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Investigating the impact of sorghum variety and type of flour on chemical, functional, rheological and baking properties

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ABSTRACT

The objective of this study was to define quality parameters for sorghum varieties that contribute to bread-making performance of sorghum-enriched breads. Therefore, eight sorghum varieties (milled into whole grain sorghum flour (WGSF) and a flour fraction of <400 μm (RSF)) were analyzed for their chemical, rheological, baking and sensory properties. Results have shown that higher total dietary fiber (TDF) and total polyphenol content (TPC) correlated with a lower RVA peak and final viscosity and with higher Farinograph dough stability and lower dough softening, which in consequence resulted in increased bread volume and decreased bread crumb firmness. Based on these findings, the use of whole grain sorghum flour resulted in higher bread quality than refined flour. The comparison of eight sorghum varieties revealed high differences between them; in particular in terms of sensory properties. Icebergg produced favorable bread volume and crumb firmness and was the most liked in the sensory test, also Arsky and Armorik showed promising results. The variety PR88Y92 was the most disliked one. For future use, selection of sorghum species or variety is an important criterion to obtain favorable final bakery products and high consumer acceptance.

1. Introduction

Climate-smart grains have gained interest in recent years, as wheat has been negatively affected from the consequences of climate change. Hot and dry weather affected the yield of wheat crops as well as its quality (Gagliardi et al., 2020; Trnka et al., 2019). Encouraging grain biodiversity could be a benefit in compensating for wheat losses, considering that wheat is an important grain in the cereal industry. In this respect, sorghum seems to be a promising grain as it is resistant to extreme weather conditions as well as rich in health-promoting bioactive compounds (Speranza et al., 2021; Taylor and Duodu, 2018). Sorghum is widely cultivated in many parts of the world, especially in Africa and Asia. However, the grain has gained interest in the past few years due to its many nutritional benefits (Taylor and Duodu, 2018). As sorghum is a gluten-free grain, it can be consumed by people suffering from celiac disease or gluten intolerance. It is also high in protein, vitamins, and minerals, including magnesium, calcium, potassium, and iron (Tasie and Gebreyes, 2020). Sorghum is a highly nutritious grain that can be utilized in various foods, such as porridges, bakery products, soups, and stews (Taylor and Duodu, 2018). It has also been applied to a lower extent to wheat products to enhance their nutritional and technological properties. For example, one study showed that the consumption of sorghum wheat breads improved the antioxidative status of individuals. However, this study had some limitations as the intervention duration was short and just one post-intervention blood sample was analyzed (Hajira and Khan, 2022). Furthermore, sorghum was found to have a better rheological and higher baking properties compared to other gluten-free and climate-smart grains, like amaranth or millet (Rumler et al., 2023).

Products made from sorghum (porridge, flat breads, beer) have their origin mainly in Africa (Taylor and Duodu, 2018). However, until now sorghum has not been used within the Western diet. Indeed, traditional sorghum bread does not require high volume, in contrast to Western bakery products, where volume is defined as a quality parameter. A

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possible way to introduce sorghum into the Western bakery industry is to produce flour blends from sorghum and wheat.

Sorghum is found in a great range of varieties, which differ in terms of chemical composition, in particular their amount and composition of secondary plant metabolites (Tasie and Gebreyes, 2020). Therefore, it is necessary to investigate the suitability of different sorghum varieties for food production. The aim of this study was to investigate and identify which parameters or chemical components are important in order to obtain an acceptable final bread quality. For this purpose, eight different sorghum varieties, grown in Austria, were included in the study. From each variety a whole grain sorghum flour (WGSF) and a refined sorghum flour (RSF) were analyzed for their chemical, physical, rheological, baking and sensory properties. The analysis of the different flour types (WGSF and RSF) should reflect whether it is necessary to use a refined flour for improving the chemical rheological and technological bread properties. Although it is generally known that finer flours lead to better quality properties, this has not been clearly established for sorghum so far.

2. Materials and methods

2.1. Materials

Grains of eight different sorghum cultivars grown in Austria, namely Armorik, Ggolden, Arsky, Huggo, Icebergg, Kalatur, Arabesk and PR88Y92 were selected in this investigation according to their potential availability in the future. The grains were milled into wholegrain flours (WGSF) by Hochmühle Frauenlob GmbH (Plainfeld, Austria) using a pilot-scale stone mill (ABC Hansen Universal Mill, ABC Hansen, Randers, Denmark). Prior to milling, the sorghum kernels were dehusked and squeezed by a pilot scale dry flake squeezer (Goldflocke GF-40-Super, M&A Hommel GmbH, Wülfrath, Germany) in order to increase the flour yield (increase of 10 %). To produce refined sorghum flour (RSF), a part of the wholegrain flours was sifted using a <400 μm sieve (Einkasten-Plansichter, Rüter Maschinen, Hille, Germany) as suggested by Rumler et al. (2021). About one third of the whole grain flour showed a particle size of >400 μm and two thirds a particle size of <400 μm. Within the <400 μm fraction approximately 39 % had a particle size between 400 and 180 μm and the remaining was below 180 μm. The flour fraction (<400 μm) was used for the subsequent experimental trials. Refined wheat flour (RWF; ash content 0.7 % d.m.) was purchased by GoodMills Österreich GmbH (Schwechat, Austria).

2.2. Chemical analysis

Moisture was measured according to ICC standard method Nr. 110/1. Ash content was determined by following the ICC standard method Nr 104/1. For measuring the protein content, the ICC standard method Nr. 105/2 with a nitrogen conversion factor of 6.25 was used. Crude fat was measured according to ICC standard method Nr. 136. For the determination of total starch and total dietary fiber enzymatic test kits (Megazyme International Ireland Ltd., Wicklow, Ireland) were used. The total phenolic content (TPC) was analyzed by the Folin–Ciocâlteu method according to Speranza et al. (2021). All chemical measurements were carried out in triplicate.

2.3. Physicochemical and rheological properties

For the determination of the water absorption index (WAI) and water solubility index (WSI) the method of Anderson (1982) was followed. In summary, 2.5 g samples were mixed with 30 mL of distilled water and agitated for half an hour at a temperature of 30 °C, centrifuged (1739×*g* for 10 min) and separated from the supernatant. The residue was further dried for 4 h at 103 °C. WAI was reported as the quantity of water absorbed per gram of dry sample, while WSI was reported as a percentage of dry solids based on 2.5 g of dry sample. The pasting properties of the sorghum flours were evaluated by an RVA 4500 (Perkin Elmers, Waltham, USA) according to the method of Frauenlob et al. (2018). For measuring mixing properties and three-dimensional extension of sorghum wheat blends (20 % sorghum, 80 % wheat), the ICC standard method 115/1 (Farinograph with a bowl of 300 g, Brabender® GmbH & Co. KG, Duisburg, Germany) and the AACCI method 54-30.02 (Alveograph Chopin®, Villeneuve-la-Garenne Cedex, France) were used, respectively. All physical measurements were carried out in triplicate.

2.4. Baking trials

Standard wheat baking trials were carried as described by Rumler et al. (2023). RWF was replaced by 20 % of either WGSF or RSF. The percentage of substitution was chosen in pretrials based on the maximal addition, without significantly affecting the bread quality. Baking loss, volume (specific volume and volume yield), crumb firmness and elasticity were analyzed according to Waziiroh et al. (2021). The baking loss, which represents the quantity of water that evaporated during baking, was determined by dividing the weight of the dough by the weight of the loaf 24 h after baking. The bread volume analyzer BVM 6600 (PerkinElmer, Waltham, MA, USA) was used to determine the specific volume (cm^3) and the volume yield (cm^3/100 g flour) of the bread. In order to assess crumb firmness and relative elasticity, the breads were analyzed using a modified version of the AACC Method 74-09.01. Three 3 cm-thick slices were cut from each bread, resulting in 27 measurements for each formulation. A Texture Analyzer (Model TA-XT plus C, Stable Micro systems™ Co., Godalming, UK) equipped with a 50 kg load cell and a cylindrical compression probe (SMS P/100) was used to perform a 50% uniaxial compression test.

2.5. Sensory analysis

Wheat-sorghum breads were evaluated by an untrained panel consisting of 60 participants (45% men, 55% women) aged 14–62 years. Selected bread sensory attributes (crumb color, porosity, smell, taste, aftertaste, texture and overall impression) were evaluated using a 9-point hedonic scale (1 = Dislike extremely and 9 = Like extremely) to determine sensory differences between sorghum varieties. Each participant received one slice of each bread, resulting in a total of 8 sample slices. For sensory analysis, formulations made from whole grain sorghum flour (20% replacement of refined wheat flour) were chosen.

2.6. Statistical evaluation

Statgraphics Centurion 19.4.01 (Statpoint Technologies, Inc., Warrenton, VA, USA) was used for analyzing the data. In order to determine significant differences between the results an ANOVA and Fisher's least significant test ($\alpha = 0.05$) were applied. Correlations were calculated by applying the Pearson's correlations procedure ($\alpha = 0.05$).

3. Results and discussion

3.1. Chemical properties

Table 1 shows the chemical properties of the sorghum flour fractions from eight different varieties. The ash content of the WG fractions ranged between 1.51 and 1.82 % dm, the lowest was observed for Icebergg and the highest for Armorik. The RSFs had an ash content between 1.49 % (Arabesk) and 1.69 % (Huggo), which was not much lower than for the WG fractions. The fat content of the WGSF and RSF ranged between 2.85 (Icebergg) - 3.73 % dm (Armorik) and between 2.73 (Arabesk) - 3.69 % dm (Armorik), respectively. In accordance with the present findings, a previous study has demonstrated that unlike wheat, sorghum flour fractions (e.g. wholegrain or refined flour) cannot be differentiated by the ash and fat content (Rumler et al., 2021). It seems that the ash and the fat, both located within the germ, distributed

Table 1
Chemical properties of the flour fractions of eight different sorghum varieties.

	Ash [% dm]	Fat [% dm]	Protein [% dm]	Starch [% dm]	TDF [% dm]	TPC [mg FA/g dm]
WGSF						
Armorik	1.82 ± 0.03 ^{e}	3.73 ± 0.16 ^{d}	8.20 ± 0.03 ^{b}	71.97 ± 0.88 ^{a}	8.49 ± 1.09 ^{b}	1.57 ± 0.04 ^{bc}
Ggolden	1.69 ± 0.04 ^{bcd}	3.06 ± 0.07 ^{ab}	7.86 ± 0.02 ^{a}	71.33 ± 0.99 ^{a}	10.07 ± 0.94 ^{c}	1.60 ± 0.05 ^{bc}
PR88Y92	1.62 ± 0.09 ^{b}	3.17 ± 0.12 ^{b}	7.92 ± 0.03 ^{a}	72.73 ± 2.54 ^{a}	7.01 ± 0.97 ^{a}	1.43 ± 0.07 ^{a}
Icebergg	1.51 ± 0.02 ^{a}	2.85 ± 0.05 ^{a}	8.14 ± 0.02 ^{b}	73.59 ± 2.07 ^{a}	7.65 ± 0.92 ^{ab}	1.48 ± 0.08 ^{ab}
Arsky	1.74 ± 0.03 ^{d}	3.10 ± 0.06 ^{b}	8.63 ± 0.07 ^{d}	72.64 ± 0.97 ^{a}	8.64 ± 0.63 ^{b}	1.67 ± 0.05 ^{cd}
Huggo	1.66 ± 0.04 ^{bc}	3.06 ± 0.05 ^{ab}	8.53 ± 0.05 ^{c}	73.46 ± 1.99 ^{a}	9.81 ± 0.40 ^{bc}	1.79 ± 0.06 ^{d}
Kalatur	1.72 ± 0.05 ^{cd}	3.49 ± 0.29 ^{c}	8.28 ± 0.05 ^{c}	72.02 ± 1.02 ^{a}	6.54 ± 0.46 ^{a}	1.60 ± 0.04 ^{bc}
Arabesk	1.96 ± 0.02 ^{f}	3.66 ± 0.02 ^{cd}	9.52 ± 0.03 ^{e}	70.63 ± 2.62 ^{a}	7.83 ± 0.35 ^{ab}	1.51 ± 0.17 ^{ab}
RSF						
Armorik	1.66 ± 0.01 ^{ef}	3.69 ± 0.13 ^{e}	7.08 ± 0.01 ^{c}	76.29 ± 2.49 ^{a}	3.84 ± 0.39 ^{abc}	1.09 ± 0.04 ^{c}
Ggolden	1.54 ± 0.01 ^{b}	3.17 ± 0.08 ^{c}	6.86 ± 0.01 ^{a}	73.69 ± 3.76 ^{a}	3.53 ± 0.09 ^{ab}	0.98 ± 0.06 ^{b}
PR88Y92	1.60 ± 0.04 ^{cd}	2.86 ± 0.01 ^{ab}	7.16 ± 0.01 ^{d}	76.34 ± 3.48 ^{a}	4.01 ± 0.04 ^{c}	0.94 ± 0.02 ^{b}
Icebergg	1.57 ± 0.01 ^{bc}	2.95 ± 0.20 ^{b}	6.95 ± 0.01 ^{b}	77.97 ± 0.52 ^{ab}	3.89 ± 0.36 ^{bc}	0.98 ± 0.07 ^{b}
Arsky	1.64 ± 0.03 ^{de}	3.46 ± 0.18 ^{d}	7.26 ± 0.01 ^{f}	78.52 ± 0.32 ^{ab}	3.81 ± 0.08 ^{abc}	1.16 ± 0.05 ^{c}
Huggo	1.69 ± 0.02 ^{f}	2.84 ± 0.04 ^{ab}	7.42 ± 0.03 ^{g}	74.10 ± 3.36 ^{a}	4.36 ± 0.22 ^{d}	1.31 ± 0.07 ^{d}
Kalatur	1.60 ± 0.02 ^{cd}	2.98 ± 0.02 ^{b}	7.21 ± 0.01 ^{e}	82.37 ± 2.33 ^{b}	3.68 ± 0.09 ^{abc}	0.89 ± 0.03 ^{ab}
Arabesk	1.49 ± 0.04 ^{a}	2.73 ± 0.03 ^{a}	9.21 ± 0.02 ^{h}	74.14 ± 0.59 ^{a}	3.45 ± 0.07 ^{a}	0.82 ± 0.12 ^{a}

Different lowercase letters indicate a significant difference within the same fractions ($p < 0.05$). WG=Whole grain; TDF = Total dietary fiber; TPC = Total phenolic content; FA=Ferulic acid.

equally during the sieving. These results are similar to the study of A'yunin et al. (2022), who also reported that the fat content was more influenced by the variety than by the flour milling. However, in their study the ash content was mainly influenced by milling rather than the variety (A'yunin et al., 2022). The protein content of the RSF ranged from 6.86 (Ggolden) to 9.21 % dm (Arabesk) and were usually lower than in the WG fractions (7.86–9.52%). On the other hand, it was shown that TDF, TPC and starch (although less) showed different values in the WGSF and RSF. This result was already observed by Rumler et al. (2021) and Buitimea-Cantúa et al. (2013). TDF values of the WGSF were higher (6.54–10.07 %), than those found in the RSF (4.45–4.36 %). Although the contents of soluble dietary fibers (IDF) and insoluble dietary fibers (SDF) were not measured within this study, a previous study (Rumler et al., 2021) showed that sorghum contained mainly insoluble dietary fibers (IDF: 7.92 % dm; SDF: 0.89 % dm). Starch content was slightly higher in the RSF (76.29–82.37%) compared to the WGSF (70.63–73.59%); and was not significantly influenced by the variety, except for Kalatur. Regarding the TPC content, it was observed that the RSF had a lower range (0.89–1.31 mg FA/g dm) compared to the WGSF (1.43–1.79 mg FA/g dm) which was expected, as phenolic compounds are mainly located in the outer layers of the kernel.

3.2. *Physicochemical and rheological properties*

Fig. 1 displays the WAI and WSI of the two flour fractions made from different sorghum varieties. Overall, the WGSF fractions showed higher WAI values than the RSF (see Fig. 1 (a)), which is probably attributed to their higher dietary fiber content. This was also supported by the Pearson's correlation test (see Suppl. Mat. 1), which showed a strong positive correlation between WAI and TDF ($p = 0.0000$; $r = 0.9013$). The WAI also strongly correlated to TPC ($p = 0.0000$; $r = 0.9178$). This can be explained by the fact that dietary fibers are an abundant source of phenolic acids, which are esterified or etherified to the fiber structure. A negative correlation was seen between the WAI and the starch content ($r = -0.6491$), which is probably related to the high crystallinity of the native starch granules. In general, these findings are consistent with those found for other cereals. Solaesa et al. (2020) showed that WAI increased with increasing particle size of quinoa flour and a similar trend was observed for oat flour by Gu et al. (2022). The WSI of the RSF was higher than the WGSF fractions, but only small (although significant) differences were found within the varieties (Fig. 1(b)). Negative correlations were observed with TDF and TPC ($p = 0.0001$; $r = -0.8187$ and $p = 0.0007$; $r = -0.7558$, respectively). This finding supports the results from Rumler et al. (2021), where WGSF had a lower WSI than RSF. This strong correlation found between TPC and TDF may be attributed to the fact that TPC are often bound to TDF (Li et al., 2019).

The pasting properties of the WGSF and RSF are visible in Fig. 2. As expected, the RSF showed higher peak and final viscosities than the WGSF, probably due to their higher starch content as supported by the positive correlation that was found between the peak viscosity and the starch content ($p = 0.0004$; $r = 0.7796$) (see suppl.mat.1). These findings appear to be in line with previous research which revealed that fractions having more fiber and thus, less starch, had lower viscosities (Jaksics et al., 2022). Kalatur had the highest peak viscosity in both fractions, whereas the lowest peak viscosities were observed in Ggolden (WGSF) and Arabesk (RSF). Negative correlations (see Suppl.mat.2) were found for peak viscosity with the protein content ($p = 0.0039$; $r = -0.6786$), TDF ($p = 0.0000$; $r = -0.9392$) and the TPC ($p = 0.0000$; $r = -0.8776$), which was similarly found by Sharma and Gujral (2019). It is known that proteins, TDF and TPC restrict the access of water to the starch granules and thus reduce swelling, which in result may lower the pasting properties (Liu et al., 2019). Furthermore, the peak viscosity was

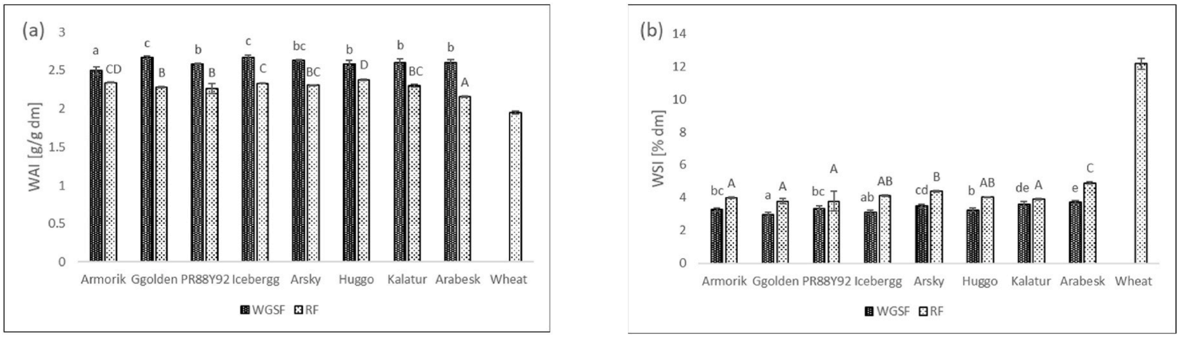

Fig. 1. (a) Water absorption index (WAI) and (b) Water solubility index (WSI) of flour fractions from different sorghum varieties. Different letters (lowercase letters for WGSF; uppercase letters for RSF) indicate significant differences within each fraction ($p < 0.05$).

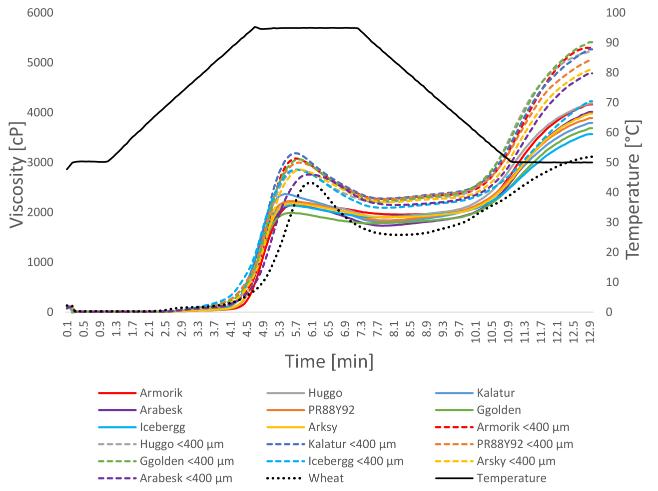

Fig. 2. RVA pasting profile of flour fractions from different sorghum varieties. Continuous line: WGSF; Dotted line: RSF.

positively correlated with starch (r = 0.7796) Armorik and Huggo showed the highest final viscosities, while within the RSF, Ggolden had the highest. Icebergg showed the lowest final viscosity in both flour fractions. Negative correlations were found between the final viscosity and protein content (p = 0.0184; r = −0.6786), TDF (p = 0.0002; $r = -0.798$) and TPC (p = 0.0012; $r = -0.7361$), which is again in line with the results of Sharma and Gujral (2019) on millets. A positive correlation was observed between the final viscosity and the starch content (p = 0.0124; r = 0.6085). The pasting temperatures ranged between 86.9-90.1 °C and 83.6–88.0 °C for the WGSF and RSF, respectively, and correlated with the protein (p = 0.0027; $r = 0.6961$), TDF content (p = 0.0024; $r = 0.7027$) and TPC (p = 0.0051; r = 0.6630) (see Suppl. mat.1.). The positive correlation between the pasting temperature and protein content could be related to the fact that proteins surround the starch granule and thus make starch gelatinization more difficult (Palavecino et al., 2016). Another explanation is that TDF may limit the amount of available water during gelatinization due to its high water absorption capacity, which may increase the gelatinization temperature (Wang et al., 2021). Additionally, a negative correlation was observed between the pasting temperature and the starch content (p = 0.0053; $r = -0.6609$).

The results of the Farinograph® and Alveograph® analyses are displayed in Table 2. The water absorptions of the WGSF fraction blends ranged between 55 and 56 % and were therefore lower than the water absorption for wheat (58.67 %). An explanation to this behavior is the hydrophobic nature of the prolamins (kafirins) in sorghum, which may contribute to the lower water absorption of the flour (Dube et al., 2020). Another explanation can be attributed to the lower swelling properties of sorghum, compared to wheat (Liu et al., 2019). The water absorptions for the RSF were slightly higher (56–57 %) than those obtained for the WGSF fractions, which is in accordance with Torres et al. (1993). A positive correlation (p = 0.0463; $r = 0.5044$; see suppl.mat.1.) was found between the water absorption and the starch content of the sorghum flours. However, strong negative correlations were seen between the water absorption and TDF ($p = 0.0014$; $r = -0.7278$), as well as TPC ($p = 0.0008$; $r = -0.7509$). According to the Farinograph® results, selecting sorghum flours with a low TDF and TPC content may be advantageous for producing sorghum-wheat breads with higher dough yields. Unlike the WAI, the Farinograph® water absorption was positively correlated with TDF/TPC (see suppl.mat.1). However, it has to be considered that WAI analyses were carried out with 100 % sorghum flour, while for the Farinograph® test wheat/sorghum blends were used. Overall, the water absorptions did not show the same trend for the two factions: The lowest WAI within the WGSF was observed for Armorik and the highest for Ggolden and PR88Y2. Regarding the RSF the lowest was reported for Arabesk and the highest for Armorik and Huggo. Regarding the Farinograph® data of the WGSF the lowest water absorption was seen for Huggo and the highest for Ggolden and Icebergg. Regarding the RSF the lowest water absorption had the variety PR88Y92 and Icebergg and the highest Arabesk.

Dough development times of all blends were lower compared to wheat, which was also reported by Dube et al. (2020). Dough stability time ranged between 8.27-11.3 min and 5.97–9.83 min for WGSF and the RSF, respectively and were not influenced by the variety, except for Icebergg in the WGSF (the lowest value) and PR88Y92 in the RSF (the highest value). Dough stability positively correlated with ash (p = 0.0138; $r = 0.6014$), TDF (p = 0.0004; $r = 0.7727$) and TPC (p = 0.0021; $r = 0.7082$) (see suppl.mat.1). Han et al. (2013) reported that the dough stability can be enhanced due to interactions between the gluten proteins and dietary fibers. Furthermore, Emmambux and Taylor (2003) showed that selected polyphenols (tannic acids and condensed tannins) were able to form complexes with the sorghum kafirins which affect protein functionality. On the other hand, TDF could also have contributed to an increased dough stability as reported by Wang et al. (2021). Based on the previous correlations it was seen that flours rich in ash, TDF and polyphenol led to higher dough stability times. However, the sorghum blends showed lower dough stabilities compared to wheat, likely due to gluten dilution. The dough softening behaved similarly to the dough stability. WG fractions showed a lower dough softening than the RSF (Table 2). The quality number, which indicates the strength of a flour, ranged between 81 and 109.67 in the WGSF fraction, in which the variety Icebergg exhibited the weakest dough. Regarding the RSF, the quality number ranged between 41.33 and 93.33. In this case, Arsky formed the weakest dough and PR88Y92 the strongest. However, no correlations were found between the chemical properties and the quality number. In general, Farinograph results indicate that the use of WGSF sorghum flours may lead to the formation of more stable sorghum-wheat doughs, compared with RSF.

As shown in Table 2., the tenacity (P) of the WGSF fraction blends ranged between 48.9 and 59.3 mm H2O (lowest: Huggo blends; highest Kalatur blends) and were on average lower than those seen in the RSF (54.4–63.9 mm H2O). These findings were not in line with those of Wang et al. (2002) and Saeed et al. (2009). Here, the authors reported a higher tenacity with an increasing amount of fiber. However, in the case of Wang et al. (2002) and Saeed et al. (2009) fibers from other plant materials were used that differed in composition and solubility (IDF:SDF ratio) which could explain the different results. Within the RSF, the lowest and highest tenacity was observed in blends with Arabesk and PR88Y92, respectively. No correlations were found between the tenacity and the chemical composition (see suppl.mat.1). While the extensibility (L) for wheat was 141.11 mm, extensibilities for the blends were by far lower. This finding is consistent with that of Sibanda et al. (2015) and can be explained by the absence of gluten in sorghum, which leads to poor viscoelastic dough properties. In contrast, high dough extensibility was expected for wheat due to the strong network-forming ability of gluten (Day et al., 2006). Armorik showed the lowest extensibility (47.38 ± 5.15 mm), while Icebergg displayed the highest values (53.3 ± 10.23 mm) in the WGSF fractions. Overall, the extensibilities of the RSF blends were higher compared to those of the WGSF fraction blends. Contrary to the WGSF fraction blends, the highest extensibility was observed for the Armorik blends, and the lowest for the PR88Y92 blends. The obtained Alveograph values are in accordance to Sibanda et al. (2015), who characterized flour blends with 20 % sorghum. A negative correlation was found between the extensibility and the TDF, which was also found by Packkia-Doss et al. (2019). The swelling indices for the WGSF and RSF were between 15.63-17.13 and 15.71–19.59, respectively. P/L ratios were higher for the blends compared to wheat which is in accordance to TAPSOBA et al. (2022). As can be seen from Table 2, the highest P/L ratio for the WGSF blends was found in Armorik blends and the lowest in Huggo. Within the RSF, PR88Y92 showed the highest

Table 2
Rheological properties of composite flours made of wheat flour (80%) and flour fractions (wholegrain/refined) from different sorghum varieties (20%).

Sorghum variety	Wheat (100%)	Armorik (20%)	Ggolden (20%)	PR88Y92 (20%)	Icebergg (20%)	Arsky (20%)	Huggo (20%)	Kalatur (20%)	Arabesk (20%)
WGSF									
Farinograph									
WA [500 BU]		55.71 ± 0.1 ^{de}	55.91 ± 0.1 ^{ef}	55.3 ± 0.11 ^{b}	56.07 ± 0.15 ^{f}	55.47 ± 0.21 ^{bc}	55.03 ± 0.15 ^{a}	55.77 ± 0.06 ^{de}	55.63 ± 0.12 ^{cd}
DDT [min]		1.87 ± 0.15 ^{ab}	2.53 ± 0.15 ^{c}	2.53 ± 0.15 ^{c}	1.77 ± 0.06 ^{a}	1.93 ± 0.12 ^{ab}	2.01 ± 0.01 ^{ab}	2.50 ± 0.17 ^{c}	2.11 ± 0.17 ^{b}
DSTAB [min]		11.27 ± 0.97 ^{b}	10.23 ± 1.01 ^{b}	10.2 ± 0.95 ^{b}	8.27 ± 1.52 ^{a}	11.1 ± 0.61 ^{b}	10.67 ± 0.57 ^{b}	10.9 ± 0.98 ^{b}	11.3 ± 0.75 ^{b}
DSOFT [BU]		46.00 ± 6.01 ^{a}	54.67 ± 8.62 ^{a}	55.67 ± 8.96 ^{ab}	68.67 ± 14.64 ^{b}	45.67 ± 7.51 ^{a}	52.33 ± 2.52 ^{a}	49.33 ± 4.04 ^{a}	47.67 ± 3.51 ^{a}
QN		99.00 ± 5.29 ^{b}	96.67 ± 4.93 ^{ab}	97.33 ± 7.09 ^{b}	81.00 ± 12.17 ^{a}	104.33 ± 12.58 ^{b}	98.67 ± 8.14 ^{b}	111.33 ± 10.12 ^{b}	109.67 ± 10.97 ^{b}
Alveograph									
P [mm H2O]		57.13 ± 4.85 ^{c}	56.67 ± 2.24 ^{c}	52.90 ± 2.77 ^{b}	51.22 ± 3.15 ^{ab}	52.20 ± 2.74 ^{b}	48.90 ± 2.77 ^{a}	59.30 ± 3.23 ^{c}	53.63 ± 2.56 ^{b}
L [mm]		47.38 ± 5.15 ^{a}	49.63 ± 6.41 ^{ab}	53.3 ± 10.23 ^{abcd}	59.44 ± 5.61 ^{d}	49.6 ± 7.53 ^{ab}	55.7 ± 8.18 ^{bcd}	51.7 ± 8.43 ^{abc}	58.13 ± 6.13 ^{cd}
G		15.68 ± 1.41 ^{a}	15.84 ± 1.28 ^{ab}	16.19 ± 1.56 ^{abc}	17.13 ± 0.78 ^{c}	15.63 ± 1.21 ^{a}	16.54 ± 1.22 ^{abc}	15.9 ± 1.41 ^{ab}	16.98 ± 0.88 ^{bc}
P/L		1.19 ± 0.27 ^{c}	1.16 ± 0.18 ^{c}	1.03 ± 0.21 ^{abc}	0.87 ± 0.12 ^{a}	1.08 ± 0.21 ^{bc}	0.90 ± 0.16 ^{a}	1.18 ± 0.22 ^{c}	0.93 ± 0.11 ^{ab}
Ie [%]		49.91 ± 1.35 ^{ab}	50.59 ± 1.53 ^{b}	50.79 ± 2.15 ^{b}	49.3 ± 1.34 ^{ab}	48.39 ± 2.35 ^{a}	49.83 ± 1.52 ^{ab}	49.9 ± 1.68 ^{ab}	48.29 ± 1.72 ^{a}
RSF									
Farinograph									
WA [500 BU]	58.70 ± 0.17	56.20 ± 0.01 ^{b}	56.37 ± 0.15 ^{bc}	55.70 ± 0.62 ^{a}	56.10 ± 0.17 ^{ab}	56.73 ± 0.06 ^{c}	56.40 ± 0.11 ^{bc}	56.73 ± 0.06 ^{c}	57.40 ± 0.17 ^{d}
DDT [min]	3.10 ± 0.75	2.07 ± 0.12 ^{ab}	1.73 ± 0.15 ^{a}	2.23 ± 0.4 ^{b}	1.97 ± 0.25 ^{ab}	1.83 ± 0.12 ^{ab}	2.00 ± 0.21 ^{ab}	1.97 ± 0.21 ^{ab}	1.83 ± 0.29 ^{ab}
DSTAB [min]	17.50 ± 1.08	7.47 ± 0.67^{abc}	8.37 ± 1.08 ^{cd}	9.83 ± 1.1 ^{d}	8.17 ± 1.36 ^{bcd}	6.63 ± 0.45 ^{ab}	5.97 ± 0.21 ^{a}	7.13 ± 1.61 ^{abc}	6.67 ± 0.29 ^{ab}
DSOFT [BU]	31.33 ± 1.15	71.00 ± 5.01 ^{bc}	65.00 ± 9.17 ^{ab}	56.00 ± 8.72 ^{a}	71.00 ± 12.77 ^{bc}	76.33 ± 4.16 ^{bc}	81.67 ± 2.08 ^{c}	71.00 ± 10.15 ^{bc}	73.00 ± 3.61 ^{bc}
QN	143.33 ± 12.22	61.67 ± 11.06 ^{bc}	67.67 ± 15.89 ^{cd}	93.33 ± 6.43 ^{e}	81 ± 12.17 ^{de}	41.33 ± 3.06 ^{a}	44.67 ± 0.58 ^{ab}	54.67 ± 16.92 ^{abc}	48 ± 7.81 ^{ab}
Alveograph									
P [mm H2O]	51.67 ± 2.83	60.20 ± 2.53 ^{c}	60.70 ± 4.3 ^{cd}	63.90 ± 4.2 ^{d}	58.1 ± 4.07 ^{bc}	59.3 ± 3.56 ^{bc}	59.00 ± 5.01 ^{bc}	56.10 ± 2.28 ^{ab}	54.40 ± 1.58 ^{a}
L [mm]	141.11 ± 16.86	78.1 ± 12.78 ^{e}	69.30 ± 9.74 ^{cd}	50.1 ± 8.88 ^{a}	55.8 ± 8.31 ^{ab}	67.00 ± 9.81 ^{cd}	54.11 ± 8.87 ^{ab}	61.2 ± 8.44 ^{bc}	74.9 ± 7.22 ^{de}
G	26.41 ± 1.55	19.59 ± 1.73 ^{e}	18.48 ± 1.35 ^{cde}	15.71 ± 1.31 ^{a}	16.59 ± 1.24 ^{ab}	18.17 ± 1.37 ^{cd}	16.32 ± 1.33 ^{ab}	17.38 ± 1.19 ^{bc}	19.24 ± 0.91 ^{de}
P/L	0.37 ± 0.06	0.80 ± 0.23 ^{ab}	0.90 ± 0.21 ^{abc}	1.31 ± 0.24 ^{e}	1.07 ± 0.22 ^{cd}	0.91 ± 0.18 ^{abc}	1.13 ± 0.27 ^{de}	0.93 ± 0.16 ^{bc}	0.73 ± 0.07 ^{a}
Ie [%]	55.06 ± 1.61	49.4 ± 1.44 ^{cd}	52.29 ± 1.14 ^{f}	50.46 ± 1.93 ^{de}	49.7 ± 1.42 ^{de}	50.77 ± 1.05 ^{e}	46.73 ± 1.71 ^{a}	47.87 ± 1.34 ^{ab}	48.41 ± 1.02 ^{bc}

Different lowercase letters within each row indicate significant differences within the same flour fraction ($p < 0.05$). Wheat was added as a reference value and was not included in the statistical analysis. WGSF = whole grain sorghum flour; RF = refined (sorghum) flour; WA = water absorption; DDT = dough development time; DSTAB = dough stability time; DSOFT = dough softening after 12 min; QN = quality number; P = tenacity; L = extensibility; G = swelling index; P/L = configuration ratio; IE = elasticity.

configuration ratio, Arabesk the lowest. The elasticity index (I.e.) significantly decreased when sorghum was added to wheat due to the absence of gluten. The elasticity indices between the WGSF and RSF blends were similar, ranging between 48.39-50.79 % and 46.71–50.46 %, respectively. This behavior was also seen by Sibanda et al. (2015).

3.3. Baking properties

The baking properties of breads baked with different fractions and sorghum varieties are summarised in Table 3. The bread slices of the samples can be taken from the Suppl.mat.3 and Suppl.mat.4. Baking losses were similar between varieties and fractions and ranged from 11.52 to 13.91 % and 11.51–13.61 % for the WGSF and RSF, respectively (see Table 3). Interesting results were obtained for bread specific volumes (cm^3/g bread). Similar specific volumes were mostly observed within varieties, although partly higher specific bread volumes were found in the WGSF compared to the RSF (e.g. Arabesk). The difference in volume could be due to the different particle sizes as well as the composition of the fraction. However, Trappey et al. (2015) reported that sorghum with lower particle sizes caused a lower bread volume compared to sorghum flours with higher particle sizes. Moreover, these results are in accordance to that observed in the rheological characterization of the flours, as several Farinograph® and Alveograph® parameters were higher in the WGSF than in the RSF, indicating more stable and stronger WGSF doughs. The lowest specific volumes within the WGSF were observed for the breads from Huggo or Kalatur. The breads including WGSF of Armorik, Icebergg, Arsky and Arabesk showed the highest specific volumes, although the differences between specific bread volumes of the blends were small. The specific volume of wheat bread was higher with a value of 2.67 ± 0.02. However, no optimization was carried out for each variety when blended with wheat, which could lead to an improved bread quality. Similar results were observed in case of the volume yield (cm^3/100 g flour) (Table 3). Volume (specific volume and volume yield) was positively correlated with dough stability (*p = 0.047; r = 0.5031* and *p = 0.0373; r = 0.5239*, respectively), and negatively with dough softening (*p = 0.0489; r = -0.4993* and *p = 0.0442; r = -0.5087*, respectively), peak viscosity (*p = 0.039; r = -0.5201* and *p = 0.0294; r = -0.5439*, respectively) and final

Table 3
Baking properties of the wheat-sorghum breads baked with fractions of different sorghum varieties.

		Baking loss [%]	Spec. vol. [cm^3/g]	Vol. yield. [cm^3/100g flour]	Crumb firmness [N]	Rel. Elasticity [%]
Wheat (100%)		12.88 ± 0.97	2.67 ± 0.02	381.02 ± 4.94	30.09 ± 2.32	45.45 ± 0.55
Armorik (20 %)	WGSF	13.47 ± 0.20 ^{de}	2.42 ± 0.04 ^{d}	342.79 ± 5.36 ^{c}	37.99 ± 4.15 ^{a}	44.08 ± 0.76 ^{b}
	RSF	12.46 ± 0.31 ^{BC}	2.23 ± 0.07 ^{BC}	319.56 ± 10.75 ^{ABCD}	49.31 ± 6.59 ^{BC}	45.46 ± 2.50 ^{B}
Ggolden (20 %)	WGSF	12.37 ± 0.56 ^{b}	2.33 ± 0.08 ^{bc}	333.65 ± 10.52 ^{bc}	45.94 ± 6.50 ^{de}	44.43 ± 0.61 ^{bc}
	RSF	12.58 ± 0.88 ^{C}	2.21 ± 0.09 ^{AB}	314.83 ± 10.29 ^{AB}	47.52 ± 7.42 ^{AB}	44.59 ± 0.75 ^{AB}
PR88Y92 (20 %)	WGSF	11.52 ± 0.47 ^{a}	2.27 ± 0.09 ^{ab}	328.65 ± 13.04 ^{b}	44.19 ± 6.00 ^{cd}	44.15 ± 1.06 ^{b}
	RSF	12.36 ± 0.23 ^{BC}	2.33 ± 0.05 ^{D}	334.42 ± 6.34 ^{E}	47.51 ± 3.87 ^{AB}	44.05 ± 1.67 ^{AB}
Icebergg (20 %)	WGSF	12.95 ± 0.55 ^{cd}	2.38 ± 0.05 ^{cd}	338.88 ± 5.04 ^{c}	40.18 ± 4.83 ^{ab}	43.12 ± 0.89 ^{a}
	RSF	11.91 ± 0.25 ^{AB}	2.28 ± 0.03 ^{CD}	328.33 ± 5.23 ^{CDE}	48.02 ± 4.45 ^{ABC}	45.21 ± 0.86 B
Arsky (20 %)	WGSF	13.27 ± 0.46 ^{d}	2.38 ± 0.06 ^{cd}	337.38 ± 7.13 ^{bc}	42.13 ± 4.89 ^{bc}	43.85 ± 1.01 ^{b}
	RSF	13.61 ± 0.31 ^{D}	2.33 ± 0.08 ^{D}	329.29 ± 10.95 ^{DE}	44.59 ± 4.52 ^{A}	44.71 ± 3.29 ^{AB}
Huggo (20 %)	WGSF	12.51 ± 0.67 ^{bc}	2.21 ± 0.05 ^{a}	316.92 ± 5.11 ^{a}	47.91 ± 5.44 ^{e}	43.91 ± 1.32 ^{b}
	RSF	11.51 ± 0.26 ^{A}	2.14 ± 0.04 ^{A}	310.56 ± 5.94 ^{A}	51.33 ± 3.49 ^{CD}	44.96 ± 0.84 ^{AB}
Kalatur (20 %)	WGSF	11.78 ± 0.44 ^{a}	2.21 ± 0.07 ^{a}	317.92 ± 9.43 ^{a}	47.51 ± 4.42 ^{de}	44.86 ± 0.88 ^{c}
	RSF	12.36 ± 0.86 ^{BC}	2.24 ± 0.08 ^{BC}	321.06 ± 10.52 ^{BCD}	54.44 ± 4.25 ^{D}	44.76 ± 1.00 ^{AB}
Arabesk (20 %)	WGSF	13.91 ± 0.43 ^{e}	2.39 ± 0.03 ^{cd}	336.24 ± 3.38 ^{bc}	40.05 ± 4.12 ^{ab}	44.13 ± 0.79 ^{b}
	RSF	12.28 ± 0.18 ^{BC}	2.22 ± 0.02 ^{BC}	318.97 ± 3.66 ^{ABC}	49.74 ± 5.95 ^{BC}	45.25 ± 0.69 ^{B}

Different lowercase and uppercase letters within each row indicate each significant differences within the same flour fraction ($p < 0.05$). Wheat was added as a reference value and was not included in the statistical analysis Different lowercase or uppercase letters within each column indicate significant differences between the samples ($p < 0.05$). WGSF = whole grain sorghum flour; RSF = refined sorghum flour.

viscosity ($p = 0.044$; $r = -0.5092$ and $p = 0.0224$; $r = -0.5654$, respectively). A positive correlation between dough stability and specific volume was also found by Chisenga et al. (2020), who substituted wheat with different cassava varieties. In contrast, Torbica et al. (2019) substituted wheat with sorghum, rye, triticale, barley or oat and millet and found a negative correlation between the dough stability and the specific volume.

Crumb firmness within the breads from the WGSF was lowest in breads with Armorik and Icebergg, and highest with Ggolden, Huggo and Kalatur addition. In the breads from the RSF addition of Arsky, Icebergg, PR88Y92 and Ggolden produced the softest breads; Huggo and Kalatur addition caused the highest crumb firmness. In contrast, a softer crumb texture was found in wheat breads compared to the blended breads. Although the relative elasticity showed differences among the samples (Table 3), the values did not range to a large extent (43.12–44.43 and 44.05–45.46 for WGSF and RSF, respectively). Positive correlations for crumb firmness (Suppl.mat.2) were observed with the starch content ($p = 0.012$; $r = 0.6107$), Farinograph dough development time ($p = 0.0223$; $r = 0.5661$) and dough softening ($p = 0.018$; $r = 0.5822$), and RVA peak ($p = 0.0018$; $r = 0.7152$) and final viscosity ($p = 0.0073$; $r = 0.6424$). The positive correlation between the crumb firmness and starch content was surprising as it is well known that starch contributes to a soft crumb (Calvin, 2016). Negative correlations were also found between crumb firmness and TDF ($p = 0.012$; $r = -0.6014$), TPC ($p = 0.0197$; $r = -0.5755$), WAI ($p = 0.0197$; $r = 0.5938$), dough stability ($p = 0.012$; $r = -0.6105$) and RVA pasting temperature ($p = 0.0292$; $r = -0.5445$).

To conclude the baking trials, it can be said that using WGSF in wheat bread led to higher bread qualities than when using RSF. This result was surprising, since in wheat the use of whole wheat flour usually leads to a lower volume compared to refined flour (Ngozi, 2014). However, the presence of dietary fibers may have also had an effect on the dough strength and stability, as seen by the rheological analyses, which has also been seen before (Wang et al., 2021), although possible interactions with the proteins cannot be excluded either (Han et al., 2013). The varieties Armorik and Icebergg seemed to be the most promising varieties as they resulted in higher loaf volumes and softer crumb textures compared to the other varieties. Further analysis could be carried out to examine the dough structure. Microscopic analysis of the dough could reveal how the individual components of sorghum behave and interact within the dough.

3.4. *Sensory evaluation*

The results of the sensory evaluation are visible in Fig. 3. Generally, significant sensory differences were found between the varieties.

It can be seen that the acceptance of the test panels was not affected by the crumb color, despite the differences in sorghum varieties used (red varieties like Armorik and Huggo Arsky, and white varieties: Ggolden, PR88Y92, Icebergg, Arabesk, and Kalatur). This indicated that the pericarp color was not a crucial factor when selecting sorghum for baking. In general, the pore structures of the wheat-sorghum breads were well accepted by the panel, considering that 4.5 was the neutral point of the 9-point hedonic scale. Closer inspection of Fig. 3 shows that the pore structure of Ggolden was the least liked and the pore structure of the breads including Icebergg was liked the most. As the pore structure develops during the fermentation and is formed through the CO_2, it

Fig. 3. Results of the sensory evaluation of the wheat/sorghum breads. (a) Porosity, crumb color, odor, taste, after taste; (b) overall impression. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

is possible that Ggolden had a lower gas holding capacity compared to Icebergg. Odor was different between the sorghum varieties; in particular variety PR88Y92 was the least liked (4.2) while Icebergg was the most liked (6.1). Large differences were noticed for the taste, breads containing Icebergg were liked twice as much as the PR88Y92 breads. Overall, all wheat-sorghum breads received acceptable rates for taste (average result 5.2). Also, no adverse aftertaste was stated by the panelists. An exception here was again, the variety PR88Y92, which was far under the average ratings. Comments of the panelists, mentioned bitter taste and aftertaste for PR88Y92. Previous findings showed that bitterness was linked to selected polyphenols (Kobue-Lekalake et al., 2007). Future research with focus on the correlation between the sensory attributes and the polyphenolic compounds is therefore suggested. The texture was comparable among the samples, whereby this time Huggo scored lowest in terms of texture. Fig. 3 also presents the results obtained for the overall impression. As expected, PR88Y92 was found to be liked the least in general. The best overall impression was seen for the wheat-sorghum breads including the variety Icebergg. The result of Icebergg (6.2) was almost twice as high as the result of PR88Y92.

4. Conclusion

This study has revealed that the sorghum variety plays a significant role on the final quality of bakery products. The eight sorghum varieties used in this study showed significant differences in their chemical composition, although these were rather low. From this perspective it did not allow to identify any variety with superior nutritional properties, but still these small differences influenced rheological and baking performance in the end. Overall, the rheological evaluation of sorghum-wheat (20:80) flour blends revealed that sorghum varieties with a lower TDF/TPC and higher starch content may be advantageous for producing sorghum-wheat breads with higher dough yields. WGSF formulations led to the formation of more stable sorghum-wheat doughs and resulted in a more favorable bread quality, especially in varieties such as Arabesk, Armorik, Ggolden, Huggo and Icebergg, compared to RSF formulations. This finding is opposite to what is usually found in wheat breads, where wholegrain flour usually decreases bread volume. However, the differences in baking properties between sorghum varieties were small, except for the crumb firmness, which was considerably affected by the variety used. In contrast, it was found that the sorghum varieties substantially affected the sensory properties of the breads. Breads from the variety Icebergg were rated significantly better, while the variety PR88Y92 was rejected, mostly due to its bitter taste. This underpins, that for future use of sorghum in human nutrition, the selection of sorghum variety is of great importance, in order to obtain high quality as well as palatable products from sorghum.

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CRediT authorship contribution statement

Rubina Rumler: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Project administration. **Denisse Bender:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Project administration, Writing – review & editing, Supervision, Funding acquisition. **Alessandra Marti:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration. **Stefan Biber:** Validation, Formal analysis, Investigation, Writing – original draft. **Regine Schoenlechner:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

Dear Editorial Board:

We wish to confirm that there are no known conflicts of interest associated with this publication.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcs.2024.103881.

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