



## Original article

# Implications of husking process on the nutritional composition of sorghum grains: diverse varieties and regions

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**Summary** Sorghum, known for its nutritional value, health benefits and gluten-free status, is now widely produced and suitable for human consumption in developed regions due to advancements in sorghum research and processing techniques. The research looked at how well the husking fraction time unit (HFTU) technique worked by examining its effects on the nutritional value of three varieties of sorghum grain. The efficiency of the husking process was assessed at 87% for concentrated and redistributed nutritional contents and 60% for variation of mineral contents based on bran/ endosperm. The technique reduced the T.K.W. compared to whole grain to the endosperm (grits). Moreover, the redistribution of the crude protein % showed the precision of the HFTU procedure by demonstrating an average of 26.6% as a variation ratio of the bran/endosperm in the data set. Contrary to the content of the total dietary fibre content, for example, the variation of TDF % attributed to bran/endosperm was 10.9%. On the other hand, the average ash % of whole grains (hummer) and husked products (TM05C) was increased by 33.2% based on averages of 1.5% and 2.1%, respectively. Accordingly, it was approved that the HFTU procedure effectively separated the endosperm (grits) and bran. This study also found that minerals such as Ca, Cu, Fe, K, Mg, Mn, Na, P, S and Zn changed over 30-to-80-time units by 29%, 13%, 8%, 4%, 17%, 18%, 1%, 13%, 6% and 12% in the bran and endosperm. The HFTU process has influenced the colour attributes of variation sorghum varieties, particularly within a time scale of 80 (S) units. The research revealed that the husking technique substantially impacted the different sorghum grain varieties' nutritional composition and colour properties. The method can be useful for developers in enhancing sorghum grain products' nutritional properties attributed to various varieties and regions, allowing them to provide high nutritional quality sourced from sustainable products.

**Keywords** Colour characteristics, husking process, nutritional properties, region property, sorghum grains, variety.

## Introduction

Sorghum, scientifically called *Sorghum bicolor*, is a widely cultivated crop in the Gramineae family. The crop has successfully naturalised in several places worldwide, including the Americas, Asia and Europe. Sorghum is mostly grown in Africa (39.2%), the Americas (38.2%) and Asia (18.3%), according to (Rumler *et al.*, 2022). *S. bicolor* is known as an SDG crop globally; recently, sorghum has replaced maize and wheat in several regions due to climatic change

and CO<sub>2</sub> emissions (Henley, 2010; George *et al.*, 2022). Sorghum crop is commonly known as a profit cereal grain due to its productivity and efficient resilience to various environments. It is a crucial component in agricultural practices across various regions (Jóvér *et al.*, 2020; Thilakarathna *et al.*, 2022). Climate change has led to an increase in the utilisation of sorghum in the Mediterranean due to advancements in agricultural practices for production and health benefits; addressing new challenges can contribute to food science research to expand sorghum production in the European region (Dahlberg *et al.*, 2011; Höhn & Rötter, 2014; Jóvér *et al.*, 2018). Hence, Research and

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development approaches are required to enhance sorghum-based products' physical characteristics and nutritional properties (Deribe & Kassa, 2020). Resulting in consider grain processing as one of the strategies for improving the bioavailability of minerals in processed sorghum grain (Aslam *et al.*, 2018). Previous studies outlined the urgent need for modern processing technology to improve the quality of sorghum-derived foodstuffs, highlighting the common traditional treatments in the processing of sorghum grains (Taylor, 2018; Abdelhalim *et al.*, 2019; Aguiar *et al.*, 2023). These methods involved soaking, germination, fermentation and technical processes such as heat treatments and irradiation to eliminate or reduce anti-nutritional components (Punia *et al.*, 2021; Rashwan *et al.*, 2021). Despite to process advantages, the most common traditional technique of processing sorghum grain consumes time. For instance, a recent paper on sorghum germination indicated that nutritional improvements were seen after 7 days of the procedure (Kayisoglu *et al.*, 2024), confirming, to literature as outlined sorghum processing issues addressing the inefficiency of germ removal and time-consuming, which can leads to decreased shelf life and discolouration, ultimately affecting the quality and appearance of the final product (Li *et al.*, 2022; Khoddami *et al.*, 2023). Hence, it is necessary to involve more effective time processing, as the HFTU procedure provides. Furthermore, the modern grain processing equipment prioritises environmental protection requirements and operational safety, ensuring a people-centric and sustainable approach (Lovegrove *et al.*, 2023). Scientific literature emphasises that the dry-fractionation approach is beneficial in enhancing the nutritional profile of cereal grains (Kołodziejczyk *et al.*, 2018; Langó *et al.*, 2018). Sorghum dry milling includes steps such as bran and germ removal, kernel breaking and decortication milling (Khoddami *et al.*, 2023). Which were supported to (Proietti *et al.*, 2013), the authors were examined the impact of several parameters on the chelation characteristics, trace mineral levels and bioavailability in sorghum food. Nutrition is crucial for body function, requiring a balanced diet with macro- and micronutrients to sustain metabolism and prevent uncommunicable diseases and poor health (Kiani *et al.*, 2022). Therefore, the increasing of the sorghum grain processing had influenced on the interest in sorghum utilisation due to its nutritional properties can contribute to human diet, addressing in the high protein content (4.4–21.1%), total carbs (57.0–80.6%), crude fibre (1.0–3.4%), fat (2.1–7.6%), starch (55.6–75.2%), total ash (1.3–3.3%) and total minerals (179–1360 mg/100 g; Baholet *et al.*, 2018; Maurya *et al.*, 2023). In addition, sorghum ash content, can indicates the mineral richness of the grains depending on the variety and anatomical parts (Adebo &

Kesa, 2023). Despite distinct nutritional compositions, sorghum's nutritional composition is properly limited, focusing on starch levels, protein digestibility and anti-nutritional compounds (Rodríguez-España *et al.*, 2022).

Sorghum is a versatile ingredient used in different recipe, particularly in developed countries seeking gluten-free and high quality alternatives (Dahir *et al.*, 2015; Zhou *et al.*, 2023). Sorghum used for human consumption must confirm the specified standard parameter (East Africa Communities, 2011; WHO, 2019). Table A1 demonstrates the recommended daily allowance of the element supplements for diverse age groups.

According to the literature, processing cereal grains for human consumption is crucial due to their geographical influence on their nutritional properties (Ikem *et al.*, 2023; Rubio-Armendáriz *et al.*, 2023).

The findings of these tests may be linked to the final product's performance and used to verify that the husked grain fulfils the customer's criteria for a healthy diet (Ertl & Goessler, 2018; Souza *et al.*, 2023). Specifically, the previous investigations indicated the efficiency of time-unit processing on sorghum nutritional properties (Sruthi *et al.*, 2021).

Grain colour profile is a crucial parameter since it directly impacts the grain's nutritional composition and overall quality (Black & Panozzo, 2004). Sorghum exhibits variations in pericarp colour, including white, black and red, which might affect the nutritional and antioxidant characteristics of the grain (Sedghi *et al.*, 2012). Moreover, in industry, it is advantageous for the grain colour variation to enhance the texture and appearance of end product responses within a product shape quality, which can allow for the creation of novel products based on the colour variation properties (Thilakarathna *et al.*, 2022; Omer *et al.*, 2023). All the mentioned characteristics indicated the crucial role of colour measurement for our tested sorghum varieties (Li *et al.*, 2023). The investigation employed the Konica Minolta CR-410 colorimeter for general colour profile categorisation (Konica Minolta, 2002; Steinberg *et al.*, 2020).

The research aimed to evaluate the efficiency of the husking approach used for sorghum grains and its implications for the nutritional composition and colour characteristics of diverse varieties obtained from various regions of Hungary. The study assessed how a particular technique affects the quality of husked grain by examining the influence of two distinct time intervals, especially 30 (s) and 80 (s), on the nutritional composition. This assessment was essential to verifying that the husked sorghum grain raw material aligns with the necessary nutritional parameters, establishing it as a suitable and nutritious food for human consumption.

## Materials and methods

### Materials and sample preparation

We obtained identical samples of three sorghum grain varieties (ES Föehn, ES Monsoon and AS2 2021IMI) from three locations inside Hungary. The regions were categorised based on the soil types as follows: Nyíregyháza (sandy), Esztár (Luvisol) and Hortobágy (humic gley). The samples were analysed at the Central Chemistry Laboratories of the University of Debrecen. The samples were dried and finely ground using the Retsch SK-3 hammer mill, equipped with a 1 mm sieve. The meticulous grinding procedure, ensuring the samples achieved homogeneity, was crucial in generating precise and consistent analytical outcomes. The processed whole grains, obtained via a hummer mill, were compared to the husked grain for the results and two processed grains were passed through all procedure protocols. The codes and origin sources of the varieties are listed in Table A2.

### Thousand kernel weight

A sensitive weighing scale was counted and weighed for 1000 kernels in three replications and the mean value was recorded per (g).

### Application of grain husking process

The sorghum grains were processed using the husker machine (TM05C, Satake Engineering Co., Hiroshima, Japan). The employed Satake TM05C grain testing mill has features of various controllable time units (Wang, 2005). The procedure was applied by weighting 50 g of sorghum grains into the husker (TM05C, Satake Engineering Co., Hiroshima, Japan) fitted with an abrasive wheel (46–60 mesh) and 54 Kw (SATAKE, 1896). The abrasive wheel's rotation speed was operated at 800–1100 rpm and screened on a No. 60 mesh sieve (4760 µm). According to our investigation, the efficient grain size diameters ranged from 3.0, 3.2, 3.6, 4.0 and 4.5 mm, respectively. The diameter of 4.0–4.5 mm of grain size was the most efficient size and was admitted for the study investigation for the HFTU process.

### Determination of the crude protein

The nitrogen content of sorghum samples was determined using the Kjeldahl method (ISO 20483:2013, 2013). The technique is based on a three-step process: digestion, distillation and titration.

Samples were broken down by concentrated sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and a catalyst (CuSO<sub>4</sub>·5H<sub>2</sub>O) and the compositions were mixed in the specified proportions, which changed nitrogen molecules into ammonium ions.

Distillation: The ammonia produced in the digestive process is evaporated and collected in a solution with boric acid (H<sub>3</sub>BO<sub>3</sub>).

Titration is used to evaluate the nitrogen content in the sample by titrating the collected ammonia with a standardised acid, usually hydrochloric acid (HCl).

The nitrogen-to-protein conversion factor was considered when calculating protein content based on the protein source. Therefore, the conversion factor of 6.25 was used for the total protein calculation and the expression unit of a mass fraction of the dry product is represented as a percentage.

### Determination of the total fibre content

The enzymatic-gravimetric technique for assessing dietary fibre includes extracting starch, protein and fat from grain samples to generate a dried and weighed residue. The residual protein and ash were adjusted and the outcome was presented as a ratio of the initial material. This approach is based on the concepts outlined in AOAC 985.29 and AACC 32-07.01. Several nations have widely accepted it as the official technique for analysing dietary fibre. The Megazyme Total Dietary Fibre Kit is based on the approach described by Megazyme (2017).

### Determination of ash content

The crude ash content of a sample was calculated by incinerating it at 550 °C and measuring the residue left, then expressing it as a percentage of the sample's weight.

Measure 4 g of the homogenised test sample with an accuracy of 0.001 g and place it in a warmed and cooled ash pan.

Place the crucibles in an annealing furnace at 200 °C for 1 h, then at 550 °C for 3 h. Inspect for carbon particles and re-anneal if needed.

Cool the crucibles in a desiccator and measure the mass using an analytical balance.

Determine the ash content by using the formula: ash % =  $(M_3 - M_1)/(M_2 - M_1) \times 100$ , where  $M_1$  represents the vessel's mass,  $M_2$  is the combined mass of the sample and vessel and  $M_3$  is the mass of the ash and vessel. After combustion, the ash content is calculated using the same formula (AOAC, 2016).

### Determination of mineral elemental contents

The grain samples obtained from the experiments were analysed at the Central Chemical Laboratory of the Agricultural Centre, University of Debrecen, for our investigation, we verified the precision of the measurements using an authentic wheat sample selected as BCR CRM 189 (whole grain) from the International

Plant Exchange Network, University of Wageningen, as referenced by (John & Taylor, 2023). The measurements were conducted in multiple rounds (Kovács *et al.*, 1996). We employed inductively coupled plasma optical emission spectroscopy (ICP-OES) iCAP 7400 (Thermo Scientific) technology. The provided chemical reagents were sourced from VWR International Ltd. (Geldenaaksebaan, Belgium). to carry out element measurements at specific wavelengths: P 177.495 nm, K 404.721 nm, S 183.801 nm, Ca 183.034 nm, Mg 285.204 nm, Na 330.237 nm, Cu 324.754 nm, Fe 238.204 nm, Zn 213.856 nm, Mn 259.373 nm. We weighed 1 g of each sample. The samples were subjected to aqueous acid digestion, which included pre-digesting and digestion phases. We heated the samples at 60 °C for 30 min in a model block digestion (MIM OE-718/A) apparatus after adding 10 mL of nitric acid (HNO<sub>3</sub>, 69% v/v). After a few minutes of chilling, 3 cm<sup>3</sup> of hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>, 30% v/v) was added to the samples and they were redirected to the primary digestion stage. We heated the digester to 120 °C for 90 min before turning it off and allowing it to settle for 10–20 min. The volume was increased to 50 cm<sup>3</sup> using ultra-pure water (Millipore, S.A.S. France). Finally, we purified the homogenised suspension using an MN 640 W filter paper. The concentration of elements was expressed on a grain dry-weight basis (mg kg<sup>-1</sup>).

#### Assessment of husked *S. bicolor* grain colour

The husked grain colours were measured in terms of *L\** (whiteness), *a\** (redness), *b\** (yellowness) and *Y* (brightness) values using a colour difference metre (Chroma metre, CR-410, Minolta Co. Ltd., Japan; Konica Minolta, 2002).

#### Statistical analyses

The statistical analysis was conducted using SPSS 28 software. Descriptive data was utilised to indicate the sample size of the original data results for all respective variables, which involved three replications of mineral measurements with the units reported as mg kg<sup>-1</sup>, a thousand kernel weight (TKW) and two replications of readings for total protein, total dietary fibre and ash with the units reported as % and the average TKWs (g) for whole grain samples, as was presented as the (average). The data sets were tested for Gaussian normality, which indicated status following normality and was involved in the total protein, total dietary fibre, ash and mineral contents (Chatfield, 1989). A one-way ANOVA was performed for total dietary fibre and ash variance detection and the model was performed independently for mineral content variance determination. The linear regression was

performed to assess the total protein and colour profile variance and ascertain the statistical significance at a significance level of  $P \leq 0.05$  (Draper and Smith, 1998). Pearson correlation was conducted for colour parameter relationships. The visualisation was done using SAS 17 software.

## Results and discussion

### Assessment of *S. bicolor* nutritional properties

All the nutritional composition content was evaluated in the processed whole grains by hummer mills and the husked grains by TM05C husker based on the fraction times of 30 (s) and 80 (s). In Table A4, with a significance level of  $P < 0.05$ , lined with (Sruthi *et al.*, 2021), the authors discussed how processing grains changed their nutritional properties. They found that the nutritional content was concentrated in the grains' bran and endosperm (grits) parts and the TKWs of whole grains and endosperm (grits) were decreased. The findings revealed variations in the mineral contents based on the diverse grain varieties before and after conducting the HFTU process (Table A4), with a significance difference of  $P < 0.05$ , as were lined to lined (Balasubramanian, 2015; Rumler *et al.*, 2022). Investigations reported that sorghum processing significantly enhanced grain nutritional distribution, particularly in endosperm and bran. The levels of distinct minerals exhibited fluctuations, with some minerals being concentrated while others were decreased. We selected the ES Föehn variety from three distinct sites as a sorghum seed benchmark for its nutritional properties. The evaluation of the obtained results is detailed below.

#### Thousand kernel weight

The study findings showed a reduction in the TKW (g) after the HFTU process, as were presented for the whole grains and husked grains endosperm (grits) Table A4. Considering the physical property of TKW on flour quality and its role in defining phytochemical, milling, pasting and cooking qualities, we presented the average TKW (g) of the whole grain cases. The findings were aligned with (Sruthi *et al.*, 2021), grain processing resulted in TKW reduction.

#### Total protein

A higher protein concentration in the endosperm (grits) part of the husked grains proved the efficiency of the HFTU process; this aligned with the findings of (Khalid *et al.*, 2022; Omer *et al.*, 2023), pointing to a high concentration of crude protein in the endosperm (grits) part (Table A4). The ESMonsoon variety from Hortobágy had the highest average of 1.9% in the endosperm (grits) component. This result was

attributed to 30 (s) and 80 (s)-time units, when the averages were 1.62% and 1.64%, respectively. Although the endosperm (grits) had a higher protein % content, the bran exhibited a significant protein % concentration of 1.43%. A 12% variation between endosperm and bran showed a significance value of  $P < 0.05$ . The study showed that the protein distribution changed after the HFTU process compared to the whole grain distribution. The results suggest that the protein content in husked grain could meet dietary protein needs depending on sex and age (Poutanen *et al.*, 2022); they discussed and examined how plant protein sources optimise human health. Furthermore, flour is categorised based on the milling process and protein levels (Ejaz *et al.*, 2021), which can be evidenced by the sufficiency of the HFTU procedure in enhancing sorghum grain protein, as shown by protein content belonging to the respective varieties (Table A4).

Based on data from three regions, the ES Föehn variety benchmark had the highest protein content in the bran among the H1, E1 and Ny1 varieties, with average values of 1.8%, 1.7% and 1.5%, respectively.

#### Total dietary fibre contents

Table A4 shows that dietary fibre content varied among whole and husked grain varieties. The AS1 2021 variety from three regions had the highest concentration of dietary fibre in the endosperm (grits), 13.6% higher than in the bran, as evidence for a nutritional redistribution of *S. bicolor* after the HFTU process, as was implied from 30 (s) and 80 (s) time units with a significance level of  $P < 0.05$ , according to previous studies by (Kołodziejczyk *et al.*, 2018; Sruthi *et al.*, 2021). The study discussed the impact of dry fraction milling on enhancing the total dietary fibre content of various processed cereal grains.

#### Ash content

The findings from Table A4 show the influence of the HFTU technique on the separation between endosperm and bran based on ash results, apparent from the documented percentages of 1.9% and 2.3%, showing an increase of 22.6%. Besides that, there was further proof of the husking process's sufficiency. For example, at the demonstrated levels, the average percentage of whole grains (hummer) and husked products (TM05C) increased by 33.2% from the recorded averages of 1.5% and 2.1%, respectively, with a significance value of ( $P < 0.05$ ). The findings highlighted the beneficial impact of the HFTU approach on the degree of mineral content accumulation in both parts of the husked products. The revealed values of ash% were lined with the reported value by (Keyata *et al.*, 2021), as the investigation reported that the sorghum ash% range was 1.1%–2.4% lower than our revealed values

in our findings; however, our revealed values of ash% were in the reported range of 1.3%–3.3% by (Baholet *et al.*, 2018).

#### Phosphorus (P)

Phosphorus (P) mg kg<sup>-1</sup> was impacted by the HFTU process. When the highest average of 9004 mg kg<sup>-1</sup> was observed by the ES Föehn variety from Eszár ( $P < 0.05$ ), While the Hortobágy site showed the highest average of P mg kg<sup>-1</sup> (5115 mg kg<sup>-1</sup>) attributed to the regions in Table A3.

While the fraction times of 30 (s) and 80 (s) were recorded averages within 3601.9 and 5247.2 mg kg<sup>-1</sup> with observable variation at 46%, which can provide a good insight into P mg kg<sup>-1</sup> attributed to the HFTU process (Table A4), according to (Gutiérrez, 2013), the author discussed the connection between cardiovascular diseases and adequate dietary phosphorus consumption (Table A1).

#### Potassium (K)

Potassium (K) mineral showed an abundant content compared to other nutritional content attributed to the whole grain and husked grains Table A4. The variation of bran/endosperm was 65%. Table A3 shows that the Nyíregyháza region had the highest average for whole grains (hummer) and husked grains HFTU, at 7030 and 6871 mg kg<sup>-1</sup>, respectively, based on a significance level of ( $P < 0.05$ ).

On the other hand, the K mg kg<sup>-1</sup> content averages were attributed to 30 (s) and 80 (s) and observed at 4543.5 and 6149.2 mg kg<sup>-1</sup>, respectively.

The findings were evidence of the acceptable K mg kg<sup>-1</sup> content range, which can meet the recommended ranges for the quality requirements and human dietary needs, as observed in Tables A1 and A4 (National Academies of Sciences, Engineering, 2019). The reports recommended a daily potassium intake between 2300 and 7950 mg kg<sup>-1</sup>; based on these values and recommended values (Table A1), our revealed amounts of K mg kg<sup>-1</sup> among the investigated varieties emphasised the efficiency of fulfilling the potassium mineral dietary requirements.

#### Sulphur (S)

The content of S mg kg<sup>-1</sup> showed a noticeable increase attributed to the HFTU process among all the examined varieties, which ranged from 899 to 2061 mg kg<sup>-1</sup> aligned with (Hill *et al.*, 2023) recommendation for adequate balanced dietary sulphur for disease prevention. The findings showed a ratio of N/S at 16:1 based on (w/w), after the HFTU process, which was indicated by previous findings (Bonnot *et al.*, 2023; Hill *et al.*, 2023); their reports showed that sulphur is a vital element for ensuring the quality of seeds and the production of proteins that include high

levels of amino acids that contain sulphur, such as methionine and cysteine. In comparison, the recorded variation attributed to bran/endosperm was 36%. In comparison, the noticed variation based on the 30 (s) and 80 (s) fraction times was 18% attributed to demonstrated averages at 1197.9 and 1415.9 mg kg<sup>-1</sup> and the values implicated from both time units are detailed in Table A4.

#### Calcium (Ca)

The calcium (Ca) mineral showed a significant effect implied by the HFTU process. The average Ca mg kg<sup>-1</sup> in bran and endosperm (grits) was 1371.7 and 603 mg kg<sup>-1</sup>, respectively, as was shown in Table A4, with a significance value of  $P < 0.05$ . According to (Hill *et al.* 2023); Papanikolaou *et al.* 2020), processed grains may fulfil calcium mineral dietary requirements, as represented in Table A1. At the same time, the Nyíregyháza site recorded the lowest average of 830 mg kg<sup>-1</sup>, which was higher than the reported range of 0.233–0.411 g kg<sup>-1</sup> by (Maurya *et al.*, 2023); the reported range was implied by processed sorghum. The ratio of Ca:P was revealed at 0.2:1 in the husked products, referring to the quality of the tested grain varieties.

#### Magnesium (Mg)

According to Table A4, the HFTU technique significantly impacted the Mg mg kg<sup>-1</sup> contents, as was evidenced by the averages of whole grains and husked grains outcomes ( $P < 0.05$ ), within averages of 1379.8 and 2681.0 mg kg<sup>-1</sup> within variation at 94.4%. The findings were aligned with (Papanikolaou *et al.*, 2020), a study that discussed the implications of grain processing on mineral bioavailability enhancements of whole grains and grain products.

#### Sodium (Na)

The amounts of sodium (Na) minerals among the different varieties of *S. bicolor* increased, attributed to the HFTU process. For example, the ES Monsoon variety was sourced from different sites, while the AS1 2021 IMI variety was sourced from the Nyíregyháza site (Table A3). In comparison, the Hortobágy site showed the highest average of Na mg kg<sup>-1</sup> within 116 mg kg<sup>-1</sup>, as was shown in Table A4, ( $P < 0.05$ ). The observed variation of Na mg kg<sup>-1</sup> can play various roles based on the final product, when the Na mineral concentration in processed grains is crucial for conserving nutritional content, enhancing flavour and texture, ensuring food quality, resolving public health issues and optimising processing methods (Henney *et al.*, 2010; National Academies of Sciences, Engineering, 2019), specifically when the result ensured that the lowest ratio of K:Na was 30:1 as presented by the

lowest average of K and Na mg kg<sup>-1</sup> at 2236 and 75 mg kg<sup>-1</sup>, respectively, ( $P < 0.05$ ).

The difference in Na mg kg<sup>-1</sup> resulted from 30 (s) and 80 (s) fraction times, shown at 0.38%, implied from the averages of 104.5 and 104.9 mg kg<sup>-1</sup>.

#### Copper (Cu)

Table A1 and A4 show that the copper mineral fell within the acceptable ranges ( $P < 0.05$ ) of the recommended values from the grain sources (EFSA, 2015). The report discussed the acceptable copper intake levels for different human food groups. The influence of the HFTU technique was emphasised by revealing the average of whole grains and husked grains of 3.6 and 8.3 mg kg<sup>-1</sup>, respectively.

#### Iron (Fe)

The revealed results showed the sufficient impact of the HFTU process on the iron mineral, as displayed in Table A4, with a significance value of ( $P < 0.05$ ). When the highest average of Fe mg kg<sup>-1</sup> was observed among the varieties, they were sourced from the Esztár site within 66 mg kg<sup>-1</sup> (Table A3) and the ratio variation of bran/endosperm was 62%. In comparison, the implied average of 30 (s) and 80 (s) was demonstrated at 43.2 and 59.6 mg kg<sup>-1</sup>, respectively. As evidence of the HFTU process precision and accuracy, that Fe mg kg<sup>-1</sup> was associated with N % contents, for example, H1 and Nyl varieties (Table A4), the result was aligned with previous findings (Ashok Kumar *et al.*, 2013), The research suggested that increasing the iron concentration in sorghum grains might enhance their protein content, hence improving the nutritional value and quality of the respective varieties and offering the opportunity to create unique products that meet elderly dietary requirements.

#### Zinc (Zn)

The HFTU process significantly impacted the zinc mineral bioavailability in the husked *S. bicolor* grains (Table A4), with a significant value of  $P < 0.05$ . When the variation % of 30 (s) and 80 (s) time units were recorded at 63.9%, it was attributed to an average of 18.5 and 30.3 mg kg<sup>-1</sup>, respectively.

#### Manganese (Mn)

Manganese mineral content was similar to other mineral content as implied from the HFTU process, as was observed by the average of whole and husked grains within 21.9 and 27.8 mg kg<sup>-1</sup>, respectively. Despite the good implication from the HFTU technique, the difference did not show a significant value ( $P > 0.05$ ). Additionally, Table A4 showed that the variation percentage of 30 (s) and 80 (s) was 18%.

### Detection of correlations between the mineral compositions and examined factors

A discriminant analysis test assessed the correlation feature to distinguish between mineral composition and other analysed factors, as shown in Figure A1, and it showed that the original data had a total correlation of 78.4% between C1 (69.2%) and C2 (8.6%), indicating a good connection between the main data items. The classic plot displayed the average ellipses, normal 50% contours and biplot rays. Furthermore, a substantial connection was seen among the three sites, including Nyiregyháza, Esztár and Hortobágy. Consequently, the Nyiregyháza site had a weak correlation with two other sites on C2 at 8.6%, contrary to Esztár and Hortobágy, which showed a strong correlation on C1 at 69.2%. The discriminant analysis revealed a substantial linear association among minerals such as P, Na, Ca and Zn, whereas the other minerals exhibited weak correlations. The discriminant analysis revealed a strong relationship between the mineral composition and the origin sites, such as Nyiregyháza, Esztár and Hortobágy. The correlation between the analysed variables in the data was illustrated in its raw form. For greater reliability in mineral composition correlations and quality assessment issues, the revealed findings were compared to previous studies (Ikem *et al.*, 2023; Rubio-Armendáriz *et al.*, 2023), in which the researchers reported that the associations between the nutritional composition of cereal grains vary by geographical source.

### Colour measurements analysis

Due to the quality evaluation issues, the researchers have investigated the colour parameters in Table A5. The evaluations were created attributed to the influence of HFTU process for the 30 (s) and 80 (s)-unit time compared to grinding flour by a hammer mill aligned with (Sruthi *et al.*, 2021; Adebo & Kesa, 2023), influencing the colour properties by grain processing. The explanation of the obtained results is detailed below.

According to colour profile assessments Table A5 and Figure A2, the  $L^*$  darkness parameter was reduced after the HFTU process of 30 (s) unit time showed a varied correlation between the colour component spectrum ( $L^*$ ,  $a^*$  and  $Y$ ) and diverse *S. bicolor* variety group (ES Föehn, ES Monsoon and AS1 2021IMI) as follows:  $r = 0.627$ ,  $P = 0.01$ ,  $r = 0.796$ ,  $P = 0.05$  and  $r = 0.901$ ,  $P = 0.03$ . In contrast, a weak correlation was observed in the  $b^*$  component spectrum within  $r = 0.382^*$ , while the colour correlation between the colour parameters spectrum, namely  $L^*$ ,  $a^*$  and  $Y$ , had correlation coefficients of  $r = 0.806$ ,  $P = 0.5$ ,  $r = 0.808$ ,  $P = 0.02$  and  $r = 0.895$ ,  $P = 0.04$ ,

respectively. However, a weak link was discovered between the  $b^*$  (yellow) and the *S. bicolor* variety factor being studied. The correlation coefficient was  $r = 0.349$ ,  $P = 0.21$  for 80 (s) time units. Despite the varied correlation coefficient, there is no mentionable variation for the colour parameter average and the respective varieties Figure A2. The increasing fraction time units, specifically 80 (s), had reduced the darkness and perhaps reduced the condensed tannin, which evidenced that the HFTU can enhance the physical properties of the sorghum product, similar to previous report findings by (Sejake *et al.*, 2020; Sruthi *et al.*, 2021; Rumler *et al.*, 2022).

### Conclusion

The inquiry was conducted to develop improved husking technologies to provide more efficient, cost-effective and time-efficient sorghum products to meet research advancements and market demands. We investigated the advancement of mechanised husking techniques, optimisation of husking factors and enhancement of post-husked products to evaluate the effectiveness and sustainability of sorghum grain processing.

We used two different time units, 30 (s) and 80 (s), to regulate the synthesis of husked fractions, namely endosperm (grits) and bran, to accomplish this goal. Using these time units resulted in the synthesis of two featured fractions: the HFTU technique efficiently redistributed and concentrated nutritious components such as TKW, crude protein, total dietary fibre, ash, K, S, Cu, Fe, Zn and Mn in the husked grains. This method allows for the development of unique products with varied nutritional compositions customised to individual dietary needs, as thoroughly explored in the current study literature. Statistical variations in nutritional compositions were found across regions, emphasising the impact of the husking method based on the variety's source.

Despite to no noticeable variation resulted from colour profiles assessing, the statistical analysis of colour parameters was indicated the significant impact of the HFTU process on the varieties colour characteristics, which can provide a range of goods tailored to different customer tastes based on their preferences.

The knowledge obtained during the husking process may be used as useful instructions for carrying out the HFTU procedure. Moreover, smaller producers and processors may improve the competitiveness of sorghum products on the market and promote environmentally friendly production by adopting current husking technology.

Based on the obtained results, the research suggests creating items from the analysed varieties through further physical and chemical examinations. Furthermore, it is recommended to do in vivo research to examine

the nutritional makeup of the different sorghum types to have a comprehensive knowledge of the advantages of the employed husking procedure.

### Author contributions

**Maha Khalfalla:** Writing – original draft; data curation; software; formal analysis; visualization; investigation; validation; methodology; writing – review and editing. **László Zsombik:** Methodology; conceptualization; supervision; investigation; validation; project administration. **Gerda Diósi:** Investigation; validation. **Zoltán Györi:** Supervision; data curation; resources; validation; project administration; funding acquisition; writing – review and editing; methodology; conceptualization.

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### Ethics declarations

Not applicable.

### Conflict of interest

The authors state that they have no competing financial interest or personal connections that may have impacted the study's conclusions.

### Data availability statement

The authors state that the data behind the results of this study can be found in the paper's contents. The corresponding author may provide the raw or analysed data that backs up the conclusions of this inquiry based on the request.

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## Appendix A

**Table A1** Recommended daily allowance for human age groups

Variables	Daily intake mg/100 g Grain	RDA/AI (mg day <sup>-1</sup> ) –F	RDA/AI (mg day <sup>-1</sup> ) –M	% Intake –F	% Intake –M
P	308.06–678.19	700	700	44–97	44–97
K	96.35–232.26	2600	3400	4–9	3–7
Ca	8.01–19.00	1000	1000	1–2	1–2
Mg	57.58–92.74	320	420	18–29	14–22
Cu	0.12–0.30	0.90	0.90	13–33	13–33
Fe	1.36–3.37	18.00	8.00	8–19	17–42
Zn	1.32–2.54	8.00	11.00	17–32	12–23
Na	0.30–0.54	1500	1500	0	0
Mn	0.47–1.31	1.80	2.30	26–73	20–57
Cr	0.01–0.06	0.025	0.035	32–228	23–163

AI, adequate intake; F, female (31–50 years); M, male (31–50 years); RDA, recommended daily allowance.

Source: (Jaćimović *et al.*, 2023).

**Table A2** Details of the names and geographical origins of the variety

Code	Variety	Regions
H4	ES Monsoon	Hortobágy
E4	ES Monsoon	Esztár
Ny4	ES Monsoon	Nyíregyháza
H7	AS1 2021 IMI	Hortobágy
E7	AS1 2021 IMI	Esztár
Ny7	AS1 2021 IMI	Nyíregyháza
H1	ES Föehn	Hortobágy
E1	ES Föehn	Esztár
Ny 1	ES Föehn	Nyíregyháza

**Table A3** Sorghum grain nutritional content based on the various regions

Variables	Whole grains (Hummer)				Husked grains (TM05C husker)			
	Hortobágy	Esztár	Nyíregyháza	P-value	Hortobágy	Esztár	Nyíregyháza	P-value
Total dietary fibre g kg <sup>-1</sup>	134 ± 23.0	134 ± 18.0	134 ± 17.0	0.3	149 ± 12.3	138 ± 14.1	139 ± 8.2	0.05
Total protein g kg <sup>-1</sup>	16 ± 2.0	15 ± 2.0	15 ± 2.0	0.22	16 ± 7.8	19 ± 8.2	16 ± 8.0	0.2
Ash g kg <sup>-1</sup>	15 ± 0.5	14 ± 0.1	13 ± 0.1	0.04	27 ± 0.03	21 ± 0.05	14 ± 0.07	0.01
P mg kg <sup>-1</sup>	4883 ± 1193.0	5075 ± 1096.0	4426 ± 964.0	0.44	5115 ± 3623.3	4482 ± 3258.1	4995 ± 3038.3	0.71
K mg kg <sup>-1</sup>	5901 ± 745.4	6175 ± 849.4	7030 ± 1180.0	0.04	5852 ± 3202.2	5013 ± 3013.6	6871 ± 3509.0	0.05
S mg kg <sup>-1</sup>	1280 ± 633.8	1280 ± 633.5	1234 ± 403.2	0.73	1360 ± 505.5	1264 ± 319.8	1447 ± 461.3	0.05
Ca mg kg <sup>-1</sup>	519 ± 120.2	502 ± 104.8	507 ± 127.2	0.59	1071 ± 579.7	1061 ± 557.0	830 ± 544.9	0.02
Mg mg kg <sup>-1</sup>	1356 ± 211.9	1356 ± 159.8	1400 ± 163.6	0.67	2697 ± 2114.1	2137 ± 1303.1	3210 ± 1209.0	0.05
Cu mg kg <sup>-1</sup>	3 ± 1.0	4 ± 1.0	4 ± 1.0	0.51	9 ± 4.7	9 ± 3.3	6 ± 4.4	0.03
Fe mg kg <sup>-1</sup>	66 ± 9.1	54 ± 6.5	53 ± 5.3	0.01	59 ± 33.9	66 ± 38.5	46 ± 32.5	0.05
Zn mg kg <sup>-1</sup>	20 ± 1.3	24 ± 2.3	22 ± 3.0	0.05	34 ± 25.9	28 ± 7.0	21 ± 14.4	0.04
Na mg kg <sup>-1</sup>	35 ± 13.5	35 ± 10.5	44 ± 13.5	0.14	116 ± 32.2	108 ± 27.5	93 ± 22.2	0.03
Mn mg kg <sup>-1</sup>	21 ± 6.4	28 ± 5.1	20 ± 5.5	0.02	33 ± 26.0	37 ± 24.0	30 ± 22.0	0.53

Values 0 refer to the processed grains by hammer mill, while 30 (s) and 80 (s) refer to the husked grains by TM05C, husker. mean ± SD, mineral contents were calculated from three replication readings, while the total protein, total dietary fibre and ash were calculated from two replication readings,  $P \leq 0.05$ .

**Table A4** Descriptive data analysis of the nutritional profiles of *Sorghum bicolor* grain varieties whole flour (hammer) and husked grain HFTU process

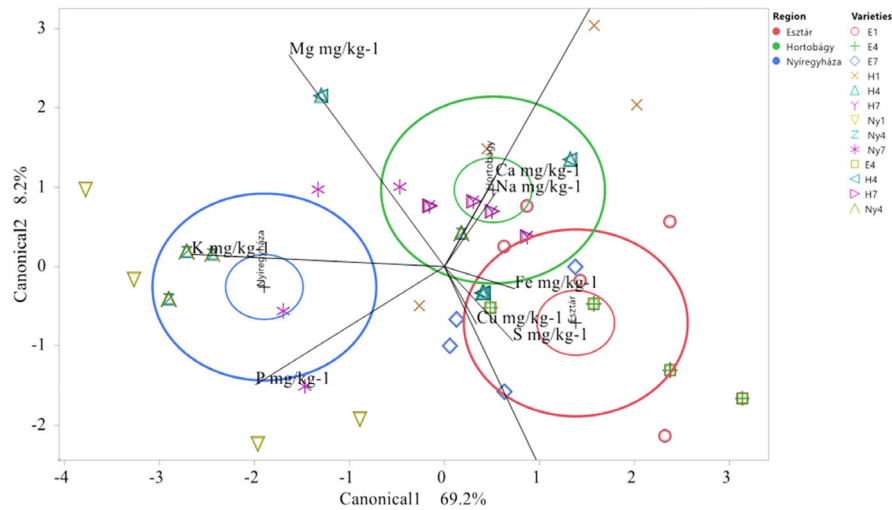
Variables	Grain parts	T	KW	Total protein	TDF	Ash	P	K	S	Ca	Mg	Cu	Fe	Zn	Na	Mn
		g	g	g kg <sup>-1</sup>	g kg <sup>-1</sup>	g kg <sup>-1</sup>	g kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>
H4	1 <sup>a</sup>	40	12 ± 1.0	135 ± 14.0	14 ± 0.42	5385 ± 527.5	6584 ± 261.4	1030 ± 77.8	571 ± 75.0	1472 ± 228.0	4 ± 1.9	65 ± 7.9	24 ± 2.9	34 ± 11.7	28 ± 5.9	
	2	32	19 ± 0.9	16.3 ± 10.0	24 ± 0.18	1709 ± 1569.0	2419 ± 971.8	1076 ± 174.2	397 ± 38.9	1155 ± 252.3	5 ± 2.0	24 ± 9.0	9 ± 4.8	80 ± 8.2	9 ± 4.0	
	3	-	16 ± 0.2	172 ± 4.0	28 ± 0.01	7657 ± 2298.7	9848 ± 71.5	1511 ± 474.9	1854 ± 148.2	2327 ± 123.4	13 ± 3.6	99 ± 1.6	59 ± 8.7	132 ± 36.3	46 ± 6.1	
E4	1 <sup>a</sup>	28	13 ± 0.5	136 ± 14.6	13 ± 0.07	5824 ± 1002.5	6150 ± 797.3	1012 ± 116.9	505 ± 179.6	1381 ± 162.0	3 ± 1.2	54 ± 2.0	22 ± 1.7	33 ± 12.5	17 ± 3.0	
	2	15	16 ± 0.7	137 ± 13.0	19 ± 0.03	3038 ± 368.6	4289 ± 778.7	1282 ± 189.3	943 ± 635.4	2092 ± 212.4	5 ± 1.5	21 ± 5.3	11 ± 3.9	95 ± 11.6	11 ± 2.5	
	3	-	14 ± 0.8	145 ± 3.1	24 ± 0.01	8706 ± 4183.9	9891 ± 95.9	1575 ± 393.6	1336 ± 543.1	3633 ± 401.0	9 ± 0.2	86 ± 34.5	60 ± 31.0	98 ± 14.7	51 ± 7.2	
Ny4	1 <sup>a</sup>	25	14 ± 0.7	118 ± 6.8	13 ± 0.04	5098 ± 473.1	7299 ± 1014.1	1018 ± 28.5	623 ± 62.7	1526 ± 90.9	4 ± 1.8	54 ± 8.9	21 ± 4.3	56 ± 8.8	22 ± 6.8	
	2	11	15 ± 0.1	124 ± 4.2	14 ± 0.70	1620 ± 1483.7	2258 ± 649.4	1032 ± 95.0	516 ± 203.0	1632 ± 236.0	9 ± 0.35	24 ± 10.0	9 ± 4.8	115 ± 35.6	9 ± 3.7	
	3	-	14 ± 0.3	139 ± 4.3	17 ± 0.01	8416 ± 274.2	9076 ± 1195.0	1596 ± 73.5	1451 ± 33.6	3431 ± 139.4	16 ± 0.4	80 ± 44.6	45 ± 5.0	101 ± 15.6	52 ± 2.6	
H7	1 <sup>a</sup>	35	16 ± 1.0	141 ± 14.5	12 ± 0.11	4302 ± 1831.1	5444 ± 1182.0	1327 ± 515.2	481 ± 197.2	1700 ± 96.5	3 ± 1.7	57 ± 12.2	23 ± 1.1	56 ± 8.9	23 ± 3.0	
	2	21	17 ± 0.2	152 ± 11.0	25 ± 0.14	2989 ± 162.0	3014 ± 537.4	1111 ± 266.0	1205 ± 611.1	1686 ± 274.3	6 ± 1.3	50 ± 13.5	14 ± 1.2	123 ± 1.3	14 ± 1.9	
	3	-	16 ± 1.0	147 ± 2.2	34 ± 0.01	8142 ± 2960.8	7662 ± 1393.3	1333 ± 226.7	1448 ± 203.3	3831 ± 560.7	10 ± 0.7	77 ± 58.6	52 ± 18.2	103 ± 2.6	54 ± 17.5	
E7	1 <sup>a</sup>	35.5	14 ± 0.2	149 ± 20.0	11 ± 0.03	4469 ± 1044.0	5327 ± 705.4	1832 ± 1028.1	508 ± 76.0	1232 ± 82.0	3 ± 0.01	51 ± 10.5	21 ± 1.3	32 ± 4.8	18 ± 3.2	
	2	17	15 ± 0.1	142 ± 5.7	184 ± 0.08	2396 ± 427.3	2971 ± 301.1	968 ± 206.9	434 ± 91.7	1254 ± 200.4	6 ± 1.1	40 ± 16.2	11 ± 6.3	81 ± 18.7	13 ± 0.2	
	3	-	15 ± 0.3	129 ± 2.6	22 ± 0.02	7123 ± 607.5	7640 ± 1133.1	2061 ± 543.1	961 ± 432.3	4004 ± 262.6	13 ± 4.4	34 ± 3.9	37 ± 4.2	101 ± 25.3	31 ± 15.2	
Ny7	1 <sup>a</sup>	29	11 ± 0.1	114 ± 1.0	12 ± 0.02	4605 ± 129.0	4997 ± 46.9	1657 ± 484.8	383 ± 102.0	1199 ± 52.3	4 ± 5.1	57 ± 2.0	24 ± 4.9	37 ± 13.3	23 ± 3.4	
	2	23	15 ± 0.8	114 ± 1.8	9 ± 0.36	1823 ± 84.4	5886 ± 417.2	1214 ± 400.3	809 ± 37.8	1717 ± 1172.0	6 ± 0.9	40 ± 2.9	7 ± 0.8	111 ± 15.1	17 ± 4.8	
	3	-	16 ± 2.1	112 ± 6.5	11 ± 0.02	8612 ± 1731.0	8432 ± 103.1	1649 ± 248.8	1760 ± 248.1	3912 ± 532.8	6 ± 2.6	88 ± 11.9	36 ± 0.1	86 ± 8.3	59 ± 9.2	
H1	1 <sup>a</sup>	29	17 ± 0.3	135 ± 13.7	12 ± 0.33	4961 ± 1080.6	6226 ± 466.1	997 ± 51.4	505 ± 86.0	1478 ± 207.4	4 ± 1.9	76 ± 5.6	23 ± 1.9	42 ± 12.6	33 ± 2.7	
	2	12	14 ± 0.6	138 ± 13.2	24 ± 0.12	1457 ± 623.2	2236 ± 615.1	899 ± 77.2	415 ± 31.5	600 ± 145.2	4 ± 0.1	28 ± 7.3	9 ± 4.6	75 ± 11.9	6.3 ± 1	
	3	-	18 ± 0.1	132 ± 12.2	29 ± 0.02	5904 ± 2292.1	8090 ± 115.2	1478 ± 1.4	872 ± 14.1	4089 ± 476.0	9 ± 0.09	84 ± 2.5	36 ± 2.8	133 ± 10.9	46 ± 6.3	
E1	1 <sup>a</sup>	36	13 ± 0.4	167 ± 10.5	18 ± 0.41	4933 ± 1136.0	6226 ± 588.0	1903 ± 51.1	494 ± 73.0	1454 ± 173.5	4 ± 1.9	56 ± 6.5	24 ± 1.8	35 ± 5.7	26 ± 7.8	
	2	15	15 ± 1.1	128 ± 11.3	19 ± 0.02	1191 ± 876.3	2339 ± 108.2	934 ± 82.2	351 ± 27.4	1502 ± 898.0	6 ± 0.1	23 ± 8.7	5 ± 1.9	87 ± 15.8	6 ± 6.5	
	3	-	17 ± 0.8	122 ± 15.1	24 ± 0.01	9004 ± 537.1	9860 ± 744.4	2105 ± 510.0	1594 ± 359.7	4320 ± 2235.1	15 ± 3.8	103 ± 91.0	47 ± 15.0	154 ± 36.8	75 ± 2.2	
Ny 1	1 <sup>a</sup>	31.7	13 ± 0.5	125 ± 9.6	13 ± 0.39	3576 ± 132.7	8072 ± 489.2	985 ± 40.6	514 ± 80.3	1381 ± 169.4	4 ± 1.4	49 ± 4.0	21 ± 1.0	35 ± 11.0	16 ± 1.9	
	2	17	14 ± 0.2	112 ± 15.0	16 ± 0.05	1682 ± 732.0	2199 ± 361.0	1026 ± 90.2	362 ± 51.9	1480 ± 540.7	5 ± 1.5	28 ± 4.8	11 ± 3.7	103 ± 30.2	11 ± 5.0	
	3	-	15 ± 0.01	124 ± 2.3	19 ± 0.01	6080 ± 3007.4	8301 ± 195.7	1551 ± 104.0	1071 ± 245.2	3591 ± 1002.1	20 ± 11.7	97 ± 23.2	40 ± 4.0	120 ± 34.6	154 ± 37.2	
P-value (wholegrains)	-	0.03	<0.001	0.02	0.05	<0.001	0.003	0.003	0.21	0.2	<0.001	0.76	0.5	<0.001	0.2	
P-value (husked grains (Endosperm+bran))	-	0.05	0.05	0.04	0.05	0.27	0.01	0.03	0.03	0.05	0.003	0.03	0.04	<0.001	0.17	

Numbers refer to 1<sup>a</sup> whole grain processed by hammer mill, 1 whole grain, 2: Endosperm, 3: Bran, values (mean ± SD), of the TKW and mineral content were calculated from three replication readings, while the total protein total dietary fibre, and ash contents were calculated from two replication readings, on dry basis,  $P \leq 0.05$ .

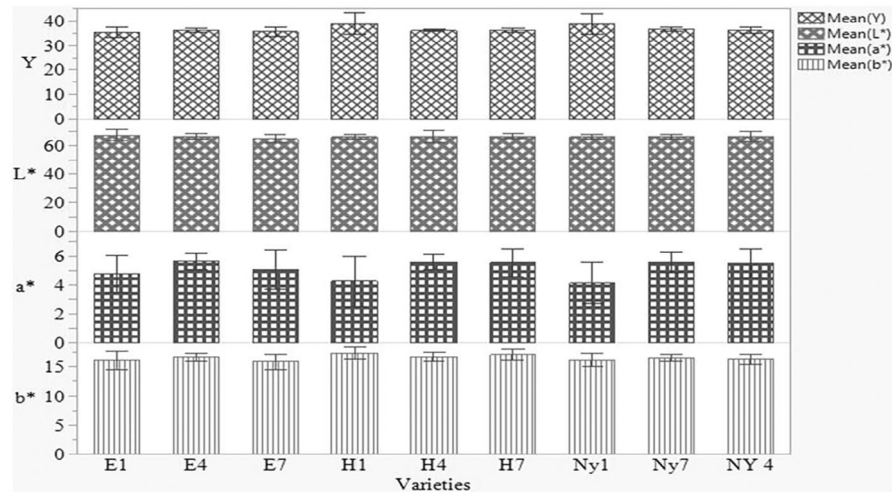
**Table A5** Statistical descriptive of the colour parameter based on whole grains and husked fraction time units

Parameters	0 (s)	30 (s)	80 (s)	P-value
L*	69.8 ± 2.9	66.3 ± 2.2	65.0 ± 1.5	0.88
a*	5.1 ± 1.0	5.2 ± 1.0	4.9 ± 1.5	0.009
b*	16.2 ± 1.1	16.4 ± 1.0	16.8 ± 1.0	0.45
Y	40.7 ± 1.1	36.0 ± 1.2	38.0 ± 3.5	0.05

Values 0 refer to the grond grains by hammer mill, while 30 (s) and 80 (s) refer to the husked grains by TM05C, husker. Mean ± SD were calculated from three replication readings.



**Figure A1** Discriminant analysis plot correlations between *Sorghum bicolor* varieties, regions and mineral patterns in the basic data,  $P \leq 0.05$ .



**Figure A2** Evaluation of colour profiles based on the *Sorghum bicolor* respective varieties  $P \leq 0.05$ .