*	10.47 ± 0.23^{a}	8.77 ± 0.34^{b}	8.52 ± 0.54^{b}	6.73 ± 0.49^{c}
b*	19.39 ± 0.26^{c}	24.64 ± 0.59^{a}	23.26 ± 0.84^{b}	19.7 ± 1.19^{c}
ΔE_{wheat}	–	9.78	9.32	12.20
ΔE_{BZ}	–	–	1.41	6.41
Powder				
L*	76.39 ± 0.14^{a}	75.75 ± 0.15^{b}	70.48 ± 0.37^{d}	71.7 ± 0.55^{c}
a*	4.41 ± 0.06^{d}	5.56 ± 0.14^{c}	6.63 ± 0.13^{a}	6.38 ± 0.08^{b}
b*	14.33 ± 0.06^{c}	19.51 ± 0.45^{b}	21.9 ± 0.33^{a}	21.77 ± 0.21^{a}
ΔE_{wheat}	–	5.34	9.85	9.01
ΔE_{BZ}	–	–	5.88	4.71

Average (n = 10) ± SD. BZ – puffed grain without coating, BV – puffed grain with vanillin and sugar, MC – puffed grain with whey powder, ΔE_{wheat} – total colour difference compared to wheat grain, ΔE_{BZ} – total colour difference compared to puffed wheat without coating. Different letters in the same row indicate significant differences at $p \leq 0.05$.

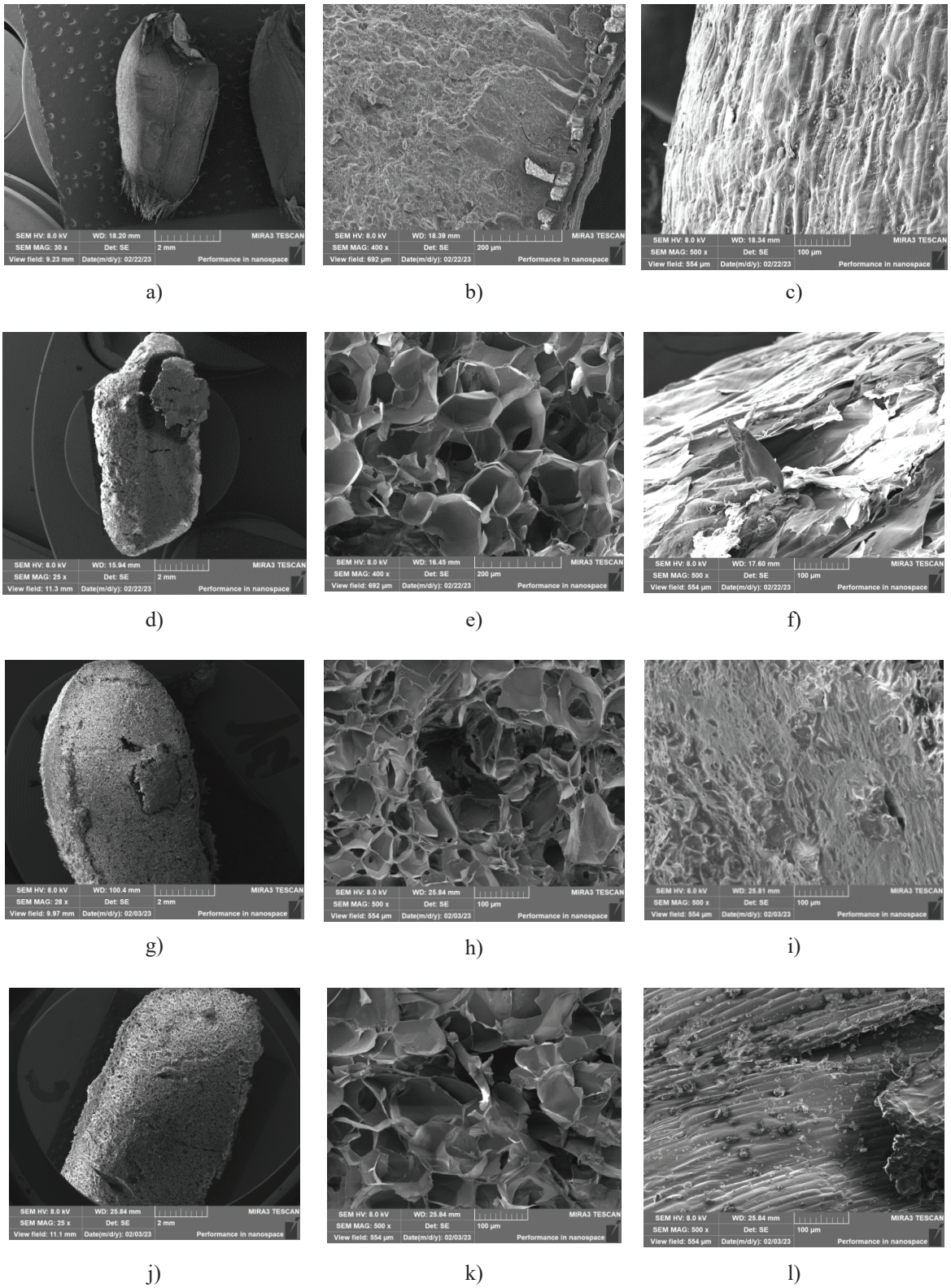


Figure 1. Microstructure of wheat (a, b, c), puffed wheat (d, e, f), puffed wheat with vanillin and sugar (g, h, i), puffed wheat with whey powder (j, k, l).

Left column shows the view of whole grain, middle column – the cross section, right column – the surface of the respective product.

are smooth, non-porous, round or oval in shape and relatively thick, while gelatinised starch grains are either swollen or broken with chipped surfaces.

Covering the grains after the puffing with coating materials composed of a mixture of vanillin and sugar (BV) and whey powder (MC) made it attainable to achieve the nearly homogeneous structure of the grains' surface with no visible signs of epidermal cracking or decomposition (Figure 1 i and 1 l). The formation of a varnish-like coating in BV and MC samples was confirmed microscopically. However, it should also be noted that no coating agents were observed on the inner side of the grains. Similar to grains with no coating, the absence of starch granules was revealed in samples with coatings. In all cases, the presence of void spaces with a size of approximately 130 × 50 μm where starch granules shall be located can be seen.

Conclusions

1. The observed results in this study confirmed that the technological process during wheat grain puffing affected both the physico-chemical and structural features of grains.
2. Puffing of wheat grains has led to an increase in dry matter content, volume of grains estimated by thousand kernel weight, and a decrease in water activity compared to raw unprocessed wheat grain.
3. Loss of moisture during grain processing, and the application of coating materials, i.e., vanillin, sugar, whey powder, and oil, ensured relatively better crispness of the puffed wheat grains. In addition, the positive effect of coating, especially vanillin and sugar, on puffed grain hardness has been revealed.
4. Morphological changes caused by high-pressure wheat grain processing were observed by scanning electron microscope.
5. The formation of dextrin and other soluble polysaccharides due to starch degradation during wheat grain processing with high pressure was perhaps the main factor affecting the increase in WAI and WSI.
6. Application of coating materials after the puffing gave the grains a nearly homogeneous structure, as no visible signs of epidermal cracking or decomposition were observed.

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