

Influence of particle size distribution on in vitro digestibility and nutritional quality of differently coloured wholegrain maize flours

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Summary

Maize (*Zea mays* L.) is one of the most important cereal crops in the world, along with wheat and rice. Considering that many physical and chemical factors influence the digestibility of food and feed ingredients, this study aimed to determine the effect of particle size on the in vitro digestibility and nutritional properties of various wholegrain maize flour fractions. Maize grains of various genetic backgrounds and kernel colours were used in this study, namely, white dent, yellow popcorn, red dent and blue popcorn. After grinding maize grains on a stone mill, the wholegrain flour was dry-sieved through three mesh sieves: 1700 μm , 710 μm and 212 μm . The medium particle size fraction (710–212 μm) was dominant. The in vitro digestibility testing showed that the powder fraction ($< 212 \mu\text{m}$) was the most digestible in all investigated samples, while the coarse fraction was the least digestible. The yellow popcorn genotype showed the highest overall digestibility. An increase in the protein content was observed with a decrease in the particle size of the fraction. The findings of this study offer new possibilities for incorporating various wholegrain maize flour fractions in food or feed to meet the specific needs of various categories of consumers.

Keywords

Zea mays L.; wholegrain maize flour; in vitro digestibility; nutritive properties; particle size; coloured grain

Maize (*Zea mays* L.) is considered one of the most significant cereal crops used as a raw material for food, feed, energy and industrial purposes. Approximately 109t of maize were produced worldwide in the 2021–2022 period, according to data provided by Statista (2022) [1]. Although maize is a significant food crop, demand for it as livestock feed has increased significantly during the past two decades. This was mainly due to the rapid economic expansion in the densely populated areas of Asia, the Middle East and South America, which increased the demand of wealthier consumers for food products from poultry and cattle [2, 3].

Due to the growing awareness of the connections between food and health, the food industry has increasingly become interested in the multi-scale process of food digestion. Both in vitro and in vivo models can be used to study how food is digested, each with its own benefits and drawbacks [4]. It is a common practice to study the gastro-

intestinal behaviour of food or pharmaceuticals using in vitro methods that simulate digestion processes. Although human nutritional studies are still the “gold standard” for addressing diet-related issues, in vitro techniques have the advantage of being quicker, cheaper, less labour-intensive and less subject to ethical constraints [5]. The differences in chemical composition and intrinsic kernel structure play a crucial role in complex processes of food degradation by digestion enzymes [4]. The physical and chemical properties of the grain cause complex correlations between its constituents, which result in digestibility differences [6].

The maize grain is made up of starch 60–70 %, followed by proteins 9–11 %, lipids 4–5 % and dietary fibre 10–11 % (expressed per dry matter) [7]. The broad and widespread use of maize grain in many food products makes this cereal a substantial source of these macronutrients. Due to its high starch content in grain, maize is both a desirable crop for human consumption and animal

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feed, as well as a significant source of raw materials for industrial processing [8]. Considering that maize is naturally gluten-free and safe for consumption by persons suffering from celiac disease or gluten intolerance, wholegrain maize flour is currently trending in the functional food market [9]. Depending on the genetic makeup that affects the colour of the pericarp, aleurone, germ and endosperm, maize grains can range in colour from white and yellow to orange, red, burgundy, blue and purple to brown. White and yellow maize are the primary varieties used for human consumption. Maize types with different kernel colour, which is a result of the anthocyanins contained in the pericarp and the aleuronic layer of the grain, such as blue, red or black, were until recently predominantly consumed by the indigenous population of the Central and South America. Nonetheless, the human intake of coloured maize has increased as anthocyanins are considered positive for their functional properties, in particular their antioxidant activity [10]. Yellow maize contains carotenoids, both provitamin and non-provitamin A, which may be beneficial to human health. Coloured maize contains a variety of secondary metabolites throughout the entire kernel, including phenolic compounds, the majority of which are phenolic acids and flavonoids, with some types existing in soluble, free or conjugated configuration, or can be insoluble, bound [11].

Grinding is a key step in both flour and cornmeal production, as well as in feed manufacturing processes. Wholegrain flour, in contrast to refined products of grain milling, is a source of bioactive ingredients and dietary fibre that have several health benefits. On the other hand, refined flour consumption has been associated with various health issues and disorders, including type 2 diabetes, coronary atherosclerosis, chronic cardiovascular disease, colon cancer and obesity, according to epidemiological studies conducted recently [12]. The pericarp and aleurone, which are normally removed during grain milling and the production of cereal flour, contain the majority of the vitamins, minerals, dietary fibre and phytochemicals in the grain [13].

Particle size is an important parameter of flours. Several methods are available for expressing and quantifying particle size, namely, dry sieving, wet sieving, microscopy, laser diffraction, static image analysis and dynamic image analysis. The most used approach for examining particle size in animal nutrition at the moment is dry sieving, which separates particles into size classes and translates these to mass [14].

The digestibility of nutrients can be increased

by reducing the mean particle size of food or feed ingredients due to an increased surface area to volume ratio that exposes more nutrients to digestive enzymes [15, 16]. Most bioactive components are attached to fibre, allowing them to pass through the digestive system and arrive intact in the colon, where they promote an environment that is antioxidant-friendly [17]. The information regarding different particle size fractions, their nutrient level and digestibility is still scarce despite the large number of studies that have been published on the impact of mean particle size of products or diets on digestion. Numerous studies related to *in vitro* digestibility and distribution of nutritional components among flour fractions with different particle sizes have so far been conducted on various cereals and legumes, while the results related to maize are few [15].

Regarding digestibility determination, a study by EGGER et al. [18] compared the *in vitro* digestion method by MINEKUS et al. [5] based on the digestion process occurring in the human gastrointestinal tract with the *in vivo* data obtained from pigs. In particular, the harmonized *in vitro* methodology proved appropriate for protein digestion investigation, screening experiments and others, being representative at the stomach and intestinal endpoints of *in vivo* conditions.

During the past several decades, there has been interest in the ideal particle size distribution (PSD) of animal diets. These studies showed that the link between pig performance and the particle size of diet or feed ingredients is straightforward: finely ground particles can improve animal performance, while the coarse fraction of particles can help maintain pigs' intestinal health [14]. Furthermore, incorporating ingredients of different particle sizes into bakery products can influence changes in the functional and sensory properties of the food [19, 20].

The objective of this study was to assess the *in vitro* digestibility and nutritional properties of different particle size fractions of the wholegrain maize flour obtained from maize genotypes varying in colour and physical properties of the grain in order to determine their suitability for application in food and feed production.

MATERIALS AND METHODS

Plant materials

The plant materials utilized to make the wholegrain flour comprised yellow popcorn hybrid ZP 611k, red dent variety ZP Rumenka, white dent hybrid ZP 552b and a blue popping maize

landrace. In the growing season of 2021, the maize genotypes created by the Maize Research Institute, Zemun Polje, were sown at the location of Zemun Polje, Serbia (N 44° 52', E 20° 19', altitude 81 m) in accordance with the randomized complete block design. Under rain-fed conditions, conventional cropping methods were used. Maize ears were harvested at their full physiological maturity stage from the two inner rows of each replicate.

Wholegrain maize flour production and fractionation

In the production facility of the Maize Research Institute, the milling process was carried out using a specially constructed cereal stone mill with a capacity of approximately 100 kg·h⁻¹ of maize grain (particle diameter ≤1.7 mm). After grinding the maize grain on a stone mill, the wholegrain flour was dry-sieved into three fractions through custom-made laboratory prochrome sieves with mesh sizes of 1700 µm, 710 µm and 212 µm (Agroalfa, Zemun, Serbia). The proportion of individual fractions was calculated based on their weighing on a technical balance KB 2400-2N (Kern and Sohn, Balingen, Germany).

Chemicals

All chemicals were of analytical or high-performance liquid chromatography (HPLC) grade and were obtained from Sigma-Aldrich (St. Louis, Missouri, USA).

In vitro digestion protocol

The in vitro digestibility of the maize flour samples was assessed using the multi-step digestion protocol according to the method proposed by PAPILLO et al. [21] modified by HAMZALIOGLU and GÖKMEN [22]. The method's oral, gastric, duodenal and colon phases were carried out without trying to exactly replicate gastrointestinal digestion.

Chemical analyses

The content of the major chemical constituents and the in vitro digestibility of maize flour was analysed in each fraction of the dry-sieved wholegrain flour to determine the influence of the particle size on the distribution of the major nutrients in individual fractions. The dry matter content of the wholegrain maize flour was assessed using the conventional drying method at 105 °C to a constant mass. The protein content was determined using the Kjeldahl System (AutoKjeldahl Distillation Unit K-350 and Speed Digester K-439, Büchi Labortechnik, Flawil, Switzerland) by the

Kjeldahl method number 55.04 as total nitrogen multiplied by 6.25 [23]. The results were expressed in percentage of protein per dry matter. The oil content was obtained according to the Soxhlet method AOAC 920.39 [23] using FatExtractor E-500 (Büchi Labortechnik,). The starch content and soluble carbohydrates were determined according to the Ewers polarimetric method (ISO 10520:1997) [24] using a digital polarimeter Uni-Pol L 2020 (Schmidt and Haensch, Berlin, Germany). Crude fibre content was determined by Weende method adjusted for Fibretec Systems (Foss, Hilleroed, Denmark) [25]. The ash content was determined according to method AOAC 923.03 [23] by slow combustion of the sample at 550 °C in a muffle furnace (L47, 1200°C, Naber Industrieofenbau, Lilienthal, Germany).

Statistical analyses

Data from at least two separate repetitions were reported as mean ± standard deviation. Minitab (v. 19.2.0) statistical software (Minitab, Coventry, United Kingdom) was used to conduct the statistical analysis using one-way ANOVA analysis of variance along with Tukey's test. The difference between the means was considered statistically significant if the probability was $p < 0.05$. Relationships between the tested variables were visually displayed using principal component analysis (PCA). An acute angle between two parameters denoted a positive correlation, whereas an obtuse angle indicated a negative correlation.

RESULTS AND DISCUSSION

Particle size distribution

Studies have shown that the functional and physico-chemical properties of maize and wheat flours are a function of the particle size distribution [20, 26]. Particle size affects the structure and surface area of the particles, where the increased surface area also results in certain changes of these quality parameters [27].

Whole grains of maize genotypes with different kernel colour and fractions of the wholegrain maize flours obtained by dry sieving through different mesh sieves are shown in Fig. 1. The graphical presentation of the particle size distribution of wholegrain maize flours obtained from differently coloured grain genotypes after dry sieving is given in Fig. 2.

The results on particle size distribution in the fractions of the wholegrain maize flour obtained by dry sieving through different mesh sieves clearly showed that the medium particle size fraction

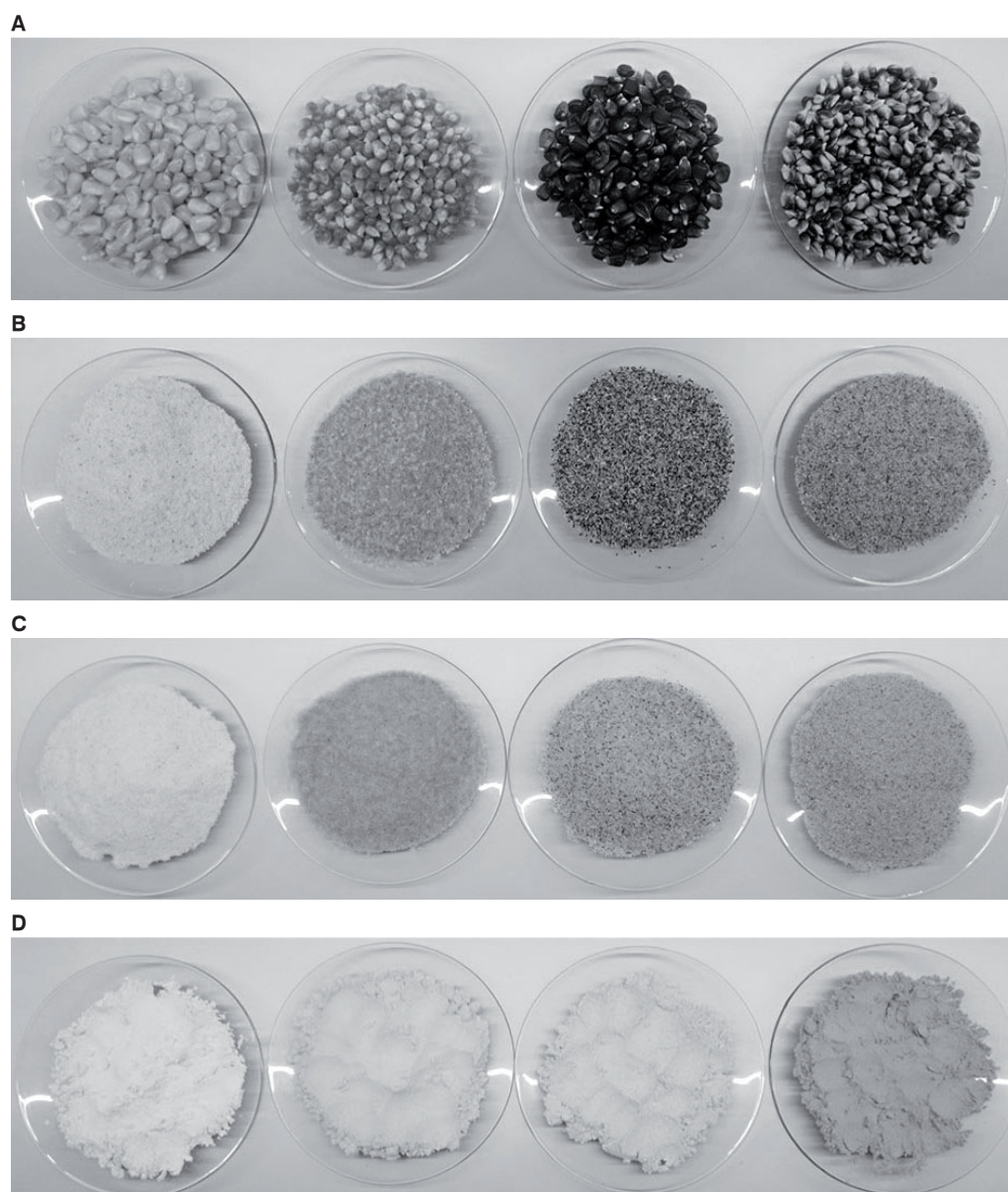


Fig. 1. Samples of the investigated maize genotypes.

A – whole grains of differently coloured maize genotypes, B – coarse fraction with particles ranging from 1700 μm to 710 μm , C – medium fraction with particles ranging from 710 μm to 212 μm , D – fine (powdered) fraction with particles < 212 μm .

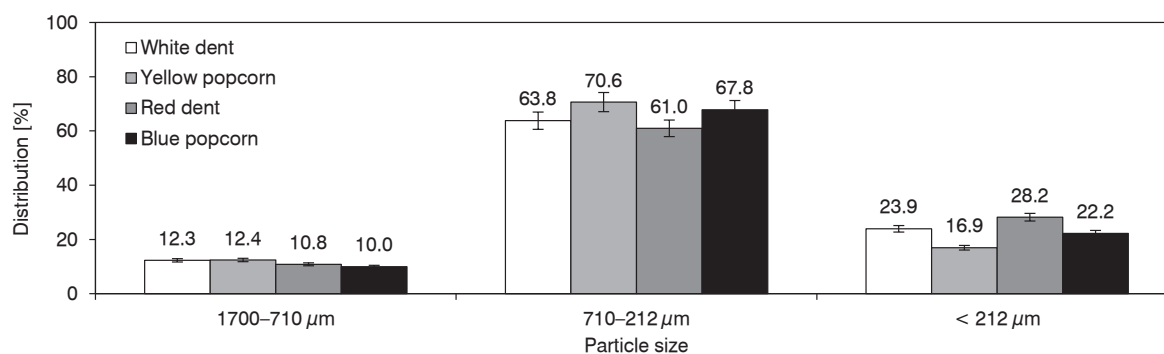


Fig. 2. Particle size distribution among wholegrain maize flour samples from differently coloured kernel genotypes obtained after dry sieving.

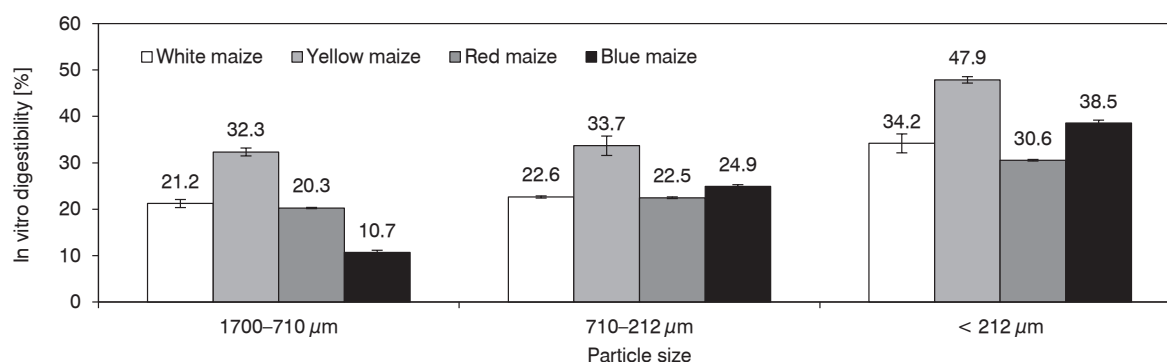


Fig. 3. In vitro digestibility of particle fractions of wholegrain maize flours.

(710–212 μm) was predominant in all maize genotypes, followed by the fine particle (< 212 μm) and coarse fraction (1700–710 μm).

In vitro digestibility of the flour fractions

The processing that the food is subjected to, such as cooking, baking or roasting, can directly affect digestibility of individual chemical components of the maize flour, predominantly of starch, as well as bioavailability of phytochemicals, and induce interactions between food components [7]. Furthermore, the particle size plays an important role in the enzymatic degradation of food and feed products [14, 15]. Even though maize is usually consumed after cooking, the in vitro digestibility in our study was determined in raw samples of flour fractions with different particle sizes as a starting point for further research in which the flour would be treated by application of thermal and/or hydrothermal processing techniques. The in vitro digestibility of wholegrain maize flour fractions with different particle size is shown in Fig. 3. The highest in vitro digestibility was determined in the fine particle size fraction, followed by medium and coarse fractions. The yellow popping maize showed the highest enzymatic degradability (47.9 %, 33.7 % and 32.3 % in fine, medium and coarse particle size fractions, respectively), followed by blue, white, and red maize flours. Unlike the results of our study, LYU et al. [15] reported that in vitro digestibility in maize fractions was the lowest in fraction with geometric mean diameter (GMD) of 0.594 mm and increased in smaller and larger particle size fractions. A study by KIERS et al. [28] showed that the coarsely ground white maize flour had an in vitro digestibility of 22.4 %, which is in accordance with our findings where coarse fraction of the white maize flour had digestibility of 21.2 % (Fig. 3). The discrepancy in the results obtained by different researchers may imply that various fac-

tors, like the chemical composition and physical properties, such as kernel hardness, of the raw material may also be related to the differences in digestibility of different particle size fractions, which may lead to fluctuations in the nutritional properties of the flour.

Phenolic compounds, among which anthocyanins play an important role, have been previously linked to modified starch digestion, positively correlating with the contents of the slowly digested and resistant starch fractions [7]. According to BARROS et al. [29], these effects may be brought on by binding to the active sites of digestive enzymes, interfering with glucose transport across the intestinal brush border because glucose and polyphenols compete for the transporter, reducing the amount of glucose absorbed into the enterocyte, and creating crosslinked networks with starch during cooking that make structures of limited availability for amylolytic enzymes. However, the results obtained in our study and presented in Fig. 3 showed that digestibility of certain particle size fractions of the coloured maize may be higher than digestibility of white dent. This was particularly observed for the smallest particle size. There may be several possible explanations for this phenomenon. The outer layers of cereal grains, including pericarp (purple maize grain) and aleurone layer (blue maize genotypes), are where anthocyanins are concentrated [11, 30]. However, processing conditions and matrix characteristics can lead to significant losses in anthocyanin content due to their susceptibility to external factors, including temperature, pH and presence of various chemical compounds [30]. The lower starch and fibre content, as well as high oil content in the powder fraction of the maize flours (Tab. 1), may have positively impacted the overall higher digestibility rate of the coloured maize samples.

In general, digestibility of cereal-based food products can be impacted by both internal factors (such as protein, amylose, dietary fibre or lipid contents) and external factors (such as germination, processing, cooking or starch retrogradation).

Chemical composition of the flour fractions

The basic chemical contents of the food product, or the presence of macronutrients, describes its nutritional worth. In Tab. 1, data on the chemical composition of the tested maize flour fractions are presented. The primary macronutrients in maize grain are carbohydrates, in particular starch [31]. The variations in starch content with differences in particle size of the fraction did not follow a clear pattern. Specifically, the medium size fraction of white, red and blue maize genotypes had the highest starch content, while the starch content of the yellow genotype was predominant in the coarse fraction. This is in accordance with the results reported by LYU et al. [15]. The content of soluble carbohydrates was increasing with the decrease in particle size of the maize flour fraction. A slight increase regarding the protein content was noticed with the decrease of the fraction particle size, similar to previously reported findings [15, 20].

Dietary fibre is a key component of contemporary day-to-day nutrition because of its positive impacts on health, such as the lowering of

cholesterol, alteration of glycemic and insulino-mic responses, changes in intestinal function and antioxidant activity [32]. Moreover, dietary fibre consists of a variety of plant-based polymers made of carbohydrates, including cellulose, hemicellulose, pectins, and gums, which can be coupled with lignin or other non-carbohydrate components [33]. The crude fibre content in the fractions of various particle sizes varied significantly. The fibres were predominantly most abundant in the coarse fraction, followed by the fine fraction of the sieved wholegrain maize flours. The findings of our study are consistent with those previously reported by LYU et al. [15] and BRESSIANI et al. [20]. The increased dietary fibre content can have diverse effects on the techno-functional properties of the baked products. Its water-holding capacity can prevent the staling of baked goods such as bread and, on the other hand, it can decrease the specific loaf volume due to the lower gas retention.

Principal components analysis

The loading plot of the two principal components of the investigated parameters is shown in Fig. 4. The principal components analysis showed that in vitro digestibility of the samples was highly positively correlated with the ash content, followed by protein content. The negative correlation between starch content and digestibility is in accordance with the obtained results,

Tab. 1. Chemical composition of fractions of wholegrain maize flours.

Fraction particle size [μm]	Dry matter content [%]	Starch [%]	Soluble carbohydrates [%]	Protein [%]	Oil [%]	Crude fibre [%]	Ash [%]
White dent							
1 700–710	89.4 ± 0.0 ^b	66.3 ± 0.1 ^d	0.4 ± 0.0 ^f	9.8 ± 0.0 ^h	2.8 ± 0.1 ^{ef}	4.1 ± 0.5 ^a	0.9 ± 0.1 ^g
710–212	89.4 ± 0.0 ^b	71.9 ± 0.3 ^a	0.8 ± 0.0 ^e	9.9 ± 0.0 ^h	4.2 ± 0.0 ^d	1.9 ± 0.2 ^{cd}	1.1 ± 0.0 ^f
< 212	90.1 ± 0.1 ^a	61.1 ± 0.1 ^f	3.3 ± 0.0 ^a	9.9 ± 0.0 ^h	8.7 ± 0.0 ^c	1.6 ± 0.2 ^d	2.4 ± 0.0 ^d
Yellow popcorn							
1 700–710	88.1 ± 0.0 ^e	65.4 ± 0.0 ^e	0.1 ± 0.0 ^{ij}	13.2 ± 0.1 ^c	1.5 ± 0.1 ^g	3.6 ± 0.1 ^a	0.7 ± 0.0 ^h
710–212	88.0 ± 0.0 ^e	50.8 ± 0.0 ^b	0.3 ± 0.0 ^g	13.5 ± 0.0 ^b	3.0 ± 0.0 ^e	1.8 ± 0.0 ^{cd}	1.1 ± 0.0 ^{ef}
< 212	89.0 ± 0.1 ^c	50.8 ± 0.0 ⁱ	2.1 ± 0.0 ^c	15.3 ± 0.0 ^a	11.1 ± 0.1 ^a	2.0 ± 0.1 ^{cd}	4.8 ± 0.0 ^a
Red dent							
1 700–710	88.6 ± 0.0 ^d	64.7 ± 0.2 ^e	0.1 ± 0.0 ^j	11.0 ± 0.0 ^g	2.7 ± 0.4 ^{ef}	3.9 ± 0.1 ^a	1.0 ± 0.0 ^g
710–212	88.4 ± 0.1 ^d	68.3 ± 0.4 ^c	0.2 ± 0.0 ^h	11.4 ± 0.0 ^f	4.2 ± 0.2 ^d	2.3 ± 0.1 ^{bc}	1.2 ± 0.0 ^e
< 212	89.4 ± 0.0 ^b	56.9 ± 0.0 ^g	2.1 ± 0.0 ^d	11.9 ± 0.0 ^e	9.6 ± 0.1 ^b	2.0 ± 0.0 ^{cd}	3.2 ± 0.0 ^c
Blue popcorn							
1 700–710	89.1 ± 0.0 ^c	64.9 ± 0.0 ^e	0.2 ± 0.0 ⁱ	10.9 ± 0.1 ^g	2.5 ± 0.1 ^f	2.8 ± 0.1 ^a	0.9 ± 0.1 ^g
710–212	89.3 ± 0.1 ^b	68.4 ± 0.2 ^c	0.3 ± 0.0 ^h	11.3 ± 0.1 ^f	4.2 ± 0.0 ^d	2.0 ± 0.0 ^{cd}	1.1 ± 0.0 ^{ef}
< 212	89.9 ± 0.0 ^a	51.9 ± 0.3 ^h	2.6 ± 0.0 ^b	12.9 ± 0.0 ^d	11.0 ± 0.0 ^a	2.4 ± 0.1 ^{bc}	3.4 ± 0.0 ^b

Means followed by the same superscript letter within the same row are not significantly different ($\alpha = 0.05$ %).

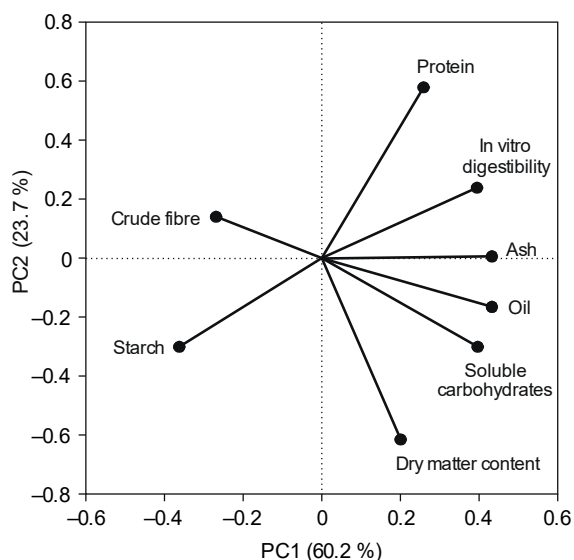


Fig. 4. Interrelationship between the mean contents of the chemical components and digestibility of all the fractions of wholegrain maize flour samples.

given that the fraction with least starch (powder) in general had the highest digestibility. A study by LYU et al. [15] reported that the *in vitro* organic matter digestibility in maize was strongly correlated with the starch content, while in soybean meal it was correlated with the crude fibre and crude fat levels. Contrarily, when NOBLET and JAGUELIN-PEYRAUD [34] used data from the experiment of BOISEN and FERNÁNDEZ [35], they came to different conclusions. They discovered that when the equation incorporated digestible organic matter, acid detergent fibre or crude fibre, and ash in mash compound feeds, the prediction of *in vitro* enzyme digestibility of organic matter was more accurate ($R^2 = 0.9$). This might be due to the high starch content of maize relative to other nutrients, which causes significant variations in fractions with different particle sizes. Furthermore, the principal components analysis indicated significant negative correlation between dietary fibre content and the overall digestibility. Previous studies also reported the negative impact of dietary fibre on starch digestibility, which was explained by the obstruction of the transport of enzymes to the binding sites in starch chains [36, 37].

CONCLUSIONS

The *in vitro* digestibility and nutritive composition varied significantly among the wholegrain flour fractions of various particle sizes obtained from the grains of four maize genotypes. In terms

of digestibility, the coarse fraction was least impacted by the digestive processes, while the fine (powdered) fraction showed the highest degree of enzymatic degradation. The crude fibre content was predominant in the coarse fraction, while protein content manifested an increase with the reduction of the particle size. The fact that the mean particle size of ground maize grains significantly influences nutrient composition and digestibility of the fraction, may provide new possibilities of incorporating wholegrain flour wholegrain flour various wholegrain maize flour fractions in food or feed to meet the specific criteria, dietary needs and preferences of various categories of consumers. Apart from paving the way towards further research on maize flour, the findings of this study open up new possibilities for reformulation of food to obtain novel products with higher content of certain nutrients, antioxidants and with specific functional properties.

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REFERENCES

1. Global corn production in 2021/2022, by country. In: Statista [online]. New York : Statista, 24 October 2022 [cited 15 May 2023]. <<https://www.statista.com/statistics/254294/distribution-of-global-corn-production-by-country-2012/>>
2. Shiferaw, B. – Prasanna, B. M. – Hellin, J. – Bänziger, M.: Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security*, 3, 2011, pp. 307–327. DOI: 10.1007/s12571-011-0140-5.
3. Delgado, C. L.: Rising consumption of meat and milk in developing countries has created a new food revolution. *Journal of Nutrition*, 133, 2003, pp. 3907S–3910S. DOI: 10.1093/jn/133.11.3907S.
4. Bornhorst, G. M. – Gouseti, O. – Wickham, M. S. – Bakalis, S.: Engineering digestion: multiscale processes of food digestion. *Journal of Food Science*, 81, 2016, pp. R534–R543. DOI: 10.1111/1750-3841.13216.
5. Minekus, M. – Alvinger, M. – Alvito, P. – Ballance, S. – Bohn, T. – Bourlieu, C. – Carrière, F. – Boutrou, R. – Corredig, M. – Dupont, D. – Dufour, C. – Egger, L. – Golding, M. – Karakaya, S. – Kirkhus, B. – Le Feunteun, S. – Lesmes, U. – Macierzanka, A. – Mackie, A. – Marze, S. – McClements, D. J. – Ménard, O. – Recio, I. – Santos, C. N. – Singh, R. P. – Vegarud, G. E. –

- Wickham, M. S. J. – Weitschies, W. – Brodkorb, A.: A standardised static in vitro digestion method suitable for food – an international consensus. *Food and Function*, 5, 2014, pp. 1113–1124. DOI: 10.1039/c3fo60702j.
6. Srichuwong, S. – Curti, D. – Austin, S. – King, R. – Lamothe, L. – Gloria-Hernandez, H.: Physicochemical properties and starch digestibility of whole grain sorghums, millet, quinoa and amaranth flours, as affected by starch and non-starch constituents. *Food Chemistry*, 233, 2017, pp. 1–10. DOI: 10.1016/j.foodchem.2017.04.019.
 7. Camelo-Méndez, G. A. – Agama-Acevedo, E. – Tovar, J. – Bello-Pérez, L. A.: Functional study of raw and cooked blue maize flour: Starch digestibility, total phenolic content and antioxidant activity. *Journal of Cereal Science*, 76, 2017, pp. 179–185. DOI: 10.1016/j.jcs.2017.06.009.
 8. Radosavljević, M. – Milašinović-Šeremešić, M. – Terzić, D. – Jovanović, Ž. – Srdić, J. – Nikolić, V.: Grain chemical composition of dents, popping maize and sweet maize genotypes. *Journal on Processing and Energy in Agriculture*, 24, 2020, pp. 77–80. DOI: 10.5937/jpea24-28790.
 9. Demirkesen, I. – Ozkaya, B.: Recent strategies for tackling the problems in gluten-free diet and products. *Critical Reviews in Food Science and Nutrition*, 62, 2022, pp. 571–597. DOI: 10.1080/10408398.2020.1823814.
 10. Bello-Pérez, L. A. – Flores-Silva, P. C. – Sifuentes-Nieves, I. – Agama-Acevedo, E.: Controlling starch digestibility and glycaemic response in maize-based foods. *Journal of Cereal Science*, 99, 2021, article 103222. DOI: 10.1016/j.jcs.2021.103222.
 11. Žilić, S. – Serpen, A. – Akillioglu, G. – Gökmen, V. – Vančetović, J.: Phenolic compounds, carotenoids, anthocyanins, and antioxidant capacity of colored maize (*Zea mays* L.) kernels. *Journal of Agricultural and Food Chemistry*, 60, 2012, pp. 1224–1231. DOI: 10.1021/jf204367z.
 12. Cheng, W. – Sun, Y. – Fan, M. – Li, Y. – Wang, L. – Qian, H.: Wheat bran, as the resource of dietary fiber: a review. *Critical Reviews in Food Science and Nutrition*, 62, 2022, pp. 7269–7281. DOI: 10.1080/10408398.2021.1913399.
 13. Francavilla, A. – Joye, I. J.: Anthocyanins in whole grain cereals and their potential effect on health. *Nutrients*, 12, 2020, article 2922. DOI: 10.3390/nu12102922.
 14. Lyu, F. – Thomas, M. – Hendriks, W. H. – Van der Poel, A. F.: Size reduction in feed technology and methods for determining, expressing and predicting particle size: A review. *Animal Feed Science and Technology*, 261, 2020, article 114347. DOI: 10.1016/j.anifeedsci.2019.114347.
 15. Lyu, F. – van der Poel, A. F. B. – Hendriks, W. H. – Thomas, M.: Particle size distribution of hammer-milled maize and soybean meal, its nutrient composition and in vitro digestion characteristics. *Animal Feed Science and Technology*, 281, 2021, article 115095. DOI: 10.1016/j.anifeedsci.2021.115095.
 16. Ball, M. E. E. – Magowan, E. – McCracken, K. J. – Beattie, V. E. – Bradford, R. – Thompson, A. – Gordon, F. J.: An investigation into the effect of dietary particle size and pelleting of diets for finishing pigs. *Livestock Science*, 173, 2015, pp. 48–54. DOI: 10.1016/j.livsci.2014.11.015.
 17. Gong, L. – Chi, H. – Wang, J. – Zhang, H. – Sun, B.: In vitro fermentabilities of whole wheat as compared with refined wheat in different cultivars. *Journal of Functional Foods*, 52, 2019, pp. 505–515. DOI: 10.1016/j.jff.2018.11.027.
 18. Egger, L. – Schlegel, P. – Baumann, C. – Stoffers, H. – Guggisberg, D. – Brügger, C. – Dürr, D. – Stoll, P. – Vergères, G. – Portmann, R.: Physiological comparability of the harmonized INFOGEST in vitro digestion method to in vivo pig digestion. *Food Research International*, 102, 2017, pp. 567–574. DOI: 10.1016/j.foodres.2017.09.047.
 19. Guiné, R. P.: Textural properties of bakery products: A review of instrumental and sensory evaluation studies. *Applied Sciences*, 12, 2022, article 8628. DOI: 10.3390/app12178628.
 20. Bressiani, J. – Oro, T. – Santetti, G. S. – Almeida, J. L. – Bertolin, T. E. – Gómez, M. – Gutkoski, L. C.: Properties of whole grain wheat flour and performance in bakery products as a function of particle size. *Journal of Cereal Science*, 75, 2017, pp. 269–277. DOI: 10.1016/j.jcs.2017.05.001.
 21. Papillo, V. A. – Vitaglione, P. – Graziani, G. – Gökmen, V. – Fogliano, V.: Release of antioxidant capacity from five plant foods during a multistep enzymatic digestion protocol. *Journal of Agricultural and Food Chemistry*, 62, 2014, pp. 4119–4126. DOI: 10.1021/jf500695a.
 22. Hamzalioglu, A. – Gökmen, V.: Formation and elimination reactions of 5-hydroxymethylfurfural during in vitro digestion of biscuits. *Food Research International*, 99, 2017, pp. 308–314. DOI: 10.1016/j.foodres.2017.05.034.
 23. Horwitz, W. (Ed.): Official methods of analysis of AOAC International. 17th edition. Gaithersburg : AOAC International, 2000. ISBN: 978-0935584677.
 24. ISO 10520:1997. Determination of starch content – Ewers polarimetric method. Geneva : International Organization for Standardization, 1997.
 25. ISO 5498:1981. Agricultural food products — Determination of crude fibre content — General method. Geneva : International Organization for Standardization, 1981.
 26. Shi, L. – Li, W. – Sun, J. – Qiu, Y. – Wei, X. – Luan, G. – Hu, Y. – Tatsumi, E.: Grinding of maize: The effects of fine grinding on compositional, functional and physicochemical properties of maize flour. *Journal of Cereal Science*, 68, 2016, pp. 25–30. DOI: 10.1016/j.jcs.2015.11.004.
 27. Protonotariou, S. – Drakos, A. – Evageliou, V. – Ritzoulis, C. – Mandala, I.: Sieving fractionation and jet mill micronization affect the functional properties of wheat flour. *Journal of Food Engineering*, 134, 2014, pp. 24–29. DOI: 10.1016/j.jfoodeng.2014.02.008.
 28. Kiers, J. L. – Nout, R. M. – Rombouts, F. M.: In vitro digestibility of processed and fermented soya

- bean, cowpea and maize. *Journal of the Science of Food and Agriculture*, *80*, 2000, pp. 1325–1331. DOI: 10.1002/1097-0010(200007)80:9<1325::AID-JSFA648>3.0.CO;2-K.
29. Barros, F. – Awika, J. M. – Rooney, L. W.: Interaction of tannins and other sorghum phenolic compounds with starch and effects on in vitro starch digestibility. *Journal of Agricultural and Food Chemistry*, *60*, 2012, pp. 11609–11617. DOI: 10.1021/jf3034539.
 30. Žilić, S. – Simić, M. – Nikolić, V.: Colored cereals: Food applications. In: Punia, S. – Kumar, M. (Eds.): *Functionality and application of colored cereals: Nutritional, bioactive, and health aspects*. London : Academic Press, 2023. pp. 73–109. ISBN: 9780323997331. DOI: 10.1016/B978-0-323-99733-1.00006-6.
 31. Milašinović-Šeremešić, M. – Radosavljević, M. – Đuragić, O. – Srdić, J.: Starch composition related to physical traits in maize kernel. *Journal on Processing and Energy in Agriculture*, *25*, 2021, pp. 78–81. DOI: 10.5937/jpea25-31593.
 32. Lal, M. K. – Singh, B. – Sharma, S. – Singh, M. P. – Kumar, A.: Glycemic index of starchy crops and factors affecting its digestibility: A review. *Trends in Food Science and Technology*, *111*, 2021, pp. 741–755. DOI: 10.1016/j.tifs.2021.02.067.
 33. Nikolić, V. – Žilić, S. – Simić, M. – Perić, V.: Black soya bean and black chia seeds as a source of nutrients and bioactive compounds with health benefits. *Food and Feed Research*, *47*, 2020, pp. 99–107. DOI: 10.5937/ffr47-29424.
 34. Noblet, J. – Jaguelin-Peyraud, Y.: Prediction of digestibility of organic matter and energy in the growing pig from an in vitro method. *Animal Feed Science and Technology*, *134*, 2007, pp. 211–222. DOI: 10.1016/j.anifeeds.2006.07.008.
 35. Boisen, S. – Fernández, J. A.: Prediction of the total tract digestibility of energy in feedstuffs and pig diets by in vitro analyses. *Animal Feed Science and Technology*, *68*, 1997, pp. 277–286. DOI: 10.1016/S0377-8401(97)00058-8.
 36. Rodríguez-Huezo, M. E. – Valeriano-García, N. – Totosa-Sánchez, A. – Vernon-Carter, E. J. – Álvarez-Ramírez, J.: The effect of the addition of soluble fibers (polydextrose, corn, pea) on the color, texture, structural features and protein digestibility of semolina pasta. *Applied Food Research*, *2*, 2022, article 100187. DOI: 10.1016/j.afres.2022.100187.
 37. Kong, H. – Yu, L. – Gu, Z. – Li, C. – Cheng, L. – Hong, Y. – Li, Z.: An innovative short-clustered maltodextrin as starch substitute for ameliorating postprandial glucose homeostasis. *Journal of Agricultural and Food Chemistry*, *69*, 2020, pp. 354–367. DOI: 10.1021/acs.jafc.0c02828.

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