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Effect of Microwave and Decortication on Functional, Nutritional and Sensory Properties of Sorghum

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ABSTRACT

Background: This study investigated the effect of microwave pretreatment (1000 W for 10 min) and decortication at different levels (0%, 5%, and 10%) of sorghum grain on cooking quality, nutritional, functional, and sensory properties.

Results: Findings indicated that microwave pretreatment of sorghum grains significantly ($p \leq 0.05$) reduced cooking time from 60 min to about 20 min for whole grains, with decortication reducing cooking time further by exposing the endosperm (reducing cooking time to 10 min). Microwave pretreatment reduced endothermic transition enthalpy, indicating starch pregelatinization. Microwave pretreatment and cooked sorghum grain had far lower starch digestibility than white bread (a reference food). However, decortication and microwave treatment in combination, increased starch digestibility with an increase in rapidly digestible starch (RDS) and a decrease in resistant starch (RS) compared to untreated grains. The treatments also decreased in vitro protein digestibility. Flavor of cooked decorticated sorghum grains was milder, less sweet with lower maize flavor intensity than cooked whole sorghum grains.

Conclusion: Combining microwave pretreatment and decortication effectively reduces cooking time, yielding a quick-cooking sorghum grain.

Significance: This study demonstrates that microwave pretreatment and decortication can be used to manufacture a convenient, quick-cooking sorghum grain for health-conscious consumers seeking nutritious food options.

1 | Introduction

Sorghum grain (*Sorghum bicolor (L.)* "Moench") is one of the top five most cultivated cereal crops in the world (Ratnavathi et al. 2016) and is a staple food of many regions of Africa, Asia, and Latin America (Kamble et al. 2019). Sorghum flour is a functional ingredient and is used in the production of a variety of food products, such as bread (Wolter 2013), tortillas (Winger et al. 2014), and pasta (Cisse et al. 2018). Sorghum could also be a good alternative for diabetics and Celiac disease sufferers since it is rich in resistant starch and does not contain gluten proteins, respectively. The low number of short-branch carbon chains in sorghum amylopectin (Ai 2013) is responsible for the higher gelatinisation temperature (68°C–78°C) and lower starch digestibility compared to other cereals (Collar 2017). Lower starch digestibility might also be due to starch–protein and starch–phenolic compound interactions in the grains to reduce amylolytic enzyme accessibility to the starch granules (Barros et al. 2012).

One factor that hinders sorghum's utilisation as food is its poor protein quantity and quality in terms of digestibility. The different types of kafirin proteins in sorghum were reported to be bound to one another via disulfide bonds to form a protein network, which reduces their digestibility (Wong et al. 2009). The digestibility of sorghum protein is also affected by anti-nutritional factors such as phenolic compounds, phytate, and non-starch polysaccharides (Duodu et al. 2003).

The tough fibrous seed coat (integument) and high phytochemical contents of sorghum grain are responsible for the grain's long cooking time (55–90 min depending on sorghum types); chaffy nature, dark color and flavor attributes that have discouraged consumers from including it in their meals (Kebakile et al. 2008; Taylor and Dewar 2001; Suhendro et al. 2000). It is noted that the fast-paced modern lifestyle has driven a growing demand for quick-cooking grains (Lang et al. 2022), offering a time-saving advantage in line with the global shift towards convenient food choices. This shift in food consumption habits, especially noticeable in developed countries, has resulted in an increased interest in quick-cooking foods (Batista et al. 2019). Therefore, it is essential to develop pre-processed or quick-cooking sorghum grains with good nutritional and sensory attributes.

Traditionally, chemical (Nixtamalization for 40 min) (Gaytán-Martínez et al. 2017), and biological (fermentation for 72–96 h) (Mohapatra et al. 2019), technologies have been employed to increase the nutritional properties, functional properties, and consumer acceptability of sorghum grain. Also, physical processing like soaking the grains for 12 h and microwaving (400 W for 50 s) before cooking have been used to reduce the cooking time of black rice from 30.3 to 26.6 and 24.3 min, respectively (Xiong et al. 2023). However, these traditional processes are often labor-demanding and time-consuming, with a high risk of introducing microbial contaminants due to poor home hygiene conditions, thereby compromising food safety (Liu et al. 2023).

So far in our literature search, microwave energy has not been used for producing quick-cooking sorghum grain. Microwave energy has been used to produce quick cooking grain such as rice (Xiong et al. 2023), finger millet (Ananthu et al. 2023), and Bambara groundnut seeds (Mukwevho and Emmambux 2022) with hard-to-cook defects. Microwave is a volumetric heating method in which thermal energy produced inside the food by vibrational movement of dielectric and polar molecules like water reduces the excessive cooking times (Divekar et al. 2017). Mukwevho and Emmambux (2022), Ananthu et al. (2023), and Li et al. (2021) when studying the effect of microwave treatment on the hard-to-cook defects of various grains, measured the thermal, functional, and nutritional properties of the treated grains separately- and there is limited information on nutritional and sensory properties.

Microwave energy has been used to process parboiled rice. The latter generally suffered from poor hydration and quality (Prasert and Suwannaporn 2009). Saniso et al. (2020) produced parboiled brown rice using microwave (4 kW for 180 s)-assisted hot air fluidized bed drying. They reported this treatment increased the head yield, redness, and yellowness of the rice grains. They also observed a decrease in the A-type crystalline starch structure and an increase in V-type amylose-lipid complexes formed. An increase in water absorption of starch and starch swelling properties reduces cooking time of grains during cooking (An et al. 2024). The increase in rice starch swelling properties and water absorption after microwave-assisted drying indicates that microwave energy has the potential to reduce the cooking time of rice. However, the oblong shape of rice is different from the spherical shape of sorghum, which could influence the uniform treatment of the grains with microwave energy.

Microwave energy has also been used to induce heat-moisture treatment to increase the relative crystallinity. Li et al. (2021) and Sharanagat et al. (2019) showed that microwave pretreatment of 600 W for 6 and 15 min, respectively, of whole grain sorghum resulted in a decrease in pasting viscosity, thermal properties, and in vitro starch digestibility (IVSD) with increased resistant starch (RS) of the flour. They attributed the decrease to the ability of microwave energy to modify the structure and type of starch. Microwave energy can cause pre-gelatinization and the subsequent retrogradation of a fraction of starch upon cooling, leading to resistant starch formation (Alsaffar 2010). The decreased thermal properties were also due to the disordered molecular arrangement of the amylopectin induced by the microwaves, leading to partially gelatinized starch. However, these authors did not determine microwave treatment's effect on grain cooking quality and sensory properties.

Decortication is a process which involves the use of abrasion to remove the tough fibrous outer pericarp layer of cereal grains. The removal of the pericarp results in the loss of various nutrients and phytochemicals concentrated in the pericarp of the cereal grains such as phytates, phenolic compounds including tannins (Taylor and Duodu 2015) and loss of dietary fiber. The loss of phytochemicals and fiber improved palatability by reducing the astringency and chaffiness of the grain. Furthermore, decortication can increase the digestibility of protein and starch (Buitimea-Cantúa et al. 2013). Thus, decortication of sorghum grain can be hypothesised to reduce the negative attributes of the outer pericarp of sorghum.

Unlike previous studies that have examined these processes (microwave and decortication) independently, our study elucidates the combined effect of decortication and microwave heat moisture treatment on starch functionality, in vitro digestibility, cooking quality of treated grains, and the overall sensory appeal of the cooked grains by potential consumers. Therefore, this study determined the effects of microwave pretreatment and decortication on the cooking quality, techno-functional properties, nutritional properties, and sensory properties of sorghum grains with the aim of developing a quick-cooking and convenient sorghum grain with a high consumer appeal and acceptance.

2 | Materials and Methods

2.1 | Decortication of White Sorghum Grains

Whole grain white type I non-tannin sorghum (Macia) was decorticated to 5% and 10% (w/w) using tangential abrasive dehulling device (TADD) (Norton R284 Metalite; Saint-Gobain Abrasives, Isando, South Africa) fitted with a 60-grit sand paper. The degree of decortication was determined by collecting and weighing the bran part after decortication. The percentage decortication was calculated as the percentage by weight of bran collected of the whole grain before decortication.

2.2 | Hydration and Microwave Treatment of White Sorghum Grains

Sorghum grains (100 g) were hydrated with 100 mL water for 4 h to reach saturation (40% moisture content). The grains were then placed in a single layer in glass petri dishes, covered, and microwaved in a conveyor belt microwave (Microwave Tunnel, MW180, designed by Delphius, Pretoria, South Africa) at 1000 W for 10 min. The specific time and power parameters were determined based on preliminary trials that effectively pre-cooked the grains without causing them to burn. After microwave treatment, the sorghum grains were dried in an oven at 40°C overnight. The dried grains were stored in ziplock bags at 4°C until analysis.

2.3 | Functional Properties

2.3.1 | Cooking Time

Cooking time of whole grain and decorticated white sorghum grains was determined by cooking the grains in boiling water. Every 5 min, 3–5 grains were removed and pressed between two microscope slides. The cooking time was taken as the time when the white centre of the sorghum grain became translucent.

2.3.2 | Pasting Properties

Pasting properties of flours from untreated and microwaved sorghum grain were determined using a method by Wokadala et al. (2012) with modifications as per Venter et al. (2024). The grains were milled to produce flours with particle size less than 500 µm. The pasting cycle began with a stirring speed of 960 rpm at 50°C for 30 s followed by a speed of 160 rpm for the remaining period. The temperature was increased at a rate of 5.5°C/min to 91°C, this temperature was held for 5 min for short pasting. The pastes were cooled to 50°C at a rate of 5.5°C/min.

2.3.3 | Thermal Properties

Thermal properties of untreated and microwaved sorghum grain flours were determined using a method by Wokadala et al. (2012) with modifications using a high-pressure DSC system (HPDSC-827; Mettler Toledo) with STARe® software. Indium (Tp = 156°C, heat endothermic flow = −28.6 J/g) was used to calibrate the instrument in terms of temperature and enthalpy. A weight of 10 mg (db) of treated and untreated flour samples was added to 30 mg of distilled water in a sealed aluminium pan. The samples were allowed to equilibrate at ambient temperature overnight. Scanning of samples was done at 40°–150°C at a rate of 10°C/min and at pressure of 40 ± 0.01 MPa with a flow rate of 60 mL/min. An empty pan was used as a reference. Melting enthalpy (ΔH in J/g) was measured. Measurements were done in duplicate.

2.4 | Nutritional Properties

2.4.1 | IVSD

The Goñi et al. (1997) method was used with modifications performed by Oladiran and Emmambux (2017). Cooked sorghum grain samples were manually and gently crushed using a pestle and mortar to simulate mastication. A 50 mg sample, based on dry weight, was used for IVSD analysis. The sample were subjected to protease followed by alpha amylase, and then amyloglucosidase. IVSD rates were calculated as the percentage of starch hydrolysed at predetermined intervals: 0, 8, 20, 60, 90, 120, and 180 min. Bread was used as a standard for starch digestibility.

2.4.2 | In Vitro Protein Digestibility (IVPD)

Cooked grain samples, following their respective cooking times, were mashed using a mortar and pestle to simulate oral mastication. A weight equivalent to 200 mg dry weight basis was then used for IVPD determination according to the method described by Hamaker et al. (1987). The IVPD was expressed as a percentage of soluble nitrogen content to total nitrogen of cooked samples.

2.5 | Light Microscopy

A small quantity of flour from uncooked grain was deposited onto a slide, followed by glycerol. Iodine staining was done by the addition of a drop of iodine onto the flour. Subsequently, the suspension was thoroughly mixed. The slides were observed using a Nikon optiphot transmitted light microscope from Tokyo, Japan, equipped with suitable illumination sources and filters. Images were captured employing a Nikon digital camera DXM120 (Tokyo, Japan).

2.6 | Descriptive Sensory Analysis

A sensory panel comprising 11 individuals was trained for 8 h over 2 days using a lexicon adapted from Kobue-Lekalake et al. (2007) (Table S1). On each evaluation day, the panellists evaluated 6 samples. Treated and untreated sorghum (100 g) were cooked separately in excess water in stainless-steel cooking pots with optimal cooking times as above. Samples were kept warm at 50°–60°C in a Bain-Marie until serving. Cooked samples (15 g each) were served blind-coded with 3-digit codes in glass ramekins, covered with aluminium foil. Sample presentation order followed a Williams Latin square design. Water served as a palate cleanser before and between samples. The evaluation was conducted in a sensory evaluation laboratory with individual booths. Panellists recorded their responses directly into Compusense® 20 (Compusense, Guelph, Ontario, Canada).

2.7 | Statistical Analysis

The effect of the decortication and microwave pretreatment of grains on the measured properties was assessed through analysis of variance (ANOVA). The independent variables included microwave treatment (0 and 1000 W), decortication, and their combination. Where significant differences were noted, Fisher's least significant difference test ($p \leq 0.05$) was applied to separate means. Principal component analysis was used to summarise the effects of the treatments on the descriptive sensory properties of the cooked grains. The R statistical software was used to analyse the data and compare at a significance level of $p \leq 0.05$ using Tukey test followed by Fisher's Least Significant Difference (LSD) test for evaluating the nutritional and functional properties of the sorghum grain samples.

3 | Results and Discussion

3.1 | Cooking Time

Table 1 shows the cooking time of microwave-treated whole grain and decorticated white sorghum. The unsoaked and soaked white sorghum untreated grains had the longest cooking time of 60 min followed by the 5% decorticated and 10% decorticated white sorghum with cooking times of 20 to 45 min.

TABLE 1 | Cooking time of microwave (MW) treated whole and decorticated white sorghum grains.

Treatment	Sorghum grain	Cooking time (min)
0% Decorticated	Raw	60.0^{f}
(Whole)	Soaked (control)	60.0^{f}
	MW Treated	20.0^{b}
5% Decorticated	Raw	45.0^{e}
	Soaked (control)	30.0^{c}
	MW Treated	15.0^{b}
10% Decorticated	Raw	40.0^{d}
	Soaked (control)	20.0^{b}
	MW Treated	10.0^{a}

Note: The amount of sorghum per treatment was 100 g. Values are means ($n = 3$). Means followed by different values in a column that do not share a letter are significantly different ($p \leq 0.05$). Microwave power is 1000 W for 10 min.

The cooking time of microwave pretreated soaked whole and decorticated grains (both levels) was significantly ($p \leq 0.05$) reduced, up to 4 times shorter.

Decortication removes the sorghum grain's outer pericarp and aleurone layers. The outer pericarp is rich in dietary fiber constituents and exhibits hygroscopic properties, enabling it to absorb and retain water, but not as high as the endosperm. By removing the outer pericarp and aleurone layers, the inner cotyledon and endosperm are exposed, potentially reducing cooking time by allowing more water access to the starch and protein components of the grain (Khoddami et al. 2023; Taylor and Dewar 2001; Kebakile et al. 2008). Thus, starch was gelatinised at a faster rate to reduce the cooking time. Furthermore, microwave pretreatment lowered the transition enthalpy, indicating the occurrence of starch pre-gelatinization and protein denaturation (Mukwevho and Emmambux 2022; Deng et al. 2022).

3.2 | Pasting and Thermal Properties of the Resultant Flour

Figure 1 shows the pasting viscosity of flour from microwave pretreated whole grain and decorticated white sorghum grains. The soaked untreated controls for whole grain and decorticated flour had significantly ($p \leq 0.05$) higher pasting viscosities as compared to flour from microwave pretreated white sorghum. The flour from whole grain microwave pretreated sorghum grain had the lowest pasting viscosity, followed by the decorticated microwaved samples. The microwave pretreatment also delayed pasting time compared to the soaked untreated control (Figure 1). The microwave pretreated sorghum samples of whole, 5% and 10% decorticated flour samples also had little to

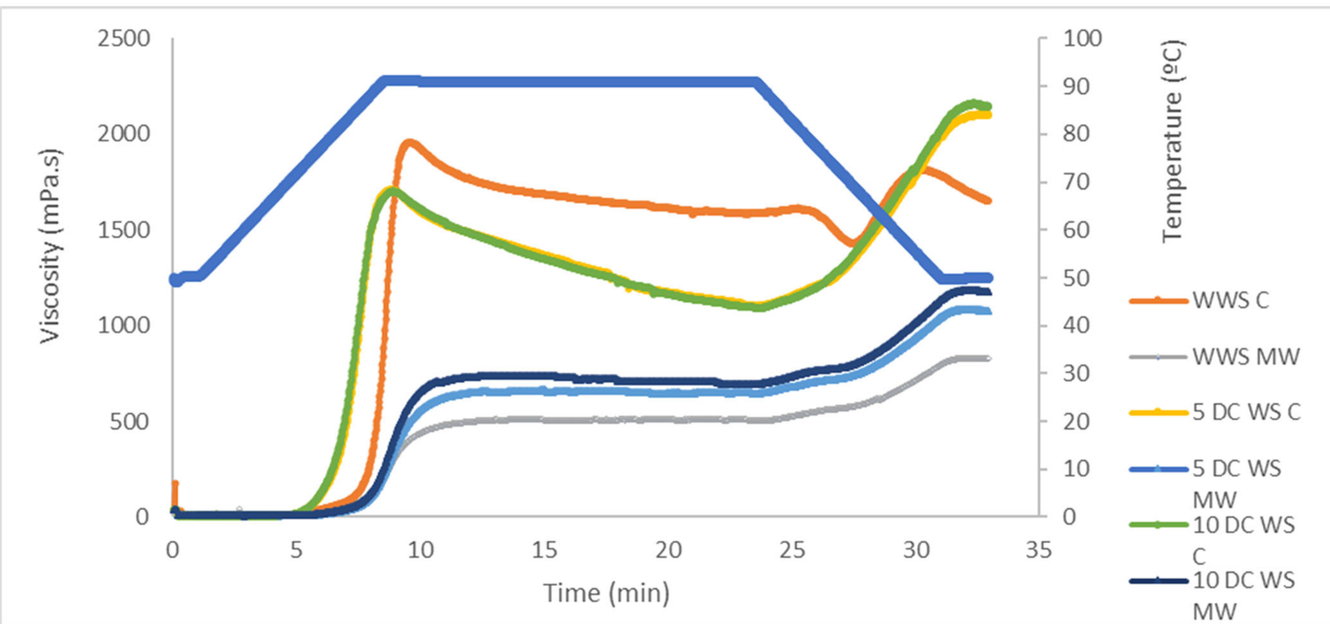

FIGURE 1 | Pasting property of flour from soaked and microwave-treated whole and decorticated sorghum grain. WWS C, flour from soaked whole grain white sorghum; WWS MW, flour from soaked whole grain microwave-treated white sorghum; 5 DC WS C, flour from 5% decorticated soaked white sorghum; 5 DC WS MW, flour from 5% decorticated soaked and microwave-treated white sorghum; 10 DC WS C, flour from 10% decorticated soaked white sorghum; 10 DC WS MW, flour from 5% decorticated soaked and microwave treated white sorghum.

no breakdown viscosities compared to the untreated control samples.

The reduction in pasting viscosities of microwave samples can be explained by the microstructural changes as observed by light microscopy (Figures 2 and 3). The microwave-treated samples showed a higher degree of aggregation, most likely made up of starch and protein. These starch-protein aggregated particles could be denatured proteins surrounding pre-gelatinized starch granules (Mukwevho and Emmambux 2022). These complexes could impede the uptake of water by the starch granules, thereby reducing the starch swelling and starch granular disruption to form a high viscosity paste and limited breakdown viscosity.

The increased pasting viscosities observed in the decorticated samples in comparison to the whole grain sorghum flours can be attributed to the elimination of the pericarp. Thus, a higher endosperm starch content than whole grain resulted in higher pasting viscosity. The outer layer of sorghum grains contains insoluble fiber, phytate, and phenolic compounds, and these biomolecules have been found to decrease viscosity compared to endosperm flour (Taylor and Duodu 2015).

Table 2 shows the thermal properties of flour from microwave pretreated whole grain and decorticated white sorghum grains in terms of transition enthalpy (ΔH). Microwave pretreatment of whole and decorticated white sorghum resulted in a significant ($p \leq 0.05$) reduction in transition enthalpy (ΔH) of the resulting flour as compared to the soaked untreated control (Table 2). No significant difference ($p > 0.05$) was observed between transition enthalpies of whole grain and decorticated samples.

The onset temperature (T_o), peak temperature (T_p), and endset temperature (T_c) all showed significant ($p \leq 0.05$) increases during microwave pretreatment of sorghum grains. Similar results were found for heat-moisture-treated and microwaved sorghum meal by Baah et al. (2024). They attributed this to the formation of more perfect crystallites which is produced by more effective crosslinks in the amorphous regions of starch as well as disordered hydrogen bonds in the crystalline regions

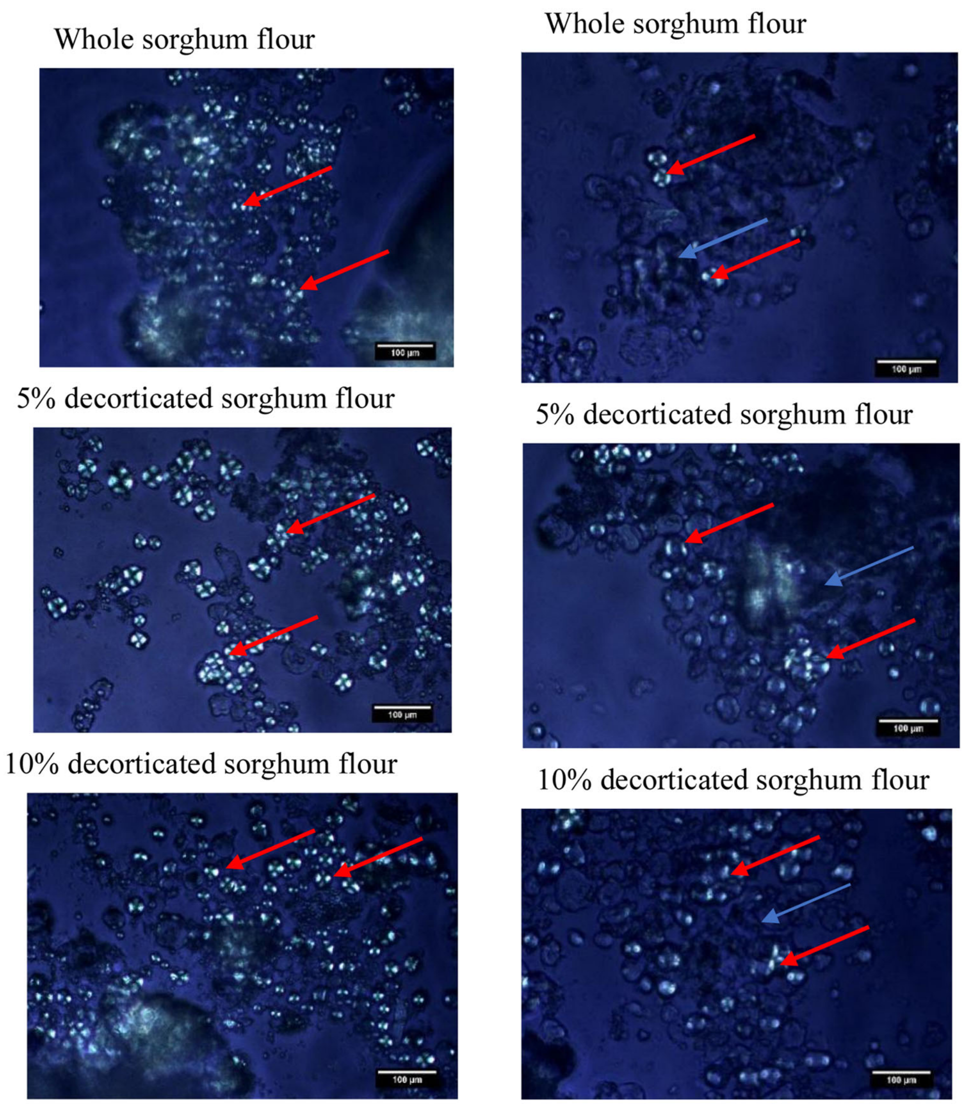

FIGURE 2 | Polarised light microscope images of untreated and microwave pretreated whole and decorticated white sorghum flour. Scale bars = 100 µm, red arrows: ungelatinised starch, blue arrows: areas of starch gelatinisation/partially gelatinised starch.

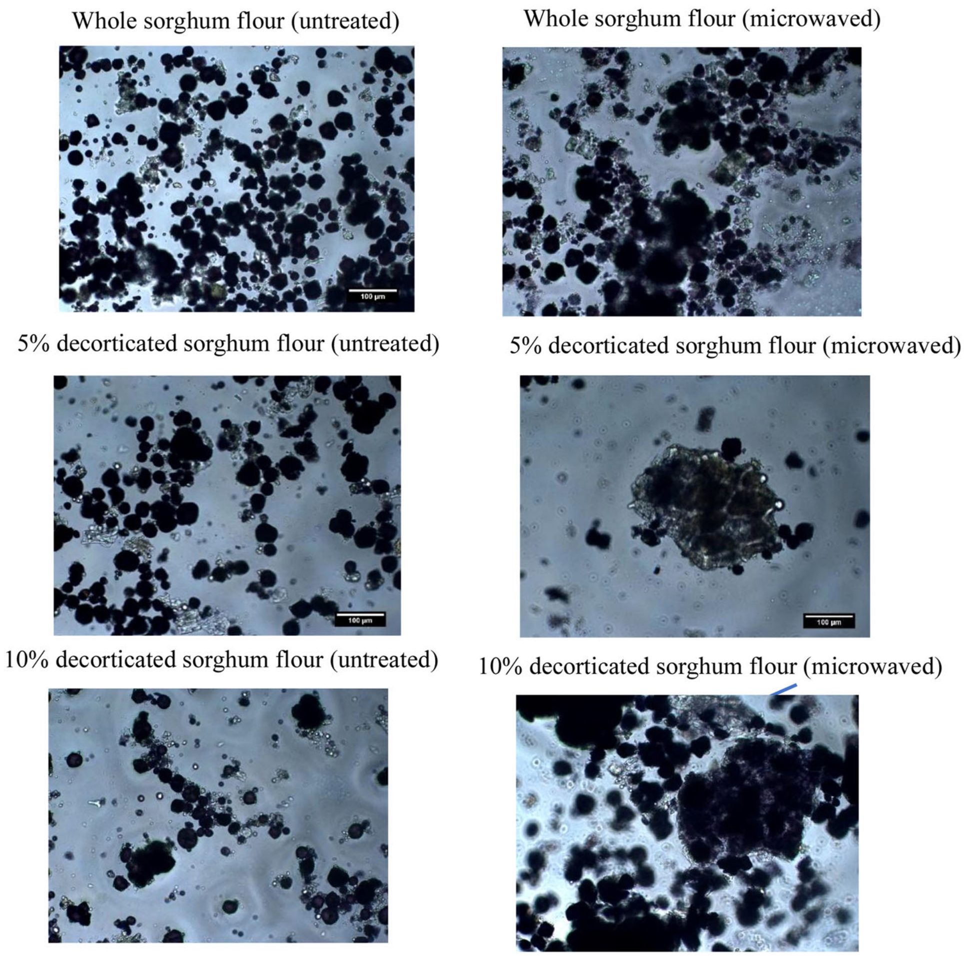

FIGURE 3 | Polarised light microscope images of iodine-stained untreated and microwave pretreated whole and decorticated white sorghum flour. Scale bars = 100 μm, red arrows: ungelatinised starch, blue arrows: areas of starch gelatinisation/partially gelatinised starch.

TABLE 2 | Effect of microwave pretreatment on endothermic enthalpy of flours from white sorghum.

Sorghum grain	Treatment	Onset temperature [T_0] (°C)	Peak temperature [T_p] (°C)	Endset temperature [T_c] (°C)	ΔH (J/g)
0% Decorticated	Raw and soaked (control)	$68.4^{ab} \pm 3.5$	$74.6^{ab} \pm 1.4$	$80.6^{ab} \pm 1.4$	$-5.2^{b} \pm 0.8$
(Whole)	MW-treated	$73.9^{c} \pm 0.0$	$79.3^{d} \pm 0.0$	$85.0^{c} \pm 0.2$	$-2.0^{a} \pm 0.1$
5% Decorticated	Raw and soaked (control)	$66.7^{ab} \pm 0.0$	$73.1^{a} \pm 0.0$	$79.4^{a} \pm 0.0$	$-3.7^{ab} \pm 0.0$
	MW-treated	$71.7^{bc} \pm 0.5$	$78,2^{cd} \pm 0.0$	$84.7^{c} \pm 0.4$	$-2.8^{a} \pm 0.4$
10% Decorticated	Raw and soaked (control)	$64.8^{a} \pm 0.9$	$75.5^{abc} \pm 0.5$	$81.7^{b} \pm 0.1$	$-5.3^{b} \pm 1.0$
	MW-treated	$67.9^{ab} \pm 0.3$	$76.5^{bcd} \pm 0.5$	$84.3^{c} \pm 0.4$	$-2.9^{a} \pm 0.0$

Note: Values are means ± standard deviation ($n = 3$). [ab]Means in a column that do not share a letter are significantly different ($p \leq 0.05$), microwave pretreatment was for 10 min at 1000 W.

(Sui et al. 2015). A decrease in transition enthalpy with increase in T_p between untreated and microwave pretreated sorghum in this study supports the results of Sui et al. (2015).

The decrease in transition enthalpy (ΔH) and pasting viscosities of flours from microwave pretreated compared to the controls was due to the changes in chemical and physical characteristics of the flour components, such as starch and protein of the sorghum grains during microwave treatment. These changes can be explained with the light microscope images (Figures 2 and 3). The microwave-treated samples showed areas of partially gelatinised starch aggregates (blue arrows) as compared to untreated samples which showed ungelatinised starch as birefringence under polarised light (red arrows). Iodine-staining (Figure 4) revealed the partially gelatinised starch aggregates as black spots (blue arrows) most likely embedded in a hydrophobic protein matrix (Mukwevho and Emmambux 2022).

The reduction in endothermic enthalpy was attributed to the progressive starch gelatinisation caused by the treatments (Mukwevho and Emmambux 2022). Microwave heating, known for its high penetration depth of up to 122 mm at 2.45 GHz (Tiwari and O'Donnell 2012), induced dipolar rotation and ionic conduction of water and other polar biomolecules within the food, leading to localised heating and molecular movement. This localised heating could result in partial gelatinisation of starch within the grain, especially when the grains are moisture conditioned (Mukwevho and Emmambux 2022). In our study, the sorghum grain was pre-conditioned to moisture levels around 40% before undergoing the heat microwave treatments. The moisture content of grains has been found to be crucial during microwave heat treatment as water, with its dielectric properties, could absorb microwave energy, generating heat through molecular friction (Román et al. 2015). The moisture content in the grains influenced the extent of starch gelatinisation and protein denaturation (Mukwevho and Emmambux 2022).

3.3 | IVSD

Figure 4 shows the IVSD of microwave-treated whole and decorticated white sorghum. Overall, no significant ($p > 0.05$) changes in starch digestibility were observed for cooked control (soaked), raw, and microwave-treated white whole sorghum samples. The starch digestibility of sorghum samples (less than 50%) was far lower compared to white wheat bread as a control. Sorghum, in general, was found to have lower digestibility due to higher amounts of resistant and slowly digestible starch (Duressa et al. 2018) compared to white wheat bread. Microwave treatment increased the starch digestibility probably due to more microwave-induced gelatinisation which results in molecular changes leading to the opening of the structure aiding in enzymatic access, or even some thermally induced hydrolysis of starch into smaller chains (Vadivambal and Jayas 2007; Warchalewski et al. 2011).

Microwave treatment and decortication generally, increased the RDS and SDS while decreasing the amount of RS (Table 3). As mentioned, decortication removes the barrier created by the pericarp. The pericarp is rich in tannins and phytates which could bind with amylase enzymes thereby, decreasing starch digestibility (Taylor and Duodu 2015), while the microwave thermal treatment resulted in starch molecular disorder, thereby creating more digestible starch.

3.4 | IVPD

Table 4 shows the IVPD for microwave-treated whole grain and decorticated white sorghum grains. The effect of microwave treatment on IVPD of sorghum grain was dependent on decortication. Overall, the IVPD decreased in the order raw < control < microwave pretreated sorghum while IVPD increased with increased percentage decortication levels from 0% > 5% > 10%. The combination of microwave pretreatment and decortication level, however, produced a significant ($p \leq 0.05$) reduction in IVPD.

Decortication reduced the concentration of phenolic compounds, phytate, and fiber in the pericarp of sorghum, facilitating enhanced enzyme accessibility to the protein for hydrolysis. as stated before, phenolic compounds as anti-nutrients have the ability to bind to enzymes, thereby inhibiting their functionality (Kiranmayi 2014). On the other hand, the microwave-induced denaturation of protein, and the consequent formation of starch-protein network (Figure 3) could have hindered enzyme action thereby, reducing IVPD.

3.5 | Descriptive Sensory Attributes

The effect of decortication and microwave treatment of sorghum grain on cooked sorghum descriptive sensory attributes is shown in

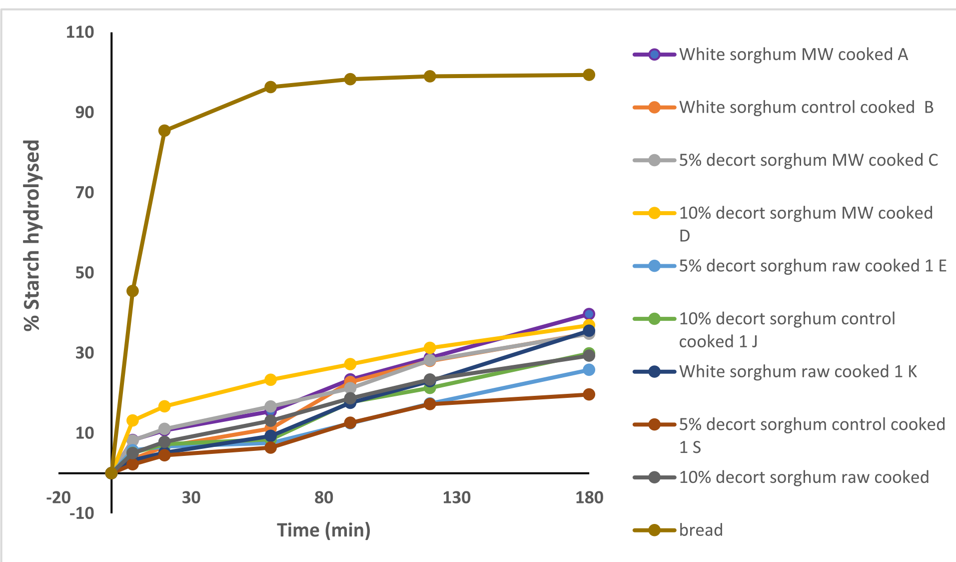

FIGURE 4 | In vitro starch digestibility (IVSD) of microwaved whole and decorticated white sorghum.

TABLE 3 | In vitro starch digestibility parameters and percentage starch fractions of cooked microwaved whole and decorticated white sorghum grains.

Sample	Treatment	k (min^{-1})	AUC	HI	eGI	%RDS	%SDS	%RS
Whole grain	Raw	0.0081	3031.17	$19.3^{a} \pm 0.3$	$50.3^{a} \pm 2.8$	$5.1^{a} \pm 0.7$	$17.8^{b} \pm 0.6$	$63.8^{cd} \pm 3.6$
	Raw and soaked (control)	0.0096	3295.06	$21.0^{b} \pm 0.4$	$51.2^{a} \pm 1.2$	$6.6^{a} \pm 0.9$	$21.4^{bc} \pm 0.7$	$64.4^{cd} \pm 1.9$
	Microwave	0.0096	3746.36	$23.9^{bc} \pm 1.7$	$52.8^{a} \pm 1.5$	$10.7^{b} \pm 1.1$	$18.1^{b} \pm 0.3$	$59.7^{c} \pm 4.0$
5% decorticated grain	Raw	0.0153	3667.97	$23.4^{bc} \pm 0.4$	$52.5^{a} \pm 3.6$	$7.0^{ab} \pm 1.5$	$20.0^{b} \pm 0.6$	$68.5^{d} \pm 2.3$
	Raw and soaked (control)	0.0076	2905.35	$18.5^{a} \pm 0.7$	$49.9^{a} \pm 4.3$	$9.2^{b} \pm 0.6$	$14.7^{a} \pm 1.7$	$63.9^{cd} \pm 2.7$
	Microwave	0.0118	5760.76	$36.7^{d} \pm 1.0$	$59.9^{b} \pm 3.6$	$17.4^{c} \pm 0.7$	$26.9^{c} \pm 0.8$	$44.7^{b} \pm 1.9$
10% decorticated grain	Raw	0.0121	4701.80	$30.0^{c} \pm 2.1$	$56.2^{ab} \pm 0.8$	$11.8^{b} \pm 1.2$	$23.4^{bc} \pm 1.4$	$55.3^{c} \pm 0.8$
	Raw and soaked (control)	0.0095	3855.30	$24.6^{bc} \pm 0.8$	$53.2^{a} \pm 1.2$	$10.0^{b} \pm 0.6$	$19.3^{b} \pm 1.0$	$58.3^{c} \pm 0.7$
	Microwave	0.0136	6543.60	$41.7^{d} \pm 1.1$	$62.6^{b} \pm 0.2$	$26.2^{d} \pm 2.1$	$22.9^{bc} \pm 1.3$	$41.4^{a} \pm 0.9$
Reference	WWB	0.0451	15683.41	100.0	94.6	85.4	13.6	0.0

Note: Values are means ± standard deviation (n = 3).
Control: Raw soaked sorghum grains. abcd Means in a column with different letters are significantly different ($p \leq 0.05$). Microwave pretreatment was for 10 min at 1000 W.
Abbreviations: AUC, area under the curve of the starch digestion kinetics; eGI, estimated glycemic index; HI, hydrolysis index; k, starch digestibility kinetic constant for sample; RDS, rapidly digestible starch; RS, resistant starch; SDS, slowly digestible starch; WWB, white wheat bread.

TABLE 4 | In vitro protein digestibility (%) (IVPD) of microwaved whole grain and decorticated white sorghum.

Sorghum grain	Treatment	IVPD (%)
0% Decorticated (Whole)	Raw	$36.2^{b} \pm 1.4$
	Control	$27.1^{d} \pm 1.6$
	Microwave	$24.6^{d} \pm 0.9$
5% Decorticated	Control	$39.0^{ab} \pm 2.3$
	Raw	$38.5^{ab} \pm 1.8$
	Microwave	$30.9^{c} \pm 1.2$
10% Decorticated	Raw	$40.7^{a} \pm 1.5$
	Control	$39.1^{ab} \pm 1.1$
	Microwave	$26.8^{d} \pm 0.2$

Note: Values are means ± standard deviation ($n = 3$). Abcd: Means in a column that do not share a letter are significantly different ($p \leq 0.05$). Microwave power is 1000 W for 10 min.

Table S2 and Figure 5. The treatments had a significant effect ($p < 0.05$) on selected aroma, appearance, flavor, mouthfeel, and aftertaste attributes. Decortication of grain had a greater impact on the sensory properties of cooked sorghum grain than the microwave treatment. Decortication affected the appearance of the cooked sorghum as the cooked grain appeared popped/not intact, and the effect was greater as the decortication level increased. Decorticated grains were softer, less chewy, and less grainy, with fewer residual particles and generally less intense flavor. Microwave pretreatment had minor effects on the sensory properties of sorghum grain. It increased the toasted aroma intensity of whole sorghum grains but decreased this attribute for 10% decorticated grains.

Decortication eliminates barriers, allowing for expansion when heated (Taylor and Dewar 2001) leading to a softer texture, consistent with the findings of Dharmaraj et al. (2014) in their research on finger millet. More specks in whole and 5% decorticated sorghum are probably due to the greater presence of bran fragments, as reported by Kebakile et al. (2008).

Decorticated grains were milder in flavor than whole grain, due to pericarp removal. The pericarp of sorghum grain contains phenolic compounds, contributing to stronger flavor and astringency in sorghum products (Kebakile et al. 2008). Taylor and Dewar (2001) reported that consumers preferred decorticated sorghum grain for making sorghum flour due to its lower astringency.

4 | Conclusions

The combined application of microwave treatment and decortication reduces the cooking time of sorghum to produce a quick-cooking sorghum grain. Microwave pretreatment induces starch pre-gelatinization and protein denaturation, reducing pasting viscosity, transition enthalpy, and subsequent reduction in cooking time. Decortication further enhances this effect by exposing the inner cotyledon and endosperm. Microwave treatment have less contribution to sensory attributes then decortication while decortication cause reduced sweetness and maize flavor intensity and increase the softness compared to whole grain samples. Microwave treatment and decortication increase starch digestibility but decrease protein digestibility. Considering the nutritional significance of sorghum, particularly for health-conscious individuals with time constraints, this study indicates the potential of microwave treatment and decortication in the production of quick-cooking sorghum grain. These findings suggest effective strategies for upscaling the production of quick-cooking sorghum grain to meet market demands and address the needs of time-strapped, health-conscious consumers.

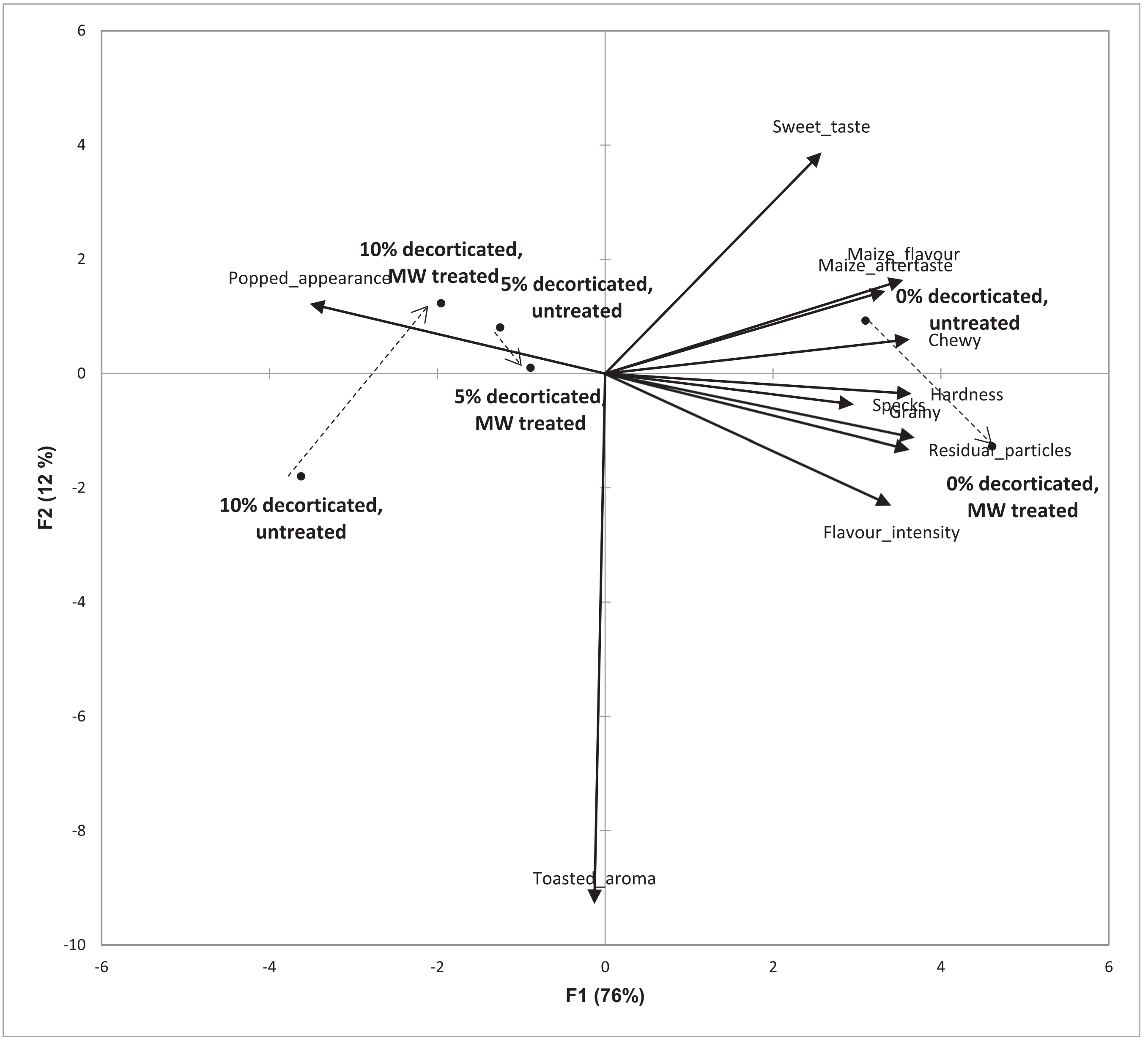

FIGURE 5 | Principal component analysis of the descriptive sensory attributes showing significant differences ($p < 0.05$) for the decorticated and/or microwave (MW) pretreated cooked sorghum grain samples. Values are mean ratings for duplicate evaluation by a trained panel ($n = 11$). The definition of attributes is shown in Table S1. The dash lines indicate the effect of microwave treatment on the grains at the different decortication levels.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available on request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.
Supporting Table S1. Related to Table 1: Sensory descriptors and evaluation guidelines used by sensory panel to evaluate sorghum grain samples. **Supporting Table S1. Related to Table 2:** Comparison of the descriptive sensory profiles of decorticated and/or microwave (MW) pre-treated cooked sorghum grain.