Effects of soaking and malting on thermal, functional and antinutritional properties of finger millet (*Eluesine coracana L. Gaertn*) flour

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DECLARATION

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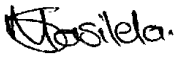
…  …… …04/08/2025……

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ACRONYMS

ANOVA	Analysis of variance
AOAC	Association of Official Analytical Chemists
AR	Aldose reductase
BU	Brabender Unit
CCRD	Central composite rotatable design
DBFM	Dark brown finger millet
EXP	Experimental
FAO	Food and Agriculture Organisation of the United Nations
FAOSTAT	Food and Agriculture Organisation Statistics
FM	Finger millet
FTIR	Fourier transform-infrared
ICAR	Indian Council of Agricultural Research
LM	Little millet
LBFM	Light brown finger millet
LBD	Loose bulk density
MT	Megatonne
OAC	Oil absorption capacity
PBD	Packed bulk density
PB	Protein bodies
PM	Pearl millet
PRE	Predicted
SG	Starch granules
SF	Sorghum flour
TIU	Trypsin inhibitor units
TTA	Total titratable acidity
USDA	United States Department of Agriculture
WAC	Water absorption capacity
XRD	X-ray diffraction ray

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ABSTRACT

In sub-Saharan Africa and India, finger millet (*Eleusine coracana L. Gaertn*) is a crucial food crop, holding the sixth position in cereal productivity, just after maize, wheat, rice, and sorghum. Despite its nutritional value, the underutilisation and neglect of finger millet have been widely documented. This research explored how soaking and malting impact the colour, pasting behaviour, thermal properties, crystallinity, and functional characteristics of both light and dark brown finger millet, along with sorghum (*Sorghum bicolor*) (included as reference). A central composite rotation design was applied with Design Expert software, focusing on soaking and malting durations of 24, 48, and 72 h. Sorghum flour exhibited high values for b*, c and hue, while the dark brown finger millet flour (DBFM) showed the highest L* value. The light brown finger millet flour (LBFM) recorded the highest redness (a) value. Gelatinisation onset temperatures were highest in LBFM, reaching 110.67°C, compared to 109.67°C for DBFM and 109.24°C for sorghum flour (SF), indicating slight thermal variation among the flours. The highest peak viscosity was observed in DBFM after 18 h of soaking and 24 h of malting. Tannin content ranged from 0.06 to 0.62 mg/100 g in LBFM, 0.15 to 0.84 mg/100 g in DBFM, and 0.21 to 0.77 mg/100 g in SF. Oxalic acid levels varied from 0.64 to 1.93 mg/100 g in LBFM, 0.93 to 1.56 mg/100 g in DBFM, and 0.50 to 1.45 mg/100 g in SF. Significant tannin models were identified in LBFM and SF, while all oxalic acid models were statistically significant across all flour varieties. Regarding functional properties, DBFM exhibited the highest pH, titratable acid (TTA), loose bulk density, and dispersibility. Sorghum flour demonstrated higher oil absorption capacity (OAC) and water absorption capacity (WAC), whereas LBFM exhibited the highest packed bulk density. Results indicated that soaking and malting significantly influenced the pasting properties and crystallinity of the flours. Scanning electron microscopy revealed structural modifications due to enzymatic activity during processing. Surface plots were generated, and ANOVA and regression analyses were performed to assess the data. These results offer important information for food processors on improving the colour characteristics, pasting behaviour, thermal and overall functional quality of finger millet and sorghum throughout processing. The models developed to evaluate these properties were dependable, as the lack-of-fit tests were not significant, and the coefficients of determination (R^2) were relatively high, ranging from 0.3403 to 0.8721 on functional properties of the flour, indicating strong model performance. These results emphasise that soaking and malting have a considerable impact on the microstructure and functional properties of finger millet and sorghum flours. By optimising these processing conditions, the bioavailability of nutrients and beneficial compounds can be improved, leading to better flour quality for diverse uses.

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Keywords: Finger millet, sorghum, soaking, malting, thermal properties, functional attributes

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CHAPTER 1: INTRODUCTION

1.1 Background of the study

Millets belong to *Poaceae* (formerly Gramineae) family. Millets comprise several species of the grass family, *Poaceae,* including pearl millet (*Pennisetum glaucum*), which contributes to 40% of global production, foxtail (*Setaria italica*), proso (white) millet (*Panicum miliaceum*) and finger millet (*Eleusine coracana*) (Amadou et al., 2013). Additional species include kodo millet (*Paspalum setaceum*), little millet (*Panicum sumatrense*), and barnyard millet (*Echinochlos utilis*). Millets are small-grain cereals with varying levels of phenolics and antioxidant activity depending on the variety and region of origin (Kumari et al., 2017). Currently, the global millet production is 30.73 million tons, with India producing 11.42 million tons, which represents about 37% of the total, making it the leading producer globally (Kaur et al., 2024). Millets are drought-resistant grains well suited for regions with high population densities and limited water resources, such as the tropical regions of Africa and the Asian subcontinent. As the most drought-tolerant grain globally, finger millet ranks as the 6th most important agricultural crop (Amadou et al., 2013; Tiwari et al., 2022; FAO, 2023). Compared to other major grains, finger millet is also exceptionally pest and disease-resistant, has a fast growth rate, thrives in less fertile soil, and produces excellent yields in severe heat and drought (Pasha et al., 2018).

The African continent and the Indian subcontinent grow finger millet (*Eleusine coracana L.*), both known as *uphoko* (IsiZulu, South Africa) and *ragi* (India) (Karki et al., 2020). It belongs to the *Chloridoideae* subfamily (Udeh et al., 2025) and is tetraploid (2n = 4x = 36) (Gimode et al., 2016). Finger millet (FM) may thrive in dry, non-irrigated environments with rainfall ranging from 200 to 500 mm. Finger millet (FM) is a small cereal with a light brown to brick ruddy seed coat and a dim brown seed coat high in phytochemicals like polyphenols and dietary fibre (Karki et al., 2020). Africa generates 2.5 million MT of finger millet per year, whereas India generates 1.2 million MT, accounting for almost 85% of millet produced in the country (Sakamma et al., 2018; Mundada et al., 2020).

The finger millet grains are an excellent source of nutrients, particularly calcium, fibre, antioxidants and phytochemicals, which aid in slow and easy digestion, thereby helping to regulate blood sugar levels in diabetics (Murungweni et al., 2023). FM is recognised as a beneficial nutrient for diabetics because of its low sugar content and the gradual release of glucose into the body (Bhasker et al., 2017; Kaur et al., 2024). It can also be incorporated into diets for pregnant and breastfeeding women, along with growing children, and it helps prevent or diminish the chance of osteoporosis (Poutanen, 2012; Verma & Patel, 2013; Anitha et al., 2021). The flour can be utilised to prepare different nutrient-rich formulas that can be utilised for

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supplementary bolstering (Bhosale et al., 2020). The flour can be used to make steamed dishes such as (*halape* and *pittu*), unfermented flatbread, and lean and thick porridges (Kumari et al., 2019). Brown FM can be utilised in planning geriatric and newborn child foods in natural and malted formsains are processed into flour to prepare puddings, pancakes, cookies, roti, bread, and other snack foods. When malted, it helps provide whole food for diabetics and nutritious food for infants (Gull et al., 2014). In southern Africa, the brown FM variety is used to brew the opaque traditional beer (Udeh et al., 2025), while in India and Nepal, it is consumed as unleavened bread, ragi-bolls (*mudde*), puffed grain, and fermented beer (Sood et al., 2017). In previous research, millet's phenolic content is altered by processing (Pradeep & Guha, 2011; Chandrasekara & Shahidi, 2012; Liang et al., 2019).

Many health advantages have been associated with FM flour, including weight management, bone health, reduced blood cholesterol, anaemia prevention, and the management of other ailments (Shaikh et al., 2018; Karki et al., 2020). These benefits are largely attributed to FM's high calcium, phosphorus, and iron content, as well as the presence of slow-digesting and resistant starch (Chandra et al., 2016; Wafula et al., 2018; Karki et al., 2020). Given these attributes, FM has gained recognition as a functional food, especially as consumer demand shifts toward ingredients with proven health benefits (Wadikar et al., 2007; Harshitha & Jayaram, 2019). In the context of the current study, which examines how soaking and malting affect thermal, functional, and anti-nutritional properties, understanding FM's inherent nutritional composition is crucial. If processing improves mineral bioavailability and enhances antioxidant potential linked to phenolic content and flavonoids (Adewale et al., 2010; Abioye et al., 2018), then it could strengthen FM's potential to address nutritional deficiencies and prevent oxidative stress-related conditions. Therefore, assessing how these processing techniques influence such components is directly aligned with the study's objective.

Anti-nutrients, including saponins, tannins, phytates, and others, are commonly found in FM. The bioavailability of micronutrients present in FM is reduced due to antinutrients (Abioye et al., 2018; Bekele & Admassu 2023). The presence of nutrient-inhibiting compounds limits the maximum utilisation of the nutrient potential FM (Singh & Raghuvanshi, 2012; Kumar et al., 2016). They can also inhibit growth and cause pathological changes in the liver, through their negative effect on the functioning of the pancreas and thyroid (Ramashia et al., 2019). Tannins lower the apparent digestibility of both protein and energy. Tannin compounds can also affect the colour and flavour of the grain and products made from it (Shashi et al., 2007; Ramashia et al., 2019). Phytates, especially those affecting calcium and zinc, are known to hinder mineral absorption in FM. On the other hand, oxalates interfere with peptic digestion by affecting calcium and

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magnesium metabolism and binding with proteins to form complexes (Abioye et al., 2018). In any case, these anti-nutrients can be removed through a variety of methods such as germination, splashing, broiling, ageing, and dehulling, among others. Numerous researchers have long reported on the reduction of such antinutritional variables through preparation strategies such as soaking, waxing, cooking, malting, and ageing. Germination may boost the nutritional content of grains and vegetables, according to some theories. Germination has also been shown to reduce antinutrient levels in grains while increasing amounts of several helpful supplements (Abioye et al., 2018).

Sorghum (*Sorghum bicolor*) is also known as a multipurpose crop that serves as food, fibre, and fuel (Rosas-Quijano et al., 2021). It contains the same attributes as those found in FM in terms of nutritional qualities and functionality. It is also classified as an underutilised crop with immense nutritional benefits like finger millet. It is cheap to cultivate, and when compared to other millet, sorghum has been extensively studied in malted form and production of alcoholic beverages such as gluten-free beer (Paliwal & Sharma, 2020).

Soaking assists in bringing grain moisture to a suitable level for respiratory and metabolic activity, as well as the mobilisation of primary and secondary metabolites, enabling germination. A considerable portion of phytic acid is removed from most germinated grain products (Coulibaly et al., 2011). Soaking millet flour before cooking increases the availability of zinc by activating phytases (Abubakar et al., 2015). Finger millet malting minimises tannin and phytate content in brown millet while increasing ionisable press and solvent zinc content (Hejazi et al., 2016).

Malting is mainly employed to produce enzymes (such as endogenous α-amylase) and to break down the cell walls surrounding starch granules, facilitating easier digestion. One of the key physicochemical changes during malting is the breakdown of the protein matrix surrounding the starch granules in the endosperm cells and its subsequent transformation. Peptides and amino acids are converted into soluble peptides and amino acids to provide substrates for protein synthesis in the developing embryo (Setia et al., 2019). Starch is a thickener, colloidal stabiliser, gelation agent, bulking agent, fluid retention agent and adhesive agent that contributes significantly to the structural properties of a wide variety of foods (Bhupender et al., 2013).

Functional properties are essential for evaluating and potentially predicting behaviour of new proteins, lipids, fibres, and carbohydrates in particular systems. They also help determine whether these proteins can be a supplement or substitute for existing protein sources. The use and use of food materials for different food items is often determined by their functional properties (Bora & Das, 2020). Germination is a classic processing method that helps cereal grains improve their nutritional and functional qualities, notably their digestibility (Ahmed, 2019).

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Processing techniques that alter the functional groups in starch molecules affect the pasting, gelatinisation and retrogradation properties of the flour and starch (Dasa & Binh 2019). Amylopectin is required for starch granule crystallinity; amylose reduces the melting point of the crystalline domain and the energy required to initiate gelatinisation (Bhupender et al., 2013). The amylose-to-amylopectin margin describes how much the functional group of starch changes during processing, depending on their efforts to the standard of its gelatinisation potential, onset (T_o), melting temperature (T_p), completion temperature (T_c) and gelatinisation radius and enthalpy (J/g) parameters are calculated (Anyasi et al., 2017).

Therefore, this study will evaluate the effects of soaking and malting on the thermal, functional and some antinutritional properties of finger millet flour. Soaking and malting are important unit operations for improving food quality during processing (Olamiti et al., 2020). The malting process triggers biochemical changes during controlled germination, enhancing both nutritional content and the bioactive compounds (Dahiya et al., 2018).

1.2 Justification

The literature has extensively documented the under-exploitation and neglect of this crop (Adhikari et al., 2017), and several studies have reported on the effects of soaking and malting on its nutritional and anti-nutritional properties (Abioye et al., 2018; Rathore et al., 2019). However, many of these studies applied fixed processing conditions, with limited focus on optimising the parameters that influence product quality. The present study addresses this gap by applying Response Surface Methodology (RSM) to systematically optimise the soaking and malting conditions. This approach allows for a more precise evaluation of how processing variables affect thermal, functional, and anti-nutritional characteristics. By focusing on optimisation, the study supports the development of consistent, high-quality finger millet flour with potential advantages in shelf stability, functional application, and processing scalability, an angle not fully explored in previous research.

1.3 Problem statement

While finger millet (FM) is recognised for its high nutritional value, improving the absorption of vital minerals such as iron and calcium remains essential. Effective processing techniques can lower the levels of antinutritional compounds, including tannins, phytates, and enzyme inhibitors, which are known to impair nutrient absorption (Sarita, 2016; Platel & Srinivasa, 2016; Rathore et al., 2019; Tharifkhan et al., 2021). These anti-nutritional factors can also influence starch digestibility and the overall colour attributes of the finger millet, thereby impacting its food value.

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These substances can lead to a less vibrant or darker colouration in the grain or its flour, which is frequently linked to diminished nutrient bioavailability. Therefore, the visual appearance of colour can act as an indirect measure of nutritional quality, signalling the possible presence and effects of anti-nutritional factors. Despite the significance of these factors, there is a notable gap in research on the optimisation of bioprocessing techniques such as soaking and malting using mathematical models like Response Surface Methodology (RSM).

Optimisation models provide a structured approach to identifying ideal processing conditions that enhance nutrient bioavailability, functional properties, and storage stability. This is especially important for underutilised grains like finger millet, where improving process efficiency and product consistency could support broader adoption in commercial food applications. In contrast to major cereals like maize and wheat, where industrial processing is already well-established, finger millet remains largely underexploited due to processing limitations. Therefore, using mathematical modelling to optimise processing may unlock new possibilities for large-scale utilisation, helping to bridge nutritional gaps in vulnerable populations and contributing to food system diversification.

1.4 Aim of the study

The study seeks to determine whether soaking and malting would indeed enhance the colour, thermal, pasting, nutritional, and functional properties of finger millet flour.

1.4.1 Specific objectives

The study's specific objectives are to:

I. To determine the effect of soaking and malting on the concentration of anti-nutritional factors (tannins and oxalic acid) of finger millet flour
II. Measure the physiochemical properties (colour attributes) of the soaked and malted finger millet flour
III. Evaluate functional attributes (thermal properties, pasting properties, crystallinity levels and microstructure) of soaked and malted finger millet flour

1.5 Hypotheses

I. Alternative: Soaking and malting will improve the colour, thermal, pasting, nutritional, and functional properties, while reducing some anti-nutritional properties of FM flour.
II. Null: Soaking and malting will not improve the colour, thermal, pasting, nutritional, and functional properties, while reducing some anti-nutritional properties of FM flour.

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CHAPTER 2: LITERATURE REVIEW

This chapter provides an overview of finger millet (FM), focusing on its significance to this research. Furthermore, it provides an insight into the structural and morphological characteristics, chemical composition and nutritional value, health benefits, antinutritional factors, processing methods (soaking and malting) and functional properties.

2.1 Structure and morphological features of finger millet grain

Finger millet is a cereal crop that undergoes self-pollination (Kumari et al., 2018). The plant and grain are drought, pest and pathogen-resistant (Karki et al., 2020). In a harsh range of ecological conditions, its productivity is better than other millets, even in low nutrient input conditions (Kumar et al., 2018). The grains are little, profound ruddy seeds, tinier than those of pearl millet (PM), and the seed weight of 1000 FM is about 2.6 g (Singh et al., 2019). FM is distinguished from other millets by its five-layered testa (Chandra et al., 2018).

The pericarp is present in both finger and foxtail millet (Birania et al., 2020). FM's pouch pericarps are only tenuously attached to the endosperm at one point (Hassan et al., 2021). In the case of utricle-type kernels, it separates, exposing the inner endosperm beneath the seed coat (Birania et al., 2020). The embryo is in a depression surrounded by a prominent crest, and the hilum is next to the germ (Shobana, 2009). Core weight is extremely low for FM without true caryopsis (FAO 2007; Gull et al., 2016). With a diameter ranging from 1 to 1.8 mm, the grain core could be spherical, globular, or oval (Figure 1). Because the pericarp is an inedible tissue, it is removed from the kernel before further processing (Patel & Verma, 2015). The endosperm is the most important anatomical part of the nucleus. It is connected to the seed coat and is used in flour production (Palanisamy et al., 2012).

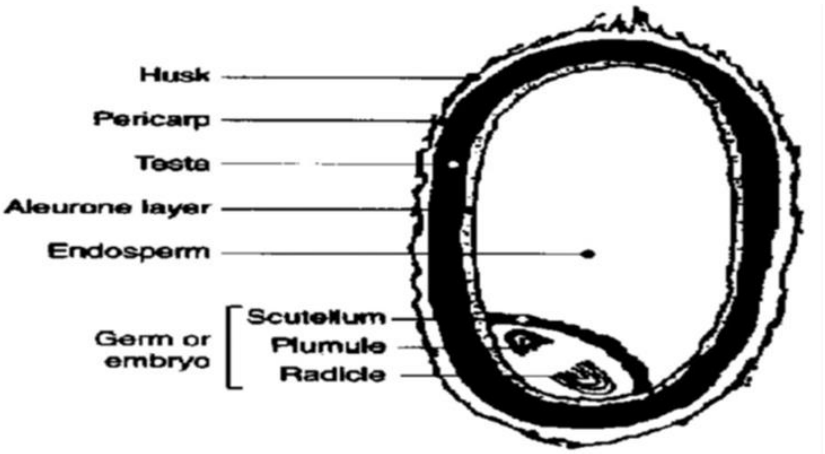

Figure 1. Finger millet grain structure. Source: Ramashia et al. (2021).

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The size of the mealy and grainy endosperm determines the millet's core texture. The floury endosperm is 83% whole grain (Gull et al., 2016) compared to granular endosperm found in soft textured grains; however, firm grains have thicker-filled granular endosperm. FM has an even distribution of endosperm between grainy and mealy areas. These endosperms are distinguished by their intermediate texture (Hassan et al., 2021). The soft endosperm is preferred for unleavened and fermented bread (Rooney et al., 1986; Hassan et al., 2021). Starch granules can have spherical, polygonal, or lenticular shapes. The starch in FM consists of a 25:75 ratio of amylose to amylopectin (Gull et al., 2016).

Finger millet grain has numerous health-promoting characteristics and a pleasing fragrance when cooked or broiled. The grain has a significant harvest for starvation-inclined zones due to its ability to stand without any creepy crawly harm when stored for quite a long time. Harvesting FM produces food crops and straw, valuable as fodder, particularly in rain-fed areas (Karki et al., 2020). It is among the most nutrient-rich crops, offering high levels of protein, minerals (such as calcium and iron), and amino acids (including methionine, an essential amino acid that is often lacking in the diets of many people living on monotonous foods like cassava, plantain, refined rice, and corn soup). Its calcium content is 8 to 10 times higher than that of wheat or rice. When compared to other major grains like wheat, rice, and sorghum, it is particularly rich in protein and minerals (Gupta et al., 2017).

2.1.1 Grain colour

The FM germplasm collection from Southern and Eastern Africa featured grain colours such as dark brown, light brown, *ragi* brown, reddish, and white (Figure 2). The most prevalent accessions were light brown (57.2%), reddish brown (22.3%), dark brown (10.2%), *ragi* brown (8.4%) and white (1.9%) (Upadhyaya et al., 2007; Karki et al., 2020).

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Figure 2. Finger millet grain and flour (Bharat 2020).

2.2 Finger millet grain chemical composition and nutritional value

Like rice, wheat, corn, and other millet grains, finger millet grains contain 81.5% carbohydrates, 9.8% protein, 4.3% crude fibre, and 2.7% minerals (Table 1). FM contains substantially high amounts of crude fibre and minerals compared to wheat (1.2% fibre and 1.5% minerals) and rice (1.2% fibre and 0.6% minerals). Amylopectin constitutes approximately 80 - 85% of FM starch, while the remaining 5 - 20% is composed of amylose (Wankhede et al., 1979). The quality of protein is largely defined by its composition of essential amino acids. In FM, essential amino acids make up 44.7% of its protein content (Mbithi-Mwikya et al., 2000). FM stands out among cereals and millets for its exceptionally high calcium content (344 mg%) and potassium levels (408 mg%) (Korir, 2019; Karki et al., 2020). The grain has a higher total ash content than any other commonly consumed cereal grain, ranging from 1.7 to 4.13% (Karki et al., 2020; Kaur et al., 2020). It is rich in both calcium and iron. Cereals are important to our diet because they contain the most calcium and iron. The grain aids in the treatment of calcium deficiency, which causes bone and dental disease, and iron deficiency, which causes anaemia (Rathore et al., 2019; Karki et al., 2020; Kaur et al., 2020).

The nutritional value of FM can be limited by the presence of tannins, phenols, phytates, and enzyme inhibitors. However, various processing methods like roasting, popping, malting, and fermentation are employed to mitigate the impact of these anti-nutrients. This processing technique enhances the absorption of essential minerals like calcium and iron. It is particularly beneficial for infants, the elderly, and pregnant women. Additionally, it supports breastfeeding mothers by helping them produce sufficient breast milk for their babies. It also aids in the prevention of malnutrition and degenerative diseases by increasing haemoglobin levels (Reddy, 2017).

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Table 1. The nutritional value of finger millet grain

Nutrients	g/ 100 g	References
Moisture	5.58 – 13.1	Amadou et al., 2013; Patil et al., 2017; Audu et al., 2018; Chuahan & Sarita, 2018.
Ash	2.51 – 3.51	Saleh et al., 2013; Thapliyal & Singh, 2015; Patil et al., 2017; Audu et al., 2018; Chuahan & Sarita, 2018.
Protein	5.9 - 13.1	Amadou et al., 2013; Thapliyal & Singh 2015; Adebiyi et al., 2016; Chandra et al., 2016; Lansakara et al., 2016; Patil et al., 2017; Audu et al., 2018; Chuahan & Sarita, 2018; Katake et al., 2018; USDA, 2018.
Fat	1.3 – 1.8	FAO, 2012; Amadou et al., 2013; Adebiyi et al., 2016; Chandra et al., 2016; Lansakara, et al., 2016; Patil et al., 2017; Chuahan & Sarita, 2018; Katake et al., 2018; Kumari et al., 2018; USDA, 2018.
Crude fibre	2.0 – 3.6	FAO, 2012; Saleh et al., 2013; Thapliyal & Singh 2015; Chandra et al., 2016, Lansakara et al., 2016; Sarita, 2016; Patil et al., 2017; Audu et al., 2018; Katake et al., 2018; Kumari et al., 2018.
Carbohydrates	72.0 – 85.6	FAO, 2012; Saleh et al., 2013; Thapliyal & Singh 2015; Adebiyi et al., 2016; Chandra et al., 2016; Patil et al., 2017; Audu et al., 2018; Katake et al., 2018; USDA, 2018.
Energy	328 – 380	Adebiyi et al., 2016; Chandra et al., 2016; Lansakara et al., 2016; USDA, 2018; Katake et al., 2018.
Minerals	**mg/ 100 g**	
Calcium	70.89 – 398	Amadou et al., 2013; Adebiyi et al., 2016; Chandra et al., 2016; Audu et al., 2018; Kumari et al., 2018; Hiremath et al., 2018.
Phosphorus	228 – 283	Adebiyi et al., 2016; Chandra et al., 2016; Hiremath et al., 2018.
Magnesium	78 – 201	Adebiyi et al., 2016; Chandra et al., 2016; Hiremath et al., 2018; Kumari et al., 2018; Ramashia et al., 2021; Hassan et al., 2021.
Iron	0.74 – 3.9	Adebiyi et al., 2016; Chandra et al., 2016; Audu et al., 2018; Hiremath et al ., 2018; Kumari et al., 2018.
Zinc	0.45 - 2.79	Adebiyi et al., 2016; Chandra et al., 2016; Audu et al., 2018; Hiremath et al., 2018; Kumari et al., 2018, .
Manganese	5.49 – 25	Adebiyi et al., 2016; Chandra et al., 2016; Audu et al., 2018; Hiremath et al., 2018.
Potassium	408	Adebiyi et al., 2016; Chandra et al., 2016; Kumari et al., 2018.

2.3 Health benefits of finger millet

Finger millet has been associated with several health benefits, including hypoglycemic and cholesterol-lowering effects, as well as nephroprotective activity (Chandra et al., 2016; Abioye et al., 2022). These effects are largely attributed to its bioactive compounds such as polyphenols, dietary fibre, and essential amino acids. For example, phenolic compounds like quercetin are known to inhibit aldose reductase activity in the outer seed layer, thereby preventing aldose

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reductase-induced cataractogenesis (Chandra et al., 2016; Nayak & Satish, 2024). Green FM has also been recommended for individuals with hypertension, asthma, liver disease, and cardiac insufficiency, and is even used to support lactating mothers with low milk production (Vaishnava, 2020; Praveen et al., 2022). Furthermore, the presence of tryptophan, an amino acid involved in appetite regulation, may assist with weight loss (Praveen et al., 2022; Kaur et al., 2024). The high fibre content of FM also contributes to satiety and reduced food intake. These health-promoting effects are directly linked to the nutritional and functional quality of FM flour. Therefore, improving the bioavailability of nutrients and the retention of functional compounds during processing through techniques such as soaking and malting can enhance the flour's contribution to health.

2.3.1 Anti-diabetic properties

Myriad studies reported that FM grains have a low glycemic index, making them better suited for diabetics (Aljobair, 2022; Patil et al., 2023; Kalsi et al., 2023; Joseph et al., 2024; Murungweni et al., 2023; Simran et al., 2024; Udeh et al., 2025). The phenolic compounds found in brown millet are 96% higher than in the white variety (Thomas & Karuna, 2019). A FM-centric diet, with its higher fibre content compared to rice and wheat, leads to significantly lower plasma glucose levels, reduced peak rises, and a smaller area under the curve. Millet contributes to lowering blood sugar levels and enhancing insulin response. (Chandra et al., 2016; Anitha et al., 2024). They also help heal skin wounds (Kimeera & Sucharitha, 2019; Nayak et al., 2024).

The glycaemic index of finger millet is considerably lower when fermented and roasted, in contrast to its unprocessed form. Both processing methods are recommended as they can support the body's insulin levels (Aisoni et al., 2018). Chandra et al. (2016) recommended FM supplements for diabetics due to their supportive potency and lower glycaemic responses in subjects. The existence of antinutritional factors in food that can minimise starch digestibility and absorption could explain the lower glycemic responses observed in processed millet. Compared to other grains, FM has the lowest blood sugar levels, blood cholesterol and triglyceride levels (Chapke & Tonapi, 2016; Chandra et al., 2016; Aisoni et al., 2018; Singh et al., 2020).

Hyperglycemia is a type 2 diabetes symptom that causes changes in protein, carbohydrate, and lipid metabolism, as well as non-enzymatic glycosylation of numerous proteins, resulting in chronic complications (Anjum et al., 2021; Rotela et al., 2021). FM supplements are recommended for people with diabetes because they are slowly digested and absorbed, which helps lower post-meal blood glucose levels (Nayak & Meti, 2021; Jagati et al., 2021). Regular consumption of FM lowers the likelihood of developing type 2 diabetes and gastrointestinal disorders (Nayak & Meti, 2021). Reducing postmeal hyperglycemia, or glucose spikes, is a

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diabetes mellitus prevention strategy that involves inhibiting or decreasing the activity of carbohydrate-hydrolysing enzymes. In the human digestive system, key enzymes such as α-amylase and α-glucosidase play a crucial role in converting carbohydrates into glucose for absorption. Regulating these enzymes may be vital for managing specific metabolic conditions, especially diabetes (Udeh et al., 2017). This highlights the importance of processing methods that retain or enhance these functional properties. Since soaking and malting can influence starch digestibility, enzyme inhibitor levels, and phenolic content, examining their effects on FM flour's anti-diabetic potential aligns directly with the current study's scope to optimise processing for improved nutritional and functional outcomes.

2.3.2 Antibacterial activity

Antibacterial or antimicrobial agents can kill or inhibit bacterial action without causing harm to neighbouring cells or tissues. These polyphenols also demonstrate antimicrobial activity (Călinoiu & Vodnar, 2018). Banerjee et al. (2012) measured the antimicrobial properties of polyphenol extract, as well as its phenolic components. Millet extract demonstrated inhibitory effects on the growth of *Escherichia coli, Listeria monocytogenes, Bacillus cereus, Streptococcus pyogenes, Staphylococcus aureus, Bacillus cereus, Serratia marcescenes, Proteus mirabilis, Klebsiella pneumoniae, Pseudomonas, and Yersinia enterocolitica*. The study by Jayawardana et al. (2020) demonstrated that antibiotic-sensitive strains of *Bacillus subtilis* (ATCC® 23857™) and *S. aureus* (ACC® 6538™) exhibited β-lactamase and antibacterial enzyme inhibition when treated with ethanolic and methanolic extracts of Sri Lankan finger millet varieties. It has been proposed that millet's high phenol content inhibited microbial enzymes and oxidised microbial membranes, resulting in bacterial cell proliferation (Kaur et al., 2024). Among the phenolic compounds tested, the phenolic compound quercetin demonstrated the greatest antiproliferative activity. This compound is widely recognised for its therapeutic benefits, including antioxidant, anti-proliferative and anti-apoptotic activities (Banerjee et al., 2012). Processing methods such as soaking and malting have positively influenced the phenolic content and bioactive compounds in finger millet flour, making it essential to understand their effects on its antibacterial properties.

2.4 Anti-nutritional properties of finger millet flour

When antinutritional factors are present in food, they reduce nutrient availability (Samtiya, 2020). The presence of these compounds in pearl millet and FM is believed to lower starch and protein digestibility, impair mineral absorption, and suppress the activity of proteolytic amylolytic enzymes (Hassan et al., 2021). Tannins, protease inhibitors, oxalates and phytates are

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antinutritional factors found in FM that are thought to affect nutrient digestibility in the opposite direction (Kumar et al., 2016; Hassan et al., 2021). In addition, Singh (2012) and Hassan et al. (2021) discovered that anti-nutritional components in FM, which include phytates, phenols, and tannins, impair nutrient utilisation. Malting wheat, barley, sorghum, pearl millet, oats, rice, and other cereal grains decreases antinutrients while increasing vitamins (A, B, C & E), minerals (calcium, manganese, copper & zinc) and protein content (Coulibaly & Chen, 2011).

2.4.1 Tannins

When comparing FM with other millets, it was stated that a high amount of tannin content is found in FM, ranging from 0.04 to 3.47% (Singh et al., 2019). However, this tannin content is not uniform across all FM varieties. Studies indicate that factors such as genotype, seed coat pigmentation, and environmental growing conditions influence tannin levels, with darker-coloured varieties (e.g., brown and dark) typically containing more tannins than white ones (Parida et al., 1989; Kumar et al., 2016; Abioye et al., 2022). The tannins in FM are primarily condensed tannins (proanthocyanidins), which have been shown to form complexes with proteins and minerals, potentially reducing their digestibility and absorption. In contrast, hydrolysable tannins, although less common in FM, differ structurally and may have a lesser impact on nutritional quality (Kumar et al., 2016; Das et al., 2020). Additionally, FM is a rich source of various phenolic compounds such as catechins, ferulic acid, protocatechuic acid, and quercetin derivatives. While these polyphenols contribute to the grain's antioxidant potential, they may also interact with essential nutrients, influencing their bioavailability (Abioye et al., 2022). Processing methods like germination, soaking, and high-pressure treatment have been shown to lower the content of tannins and other polyphenols, thereby enhancing the nutritional quality of FM-based foods without significantly compromising their health-promoting properties (Devi et al., 2014; Chauhan & Sarita, 2018; Abioye et al., 2022). Tannins have the potential to reduce food consumption and efficiency (Kumar et al., 2016). Because of the high tannin content (low ionisable iron), iron availability is low in brown FM varieties, negatively impacting nutritional properties (Chauhan & Sarita, 2018). Tannin has adverse effects on the digestive tract and metabolism (Ene-Obong 1992; Abioye et al., 2018), implying that sprouting reduces the presence of tannin in FM flour, thereby reducing this deleterious effect (Abioye et al., 2018).

2.4.2 Phytate and oxalates

The grains contain 240 to 300 mg/100 g of phytate, an anti-nutrient (Shobana et al., 2013; Abioye et al., 2022). In FM, phytates are known to hinder the absorption of minerals, especially

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zinc and calcium, while oxalates impact the metabolism of magnesium and calcium. Additionally, oxalates combine with proteins to create complexes that obstruct peptic digestion (Abioye et al., 2018). Oxalic acid can form strong bonds with various minerals, including sodium, potassium, magnesium, and calcium. As this happens, the resulting compounds are known as oxalate salts. As a result, the term "oxalate" typically refers to an oxalic acid salt, one of which is calcium oxalate (Liebman, 2002; Baranwal et al., 2014). Oxalic acid and its constituents negatively affect human nutrition and health by reducing calcium absorption and contributing to the formation of kidney stones (Savage, 2002). Furthermore, antinutrients in FM are assumed to differ depending on the environment, as demonstrated by (Shibairo et al., 2014; Hassan et al., 2021). An extended malting time lowers the phytic acid content. According to many studies, Malt FM reduces phytic acid by 23.9% within 72 h and 45.3% within 96 h (Makokha et al., 2002). The reduction is due to the hydrolytic activity of phytase on phytate, resulting in the production of myoinositol phosphate and phosphate (Abioye et al., 2018; Chauhan & Sarita, 2018; Abioye et al., 2022). Other studies suggest endogenous phytate production was the key factor in phytic acid reduction during soaking (Lestienne et al., 2005). Germination makes minerals more accessible to our bodies (Coulibaly et al., 2011; Chu et al., 2020; Li et al., 2022).

2.4.3 Protease Inhibitors

Proteinases are enzymes that enhance proteins' nutritional and functional characteristics (Salas et al., 2018). Protein inhibitors obstruct protein digestion by limiting the availability of digestive enzymes like chymotrypsin and trypsin. They are distinguished by compensatory pancreatic hypertrophy. Budhwar et al. (2020) discovered an inhibitor in ragi that is a single functional protein factor with two distinct reactive sites that are responsible for both amylase inhibitor and trypsin inhibitor activity. Trypsin is a protein-degrading enzyme essential for human and animal digestion. α-Amylase is mainly responsible for breaking down complex carbohydrates into simpler ones. As a result, these enzymes inhibit α-amylase activity, causing carbohydrate digestion and absorption to be delayed (Budhwar et al., 2020). The increased carbohydrate digestion time slows glucose absorption, directly impacting normal postprandial blood glucose levels. The germination technique reduces anti-nutrients in FM and improves its nutritional value (Abioye et al., 2018).

2.5 Processing methods of finger millet flour

Finger millet, like other cereal grains, must go through simple processing operations such as washing, grading, and separation to remove unwanted materials such as stones, soil particles,

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stalks, chaff, grains of other crops, etc. These operations are important in raising the product's rating to achieve better returns. These operations are also crucial for growing the price of the goods so that they can be offered for a better profit (Abioye et al., 2018; Ambre et al., 2020).

2.5.1 Soaking

Grain soaking enhances mineral bioavailability by reducing antinutrients, making it a valuable household food preparation method (Sarita, 2016; Adugna et al., 2024; Kang et al., 2024). Shigihalli et al. (2018) discovered that soaking FM in distilled water effectively reduced phytic acid levels, with an average of 250 mg after 12 h, 241 mg after 24 h, and 221/100 g after 48 h. The reduction in phytic acid has been linked to direct phytase hydrolysis within the seeds or the soaking medium after it leaches into the water. Bindra (2019) discovered that soaking FM grains in water lowers iron and zinc levels, which may be largely attributable to mineral loss in the soaking water. An additional study by Naveena & Bhaskarachary (2013), discovered that overnight soaking 12 h of pearl millet and FM grains significantly decreased polyphenol content. Polyphenols were reduced by PM and FM by 241.47 to 184.43 GAE mg/100 g and 161.64 to 128.97 GAE mg/100 g, respectively. This could be due to polyphenol breakdown caused by activating the enzyme polyphenol oxidase during soaking (Naveena & Bhaskarachary, 2013).

Syeunda et al. (2021) stated that the FM digestibility improves after soaking. Soaking enhanced protein digestibility from 62.3% to 76% by eliminating antinutrients that can bind to proteins and digestive enzymes, thereby hindering protein digestion. Conversely, the enhanced starch digestibility during soaking may be attributed to the leaching of antinutrients that hinder amylase enzymes, which are essential for starch digestion (Samuel & Peerkhan, 2020). Therefore, soaking is considered a preliminary processing technique that can bring about various nutritional and functional modifications (Samuel & Peerkhan, 2020).

2.5.2 Malting

Malting is a standard processing technique used to produce softer, finer flours, enhancing formulations for infants and health foods (Suma, 2014). It is also an economical process employed in brewing (Adebiyi et al., 2018; Murungweni et al., 2023). It enhances nutritional and functional properties and synthesises some B-group vitamins while decreasing the antinutrient content of the cereal grains (Ahmed et al., 2019; Ambre et al., 2020). Furthermore, it also improves the sensory qualities of the grains (Ambre et al., 2020). According to Akinola et al (2017), germination enhances the protein content of pearl millet grains by 50%, and Abioye et al. (2022) found that it also increased the ash and protein levels. Obadina et al (2017) discovered that malting pearl

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millet grains for 24 h enhanced protein and fibre content, while also noting a reduction in fat content. During the 48 h germination of FM grains, increased enzyme and fat utilisation activities decreased fat content (Hejazi et al., 2016). It increases the amount of protein and dietary fibre in the body. It also improved calcium, iron, and vitamin C levels. Malting aids in enhancing the antioxidant properties of finger millet grains while reducing their antinutritional content (Abioye et al., 2022; Sharma et al., 2022). Although it has a reduced carbohydrate content because it is utilised as an energy source during germination, there is an increase in α-amylase activity. This enzyme breaks down complex carbohydrates into simpler, more accessible forms necessary for seed development in the early stages of germination (Chauhan & Sarita, 2018). According to (Trang et al., 2020), enhanced protein digestibility is achieved through increased enzyme activity related to improved nutritional levels. These processes contribute to reducing antinutritional content, thereby enhancing the bioavailability of vital minerals including iron, zinc and calcium (Abioye et al., 2022).

Germination facilitates the accessibility of starch granules to hydrolytic enzymes by disrupting the protein and fibre matrix. This process also stimulates the activity of endogenous α-amylase enzymes, leading to the breakdown of starch chains and improving their digestibility (Setia et al., 2019). For example, sprouting enhances nutrient availability, reduces antinutrients, and enables the preparation of various nutritious food products, helping underprivileged communities address their nutritional requirements (Yousaf et al., 2021). In Africa, malted FM grain surpasses malted sorghum and maize in nutritional quality (Banusha & Vasantharuba, 2013; Sarkar et al., 2013; Thapliyal & Singh, 2015; Gaikwad et al., 2024). Rural communities traditionally produce malted FM on a small scale for brewing local beverages (Dlamini & Siwela, 2015). The brewed grain is commonly consumed by farmers during agricultural work and as a refreshment at community gatherings (Rurinda et al., 2014).

2.6 Functional changes during millet processing

The dynamic relationship between the composition, structure, molecular conformation, and physicochemical properties of food components and the essence of the system to which they are linked and measured is represented by functional properties (Abah et al., 2020). Food processing transforms raw ingredients into a usable or cooked form, extending their shelf life, enhancing aroma, improving texture, and flavour. This process diversifies dietary options while increasing the nutritional value of the food. Typically, a single processing method cannot achieve food processing. As a result, a wide range of processing techniques is used, including traditional/domestic methods such as debarking, grinding, soaking, boiling, roasting, sprouting,

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and fermenting (Aisoni et al., 2018). Due to the application of different processing techniques, significant alterations can take place in the physical, nutritional, and functional characteristics of food (Urooj 2017; Gaikwad et al., 2024). Regularly, the grains are also subjected to a variety of processing methods. The enhanced quality of processed FM makes it ideal for developing innovative food products, thereby supporting regional food security (Akinola et al., 2017; Akpoghelie et al., 2022; Adugna et al., 2024).

2.6.1 Water absorption capacity

Water-protein interactions are critical in food systems as they affect taste and texture. The ability of dietary proteins to bind water is influenced by intrinsic factors such as amino acid composition, protein structure and surface hydrophobicity or polarity. A protein's holding capacity or uptake capacity is more important in food applications than hydration (Bora & Das, 2020). According to Devisetti et al (2014), proso millet displayed the highest WAC in whole grain flour (143.0 g/100 g), followed by polished grain flour (130.9 g /100 g) and brown grain flour (118.8 g/100 g). The water absorption capacity of two (2) varieties of husked millet, little millet flour, was determined to be 0.82 g/g for the local genotype, which was significantly lower than 0.88 g/g for the Sukshema genotype (Roopa et al., 2013).

Nazni & Bhuvaneswari (2015) explored the physicochemical and functional properties of FM and LM, finding that the water absorption capacity of millet ranged from 0.94 g/g for FM to 1.15 g/g for LM. Thilagavathi et al (2015) examined the physicochemical and functional properties of four types of millets (kodo millet, little millet, pearl millet & proso millet) and reported water absorption capacities of 74.93, 76.83, 74.08 and 75.30 ml/100 g, respectively.

2.6.2 Oil absorption capacity

Any food material must be capable of physically entrapping oil via a dynamic capillary attraction mechanism. Fat is a flavour retainer, a persistent feature, and a mouthfeel enhancer (Khattab & Arntfield, 2009). Roopa et al. (2013) found that the oil absorption capacity of the local and Sukshema genotypes of LM was 0.64 and 0.66 g/g, respectively. Devisetti et al. (2014) reported that the oil absorption capacity fractions of proso millet and fox millet (whole, brown and polished) ranged from 59.5 to 95.6 g/100 g. Nazni & Bhuvaneswari (2015) stated that FM and little millet each had oil absorption capacities of 1.04 and 1.09 g/g. According to Gull et al. (2015), FM flour has an oil absorption capacity of 1.93 g/g and PM flour has a capacity of 1.60 g/g. Thilagavathi et al (2015) found that millet flours have oil absorption capacities of 74.74, 84.36, 85.57 and 73.58 ml/100 g, respectively (little millet, pearl millet & proso millet).

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2.6.3 Bulk density

The weight of flour is measured by its bulk density. It is a critical parameter that defines a product's packaging requirements as well as how well it performs in dry mixes. It is also affected by particle fineness (Baranwal & Sankhla, 2019). When developing weaning foods, high bulk density is an issue (Onimawo & Egbekun, 2002). Ogori et al. (2013), in their study investigation of the functional properties of pearl millet flour, reported a bulk density of 1.13 g/g. Roopa et al. (2013) found that the bulk densities of the local little millet genotype and Sukshema were 0.72 and 0.73 g/ml, respectively.

2.7 Effect of processing on the crystallinity level

Starch in its natural form is a semi-crystalline starch. The crystalline part of the granule is mostly made up of well-ordered amylopectin molecules. African starches come in a variety of flavours and crystalline structures. The crystalline structure of the 'A' type starches in X-ray diffractogram (XRD) is primarily characterised by two values: 15.3, 17.8 and 23.2, whereas the crystalline pattern of 'B' type starches is defined by two values: 5.5, 15, 17, 22.2 and 24 (Jayakody et al., 2005).

Type C starches represent a combination of both ‘A' and ‘B' starch types and are typically found in legume starches (Donald 2004). Most African grain starches exhibit an ‘A’ type crystalline structure, with relative crystalline values ranging between 22 to 44%. In contrast, the majority of legume starches, except for African yam, display a C-type XRD pattern with relative crystallinity values of 37 to 44% (Emmambux & Taylor 2013). Mohan et al. (2005) reported that FM starches are more crystalline compared to rice starches. Additionally, crystallinity values are influenced by variety. For instance, red (polyphenol-rich) sorghum tends to exhibit higher crystallinity than white sorghum (Boudries et al., 2009). Higher gelatinisation temperatures are associated with higher crystallinity values (Emmambux & Taylor 2013).

2.8 Effect of processing on thermal properties

The most popular method of food preservation is thermal processing, which kills microorganisms while extending shelf life. Thermal processing, on the other hand, has long been thought to result in the loss of heat-labile nutrients, lowering nutrient benefits while increasing digestibility (Randhir et al., 2008). The gelatinisation temperatures of African legume starches are generally higher than those of African cereal starches. The higher gelatinisation temperatures are due to the crystallinity of legumes being higher than that of grain starches. The temperatures and enthalpies of gelatinisation serve as key indicators of the heat and energy necessary to gelatinise

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starch. These parameters are essential for cooking starch-based foods and facilitating biochemical reactions during processing, such as in beer brewing (Emmambux & Taylor 2013). Starch gelatinisation temperatures can be influenced by several intrinsic factors listed below:

a. Regarding thermal properties, the starches of African cereals differ from those found in widely cultivated cereals like maize, rice and wheat. FM starches, in particular, exhibit higher gelatinisation temperatures and enthalpy values compared to rice starches (Mohan et al., 2005), which can be attributed to their higher crystalline content. Similarly, pearl millet starches demonstrate higher gelatinisation temperatures than wheat and corn starches (Hoover et al., 1996).
b. Phosphate content is related to gelatinisation temperatures in a positive way (Xu et al., 2017). Wang et al (2018) reported that cereal seed starch contains a significantly lower phosphate content, measuring less than 1 nMol Glc-6-P/mg starch (equivalent to fewer than 1 phosphate group per 6000 glucose residues), compared to other starches. In contrast, potato starch exhibited a notably higher level of starch-bound phosphate at 8.33 nMol Glc-6-P/mg starch (equivalent to over 1 phosphate group per 200 glucose residues), while cassava root starch displayed a slightly lower concentration of 2.5 nMol Glc-6-P/mg starch.
c. The amylose/amylopectin ratio is known to influence starch gelatinisation temperatures (Sorour et al., 2019). Lu et al. (2013) found that, in comparison to wild-type sorghum grains, waxy millet grains with high amylopectin content hold considerable economic importance for the food and bioenergy sectors. This is attributed to their enhanced starch digestibility and greater efficiency in ethanol production.
d. Griebel et al. (2019) discovered that the thermal characteristics of starches from sorghum genotypes grown in West Lafayette were affected by both generic and environmental factors. In the hard, corneous endosperm, starch granules are densely packed, whereas in the soft, floury endosperm, the granules are less compact (Ekpa et al., 2018). The difference in crystal structure and amylopectin fine structure between sorghum mealy and grain endosperm starches is unknown, but it is thought to be influenced by genetics. Sorghum derived from red sorghum has higher gelatinisation temperatures than white sorghum due to genetic differences (Boudries et al., 2009). Beta et al. (2000) observed polyphenol-rich sorghum starches with a low enthalpy. Boudries et al. (2009) applied a combination of hypochlorite and sodium hydroxide at a constant temperature of 60ºC for the red sorghum, while Beta et al. (2000) used only sodium hydroxide at a lower temperature of 5ºC.

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e. The temperature and enthalpy of gelatinisation can be influenced by the architecture of amylopectin. Teff starches were discovered to have lower gelatinisation temperatures than corn starches (Bultosa & Taylor, 2003). Amylopectin from five teff cultivars had a radius of gyration of 156 nm, whereas cornstarch had a radius of gyration of 186 nm (Bultosa et al., 2008). According to the study, Teff starches had shorter amylopectin outer chain lengths than maize starches. As a result, amylopectin molecules with shorter chain lengths and lower gyration radius may have lower teff starch gelatinisation temperatures (Bultosa et al., 2008).

2.9 Conclusion

Finger millet (FM) as a staple food has great processing value due to its adaptability to various traditional and modern techniques such as fermentation, malting, milling, and extrusion. These processes enhance its nutritional profile, improve digestibility, extend shelf life, and allow for the development of a wide range of food products. An increase in production, utilisation and marketing will ensure that FM is recognised as a valuable food crop with immense potential to contribute to food and nutrition security. Africa's cereals, legumes, and tubers all contain a significant amount of starch. Soaking time, malting time and temperature are considered to have an impact on the crystallinity level, thermal properties and anti-nutritional factors of dark and light brown FM flour. The application of response surface methodology to FM processing challenges, particularly bioavailability, could be beneficial.

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CHAPTER 3: MATERIALS AND METHODS

3.1 Source of materials

Finger millet grains (light and dark brown variants) were adopted, and sorghum (*S. bicolor*) grains were adopted as a reference sample. Because other indigenous varieties of finger millet were difficult to come by in the region in massive quantities, sorghum grain was utilised as an external reference in the study. The grains were obtained from Thohoyandou, Limpopo Province, South Africa. Analytical reagents were obtained from Merck Life Sciences Pty (Ltd), South Africa. Finger millet varieties (light brown & dark brown), 30 mesh sieve, sulphuric acid, sodium hydroxide, methanol, distilled water, blender, spectrophotometer, muffle furnace, oven dryer, weighing balance, crucibles, beaker, and polyethylene pouches.

3.2 Processing of grains

3.2.1. Soaking of grains

The FM and sorghum grains, separately, were immersed in distilled water in a conical flask at a grain to water ratio of 1.5 (w/v) for 12, 24 and 48 h at room temperature. After soaking water was discarded, the grains were dried at 60ºC for 6 h until a constant moisture content was reached. The dried seeds were then ground into a fine powder using a laboratory mill and sieved through a 250 µm mesh and stored in an airtight polythene bag for subsequent analysis (Shigihalli et al., 2018). Figure 3 illustrates the soaking and malting process of FM.

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Figure 3. The soaking and malting of finger millet grain.

3.2.2 Malting of grains

Separately, whole grains of different varieties of finger millet and sorghum were washed and immersed in distilled water within a conical flask maintained at ambient temperature overnight. The grains were strained and evenly distributed on stainless steel trays lined with a damp white muslin cloth. Table 2 shows how the grains were germinated at specific temperatures. The malted grains were dried for 6 h at 60˚C in an oven dryer (Prolab Instrument, South Africa) until they achieved a consistent moisture content of approximately 10 to 12%. Growth portions were detached by gently rubbing. The devegetated grains were weighed, ground into powder, and prepared for subsequent experiments (Shigihalli et al., 2018).

3.3 Experimental design

A two-factor central composite rotatable design (CCRD) (Box & Hunter, 1957) was employed to investigate responses, crystallinity level, thermal properties, anti-nutritional factors and functional groups. The soaking (X_1) and malting (X_2) times were the independent variables selected to optimise the dependent variables – Y (proximate composition, thermal properties,

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crystallinity level, functional groups, and anti-nutritional factors) (Table 2). All design points were measured in triplicate except for the centre point (0, 0, 0). The experiments were conducted in random order. Individual Y responses were predicted using a quadratic polynomial regression model as presented in equation 1. For each Y response, the following model was proposed:

$$Y = \beta 0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \quad [1]$$

Where: Y is the predicted response, β_0 model constant, X_1 and X_2 are independent variables, β_1 and β_2 are linear coefficients β_{12} is the cross-product coefficient, while β_{11} and β_{22} are the quadratic coefficients.

Table 2. Independent variables and levels for the central composite rotatable design

Independent Variable	Coded levels and real values			
	Variable code	-1	0	+1
Soaking time (h)	X_1	0.00	9.00	18.00
Malting time (h)	X_2	24.00	48.00	72.00

X_1 = soaking time (h); X_2 = malting time (h)

3.4 Colour properties of the flour

The colour properties (L*, a*, b*, C* and H°) of the flour samples were measured using the Lovibond LC 100 spectrocolorimeter and SV 100 test kit (Thilagavathi et al., 2015). To quantify and represent colour characteristics as positive and negative values in the colour space, the parameters L* (whiteness/brightness), a* (redness/greenness), and b* (yellowness/blueness) were used. The hue (H°) was assessed based on various colours, including yellow, green, and blue. Chroma (C*) was defined as a grey or pure hue.

3.5 Determination of thermal properties of flour

The thermal properties were evaluated using a differential scanning calorimeter (DSC 4000, Perkin-Elmer, Shelton, CT, USA). An empty DSC pan was used as the reference, while 25 mg sample of finger millet was placed in a sealed pan on a balance. The pan was heated from 20 to 130°C at a rate of 10°C per minute. The Pyris thermal system software, linked to the DSC, was employed to record the onset, peak, conclusion temperatures, as well as enthalpy range for both soaked and malted flours (Mudau et al., 2022).

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3.6 Pasting properties of the flour

Finger millet flour was used for the testing procedures following the ICC 162 Rapid Pasting Method (2018). A 3 g portion of starch was mixed with 25 ml of distilled water. All experiments were conducted using an air-bearing Modular Compact Rheometer (MCR) and a Starch Cell, both manufactured by Anton Paar. The starch cell features an electrically heated temperature device and counter-cooling to ensure precise temperature control with rapid heating and cooling capabilities. A starch stirrer was employed to prevent sedimentation of the starch granules. The flour suspension underwent a systematic stirring and temperature profile, comprising five stages: mixing, equilibration and water uptake, heating, holding, and cooling. Each measurement was repeated twice to ensure reproducibility.

3.7 Scanning electron microscopy (SEM) of finger millet flour

FM flour samples were sputter-coated with a gold-palladium layer using a coater and positioned on a sample holder. The microstructure of the FM flours was observed using a scanning electron microscope (Model JSM 6610 LV, Chicago, IL, USA) at a magnification of 1400x and a scale of 50 µm (Gull et al., 2015).

3.8 Crystallinity level analysis of flour

The crystallinity of the flour was analysed according to Adebiyi et al. (2016). Finger millet and sorghum flours were ground and sieved to a particle size of 40 µm. Five grams of the sieved flour were placed in the XRD sample holder and compressed with a stainless-steel weight. To evaluate the crystalline characteristics and X-ray diffraction patterns of the flours, an X-ray diffractometer (Rigaku-Ultima IV, Japan) was used. It was equipped with a divergence slit and operated at 40 kV and 40 mA, with a scanning range of 5 - 90º and a scan speed of 2º/min.

3.9 Fourier transform-infrared (FTIR) spectroscopy of flour

The functional groups of FM and sorghum flours were determined following the method described by Adebiyi et al. (2016). An FTIR spectrophotometer [Thermo Scientific Smart iTR (Attenuated Total Reflectance), Thermo Fischer Scientific Inc., USA] was employed to capture the FTIR spectra of the flours. A 0.5 g sample of the flour was placed in the instrument, which conducted 16 runs per scan. The spectra were obtained, showing distinct peaks within the range of 450 to 4000 cm.

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3.10 Determination of anti-nutritional factors

3.10.1 Tannins

The tannin content was assessed using the Vanillin-HCl method, modified from Price & Butler (1977). Accurately, 2 g of the sample was combined with 20 ml of methanol and subjected to ultrasonication for 15 min. After extraction, the supernatant was collected. A 1 ml portion of the supernatant was then mixed with 5 ml of vanillin hydrochloric acid reagent, which was made by combining equal volumes of 8% hydrochloric acid in methanol and 4% vanillin in methanol. A standard catechin solution (20–100 µg) was used as the reference standard. The absorbance of both the sample and the standard solutions was measured at 500 nm after 20 min using a Jenway V7305 spectrophotometer.

3.10.2 Oxalic acid

The Mishra et al. (2017) method was followed to extract oxalate ions from samples. This was achieved by boiling the flour samples with 0.5N H_2SO_4. The oxalate concentration was then measured volumetrically by titrating the extract with a standard $KMnO_4$ solution, following the reaction in equation 2:

$$MnO_4\text{-}+5C2O_4^{2-}\text{-}+8H^+\text{+}\rightarrow Mn^{2+}\text{++}10CO_2\text{+}4H_2O \qquad [2]$$

To prepare 500 ml of 0.5N H_2SO_4, concentrated sulfuric acid with 98% purity and a density of 1.84 g/ml was used. Exactly 6.8 ml of the concentrated acid was carefully measured and then diluted with distilled water until the total volume reached 500 ml. For the preparation of 100 ml of 0.05N $KMnO_4$ solution, 0.158 g of $KMnO_4$, with a molecular weight of 158 g/mol, was mixed with 100 ml of water. To prepare the plant extract, 1 g of plant material was weighed and added to 30 ml of 0.5N H_2SO_4. This mixture was heated in a water bath for 15 min. After heating, the solution was filtered through Whatman No. 1 filter paper. The resulting filtrate was diluted with an equal volume of deionised water. Next, 10 ml of the filtered plant extract was combined with 40 ml of 0.5N H_2SO_4, to reach a final volume of 50 ml. The mixture was heated to 60°C and titrated with 0.05N $KMnO_4$ until a light pink colour remained, indicating the endpoint of the titration.

3.11 Determination of functional properties of FM flour

3.11.1 pH and total titratable acid of FM flours

The pH was measured following the AOAC (2000) method 943.02 using a calibrated pH meter. Calibration was performed with three standard buffer solutions: acidic (pH 4.0), neutral (pH 7.0), and basic (pH 9.0) to ensure precision. The sample's precise pH value was recorded to

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accurately reflect its level of alkalinity or acidity. To determine the total titratable acid (TTA), the AOAC (2005) method 920.124 was employed. 5 g of the finger millet flour were combined with 52.5 ml of water preheated to 40ºC, then homogenised in a Stomacher at high speed for 120 sec. The mixture was filtered through Whatman grade 1.41 filter paper and allowed to cool to room temperature. After cooling, the filtrate was titrated with 0.1N NaOH using phenolphthalein as an indicator, adding NaOH dropwise until a persistent light pink colour appeared, marking the endpoint. The total titratable acidity was then calculated and expressed as a percentage of lactic acid.

3.11.2 Determination of dispersibility

The dispersibility of the flours was determined following the method described by Olapade et al. (2014), where 10 g of the flour was weighed into a 100 ml measuring cylinder, and distilled water was added. The mixture was thoroughly mixed and allowed to stand for 3 h. The volume of the settled particles was calculated using equation 3, and this value was then subtracted from 100.

$$\% \text{ Dispersibility} = 100 - \text{Volume of settled particles} \quad [3]$$

3.11.3 Water absorption capacity

One gram of FM flour was added in triplicate to pre-weighed 50 ml centrifuge tubes, followed by the addition of 10 ml distilled water. The mixture was thoroughly swirled using a glass rod and incubated in a water bath at 30ºC for 30 min (Sawant et al., 2013). The tubes were then centrifuged at 300 rpm for 15 min using a Model T-8BL LabyTM centrifuge (Laboratory Instruments, Ambala Cantt, India). After centrifugation, the residues were weighed, and the supernatants were discarded. Water absorbance was calculated using equation 4.

$$\text{Water absorption capacity} = \frac{V1 - V2}{V2} \quad [4]$$

Where:

V1 = initial volume of the liquid.

V2 = final volume of the liquid

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3.11.4 Oil absorption capacity

The oil absorption capacity was assessed following the procedure described by Mudau et al. (2021). One gram of flour (W0) was weighed and placed into pre-weighed 50 ml centrifuge tubes. The flour was then thoroughly mixed with 10 ml (V1) of refined sunflower oil using a vortex mixer (Heidolph Reax top, Germany). After mixing, the mixture was allowed to sit for 30 min. It was then centrifuged for 20 min at 2000 x g using a centrifuge (Universal 320 E Hettich, Germany). Following centrifugation, the supernatant was carefully transferred into a 10 ml graduated cylinder, and the volume was recorded (V2). Oil absorption capacity (OAC) was calculated using Equation 5.

$$\text{Oil absorption capacity} = \frac{V1 - V2}{W0} \quad [5]$$

3.11.5 Bulk density

Ten grams of flour were weighed and placed into a 25 ml measuring cylinder, with the initial volume recorded as the loose volume. The cylinder was tapped on a bench until a stable volume was achieved, at which point the densely packed volume was noted. The bulk density (BD) for both loose and packed flour was calculated using equation 6, as the ratio of the flour weight to the volume it occupied before and after tapping (Amandikwa et al., 2015).

$$\text{Bulk density} = \left(\frac{g}{cm^3}\right) = \frac{\text{Weight of the flour}}{\text{Volume of the flour}} \quad [6]$$

3.12 Statistical analysis

All experiments were carried out in triplicate, with results expressed as mean ± standard deviation. Data analysis was performed using Design Expert software 8 (Statease Inc.; Minneapolis, USA, version 12), employing One-Way Analysis of Variance (ANOVA) to determine significant differences in the effects of processing on the colour, thermal, functional, and anti-nutritional properties, with a significance level set at $p < 0.05$. Furthermore, optimisation parameters such as soaking and malting durations were analysed using regression analysis, and response surface plots were created to visualise their interactions and impact on the measured variables.

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CHAPTER 4: RESULTS AND DISCUSSION

4.1 Effect of soaking and malting on the colour properties of FM flour

The level of process variables and corresponding quality parameter values for the colour properties of soaked and malted light-brown finger millet (FM) flour (Table 3), dark-brown FM (Table 4), and sorghum flour (Table 5) are presented, offering detailed insights into the colour characteristics of the flours. The L* values ranged from 66.33 ± 2.68 to 71.17 ± 0.25 for light-brown FM flour; in dark-brown FM flour, L* values ranged from 65.90 ± 0.78 to 72.03 ± 0.42, and sorghum flour ranged from 68.40 ± 0.89 to 71.37 ± 2.00. Compared to sorghum flour, dark drown FM exhibited the highest value of 72.03 ± 0.42 at 21.73 h soaking - 48 h malting. The findings showed that longer soaking and malting times resulted in lighter flour, whereas shorter durations led to decreased pigmentation in the other flour. These results of L* for both light brown and dark brown fell within the range of malted FM flour stated by Murungweni et al. (2023), which ranged from 73.92 - 76.62 and 70.56 - 74.71, respectively. These results align with the findings reported by Yenasew & Urga (2022) for the Tadesse FM variety, which recorded an L* value of 78.41.

Based on the ANOVA results in Table 6, non-significant models were attained in both light-brown finger millet (FM) and dark-brown FM, while a significant influence was exhibited on the second order (X_1^2) soaking time on L* in light-brown FM. The high L* value obtained may be attributed to the leaching of phytochemicals during the malting process and the specific type of grains used (Olamiti et al., 2020). Looking at the regression models presented in Table 7, light brown FM flour demonstrated the highest coefficient R^2 on L* of 5.61, light brown FM flour demonstrated the highest coefficient R^2 on L* of 5.61, which was the highest value of all these processed flours. Olamiti et al. (2020) reported that low R^2 values in certain models do not always imply the models lack significance. This may happen when many data points are replicated, indicating that only a small proportion of the variation in the dependent variables is explained by the independent variables. A non-significant t-test result is beneficial, as it increases the validity of the model. The lightness results of light brown FM soaking (X_1) showed linear effects, malting (X_2) and the interaction effect.

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Table 3. Level of process variables and value of the quality parameter for colour properties of soaked and malted light-brown finger millet flour

Run	Soaking time (h)	Malting time (h)	Colour				
			L*	a*	b*	C*	H°
1	18.00	24.00	66.33 ± 2.68	3.73 ± 0.25	7.97 ± 0.29	8.80 ± 0.20	64.83 ± 1.77
2	21.73	48.00	69.06 ± 0.21	3.27 ± 0.21	7.20 ± 0.46	7.90 ± 0.53	65.70 ± 0.00
3	0.00	72.00	66.70 ± 1.74	4.10 ± 0.17	8.13 ± 0.12	9.10 ± 0.10	63.27 ± 1.27
4	18.00	72.00	67.10 ± 0.79	4.70 ± 0.17	8.43 ± 0.15	9.67 ± 0.21	61.00 ± 0.46
5	9.00	14.06	66.97 ± 0.40	4.03 ± 0.12	8.17 ± 0.25	9.07 ± 0.25	63.53 ± 0.15
6	9.00	48.00	71.17 ± 0.25	3.20 ± 0.17	7.60 ± 0.17	8.27 ± 0.23	67.20 ± 0.52
7	9.00	48.00	71.17 ± 0.25	3.20 ± 0.17	7.60 ± 0.17	8.27 ± 0.23	67.20 ± 0.52
8	9.00	81.94	70.30 ± 1.06	3.67 ± 0.15	7.73 ± 0.06	8.57 ± 0.12	64.63 ± 0.49
9	9.00	48.00	71.17 ± 0.25	3.20 ± 0.17	7.60 ± 0.17	8.27 ± 0.23	67.20 ± 0.52
10	9.00	48.00	71.17 ± 0.25	3.20 ± 0.17	7.60 ± 0.17	8.27 ± 0.23	67.20 ± 0.52
11	0.00	24.00	68.87 ± 0.38	4.07 ± 0.06	8.93 ± 0.12	9.83 ± 0.12	65.33 ± 0.15
12	9.00	48.00	71.17 ± 0.25	3.20 ± 0.17	7.60 ± 0.17	8.27 ± 0.23	67.20 ± 0.52
13	3.73	48.00	67.73 ± 1.12	3.97 ± 0.15	8.57 ± 0.12	9.43 ± 0.06	65.23 ± 1.10

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Table 4. Level of process variables and value of the quality parameter for proximate compositions of soaked and malted dark brown finger millet flour

Run	Soaking time (h)	Malting time (h)	Colour				
			L*	a*	b*	C*	H°
1	18.00	24.00	68.90 ± 1.55	3.20 ± 0.17	6.83 ± 0.06	7.57 ± 0.06	65.07 ± 1.21
2	21.73	48.00	72.03 ± 0.42	2.50 ± 0.00	6.70 ± 0.30	7.13 ± 0.25	69.57 ± 0.85
3	0.00	72.00	68.07 ± 1.18	3.67 ± 0.12	7.60 ± 0.17	8.47 ± 0.12	64.23 ± 1.10
4	18.00	72.00	67.13 ± 0.47	3.90 ± 0.00	8.23 ± 0.06	9.10 ± 0.10	64.73 ± 0.25
5	9.00	14.06	67.87 ± 0.85	3.13 ± 0.15	6.83 ± 0.15	7.53 ± 0.23	65.27 ± 0.61
6	9.00	48.00	70.43 ± 0.72	2.80 ± 0.08	6.37 ± 0.25	7.00 ± 0.26	66.27 ± 0.67
7	9.00	48.00	71.17 ± 0.25	3.20 ± 0.17	7.60 ± 0.17	8.27 ± 0.23	67.20 ± 0.52
8	9.00	81.94	70.90 ± 1.42	3.60 ± 0.20	6.83 ± 0.21	7.73 ± 0.31	62.23 ± 0.71
9	9.00	48.00	70.47± 0.67	2.80 ± 0.10	6.37 ± 0.25	7.00 ± 0.26	66.37 ± 0.49
10	9.00	48.00	69.73 ± 1.05	2.87 ± 0.15	6.23 ± 0.15	6.90 ± 0.20	65.50 ± 1.28
11	0.00	24.00	65.90 ± 0.78	3.70 ± 0.17	6.95 ± 0.06	7.90 ± 0.17	61.73 ± 0.87
12	9.00	48.00	70.03 ± 0.67	2.83 ± 0.12	6.30 ± 0.17	6.97 ± 0.23	65.97 ± 0.57
13	3.73	48.00	66.30 ± 2.07	3.50 ± 0.17	7.47 ± 0.35	8.23 ± 0.40	64.97 ± 0.59

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Table 5. Level of process variables and value of the quality parameter for proximate compositions of soaked and malted sorghum flour

Run	Soaking time (h)	Malting time (h)	Colour				
			L*	a*	b*	C*	H°
1	18.00	24.00	69.67 ± 1.12	3.10 ± 0.20	16.60 ± 0.50	16.87 ± 0.55	79.40 ± 0.36
2	21.73	48.00	68.63 ± 0.90	2.87 ± 0.06	16.27 ± 0.21	16.50 ± 0.20	79.97 ± 0.38
3	0.00	72.00	69.90 ± 1.51	2.97 ± 0.23	16.87 ± 0.21	17.10 ± 0.20	80.07 ± 0.90
4	18.00	72.00	70.73 ± 0.79	2.60 ± 0.26	16.23 ± 0.25	16.43 ± 0.25	80.93 ± 0.76
5	9.00	14.06	70.10 ± 0.89	3.00 ± 0.10	16.57 ± 0.60	16.80 ± 0.56	79.80 ± 0.10
6	9.00	48.00	69.97 ± 0.64	2.77 ± 0.06	16.43 ± 0.23	16.63 ± 0.23	80.40 ± 0.10
7	9.00	48.00	69.80 ± 0.17	2.97 ± 0.15	16.37 ± 0.12	16.60 ± 0.10	79.80 ± 0.50
8	9.00	81.94	68.40 ± 0.89	3.00 ± 0.36	16.63 ± 0.47	16.93 ± 0.57	79.80 ± 0.79
9	9.00	48.00	70.17 ± 0.46	2.97 ± 0.15	16.50 ± 0.20	16.73 ± 0.15	79.83 ± 0.55
10	9.00	48.00	70.17 ± 0.46	2.97 ± 0.15	16.50 ± 0.20	16.73 ± 0.15	79.83 ± 0.55
11	0.00	24.00	71.37 ± 2.00	3.13 ± 0.21	17.17 ± 0.31	17.43 ± 0.25	79.67 ± 0.83
12	9.00	48.00	69.70 ± 0.17	2.87 ± 0.21	16.30 ± 0.00	16.53 ± 0.06	80.03 ± 0.64
13	3.73	48.00	68.57 ± 0.85	2.83 ± 0.21	16.23 ± 0.55	16.50 ± 0.60	80.10 ± 0.66

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Table 6. ANOVA models of the effect of processing on L*, a*, b*, C* and H° of soaked and malted light-brown, dark-brown finger millet (FM) and sorghum flours.

Source	L*	a*	b*	C*	H°
	P-value	P-value	P-value	P-value	P-value
			Light-brown FM		
Model	0.1215	0.1656	0.1181	0.1571	0.0793
X_1	0.6909	0.3930	0.0423*	0.0890	0.9166
X_2	0.4706	0.6778	0.3967	0.7009	0.3063
X_1X_2	0.3699	0.2789	0.1385	0.1553	0.5442
X_1^2	0.0516*	0.1411	0.1821	0.1698	0.1210
X_2^2	0.0574	0.0434*	0.1648	0.1107	0.0146*
			Dark-brown FM flour		
Model	0.2716	0.1220	0.6517	0.5113	0.0490*
X_1	0.0796	0.1117	0.6554	0.4574	0.0373*
X_2	0.3719	0.2059	0.3056	0.2674	0.5913
X_1X_2	0.2952	0.3118	0.5854	0.5117	0.3236
X_1^2	0.2612	0.3173	0.3011	0.2946	0.9345
X_2^2	0.3390	0.0505	0.4926	0.3216	0.0177*
			Sorghum Flour		
Model	0.5777	0.2386	0.0733	0.0670	0.3101
X_1	0.4365	0.2241	0.0155*	0.0152*	0.6407
X_2	0.2979	0.0961	0.3251	0.3339	0.0863
X_1X_2	0.1940	0.2164	0.8666	0.8069	0.1421
X_1^2	0.8142	0.7448	0.1296	0.1330	0.9469
X_2^2	0.9222	0.3126	0.0877	0.0721	0.6222

*Significant at $p < 0.05$, Non Significant: X_1 = linear effect of soaking; X_2 = linear effect of malting time; X_1X_2 = interaction of soaking and malting time; X_1^2 = quadratic effect of soaking; X_2^2 = quadratic effect of malting time (h).

The a* results of processed light-brown FM and dark-brown FM flour demonstrated non-significant models, and these were higher than those of sorghum flour. The highest a* results were achieved at 18 h soaking and 72 h malting of light brown FM. It can be deduced from the ANOVA results that significance in light-brown finger millet (FM) and dark-brown FM was exhibited on soaking time (X_1) for b*, while the achieved models on these flours were non-significant. Moreover, in sorghum flour, significance was registered in soaking time (X_1) of b* and c* values. The regression models presented in Table 7 light brown FM linear effect on malting (X_2) on the a*, quadratic effects on soaking (X_1^2) were exhibited high on a*, b* and c* and malting (X_2^2) exhibited a similar interaction on a*, b* and c*. While the interaction effect was exhibited on a*, b and c*. Dark-brown FM flour demonstrated that malting (X_2) had the most linear effects on a*, b* and c* values. The interaction effects of dark-brown flour (X_1X_2) were highest on the a*, b* and c*. Quadratic effects on soaking (X_1^2) were exhibited by b* and c*, while in malting (X_2^2), these were exhibited by a*, b* and c*. Moreover, sorghum flour exhibited non-significant models for the L*, a*, b*, c* and h°, and a significant quadratic effect on soaking (X_1^2) which was highly demonstrated on a*, b*, and c* and on malting, these were exhibited on a*, b*, and c*.

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Table 7. Regression models relating response and independent variables for soaked and malted light brown and dark brown finger millet (FM) and sorghum flour on L*, a*, b*, C* and H°.

Response variables	Models	Residual fit at P-value	R^2
	Light-brown FM		
L*	$+64.1460+0.2560X_1+0.2058X_2+0.0034X_1X_2-0.02159X_1^2-0.0023X_2^2$	0.0003*	5.61
a*	$+3.28-0.1589X_1+0.0614X_2+0.2350X_1X_2+0.3232X_1^2+0.3720X_2^2$	0.0030*	0.3797
b*	$+7.76-0.4071X_1-0.1203X_2+0.3150X_1X_2+0.2716X_1^2+0.2207X_2^2$	<0.0001*	0.3285
C	$+8.38-0.4311X_1-0.0709X_2+0.4000X_1X_2+0.3729X_1^2+0.3452X_2^2$	<0.0001*	0.5887
H°	$+66.97-0.0657X_1-0.5418X_2-0.4425X_1X_2-1.19X_1^2-1.69X_2^2$	<0.0001*	4.50
	Dark-brown FM		
L*	$69.97+1.55X_1+0.5862X_2-0.9833X_1X_2-1.03X_1^2-0.6733X_2^2$	0.0056*	0.5359
a*	$2.95-0.2667X_1+0.1658X_2+0.1833X_1X_2-0.1762X_1^2+0.2994X_2^2$	0.0379*	0.6506
b*	$6.67-0.1332X_1+0.2562X_2+0.1875X_1X_2+0.3562X_1^2+0.1792X_2^2$	0.3064	0.3277
C	$7.33-0.2397X_1+0.2979X_2+0.2417X_1X_2+0.3853X_1^2+0.2815X_2^2$	0.2530	0.4009
H°	$66.20+1.49X_1-0.2654X_2-0.7083X_1X_2-0.0553X_1^2-1.55X_2^2$	0.0281*	0.7410
	Sorghum flour		
L*	$69.73-0.3171X_1-0.3505X_2+0.6333X_1X_2+0.1047X_1^2+0.0337X_2^2$	0.0020*	0.3364
a*	$2.89-0.0713X_1-0.0833X_2-0.0833X_1X_2+0.0202X_1^2+0.0504X_2^2$	0.1544	0.5577
b*	$16.36-0.2649X_1-0.0715X_2-0.0167X_1X_2+0.1597X_1^2+0.1432X_2^2$	0.0251*	0.7050
C*	$16.60-0.2743X_1-0.0723X_2-0.0250X_1X_2+0.1628X_1^2+0.1574X_2^2$	0.0223*	0.7135
H°	$80.00+0.0728X_1+0.2417X_2+0.2833X_1X_2+0.0115X_1^2-0.0666X_2^2$	0.1602	0.5120

*Significant at $p < 0.05$, Non Significant: X_1 = linear effect of soaking; X_2 = linear effect of malting time; X_1X_2 = interaction of soaking and malting time; X_1^2 = quadratic effect of soaking; X_2^2 = quadratic effect of malting time (h).

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The colour change, especially in the a* value, is due to phenolic compounds like tannin found in the grain's pericarp and testa. Leaching and polyphenol oxidase activities decrease these compounds during soaking and malting (Olamiti et al., 2020). Light brown FM flour's a* value increases with longer soaking and malting times due to these phenolic compounds and pigments. In contrast, dark brown FM and sorghum exhibit a lower a* value under comparable conditions, possibly due to an increase in lightness. The reduction in redness and yellowness of the flour could be linked to the removal of bran layers during the soaking and germination processes (Yenasew & Urga, 2022).

The redness (a*) results were higher than fermented light brown FM (2.65 - 4.28) and dark brown (2.79 - 3.54) range reported by Mudau et al. (2022) and yellowness (b*) results of processed light-brown FM flour and sorghum flour were higher than dark-brown FM flour, the b* results were found to be below the range reported for malted finger millet flour by Murungweni et al. (2023) of (7.62 – 9.49) for light brown and (6.84 – 7.09) for dark brown FM. The results obtained were higher than the 1.85 recorded for the Tadesse FM variety after 72 h of germination, as reported by Yenasew & Urga (2022). The positive values observed for the a* and b* coordinates suggest that samples exhibited varying concentrations of red and yellow pigmentation. The control sample demonstrated notably higher b* and c* values, with the maximum recorded values being 17.17 and 17.43.

The chroma (c*) models for all the processed flours, including light-brown FM, dark-brown FM, and sorghum flour, were found to be non-significant. Light-brown FM flour at (0 h soaking and 24 h malting) and sorghum flour (0 h soaking and 24 h malting) were higher than dark-brown FM flour, which exhibited a high C* value with the increase in soaking and malting time. These results of C* in light-brown FM were within the range of light brown, where 8.52 – 10.02, and dark brown FM was higher than the 7.29 – 8.38 reported by Murungweni et al. (2023) and the results reported by Onipe et al. (2024) of 9.14.

The highest hue angle was observed in the sorghum flour cultivar after 18 h of soaking and 72 h of malting, while the lowest hue angle was recorded in the light-brown FM cultivar following 9 h of soaking and 48 h of malting. The H° fell within the same range as those for malted FM flour by Murungweni et al. (2023), which varied from 63.43° ± 0.41 to 71.20° ± 0.08 for light brown and 64.23 ± 0.77 for dark brown FM. Based on the ANOVA results in Table 6, light brown FM exhibited significance on the hue's second-order malting time (X_2^2). In dark-brown FM, the model demonstrated significance on soaking time (X_1) in hue and second-order mating time (X_2^2) in hue. The rest of the other parameters of this model were insignificant. Moreover, in sorghum flour, significance was registered in soaking time (X_1) of b* and c*

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values. The differences in H° values of FM flours might result from varying malting durations, which affect protein content and soluble sugar levels (Murungweni et al., 2023). It is also a qualitative attribute that differentiates one colour from another. It is essential for the perception and acceptability of colour to individuals with typical colour vision (Bhargava & Bansal, 2021; Onipe et al., 2024). Further details on the response surface method can be found in the appendices: Appendix I covers light brown, Appendix II covers dark brown FM, and Appendix III covers sorghum flour.

4.2 Effect of soaking and malting on thermal properties

The detailed findings of the thermal properties (onset, peak, endpoint, and enthalpy) for soaked and malted FM (light-brown) response surface plots were studied. Further details on the response surface plots for the other flours are provided in the appendices: dark brown FM (Appendix IV) and sorghum flour (Appendix V).

From the response surface plots illustrations in Figure 4 of soaked and malted LBFM, it can be seen that extending the soaking and malting times resulted in higher onset, peak melting, and endpoint temperatures; however, an inverse relationship was observed between the soaking and malting times and the enthalpy values. Soaked and malted DBFM flour demonstrated a negative correlation between soaking and malting durations with the peak melting, onset, end completion and enthalpy values. Similarly, soaked and malted sorghum flour also displayed an inverse relationship between soaking and malting times and the onset, peak melting, and end completion values. The observed increase in peak temperature following malting may be attributed to the activity of proteolytic enzymes produced by naturally occurring microorganisms, which likely broke down cell wall components, enhancing starch release and promoting the formation of larger crystalline structures within the sample (Murungweni et al., 2023; Mudau et al., 2022). The prolonged soaking and malting processes induced structural alteration in the starch protein-matrix, particularly affecting the interaction between amylose and amylopectin, which remained largely resistant to enzymatic breakdown into sugars by α-amylase or lactic acid bacteria during these processes (Mudau et al., 2022; Olamiti et al., 2020).

The observed inverse relationship between soaking/malting time and enthalpy indicates that structural modifications during extended treatments reduce the energy required to disrupt starch granule bonds, suggesting a loosening of the internal crystalline structure (Mudau et. al., 2022; Chinma et al., 2020). Processing through soaking and malting optimally modifies thermal and structural properties of finger millet starch, promoting better digestibility and nutrient accessibility (Gowda et al., 2025). The response surface plots visually represent the

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contour shapes and offer valuable insights into the model's accuracy and fit (Olamiti et al., 2020; Omolola et al., 2015). Details on the levels of process variables and the values of the quality parameters for soaked and malted light brown FM (Appendix X), dark brown FM (Appendix XI), and sorghum flour (Appendix XII) are provided. The ANOVA results for all the flours are presented in Appendix XIII, and the regression results are in Appendix XIV.

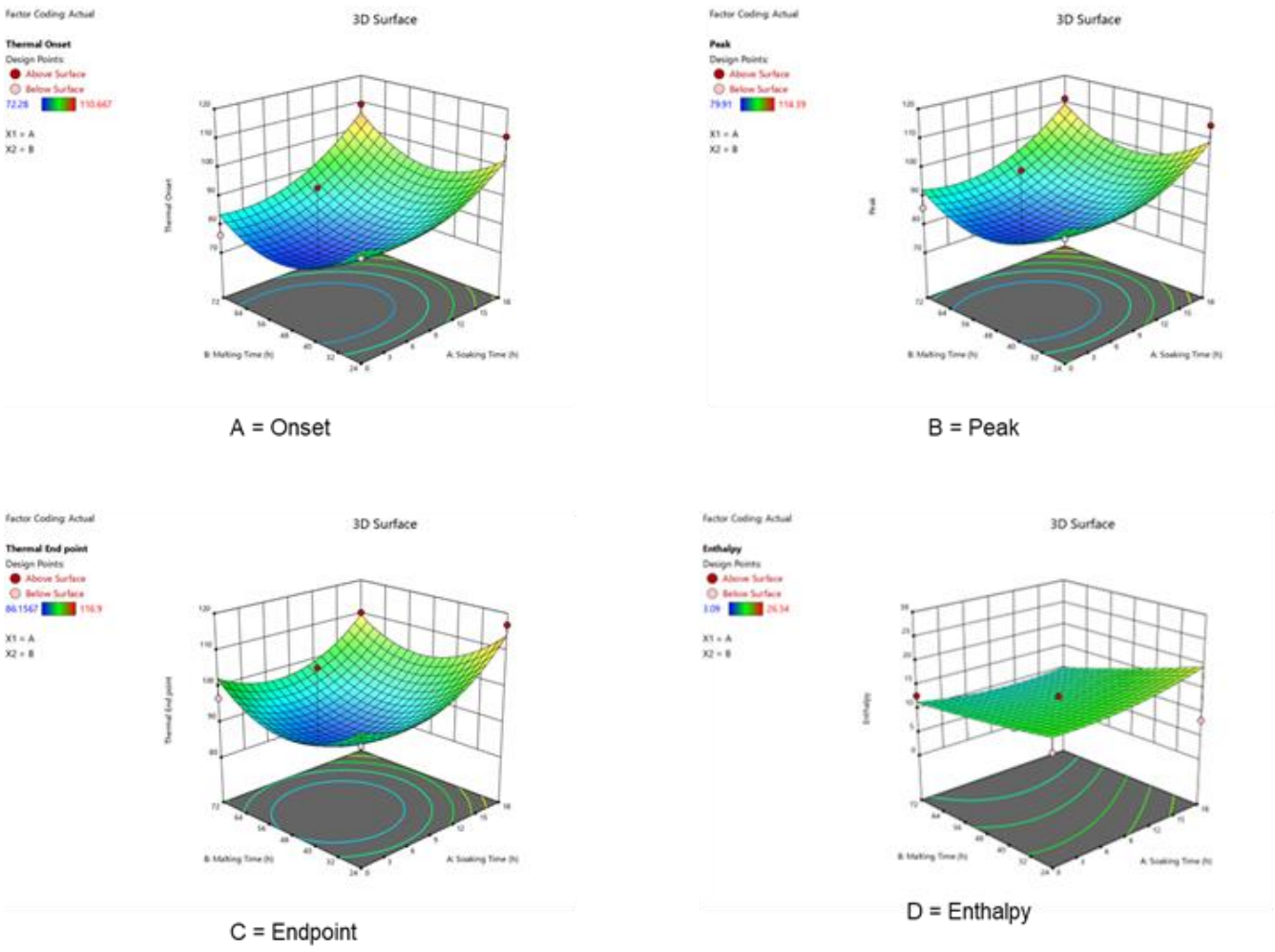

Figure 4. Response surface plots of soaked and malted light brown finger millet (LBFM) thermal properties (onset, peak, endpoint and enthalpy) temperatures.

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4.3 Effect of soaking and malting on antinutritional properties

4.3.1 Tannins of FM Flour

The tannin levels in light-brown FM (Table 8) varied between 0.06 and 0.62 mg/100 g, while dark-brown FM (Table 9) ranged from 0.15 to 0.84 mg/100 g, and sorghum flour (Table 10) ranged from 0.21 to 0.77 mg/100 g, as shown. From the result, it could be deduced that dark brown FM exhibited a high value of tannin content (0.84 mg/100 g) at soaking 21.73 h and malting time 48 h. This occurred at the expense of light-brown FM, which exhibited (0.62 mg/100 g) at soaking at 9 h and malting at 48 h, and sorghum flour (0.77 mg/100 g) at soaking at 18 h and malting at 72 h. The results obtained are lower than 1.20 and 2.23 mg/100 g mg of processed FM reported by Abioye et al. (2022).

Table 8. Level of process variables and value of the quality parameter for antinutritional factors of soaked and malted finger millet (light-brown) flour

Run	Soaking time (h)	Malting time (h)	Tannins (mg/ 100 g)	Oxalic acid (mg/ 100 g)
1	18.00	24.00	0.06 ± 0.02	0.78 ± 0.06
2	21.73	48.00	0.46 ± 0.08	1.16 ± 0.21
3	0.00	72.00	0.47 ± 0.01	0.65 ± 0.05
4	18.00	72.00	0.38 ± 0.01	1.83 ± 0.03
5	9.00	14.06	0.17 ± 0.00	1.11 ± 0.10
6	9.00	48.00	0.52 ± 0.13	1.93 ± 0.28
7	9.00	48.00	0.51 ± 0.15	1.73 ± 0.11
8	9.00	81.94	0.42 ± 0.22	1.28 ± 0.10
9	9.00	48.00	0.62 ± 0.13	1.85 ± 0.04
10	9.00	48.00	0.59 ± 0.14	1.91 ± 0.06
11	0.00	24.00	0.36 ± 0.15	0.73 ± 0.06
12	9.00	48.00	0.55 ± 0.16	1.69 ± 0.04
13	3.73	48.00	0.37 ± 0.14	0.64 ± 0.08

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Table 9. Level of process variables and value of the quality parameter for antinutritional factors of soaked and malted finger millet (dark brown) flour

Run	Soaking time (h)	Malting time (h)	Tannins (mg/ 100 g)	Oxalic acid (mg/ 100 g)
1	18.00	24.00	0.15 ± 0.02	1.27 ± 0.05
2	21.73	48.00	0.84 ± 0.11	1.56 ± 0.10
3	0.00	72.00	0.56 ± 0.02	1.39 ± 0.21
4	18.00	72.00	0.37 ± 0.13	1.44 ± 0.10
5	9.00	14.06	0.48 ± 0.03	0.98 ± 0.03
6	9.00	48.00	0.72 ± 0.11	1.03 ± 0.08
7	9.00	48.00	0.83 ± 0.05	1.05 ± 0.05
8	9.00	81.94	0.48 ± 0.00	0.93 ± 0.06
9	9.00	48.00	0.71 ± 0.10	1.07 ± 0.09
10	9.00	48.00	0.71 ± 0.02	1.08 ± 0.02
11	0.00	24.00	0.42 ± 0.02	1.67 ± 0.08
12	9.00	48.00	0.69 ± 0.16	1.14 ± 0.08
13	3.73	48.00	0.60 ± 0.12	1.42 ± 0.19

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Table 10. Level of process variables and value of the quality parameter for antinutritional factors of soaked and malted sorghum flour

Run	Soaking time (h)	Malting time (h)	Tannins (mg/ 100 g)	Oxalic acid (mg/ 100 g)
1	18.00	24.00	0.45 ± 0.05	0.99 ± 0.04
2	21.73	48.00	0.49 ± 0.14	0.50 ± 0.05
3	0.00	72.00	0.21 ± 0.15	0.70 ± 0.17
4	18.00	72.00	0.77 ± 0.04	0.85 ± 0.17
5	9.00	14.06	0.51 ± 0.12	0.96 ± 0.08
6	9.00	48.00	0.37 ± 0.02	0.83 ± 0.07
7	9.00	48.00	0.41 ± 0.04	1.03 ± 0.08
8	9.00	81.94	0.59 ± 0.04	1.45 ± 0.05
9	9.00	48.00	0.43 ± 0.16	0.92 ± 0.06
10	9.00	48.00	0.34 ± 0.00	1.01 ± 0.06
11	0.00	24.00	0.43 ± 0.07	0.68 ± 0.08
12	9.00	48.00	0.34 ± 0.02	1.02 ± 0.07
13	3.73	48.00	0.50 ± 0.12	0.70 ± 0.17

The ANOVA results in Table 11 demonstrated significant models in both light-brown FM and sorghum flour, and a non-significant model was demonstrated in dark-brown FM flour. Furthermore, significance in LBFM on the linear effect (X_2) malting time and second order malting time (X_2^2), whereas in DBFM, the model demonstrated significance on second order malting time (X_2^2) in tannins and SF demonstrated significance on the linear effect of soaking time (X_1), interaction soaking and malting time (X_1X_2) and second order malting time (X_2^2). The presence of tannins in FM contributes to its bitter taste. Reducing the tannin content through soaking can enhance the flavour and the availability of specific nutrients (Abioye et al., 2022).

4.3.2 Oxalic acid of FM flour

The results of the oxalic acid from light-brown FM flour (Table 8) ranged from 0.64 to 1.93 mg/100 g, dark-brown FM flour (Table 9) ranged from 0.93 to 1.56 mg/100 g, and sorghum flour (Table 10) ranged from 0.50 to 1.45 mg/100 g. Based on the results, it can be inferred that sorghum had the lowest oxalic acid content (1.45 mg/100 g) at 9 h of soaking and 81.94

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h of malting, compared to dark-brown FM flour, which had a higher content at 21.73 h of soaking and 48 h of malting. Light-brown FM flour exhibited the highest oxalic acid content (1.93 mg/ 100 g) at 9 h of soaking and 48 h of malting. The results obtained in this study were higher than those reported by Abioye et al. (2022) for FM flour, where values ranging from 0.39 -1.48 mg/100 g were reported. Significance was registered from the ANOVA models in Table 11 for light-brown FM, dark-brown FM and sorghum flour. Furthermore, a significant difference was shown where LBFM had a linear effect on soaking time (X_1), the second-order effect of soaking time (X_1^2), and malting time (X_2^2). The oxalic acid content in DBFM exhibited a strong impact from the linear effect of soaking time (X_1), the interaction between soaking and malting times (X_1X_2), along with the quadratic effects of soaking time (X_1^2) and malting time (X_2^2). Similarly, in SF, significant results were observed for the quadratic interaction of soaking time (X_1^2) and malting time (X_2^2). Comprehensive results from the response findings on the response surface plot for light brown, dark brown and sorghum flour can be found in Appendix VI.

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Table 11. ANOVA models of the effect of processing on tannins and oxalic acid of soaked and malted light-brown, dark-brown finger millet and sorghum flours.

Source	Tannin	Oxalic acid
	P-value	P-value
	Light-brown FM flour	
Model	0.0297*	0.0223*
X_1	0.3539	0.0220*
X_2	0.0266*	0.2158
X_1X_2	0.3233	0.1134
X_1^2	0.3365	0.0070*
X_2^2	0.0092	0.0740
	Dark-brown FM flour	
Model	0.2875	0.0005*
X_1	0.8822	0.0065*
X_2	0.4870	0.4578
X_1X_2	0.8088	0.0266*
X_1^2	0.5677	<0.0001*
X_2^2	0.0373*	0.1133
	Sorghum flour	
Model	0.0205*	0.0171*
X_1	0.0160*	0.0761
X_2	0.3599	0.1742
X_1X_2	0.0103*	0.5771
X_1^2	0.6317	0.0023*
X_2^2	0.0430*	0.0287*

*Significant at $p < 0.05$, **Non-significant at $p > 0.05$. X_1- linear effect of soaking; X_2 - linear effect of malting time; X_1X_2 - the interaction of soaking and malting time; X_1^2 -quadratic effect of soaking; X_2^2- quadratic effect of malting time (h).

The LBFM flour model demonstrated the highest coefficient R^2 on oxalic acid of 0.2222, the highest value of all these processed flours. These results are expressed in Table 12, where a linear effect on malting time (X_2) on tannins and oxalic acid soaking (X_1) and malting (X_2). An interactive influence of soaking and malting time (X_1X_2) on tannins and oxalic acid. Dark-brown FM flour demonstrated a linear impact of malting (X_2) on tannins. In contrast, the interaction effect of dark-brown flour (X_1X_2) was high on both tannins and oxalic acid. Quadratic effects on soaking (X_1^2) were exhibited by oxalic acid. Sorghum flour soaking (X_1) and malting (X_2) demonstrated a linear effect on the tannins and oxalic acid. The quadratic effect on malting (X_2^2) was highly demonstrated on tannins and oxalic acid. The interaction effects of sorghum flour were noticed on tannins and oxalic acid. Looking at the response plots, LBFM tannin levels increased as soaking times decreased and malting times increased, while oxalic acid content rose with longer soaking times and shorter malting periods. For DBFM, decreasing soaking and malting times led to higher tannins and oxalic acid levels. In SF, both tannin and oxalic acid contents increased with longer soaking times and shorter malting times.

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Table 12. Regression results of the anti-nutritional factors of soaked and malted light brown, dark brown FM and sorghum flour

Variables	Models	Residual fit at P-value	R^2
	Light-brown FM flour		
Tannins	$+0.5287-0.0426X_1+0.0973X_2+0.0522X_1X_2-0.0494X_1^2-0.1321X_2^2$	0.0282*	0.0197
Oxalic acid	$+1.76+0.4040X_1+0.1521X_2+0.02860X_1X_2-0.5801X_1^2-0.2505X_2^2$	0.0042*	0.2222
	Dark-brown FM flour		
Tannins	$+0.7142-0.0120X_1+0.0465X_2+0.0225X_1X_2-0.0522X_1^2-0.1734X_2^2$	0.0063*	0.0705
Oxalic acid	$+1.09-0.1352X_1-0.0225X_2+0.1135X_1X_2+0.3705X_1^2-0.0554X_2^2$	0.0431*	0.0130
	Sorghum flour		
Tannins	$+0.4067+0.1080X_1+0.0272X_2+0.1362X_1X_2-0.0191X_1^2+0.0730X_2^2$	0.0432*	0.0121
Oxalic acid	$+79.81+14.34X_1+3.54X_2+1.10X_1x_2-19.72X_1^2+1.72X_2^2$	0.1007**	0.0307

FM = Finger millet, *Significant at $p < 0.05$, **Non Significant: X_1 = linear effect of soaking; X_2 = linear effect of malting time; X_1X_2 = interaction of soaking and malting time; X_1^2 = quadratic effect of soaking; X_2^2 = quadratic effect of malting time (h).

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4.4 Effect of soaking and malting on functional properties

The alterations in functional properties are primarily attributed to modifications in the composition and structure of carbohydrates and proteins (Tao et al., 2015).

4.4.1 pH of Finger millet flour

The pH values for the soaked and malted light-brown (Table 13), dark-brown finger millet (Table 14) and sorghum flour (Table 15) are provided. The pH values for light-brown varied between 6.35 to 6.69, while dark-brown FM flour ranged from 5.51 to 7.23, and sorghum flour ranged from 5.28 to 6.35. From the result, it could be deduced that dark brown FM exhibited a higher pH at 3.73 h of soaking and 48 h of malting, revealing lower acidity levels under these processing conditions. Furthermore, the attained results could deduce that the different FM varieties and sorghum responded differently to these biochemical processes (soaking and malting) in terms of the changes in pH. These findings exceeded those reported by Sharma et al. (2023), where 5.5 was registered for germinated FM and 5.2 registered for germinated sorghum; seemingly, reductions in pH were registered by Nefale & Mashau (2018). These were also greater than those reported by Yenasew & Urga (2022), who recorded a pH of 5.97 in the Meba variety after 72 h of germination, and the sorghum pH of 6.32 observed by Olamiti et al. (2024) after 24 h malting and 24 h fermentation. The inherent biochemical composition of the cultivars influences the acidity levels, which impacts the deacidification process (Chethan & Malleshi, 2007; Olamiti et al., 2024). During germination, the leaching of water-soluble components and carbohydrate metabolism in the flours led to decreased pH (Yenasew & Urga, 2022). As the germination period extends, there is an increase in metabolic activity, which accelerates starch breakdown and leads to carbohydrate loss and weight reduction (Kumar et al., 2021).

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Table 13. Level of process variables and value of the quality parameter for functional properties of soaked and malted finger millet (light brown) flour.

Run	Soaking time (h)	Malting time (h)	pH	TTA (%)	LBD (g/ml)	PBD (g/ml)	OAC (g/g)	WAC (g/g)	Dispersibility (%)
1	18.00	24.00	6.54 ± 0.12	0.74 ± 0.07	0.47 ± 0.01	0.74 ± 0.16	1.77 ± 0.06	0.22 ± 0.02	77.67 ± 3.51
2	21.73	48.00	6.38 ± 0.03	0.74 ± 0.14	0.42 ± 0.01	0.61 ± 0.04	1.88 ± 0.07	0.22 ± 0.02	74.67 ± 1.15
3	0.00	72.00	6.45 ± 0.10	0.33 ± 0.17	0.41 ± 0.00	0.52 ± 0.01	1.97 ± 0.02	0.20 ± 0.03	77.33 ± 2.31
4	18.00	72.00	6.45 ± 0.05	0.65 ± 0.06	0.41 ± 0.00	0.53 ± 0.00	1.88 ± 0.08	0.23 ± 0.01	77.33 ± 3.06
5	9.00	14.06	6.37 ± 0.02	0.55 ± 0.09	0.41 ± 0.01	0.58 ± 0.02	1.86 ± 0.07	0.23 ± 0.01	79.00 ± 2.65
6	9.00	48.00	6.69 ± 0.03	0.37 ± 0.06	0.44 ± 0.01	0.64 ± 0.04	1.87 ± 0.02	0.22 ± 0.02	78.00 ± 2.00
7	9.00	48.00	6.69 ± 0.03	0.64 ± 0.19	0.44 ± 0.01	0.64 ± 0.04	1.87 ± 0.02	0.22 ± 0.02	76.67 ± 1.15
8	9.00	81.94	6.35 ± 0.03	0.91 ± 0.06	0.38 ± 0.05	0.54 ± 0.01	1.98 ± 0.04	0.19 ± 0.01	74.67 ± 1.15
9	9.00	48.00	6.69 ± 0.03	0.48 ± 0.14	0.44 ± 0.01	0.64 ± 0.04	1.87 ± 0.02	0.22 ± 0.02	78.67 ± 1.15
10	9.00	48.00	6.69 ± 0.03	0.63 ± 0.17	0.44 ± 0.01	0.64 ± 0.04	1.87 ± 0.02	0.22 ± 0.02	79.33 ± 1.15
11	0.00	24.00	6.61 ± 0.04	0.44 ± 0.34	0.48 ± 0.00	0.62 ± 0.05	1.81 ± 0.02	0.20 ± 0.02	76.00 ± 0.00
12	9.00	48.00	6.69 ± 0.03	0.92 ± 0.04	0.44 ± 0.01	0.64 ± 0.04	1.87 ± 0.02	0.22 ± 0.02	78.67 ± 1.15
13	3.73	48.00	6.53 ± 0.10	0.40 ± 0.31	0.41 ± 0.00	0.53 ± 0.03	1.89 ± 0.02	0.21 ± 0.02	78.00 ± 2.00

TTA = Titratable acid; LBD = Loose bulk density; PBD = Packed bulk density; OAC = Oil absorption capacity; WAC = Water absorption capacity.

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Table 14. Level of process variables and value of the quality parameter for functional properties of soaked and malted finger millet (dark brown) flour

Run	Soaking time (h)	Malting time (h)	pH	TTA (%)	LBD (g/ml)	PBD (g/ml)	OAC (g/g)	WAC (g/g)	Dispersibility (%)
1	18.00	24.00	6.36 ± 0.05	0.66 ± 0.00	0.48 ± 0.00	0.68± 0.00	1.73 ± 0.03	0.20 ± 0.02	79.67 ± 2.08
2	21.73	48.00	6.78 ± 0.12	0.93 ± 0.07	0.49 ± 0.04	0.73± 0.05	1.84 ± 0.01	0.19 ± 0.01	74.67 ± 1.15
3	0.00	72.00	5.54 ± 0.35	0.33 ± 0.11	0.45 ±0.02	0.70± 0.03	1.83 ± 0.02	0.20 ± 0.01	80.67 ± 1.15
4	18.00	72.00	6.79 ± 0.14	0.39 ± 0.20	0.45 ± 0.01	0.71± 0.03	1.85 ± 0.09	0.21 ± 0.01	73.33 ± 1.15
5	9.00	14.06	6.12 ± 0.09	0.55 ± 0.19	0.46 ± 0.01	0.68± 0.02	1.76 ± 0.02	0.21 ± 0.03	78.00 ± 2.00
6	9.00	48.00	6.24 ± 0.14	0.50 ± 0.17	0.45 ± 0.02	0.70± 0.03	1.77 ± 0.02	0.20 ± 0.03	79.00 ± 2.65
7	9.00	48.00	6.24 ± 0.14	0.50 ± 0.17	0.45 ± 0.02	0.70± 0.03	1.77 ± 0.02	0.20 ± 0.03	78.00 ± 2.00
8	9.00	81.94	5.51 ± 0.50	0.80 ± 0.19	0.46 ± 0.02	0.62± 0.02	1.76 ± 0.15	0.18 ± 0.01	75.33 ± 1.15
9	9.00	48.00	6.24 ± 0.14	0.50 ± 0.17	0.45 ± 0.02	0.70± 0.03	1.77 ± 0.02	0.20 ± 0.03	78.00 ± 2.00
10	9.00	48.00	6.24 ± 0.14	0.50 ± 0.17	0.45 ± 0.02	0.70± 0.03	1.77 ± 0.02	0.20 ± 0.03	79.67 ± 1.53
11	0.00	24.00	6.49 ± 0.15	0.33 ± 0.17	0.48 ± 0.01	0.68± 0.00	1.80 ± 0.05	0.22 ± 0.02	78.00 ± 2.00
12	9.00	48.00	6.24 ± 0.14	0.50 ± 0.17	0.45 ± 0.02	0.70± 0.03	1.77 ± 0.02	0.20 ± 0.03	79.67 ± 1.53
13	3.73	48.00	7.23 ± 0.36	0.26 ± 0.11	0.46 ± 0.00	0.67± 0.03	1.82 ± 0.03	0.22 ± 0.02	78.00 ± 2.00

TTA = Titratable acid; LBD = Loose bulk density; PBD = Packed bulk density; OAC = Oil absorption capacity; WAC = Water absorption capacity.

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Table 15. Level of process variables and value of the quality parameter for functional properties of soaked and malted sorghum flour

Run	Soaking time (h)	Malting time (h)	pH	TTA (%)	LBD (g/ml)	PBD (g/ml)	OAC (g/g)	WAC (g/g)	Dispersibility (%)
1	18.00	24.00	5.28 ± 0.11	0.50 ± 0.15	0.42 ± 0.03	0.62 ± 0.04	1.83 ± 0.07	0.23 ± 0.01	80.33 ± 2.08
2	21.73	48.00	6.11 ± 0.10	0.41 ± 0.03	0.40 ± 0.00	0.66 ± 0.03	1.86 ± 0.04	0.21 ± 0.03	76.00 ± 0.00
3	0.00	72.00	6.35 ± 0.28	0.46 ± 0.12	0.41 ± 0.00	0.61 ± 0.02	1.89 ± 0.05	0.23 ± 0.03	79.33 ± 3.06
4	18.00	72.00	5.85 ± 0.18	0.46 ± 0.05	0.41 ± 0.00	0.59 ± 0.04	1.93 ± 0.04	0.20 ± 0.02	78.67 ± 1.15
5	9.00	14.06	5.38 ± 0.07	0.40 ± 0.20	0.41 ± 0.00	0.59 ± 0.02	1.73 ± 0.09	0.20 ± 0.03	77.33 ± 3.06
6	9.00	48.00	5.52 ± 0.05	0.20 ± 0.01	0.41 ± 0.00	0.58 ± 0.02	1.84 ± 0.01	0.26 ± 0.02	77.33 ± 1.15
7	9.00	48.00	5.52 ± 0.05	0.19 ± 0.02	0.41 ± 0.00	0.58 ± 0.02	1.84 ± 0.01	0.21 ± 0.02	80.00 ± 0.00
8	9.00	81.94	5.76 ± 0.04	0.39 ± 0.01	0.41 ± 0.00	0.55 ± 0.02	2.01 ± 0.09	0.22 ± 0.02	77.33 ± 1.15
9	9.00	48.00	5.52 ± 0.05	0.20 ± 0.01	0.41 ± 0.00	0.58 ± 0.02	1.84 ± 0.01	0.21 ± 0.02	79.33 ± 1.15
10	9.00	48.00	5.52 ± 0.05	0.20 ± 0.01	0.41 ± 0.00	0.58 ± 0.02	1.84 ± 0.01	0.21 ± 0.02	74.67 ± 1.15
11	0.00	24.00	6.29 ± 0.05	0.25 ± 0.05	0.41 ± 0.00	0.67 ± 0.00	1.66 ± 0.15	0.20 ± 0.01	74.00 ± 2.00
12	9.00	48.00	5.52 ± 0.05	0.20 ± 0.01	0.41 ± 0.00	0.58 ± 0.02	1.84 ± 0.01	0.21 ± 0.02	79.33 ± 1.15
13	3.73	48.00	5.40 ± 0.08	0.39 ± 0.01	0.41 ± 0.00	0.59 ± 0.04	1.98 ± 0.03	0.19 ± 0.01	80.00 ± 2.00

TTA = Titratable acid; LBD = Loose bulk density; PBD = Packed bulk density; OAC = Oil absorption capacity; WAC = Water absorption capacity.

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ANOVA results in Table 16 LBFM demonstrated significance on the attained model, the second-order malting time (X_2^2) and in SF, the model attained was also significant, and this was also exhibited on the linear effect of soaking time (X_1) and seemingly on second-order soaking time (X_1^2) of the pH. The decrease in pH values observed in germinated millet flour samples can be linked to the formation of organic acids during germination, which stimulates the activation of hydrolytic enzymes (Sharma et al., 2023; Nefale & Mashau, 2018). These enzymes break down starch and proteins into sugars and amino acids, respectively. Subsequently, lactic acid bacteria and yeast metabolise these sugars, converting them into carbon dioxide, ethanol, and lactic acid (Sharma et al., 2023; Nefale & Mashau, 2018). From the regression in Table 17, LBFM flour demonstrated the highest coefficient of R^2 at a pH of 0.7752. In LBFM, significance was demonstrated in the linear interaction effect of soaking and malting time (X_1X_2). Dark brown FM demonstrated a soaking (X_1) linear effect, the interaction effect of dark-brown flour (X_1X_2) and a quadratic effect on soaking (X_1^2). Sorghum flour exhibited a significant, linear effect of malting (X_2) demonstrated linear effect, a quadratic effect on soaking (X_1^2), malting (X_2^2) and the interaction effects were noticed on sorghum flour.

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Table 16. ANOVA models of the effect of processing on functional properties of soaked and malted light-brown, dark-brown finger millet and sorghum flours.

Source	pH	TTA	LBD	PBD	WAC	OAC	Dispersibility
	P-value	P-value	P-value	P-value	P-value	P-value	P-value
Light-brown FM flour							
Model	0.0314*	0.1845	0.5057	0.1169**	0.1776	0.2022	0.3363
X_1	0.4570	0.2046	0.6118	0.1611**	0.0455*	0.4413	0.9858
X_2	0.2829	0.1693	0.1016	0.0310*	0.3740	0.0246*	0.2395
X_1X_2	0.7164	0.0668	0.8613	0.3177**	0.4091	0.6962	0.5728
X_1^2	0.0895	0.7418	0.3904	0.3721**	0.7804	0.7186	0.1054
X_2^2	0.0052*	0.4861	0.5700	0.2122**	0.2159	0.6750	0.4128
Dark-brown FM flour							
Model	0.1437	0.2634	0.0259*	0.2074**	0.1102	0.0423*	0.0050*
X_1	0.5416	0.0515	0.5737	0.6047**	0.2234	0.2242	0.0113*
X_2	0.2316	0.8672	0.0233*	0.7290**	0.0316*	0.0725	0.0356*
X_1X_2	0.1078	0.4657	0.3673	0.9765**	0.0767	0.1287	0.0030*
X_1^2	0.3070	0.8769	0.0104*	0.2855**	0.3110	0.0082*	0.3286
X_2^2	0.0837**	0.3360	0.8137	0.0353*	0.8696	0.3878*	0.0982
Sorghum flour							
Model	0.0081*	0.0292*	0.5411	<0.0001*	0.0495*	0.0395*	0.6277
X_1	0.0087*	0.4244	0.5003	0.0032*	0.2780	0.4518	0.6008
X_2	0.0531	0.4486	0.2085	0.0002*	0.0044*	0.0806	0.5753
X_1X_2	0.1943	0.1408	0.2876	0.0851	0.3091	0.0423*	0.1567
X_1^2	0.0010*	0.0337*	0.7563	<0.0001*	0.4061	0.2573	0.4860
X_2^2	0.5499	0.0149*	0.6289	0.1799	0.8614	0.0143*	0.7710

*Significant at $p < 0.05$, Non-significant: X_1 = linear effect of soaking; X_2 = linear effect of malting time; X_1X_2 = interaction of soaking and malting time; X_1^2 = quadratic effect of soaking; X_2^2 = quadratic effect of malting time (h). FM = Finger millet; TTA = Titratable acid; LBD = Loose bulk density; PBD = Packed bulk density; OAC = Oil absorption capacity; WAC = Water absorption capacity.

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Table 17. Regression results of the functional properties of soaked and malted light brown, dark brown FM and sorghum flour

Response variables	Models	Residual fit at P-value	R^2
	Light brown FM flour		
pH	$+6.67-0.0290X_1-0.0348X_2+0.0160X_1X_2-0.0811X_1^2-0.1275X_2^2$	<0.0001*	0.7752
TTA	$+1.76+0.4040X_1+0.1521X_2+0.02860X_1X_2-0.5801X_1^2-0.2505X_2^2$	<0.0001*	0.5968
LBD	$+0.4218-0.0077X_1-0.0221X_2+0.0030X_1X_2+0.0147X_1^2-0.0074X_2^2$	0.5235	0.4038
PBD	$+0.6329+0.0336X_1-0.0469X_2-0.0265X_1X_2-0.0228X_1^2-0.0255X_2^2$	-	0.6555
WAC	$+0.2156+0.0090X_1-0.0029X_2+0.0038X_1X_2-0.0012X_1^2-0.0044X_2^2$	0.2621	0.6021
OAC	$+1.88-0.0188X_1+0.0533X_2-0.0107X_1X_2-0.0096X_1^2+0.0087X_2^2$	0.5402	0.5834
Dispersibility	$+78.29+0.0113X_1-0.6417X_2-0.4175X_1X_2-1.28X_1^2-0.4641X_2^2$	0.1435	0.4965
	Dark-brown FM flour		
pH	$+6.38+0.1042X_1-0.1726X_2+0.3435X_1X_2+0.1994X_1^2-0.2835X_2^2$	<0.0001*	0.6305
TTA	$+0.4404+0.1829X_1+0.0110X_2-0.0690X_1X_2+0.0140X_1^2+0.0698X_2^2$	0.0610	0.5412
LBD	$+0.4541+0.0021X_1-0.0085X_2-0.0040X_1X_2+0.0140X_1^2+0.0008X_2^2$	0.0013*	0.7882
PBD	$+0.6960+0.0054X_1-0.0029X_2+0.0004X_1X_2+0.0129X_1^2-0.0225X_2^2$	-	0.5788
WAC	$+0.2000-0.0046X_1-0.0075X_2+0.0083X_1X_2+0.0042X_1^2+0.0005X_2^2$	<0.0001*	0.6623
OAC	$+1.77-0.0137X_1+0.0176X_2+0.0203X_1X_2+0.0417X_1^2-0.0082X_2^2$	<0.0001*	0.7529
Dispersibility	$+78.64-1.51X_1-0.9307X_2-2.25X_1X_2-0.5177X_1^2-0.7296X_2^2$	0.2458	0.8721
	Sorghum flour		
Ph	$+5.46-0.2790X_1+0.1459X_2+0.1275X_1X_2+0.4673X_1^2+0.0421X_2^2$	-	0.85199
TTA	$+0.2234+0.0275X_1+0.0211X_2-0.0617X_1X_2+0.0952X_1^2+0.0899X_2^2$	<0.0001*	0.7801
LBD	$+0.4068+0.0015X_1-0.0023X_2-0.0028X_1X_2+0.0008X_1^2+0.0009X_2^2$	-	0.3854
PBD	$+0.5778-0.0143X_1-0.0183X_2+0.0075X_1X_2+0.0495X_1^2-0.0042X_2^2$	-	0.9715
WAC	$+1.87+0.0315X_1+0.0897X_2-0.00337X_1X_2-0.0264X_1^2-0.0042X_2^2$	-	0.7402
OAC	$+0.2104+0.0038X_1-0.0079X_2-0.0135X_1X_2-0.0065X_1^2+0.0133X_2^2$	-	0.7582
Dispersibility	$+78.48+0.5269X_1+0.4583X_2-1.75X_1X_2-0.7894X_1^2-0.2520X_2^2$	0.4605	0.3403

*Significant at $p < 0.05$, Non-significant: X_1 = linear effect of soaking; X_2 = linear effect of malting time; X_1X_2 = interaction of soaking and malting time; X_1^2 = quadratic effect of soaking; X_2^2 = quadratic effect of malting time (h). FM = Finger millet; TTA = Titratable acid; LBD = Loose bulk density; PBD = Packed bulk density; OAC = Oil absorption capacity; WAC = Water absorption capacity.

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4.4.2 Titratable acids (TTA) of FM flour

The findings of the TTA of light brown (Table 13), dark-brown FM (Table 14) and sorghum flours (Table 15) are presented. From the results, it can be seen that dark brown FM exhibited a higher TTA at soaking at 21.73 h and malting time at 48 h. Higher TTA values were attained due to increased soaking and malting time, which resulted in higher organic acid production. These values are higher than the TTA reported by Yenasew & Urga (2022) of 0.59% in the Axum variety germinated at 72 h. Owheruo et al. (2019) observed that the total titratable acidity levels increased with longer germination periods in both African finger millet and pearl millet. Yenasew & Urga (2022) and Adesokani et al. (2011) state that the increase in TTA values from the production of acids by beneficial microorganisms, like lactic acid bacteria, which ferment sugars to generate lactic acid and other by-products. Additionally, the breakdown of complex organic molecules like proteins and phytate during germination leads to the formation of simpler, more acidic compounds such as phosphate and amino acids (Handa et al., 2017). This implies that extended malting time enhances microbial activity and biochemical transformations, allowing more extensive fermentation to occur. While this increase in acidity may improve the nutritional quality by enhancing mineral bioavailability and reducing anti-nutritional factors, it may also impact sensory properties such as taste, making the final product more sour, which could be desirable or undesirable depending on the product's intended use (Ranini et al., 2025; Sawant et al., 2025). The increased TTA with reduced pH results in improved digestibility of germinated FM products such as breakfast cereals, snacks for school children and baked goods (Abioye et al., 2022). From the ANOVA results in Table 16, a significant model was demonstrated in SF. Furthermore, a significant effect at ($P < 0.05$) on second-order soaking time (X_1^2) and second-order malting (X_2^2) in sorghum flour. Table 17 regression results demonstrated linear effects on soaking time (X_1), malting time (X_2) and interaction effect soaking and malting time (X_1X_2) in LBFM. Dark brown FM demonstrated soaking (X_1) linear effect, malting (X_2), quadratic effects on soaking (X_1^2) and second-order effect of malting (X_2^2). Sorghum flour had a soaking (X_1) linear effect, malting (X_2), and a quadratic effect on soaking (X_1^2) and malting (X_2^2).

4.4.3 Bulk density

In light-brown FM flour (Table 13), the bulk density varied between 0.38 to 0.48 g/ml, while dark-brown FM flour (Table 14) ranged from 0.45 to 0.49 g/ml, and sorghum flour (Table 15) exhibited a bulk density range of 0.40 to 0.42 g/ml. From the results, it can be seen that dark brown FM exhibited a higher loose bulk density (LBD) at soaking at 21.73 h and malting time at 48 h. The resulting lower bulk density in sorghum flour reveals a softer and less dense structure due to the breakdown of complex carbohydrates (Olamiti et al., 2024). The bulk

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density is influenced by the flour's density and particle size, which are crucial factors in selecting the appropriate packaging material (Godswill, 2019). Moreover, packed bulk density (PBD) results were also registered. In light-brown FM flour, the PBD varied between 0.52 to 0.74 g/ml, while in dark-brown FM flour, it ranged from 0.62 to 0.73 and for sorghum flour, it fell between 0.55 to 0.67 g/ml. From these findings, it could be deduced that light brown FM exhibited a higher PBD after soaking for 18 h and a malting time of 24 h. These influence packing characteristics and improvement in the texture qualities of the flour (Adebiyi et al., 2017; Akinola et al., 2017; Dereje et al., 2020; Olamiti et al., 2024). These findings were smaller than the PBD values reported by Murungweni et al. (2023), which ranged from 0.74 to 0.81 g/ml for LBFM and 0.73 to 0.82 g/ml for DBFM. However, these values fall within the bulk density range for Meba, Axum, Tessema, and Tadesse flours reported by Yenasew & Urga (2023) of respective results of 0.71 to 0.82 g/cm^3, 0.72 to 0.80 g/cm^3, 0.72 to 0.78 g/cm^3, and 0.71 to 0.77 g/cm^3.

Looking into the ANOVA results in Table 16, a significant packed bulk density model was attained in SF. A significant linear effect (X_2) of malting time was exhibited on PBD in LBFM. In LBD of dark-brown FM, the model demonstrated significance on second-order soaking (X_1^2) and linear effect of malting time (X_2). In the PBD of sorghum flour, significance was demonstrated in the linear effect of soaking time (X_1), malting time (X_2), and second-order soaking time (X_1^2). The bulk density decreased with the extension of the germination period (Yansew & Urga, 2022). The decrease in bulk density during germination may be attributed to the degradation of complex compounds such as protein and starch into simpler components (Yenaswe & Urga et al., 2022; Ocheme et al., 2015).

The regression results demonstrated in LBFM linear effects on soaking time (X_1) on PBD, an interaction effect soaking and malting time (X_1X_2) on loose bulk density and second-order soaking (X_1^2) exhibited on LBD. Dark brown FM demonstrated a soaking (X_1) linear effect on LBD and PBD, the interaction effects of dark-brown flour (X_1X_2) on PBD, quadratic effects on soaking (X_1^2) exhibited by both LBD, PBD, second-order effect malting (X_2^2) on LBD. Sorghum flour, soaking (X_1) linear effect on LBD, the quadratic effect on soaking (X_1^2) on LBD and PBD and malting (X_2^2) demonstrated on LBD. The interaction effects of sorghum flour were noticed on PBD. The highest R^2 coefficient was demonstrated on PBD of 0.9715. Moreover, the overall highest R^2 value was demonstrated on the PBD of sorghum flour.

4.4.4 Oil absorption capacity

Oil absorption capacity (OAC) and water absorption capacity (WAC) are important characteristics that indicate how well a flour sample can absorb oil and water when these substances are present in limited quantities (Adebiyi et al., 2016). It is crucial in enhancing the

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sensory qualities of food products by improving flavour retention and providing a better mouthfeel (Awuchi et al., 2019; Lwe et al., 2016). The results of the OAC of light brown (Table 13), dark-brown FM (Table 14) and sorghum flour (Table 15) are shown. Sorghum flour exhibited a higher OAC at soaking 9 h and malting time of 81.94 h, and a lower OAC was demonstrated in DBFM at 0 h soaking and 24 h malting. The ANOVA results exhibited a significant model on OAC of SF and a significant effect at ($p < 0.05$) on linear effect (X_2) malting time in LBFM. In DBFM, the model significance was demonstrated on second-order soaking (X_1^2), and in SF, significance was demonstrated on the interaction soaking and malting time (X_1X_2) and seemingly on the second-order malting time (X_2^2).

The increased oil absorption capacity (OAC) can be attributed to increased damaged starch and surface area (Boka et al., 2023). According to Onipe et al. (2024), one possible explanation might be variations in the presence of non-polar side chains, which could interact with the hydrocarbon side chains of the oil in the flour. The reduced oil absorption capacity (OAC) of finger millet (FM) flour may result from a lower concentration of hydrophobic proteins, which are typically more effective at binding lipids (Onipe et al. 2024; Zhu et al., 2018). These results exceeded the range reported by Murungweni et al. (2023), where malted and control FM flours showed values between 1.31 to 1.49 g/g (LB) and 1.32 to 1.48 g/g (DB). As stated by Murungweni et al. (2023), the rise in oil absorption capacity (OAC) in malted finger millet flour samples indicates an enhanced potential for use in food formulations. OAC in light brown FM regression results demonstrated a linear effect on malting time (X_2) and second-order malting time (X_2^2). Dark brown FM demonstrated a linear effect of malting (X_2) on OAC, interaction effects of dark-brown flour (X_1X_2), and a quadratic effect on soaking (X_1^2). Sorghum flour, on the other hand, exhibited a soaking (X_1) linear effect, malting (X_2), and a quadratic effect on malting (X_2^2).

4.4.5 Water absorption capacity

The WAC for light-brown FM (Table 13), dark-brown FM (Table 14) and sorghum flour (Table 15). A higher WAC was exhibited in sorghum flour at soaking 9 h and malting time 48 h. These values are below the range reported by Murungweni et al. (2023) for malted and control FM flours, which ranged from 1.55 to 1.72 g/g (LB) and 1.54 to 1.78 g/g (DB). ANOVA results in Table 16 demonstrated significance in the model attained in SF and the linear effect of malting time (X_2) in dark-brown FM and sorghum flour. The low water absorption capacity (WAC) observed in the finger millet flours suggests a low presence of water-attracting hydrophilic groups (Adebowale et al., 2005; Mudau et al., 2022). WAC in light brown FM regression results had a linear effect on soaking time (X_1) and an interaction effect on soaking and malting time (X_1X_2). Dark brown FM demonstrated the interaction effects of dark-brown flour (X_1X_2),

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quadratic effects on soaking (X_1^2), and second-order effect of malting (X_2^2). Sorghum flour only exhibited a soaking (X_1) linear effect on WAC.

4.4.6 Dispersibility

The results of the dispersibility of light-brown (Table 13), dark-brown FM (Table 14) and sorghum (Table 15) flours are shown. The results indicate that dark brown FM exhibited a higher dispersibility at soaking 0 h and malting time 72 h. An increase in soaking and malting time reduced dispersibility in these flours (LBFM, DBFM, and sorghum) and no significant difference in soaking and malting times. This reduction in dispersibility may be attributed to decreased particle size during processing, as finer particles provide more surface area for water absorption, which can lead to the formation of cohesive masses that resist re-dispersion in water (Islam et al., 2024). Comparable findings were reported by Yenasew & Urga (2023), where the dispersibility of Meba, Axum, Tessema and Tadesse flours ranged from 73.67% to 77.67%, 77% to 79.33%, 73.17% to 79.33% and 74.33% to 75.50%, at both 0 and 72 h germination. ANOVA results in Table 16 of the dark-brown FM model demonstrated significance on linear effect soaking (X_1), malting time (X_2) and interaction soaking and malting time (X_1X_2). Dispersibility indicates how well flour mixes with water (Onipe et al., 2024). High dispersibility values across all the flour samples suggest they can quickly form a smooth paste (Onipe et al., 2024; Mubaiwa et al., 2018). Regression results in light brown FM dispersibility only had a linear effect on soaking time (X_1). In contrast, dark-brown FM flour showed the highest R^2 of 0.8721 on dispersibility, and sorghum flour had linear soaking (X_1) effect and malting (X_2) on dispersibility.

The response surface plots in Figure 5 demonstrate that LBFM exhibited shorter soaking and malting times, increased pH, and dispersibility, while longer soaking times and shorter malting times elevated TTA and WAC. Similarly, OAC and bulk density were enhanced with shorter soaking and longer malting times. In DBFM, shorter soaking and malting times increased WAC, while extended soaking combined with reduced malting time elevated pH, TTA, and bulk densities. Conversely, shorter soaking and longer malting times improved OAC and dispersibility. Reduced soaking and malting times in SF led to higher bulk density, whereas longer durations enhanced WAC, dispersibility, and TTA. These findings indicate that flour soaking and malting significantly impact this flour's biochemical processes and functional attributes. Furthermore, details on other light brown parameters are found in Appendix VII, dark brown Appendix VIII and Appendix IX for sorghum flour response plots.

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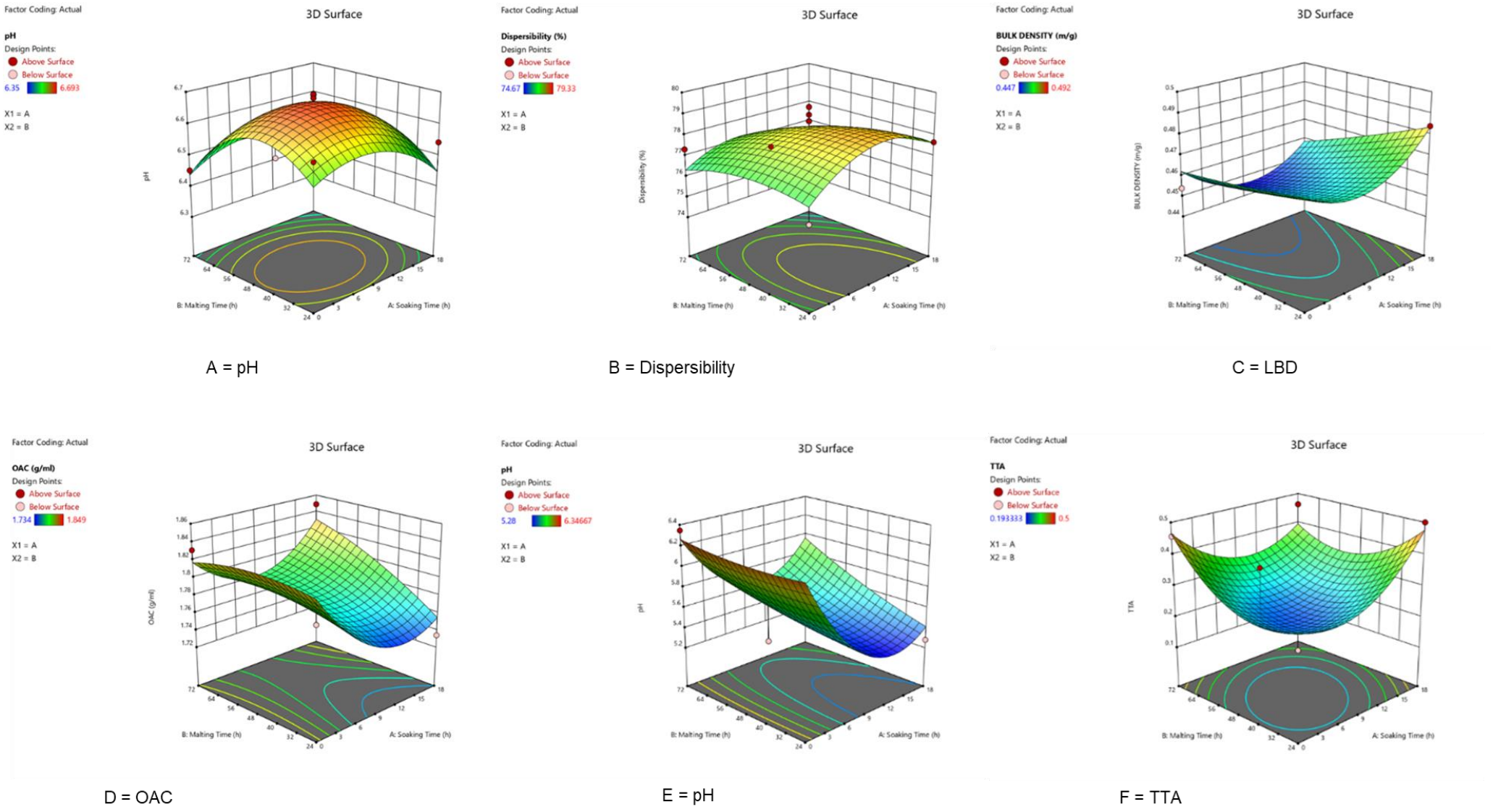

Figure 5. Response surface plots for the effect of soaking and malting time (h) on functional properties of light-brown finger millet (A & B), dark-brown finger millet (C&D) and sorghum flour (E & F). OAC = Oil absorption capacity, LBD = Loose bulk density and TTA = Titratable acid.

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4.5 Fourier transform infrared (FTIR) spectroscopy of soaked and malted finger millet (light and dark brown) and sorghum flour

Figure 6 displays the FTIR spectroscopy results for the functional groups of soaked and malted flours from finger millet (FM) varieties and sorghum. FTIR analysis provided valuable insights into the chemical composition of soaked and malted FM flours, which can be utilised to evaluate their quality and nutritional content (Kaur & Prasad, 2022; Murungweni et al., 2023).

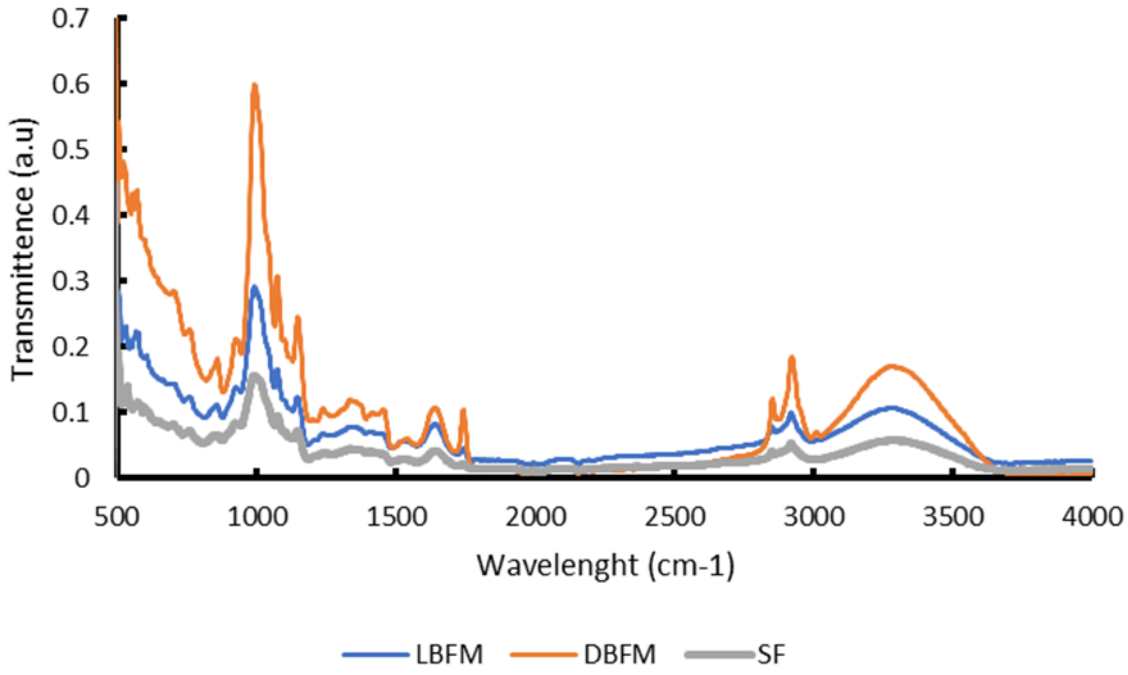

Figure 6. FTIR spectra for finger millet flours are as follows: LBFM (18 h soaked – 72 h malted) = light-brown finger millet, DBFM (0 h soaked – 24 h malted) = dark-brown finger millet and SF (0 h soaked – 72 h malted) = the sorghum flour.

The IR spectra for these flours exhibited distinct peaks with varying intensities between the soaked and the samples. The observed peaks in the OH region for soaked and malted light-brown FM (LBFM) ranged from 3307 to 3364.02 cm^{-1}. For dark-brown FM (DBFM), these peaks ranged from 3296.70 to 3415.02 cm^{-1}; for sorghum flour (SF), the range was from 3307 to 3433.38 cm^{-1}. The peaks observed in the spectra are associated with the stretching vibrations of O-H bonds (Murungweni et al., 2023). The alterations in vibrational peaks were likely due to the strong bonding associated with the moisture content of the flour (Olatimi et al., 2020). Additionally, Murungweni et al. (2023) indicated that the changes in peaks could be related to variations in fat content in the malted FM flours.

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The asymmetrical stretching of the C–H band in the soaked and malted flours of LBFM ranged from 1660.59 to 1662.63 cm^{-1}. For DBFM, the vibrational peaks were observed between 1666.67 and 1678.95 cm^{-1}, while in SF, they ranged from 1666.71 to 1674.87 cm^{-1}. These results were lower than those registered in the study of Munshi & Dashora (2024), where 2000 – 2700 cm^{-1} in millet flour. The broadening observed was likely a result of the stretching vibrations of both aromatic and aliphatic C-H bonds (Olamiti et al., 2020). The C–O stretching bonds in LBFM were found within the 981.26 to 1003.70 cm^{-1} range. For DBFM, these bonds ranged from 977.17 to 1015.93 cm^{-1} in SF. They were observed between 987.38 and 1017.98 cm^{-1}. These results are consistent with the findings reported by Mudau et al. (2022) on fermented finger millet. According to Li et al. (2021), treatment does not only impact the chemical group but also results in physical degradation, including the breakdown of granule structure, particle fragmentation, and alteration on the surface.

4.6 Scanning Electron Microscopy (SEM) of soaked and malted finger millet (light and dark brown) and sorghum flour

The variations in outputs, depicted in Figure 7, regarding the thermal characteristics, solubility, water absorption capacity (WAC), and swelling power, could be attributed to alterations in starch composition, such as structural rearrangement or loosening, observed in both malted FM flours (Murungweni et al., 2023; Khoza et al., 2021). Murungweni et al. (2023) mentioned that the control LB flour's protein bodies (PB) exhibited a compact and organised structure. However, the malting process led to the breakdown and disruption of this arrangement. Soaking caused the molecules to become round and granular in shape (Arzoo et al., 2024). Processing leads to the morphological changes of molecules and has also been associated with protein denaturation and starch gelatinisation, altering the structure and potentially affecting nutritional properties (Wang et al., 2021). The LB and DB flours consisted of starch granules (SG) of different sizes, varying from small to large. The starch granules (SG) observed from all the flours, LBFM, DBFM, and SF, ranged from small to large sizes and were found clustered within protein bodies. The DBFM flour showed a tightly packed structure of protein bodies (PB). In contrast, LBFM and SF had smaller protein bodies and a greater number of free starch granules compared to DBFM, which featured tightly packed protein bodies enclosing starch granules.

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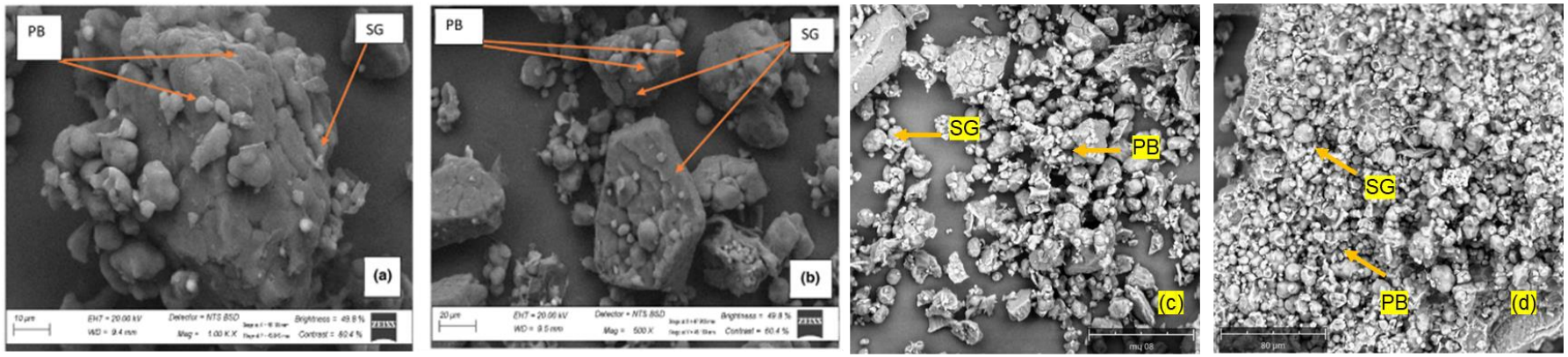
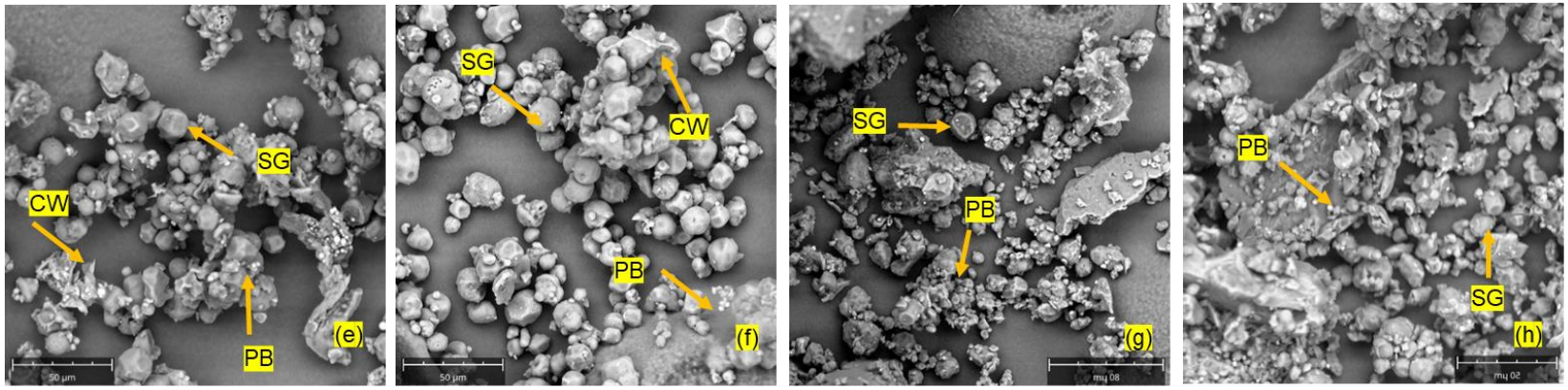


Source: Murungweni et al. (2023) LBFM (0-24) DBFM (0-24)



SF (0-24) SF (0-72) LBFM (18-24) DBFM (18-24)

Figure 7. Scanning electron micrographs of soaked and malted light-brown finger millet (LBFM), dark-brown finger millet (DBFM) and sorghum (SF) flour. (a) unmalted light-brown finger millet (LBFM); (b) unmalted dark-brown finger millet (DBFM) flour; (c) 0 h soaked – 24 h malted LBFM; (d) 0 h soaked – 24 h malted DBFM; (e) 0 h soaked – 24 h malted SF; (f) 0 h soaked – 72 h malted SF; (g) 18 h soaked – 24 h malted LBFM; (h) 18 h soaked – 24 h malted DBFM; PB = protein bodies; SG = starch granules; CW = cell walls.

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The released SG in both LBFM and SF flours displayed a range of sizes and shapes, including polygonal, spherical, and oval forms. This variation could be due to the breakdown of complex compounds into simpler molecules during soaking and malting processes. In the soaked and malted flours, additional gaps were observed between the starch granules (SGs). The increase in exhibited gaps resulted from loosening in the germinated sample, which aids in increased WAC and bulk density (Adebiyi et al., 2016). Comparable results were reported by Murungweni et al. (2023) for malted FM flour. Salmenkallio-Marttila et al. (2001) and Mudau et al. (2022) suggested that the degradation of the cell wall affects the microstructure of starch granules. Further details on scanning electron microscopy are demonstrated in Appendix XVI.

4.7 Pasting properties of soaked and malted finger millet (light and dark brown) and sorghum flour

The pasting properties attributed to how starch interacts with water when subjected to heat were studied. The peak viscosity at LBFM (soaking 0 h – malting 24 h) ranged from 4661-4550, DBFM from 1454 to 1377, and SF from 3955-3177 Cp, as shown in Figure 8. This study mainly demonstrated high peak viscosity by LBFM compared to SF and DBFM. According to Li et al. (2022), this reflects the water-binding capacity and starch expansion ability of granules during gelatinisation, which indicates a strong starch thickening potential, making it more valuable in products that require high viscosity, such as sauces. It also suggests the ability to form a stable gel upon cooling food products that have lost product quality, such as bread staling, viscosity loss, syneresis, and precipitation in soups (Miles et al., 1985; Mohamed, 2021). Moreover, high peaks may increase sensitivity during processing, as starch granules become more prone to breakdown under heat or shear. Furthermore, peak viscosity is often used as a quality indicator for starch.

A high pasting temperature of 95.1°C was used in this study. When a high pasting temperature is used, this suggests that the starch has a strong ability to bind water and exhibits resistance to swelling due to closely associated granules (Mubaiwa et al., 2018). SF demonstrated high holding strength along with the setback from the trough. LBFM demonstrated the highest breakdown value. This indicates that starch granules are more prone to disintegration under continued heat and shear during gelatinisation. This implies weaker structural integrity in starch, maintaining its viscosity when subjected to mechanical stress or high temperatures. This is often associated with starch that rapidly loses its viscosity after reaching the peak, which is likely to affect the mouthfeel and stability of the end product (Niu et al., 2021; Wang et al., 2022).

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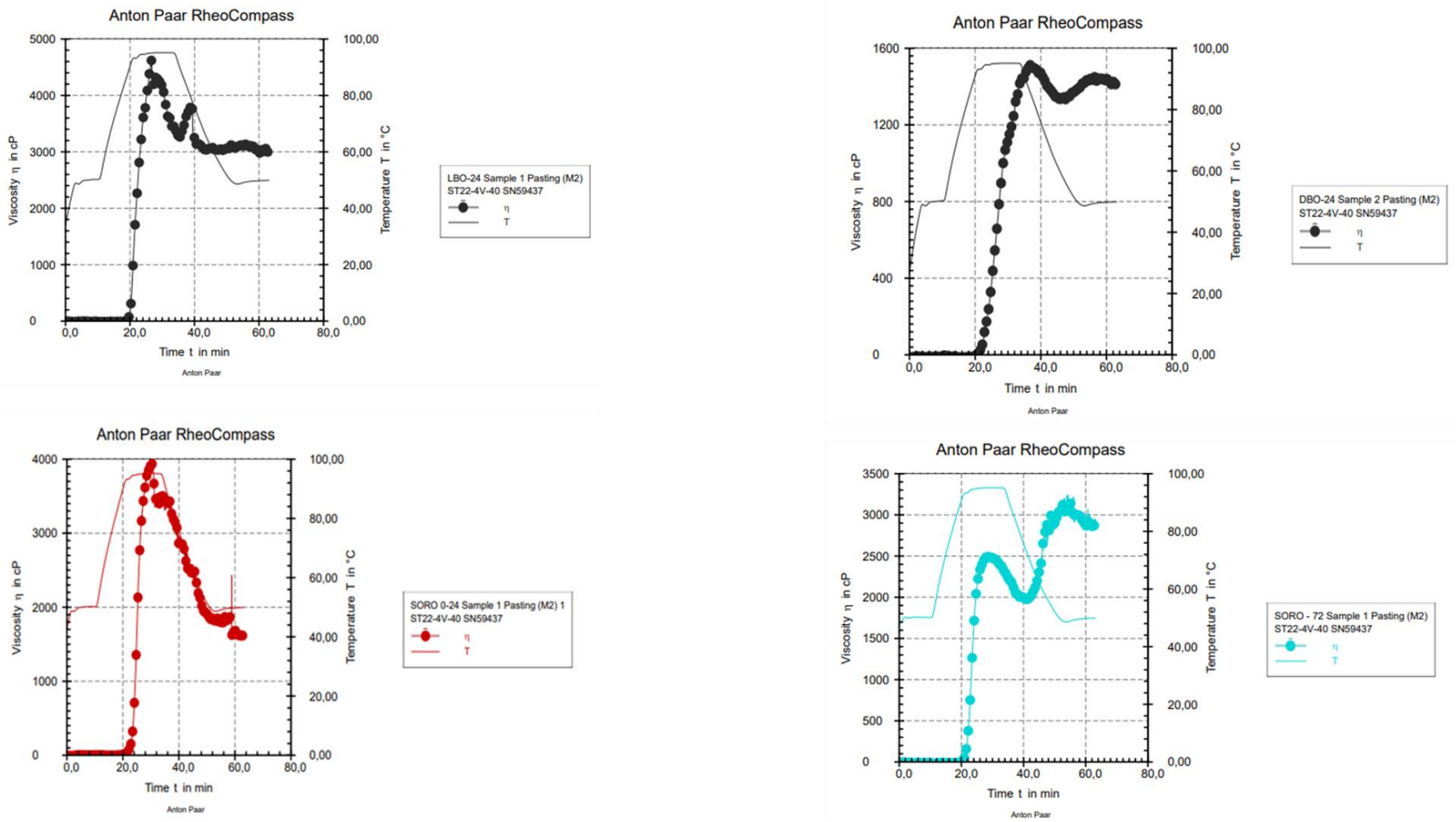

Figure 8. Temperature and viscosity profiles of a starch sample of light-brown finger millet (LBFM), dark-brown (DBFM) and sorghum flour (SF) at (soaking 0 h – malting 24 h), and (soaking 0 h – malting 72 h) throughout the pasting process.

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For the setback of all the flours, LBFM exhibited the most significant setback peak compared to DBFM and SF. A negative setback from the peak was observed in DBFM (soaking 18 h - malting 24 h, soaking 18 h – malting 72 h), and in SF (Figure 9), these were observed at (0 h soaking – 72 h malting, soaking 18 h – malting 24 h and soaking 18 h – malting 72 h). A negative setback peak indicated a reduction in starch retrogradation, which resulted in less firm gel formation and better texture stability during cooling, implying that starch is less prone to recrystallisation, leading to a softer gel with enhanced stability in food products where prolonged softness is desirable such as baked goods or frozen items (Yang et al., 2024). Retrogradation in starch-based products can contribute to beneficial attributes, such as an enhanced content of slowly digestible and resistant starch. These improvements are particularly advantageous in pasta, breakfast cereals, and comparable items (Mohamed, 2021). Generally, prolonged soaking and malting time decrease starch viscosity as a result of starch molecular degradation, affecting gelatinisation and altering textural properties. These processes reduce starch's ability to form a firm gel, leading to softer and less viscous starch-based products (Ukpong et al., 2024).

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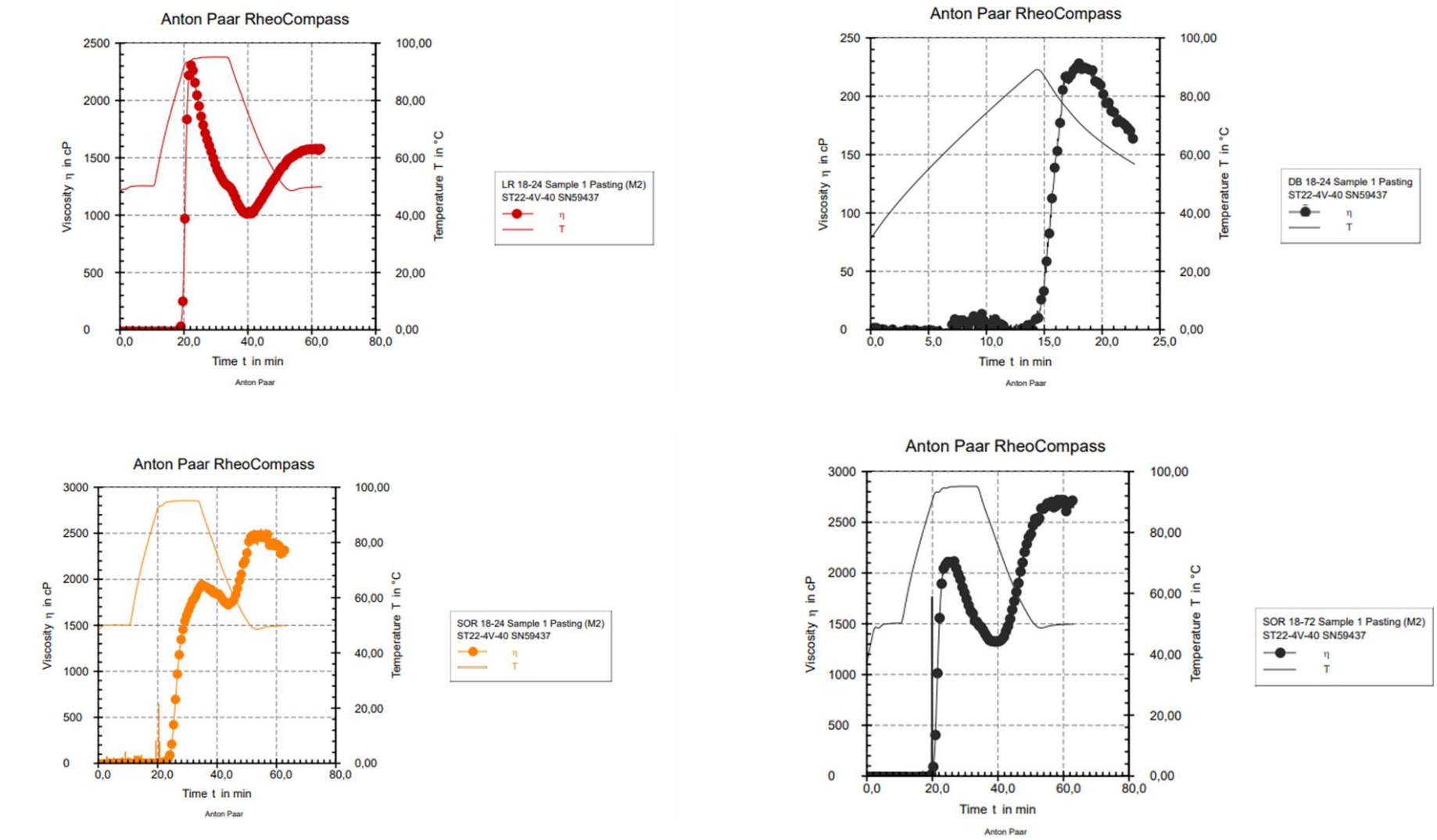

Figure 9. Temperature and viscosity profiles of a starch sample of light brown finger millet (LBFM), dark-brown finger millet (DBFM) and sorghum flour (SF) at (soaking 18 h – malting 24 h) and (soaking 18 h – malting 72 h) throughout the pasting process.

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4.8 Crystallinity level analysis of soaked and malted FM flour

X-ray diffraction was employed to analyse, in terms of diffraction patterns, the variations in crystallinity of flour influenced by soaking and malting over time. The X-ray diffraction patterns are illustrated in Figure 10. At 18 h of soaking - 24 h of malting, the diffraction patterns were recorded as follows: for LBFM at 15.13°, 18.13°, and 23.20°; for DBFM at 15.29°, 18.25°, and 23.23°; and for SF at 16.65°, 18.01°, and 23.13°. Furthermore, during the 18 of soaking - 72 h malting period, the diffraction patterns for LBFM, DBFM, SF, and SF2 at 0 - 72 h were observed as LBFM at 15.08°, 18.27°, and 23.18°; DBFM at 15.12°, 17.88°, and 22.86°; SF at 15.22°, 18.07°, and 23.23°; and SF2 at 16.62°, 17.90°, and 23.24°.

The higher diffraction angles were observed in SF soaked for 18 h and malted at 24 h and SF2 at soaked 0 h and malted at 72 h, which suggests a greater degree of crystallinity in the flour. X-ray diffraction analysis reveals how well molecules are arranged in crystalline structures. Greater diffraction intensities at these angles typically indicate more ordered crystalline regions, which can affect flour characteristics such as gelatinisation, water retention ability, and stability during processing. Increased crystallinity in grains, such as sorghum, results in substantial structural integrity and enhanced resistance to enzymatic breakdown (Zhang et al., 2022). The higher crystallinity observed in sorghum flour under these conditions suggests a more stable crystalline structure than finger millet flour.

The observed behaviour of these flours can be attributed to the enzymatic changes occurring during soaking and malting, which lead to partial disruption of their crystalline arrangements. During soaking and malting, enzymes like amylase are activated, resulting in the degradation of starch granules and a decrease in crystallinity. Sharma et al. (2023) demonstrated that this enzymatic activity can disrupt the ordered arrangements within starch, resulting in distinct alterations in the diffraction patterns. This aligns with the variations in diffraction angles recorded for LBFM, DBFM, and SF, suggesting that their crystalline structures are being modified through biochemical means.

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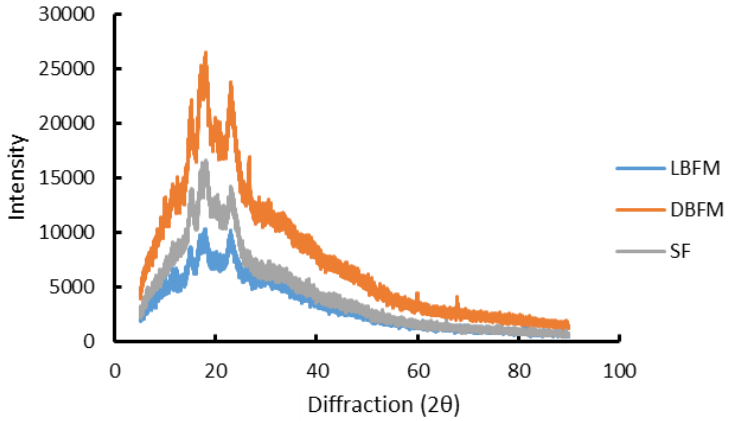
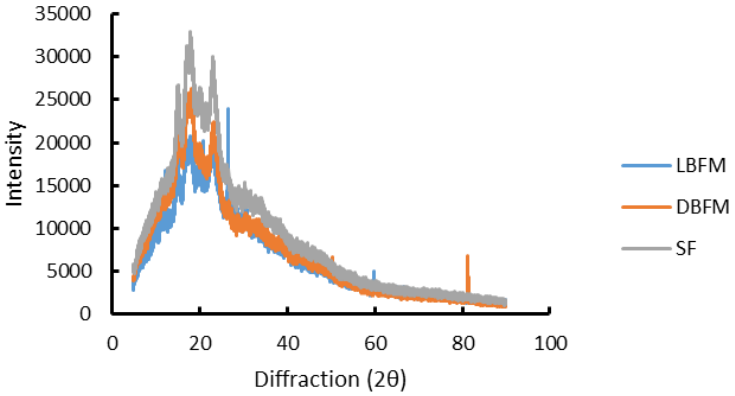
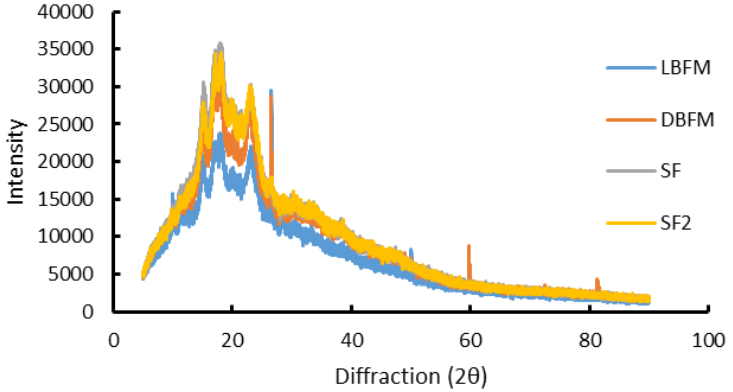


A. (0-24)



B. (18-24)



C. (18-72 & 0-72)

Figure 10. X-ray diffraction patterns of soaked and malted light-brown finger millet (LBFM), dark-brown finger millet (DBFM) and sorghum flour (SF) at different soaking and malting time intervals.

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4.9 Numerical optimisation and model validation of soaked and malted finger millet and sorghum flour

A numerical optimisation method was applied to identify the ideal processing conditions for the independent variables, ensuring the desired outcomes for each response. This was conducted based on the duration of the dependent variables while maintaining the soaking and malting times within their respective ranges. Additionally, the dependent variables were also constrained within the defined limits to achieve optimal desirability. These conditions were determined using the desirability function in Design Expert software. In LBFM, results indicated that the most suitable processing times were 10.14 h for soaking and 49.15 h for malting, achieving a desirability value of 1.00, with optimal conditions for the dependent variables pH = 6.661, TTA = 0.627, OAC = 1.87, WAC = 0.218, LBD = 0.433, PBD = 0.635, and dispersibility = 78.227. In the case of dark brown FM, the optimal soaking and malting times were 6.95 h and 24.80 h, the optimal conditions for pH = 5.829, TTA = 0.441, OAC = 1.792, WAC = 0.193, LBD = 0.453, PBD = 0.6769, and dispersibility = 79.081. While for sorghum, the best conditions were 17.79 h for soaking and 32.249 h for malting, the conditions for the dependent variables were pH = 5.542, TTA = 0.275, OAC = 1.919, WAC = 0.208, LBD = 0.406, PBD = 0.567, and dispersibility = 78.373. These were also attained at a desirability of 1.00 (Table 18). The validation results confirmed the accuracy of the model, showing a strong alignment between the predicted and experimental values for the responses (pH, TTA, OAC, WAC, LBD, PBD, and dispersibility) within a 95% prediction interval (Table 19).

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Table 18 Numerical optimum processing parameters and responses for functional properties of finger millet (light brown & dark brown) and sorghum flour

Variables	Goal	Lower limit	Upper limit	Importance	Optimal level	Model
Light-brown FM flour						
Independent variables						
Soaking	In range	0	18	3	1.00	10.409
Malting	In range	24	72	3	1.00	49.147
Dependent variables						
pH	In range	6.35	6.693	3	1.00	6.661
TTA	In range	0.33	737	3	1.00	0.627
OAC	In range	1.765	1.976	3	1.00	1.870
WAC	In range	0.193	0.229	3	1.00	0.218
LBD	In range	0.378	0.482	3	1.00	0.433
PBD	In range	0.519933	0.743	3	1.00	0.635
Dispersibility	In range	74.67	79.33	3	1.00	78.227
Dark-brown FM flour						
Independent variables						
Soaking	In range	0	18	3	1.00	3.831
Malting	In range	24	72	3	1.00	69.399
Dependent variables						
pH	In range	5.507	7.233	3	1.00	5.829
TTA	In range	0.263	0.933	3	1.00	0.441
OAC	In range	1.734	1.849	3	1.00	1.792
WAC	In range	0.182	0.22	3	1.00	0.193
LBD	In range	0.447	0.492	3	1.00	0.453
PBD	In range	0.6183	0.7263	3	1.00	0.676
Dispersibility	In range	73.33	80.67	3	1.00	79.081
Sorghum flour						
Independent variables						
Soaking	In range	0	18	3	1.00	12.380
Malting	In range	24	72	3	1.00	61.659
Dependent variables						
pH	In range	5.28	6.34667	3	1.00	5.542
TTA	In range	0.193333	0.5	3	1.00	0.275
OAC	In range	0.192	0.261	3	1.00	1.919
WAC	In range	1.65833	2.01	3	1.00	0.208
LBD	In range	0.404667	0.422667	3	1.00	0.406
PBD	In range	0.55	0.67	3	1.00	0.567
Dispersibility	In range	74.00	80.3333	3	1.00	78.373

TTA = titratable acid, OAC oil absorption capacity, LBD = loose bulk density and PBD = Packed bulk density

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Table 19 Validation of the processing time of light-brown, dark-brown finger millet and sorghum flour on functional properties

Flour	X_1 (h)	X_2 (h)	pH		TTA (%)		OAC (g ml^{-1})		WAC (m/g^{-1})		LBD (m/g)		PBD (m/g)		Dispersibility (%)	
			Pre	Exp	Pre	Exp	Pre	Exp	Pre	Exp	Pre	Exp	Pre	Exp	Pre	Exp
Light-brown FM	10.41	49.15	6.66	6.37	0.63	0.5530	1.87	1.86	0.22	0.217	0.43	0.410	0.64	0.5833	78.23	79.00
Dark-brown FM	3.83	69.39	5.83	6.79	0.44	0.39	1.79	1.85	0.19	0.2120	0.45	0.4470	0.68	0.7071	79.08	73.33
Sorghum	12.38	61.66	5.54	5.85	0.28	0.46	0.92	0.20	0.21	1.93	0.41	0.407	0.57	0.590	78.37	78.67

X_1 = soaking time (h); X_2 = malting time (h), Pre = predicted, Exp = experimented, TTA = Total titratable acidity, OAC = Oil absorption capacity, WAC = Water absorption capacity, LBD = Loose bulk density, PBD = Packed bulk density. Values in columns of different letter superscripts at significantly different $p < 0.05$

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CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

It can be inferred that soaking and malting significantly influenced the colour, thermal, pasting, and functional properties of finger millet (FM) and sorghum flours. This study provided a picture of the changes in flour characteristics subjected to soaking and malting at different time intervals. Significant effects were observed at $p < 0.05$ on colour attributes, anti-nutritional factors, thermal properties, and functional attributes. The colour results indicate that the soaking and malting duration affected colour changes, which were attributed to the presence of phenolic compounds, along with variations in hue, which is crucial for the perception and acceptability of the flour. Sorghum flour exhibited the highest b and c values, while dark brown showed the highest L* value, and light brown FM had the highest a* value. Looking at the thermal properties of these flours, LBFM exhibited the highest onset and enthalpy, while DBFM had the highest endpoint and the highest peak temperature when compared to both sorghum and light brown finger millet.

Regarding antinutritional factors, dark brown FM exhibited high tannin content. Additionally, light brown FM showed the highest level of oxalic acid, while sorghum flour had the least. With functional properties, dark brown FM demonstrated the highest pH, total titratable acidity (TTA), and loose bulk density, while light brown exhibited the highest packed bulk density, and sorghum flour had the highest water absorption capacity (WAC) and oil absorption capacity (OAC). These processing methods notably altered the crystallinity of light brown FM (LBFM), dark brown FM (DBFM), and sorghum flour (SF) due to enzymatic activity, as confirmed by scanning electron microscopy. These structural modifications enhanced functional properties such as water absorption and gelatinisation, making the flours more suitable for various food applications. These modifications increase moisture retention in baked goods, porridges, and soups; improve thickening in weaning foods, instant mixes, and gluten-free products; optimise dough performance for flatbreads, extruded snacks, and fermented foods; and enhance stability in noodles, pasta, and gravies by minimising syneresis.

The results supported the alternative hypothesis that soaking and malting improve flour characteristics while reducing some antinutritional factors. The regression models used in the study proved reliable, with high coefficients of determination (R^2) and non-significant lack-of-fit tests, validating their robustness in predicting the effects of processing on flour properties. Overall, this study highlights that soaking and malting are practical and low-cost processing interventions capable of enhancing the nutritional and functional qualities of finger millet and sorghum flours. Their strategic use, particularly when tailored to processing time and varietal differences, can optimise product quality and unlock the value of underutilised grains for

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diverse food applications. These findings offer strong potential for industrial application, in gluten-free products, infant foods, and health-promoting formulations, especially in the context of food and nutrition security.

5.2 Recommendation

Additional research is needed to explore the enzymatic mechanisms responsible for the observed improvements in flour quality, particularly through profiling of phytase, amylase, and protease activity during soaking and malting. Future studies should also incorporate *in vitro* starch and protein digestibility assessments to better evaluate nutritional outcomes. Including sensory evaluations would help determine consumer acceptability in relation to acidity, colour, and texture changes. Broader varietal comparisons are recommended to assess genotype-specific responses to processing. Furthermore, pilot-scale trials and storage stability studies should be conducted to evaluate the feasibility and shelf-life of the processed flours. These steps would strengthen the practical relevance of the findings and support the wider application of treated finger millet and sorghum flour in functional food development.

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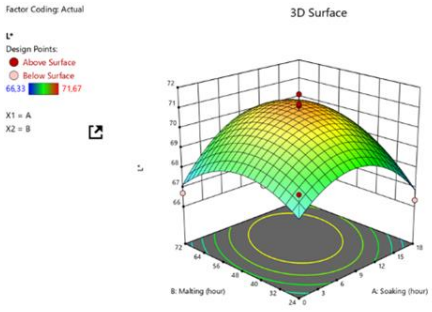
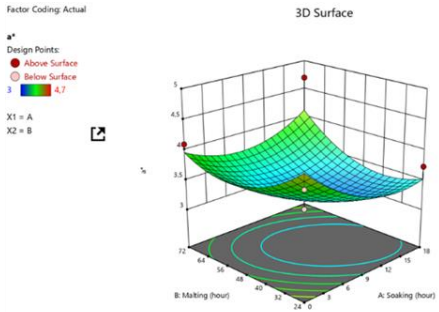
APPENDICES

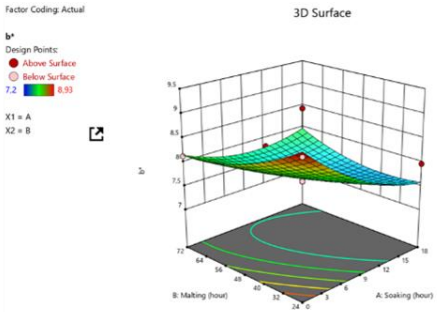
Appendix I. Response surface plots for the effect of soaking and malting time (h) on the lightness(L*), red/green(a*), yellow/blue (b*), chroma (c*) and hue angle (h°) of light-brown finger millet flour



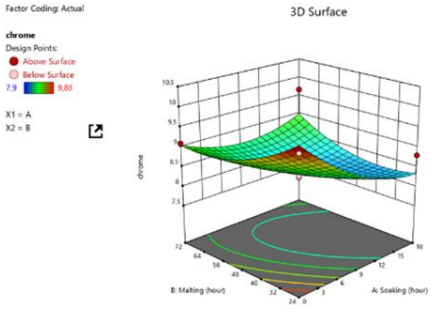
A = L*



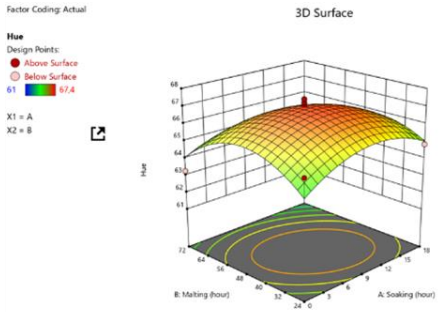
B = a*



C = b*



D = c*



E = h°

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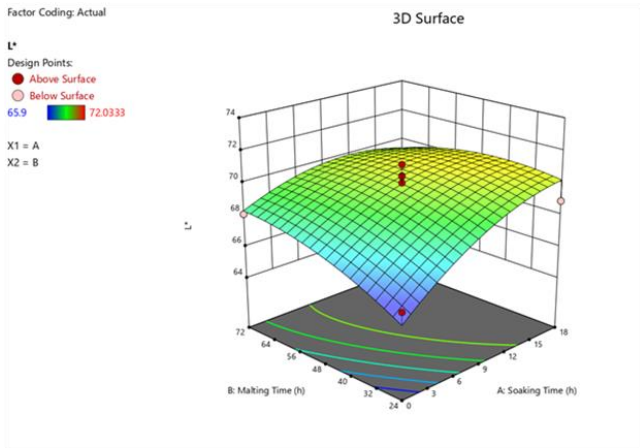
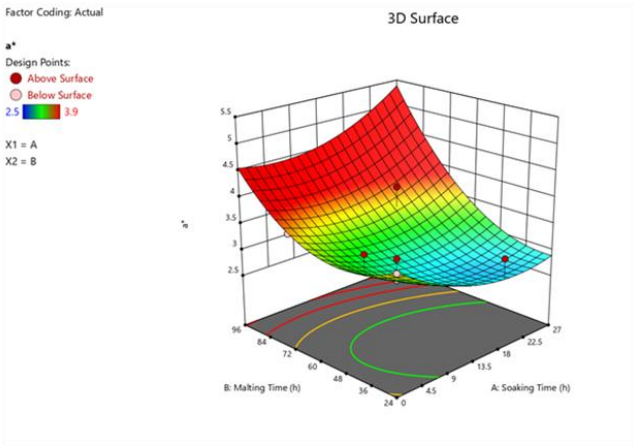
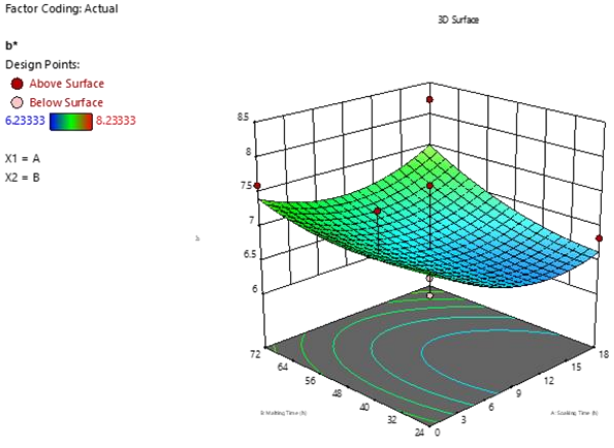
Appendix II. Response surface plots for the effect of soaking and malting time (h) on the lightness(L*), red/green(a*), yellow/blue (b*), chroma (c*) and hue angle (h°) of dark-brown finger millet flour.



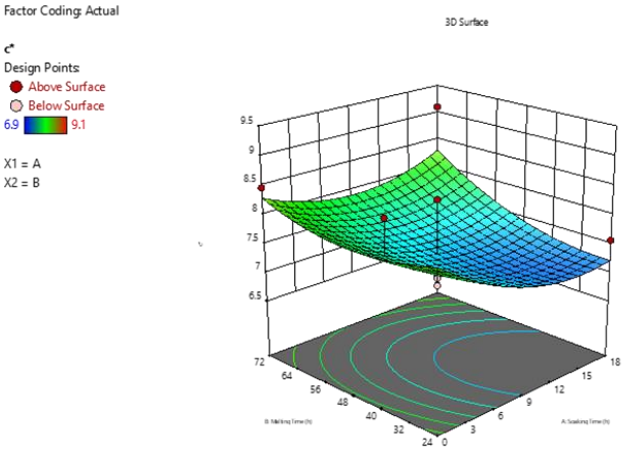
A = L*



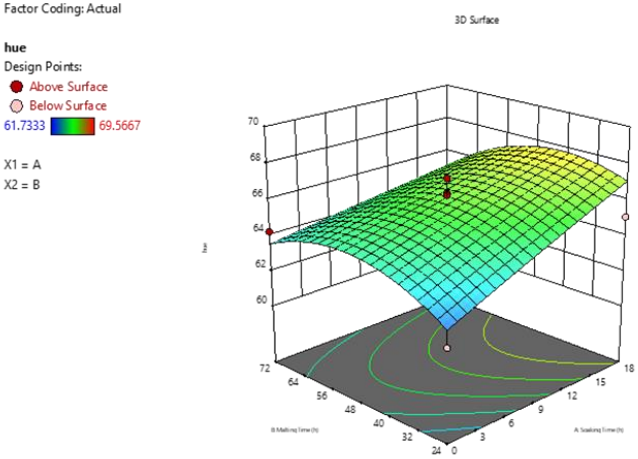
B = a*



C = b*



D = C*



E = h°

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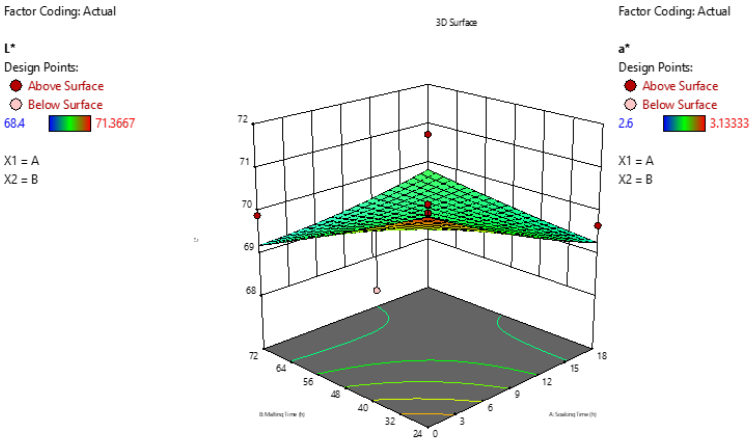
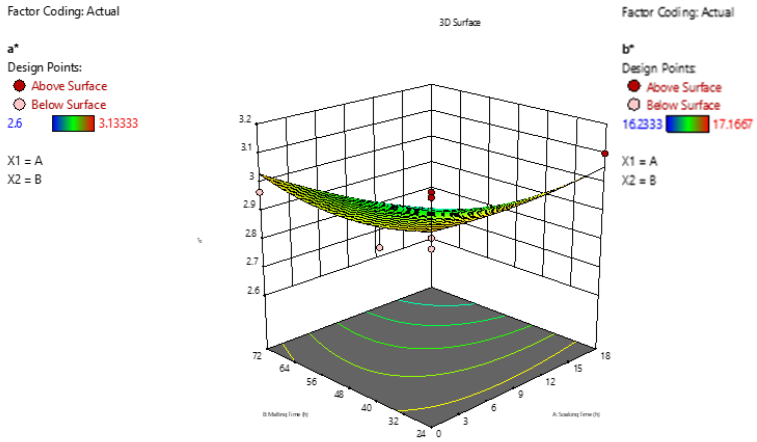
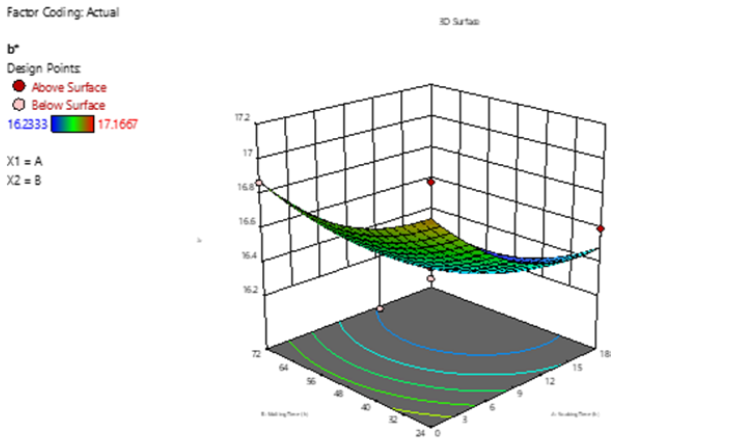
Appendix III. Response surface plots for the effect of soaking and malting time (h) on the lightness(L*), red/green(a*), yellow/blue (b*), chroma (c*) and hue angle (h°) of sorghum flour.



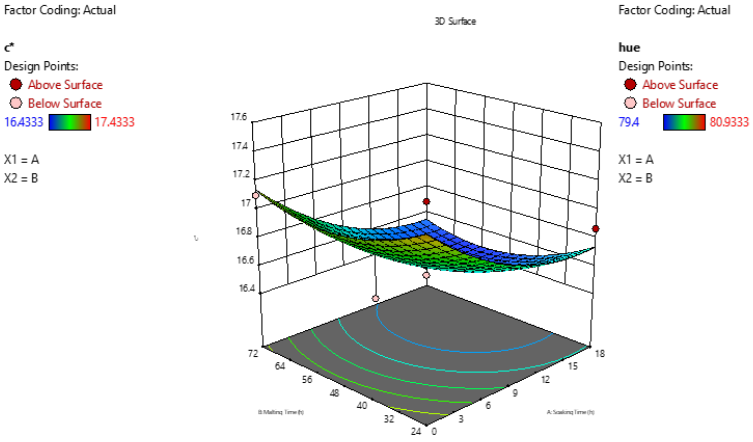
A = L*



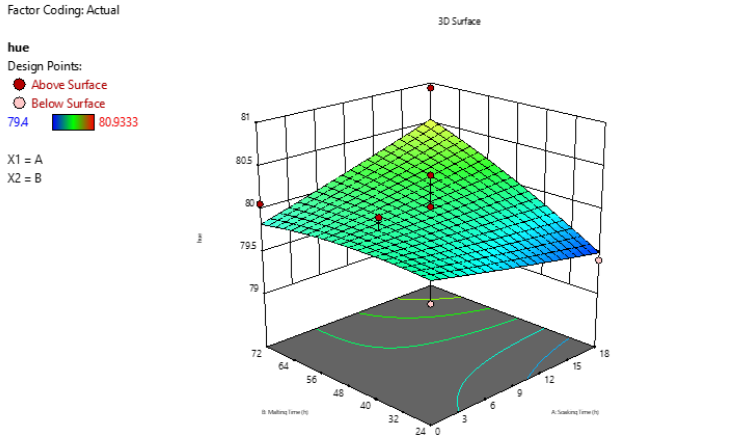
B = a*



C = b*



D = C*



E = h°

.

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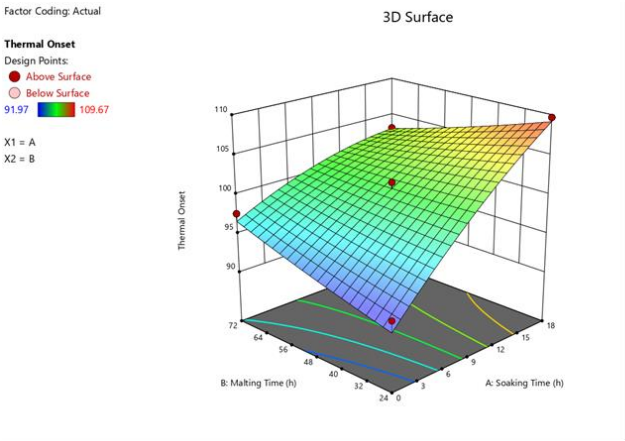
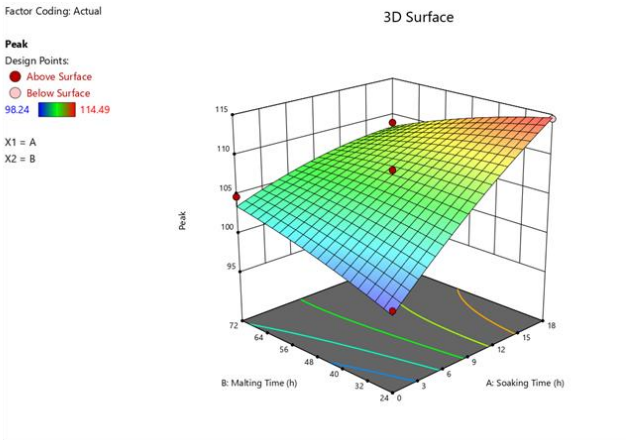
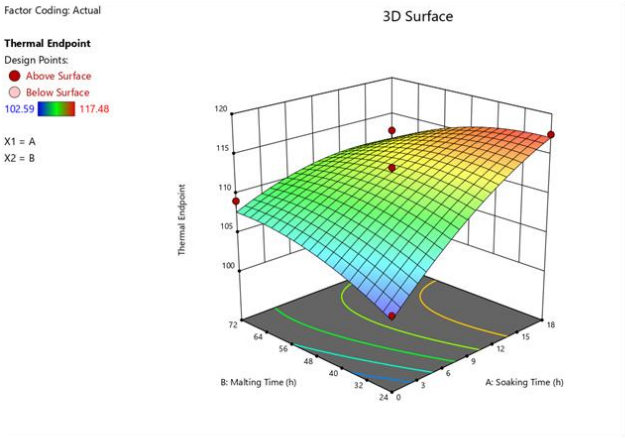
Appendix IV. Response surface plots of soaked and malted dark-brown (DBFM) thermal properties (onset, peak, endpoint and enthalpy) temperatures.



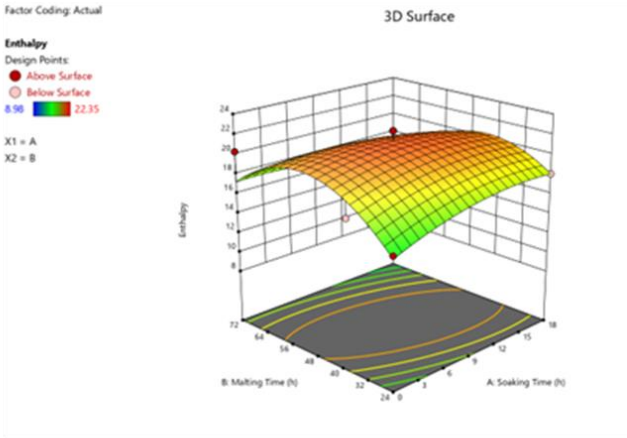
A = Onset



B = Peak



C = Endpoint



D = Enthalpy

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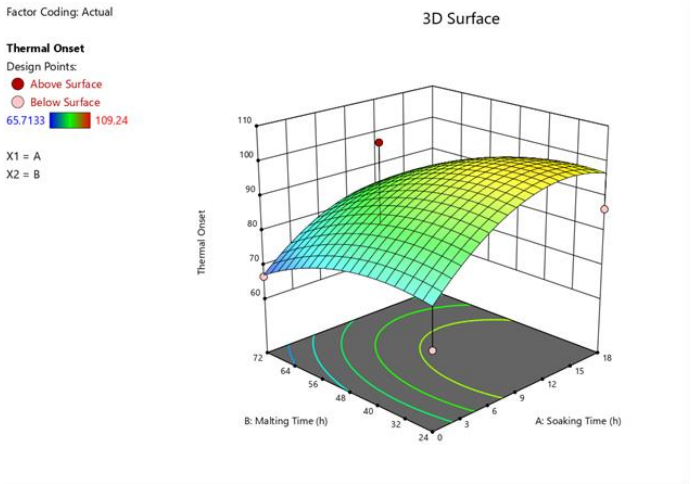
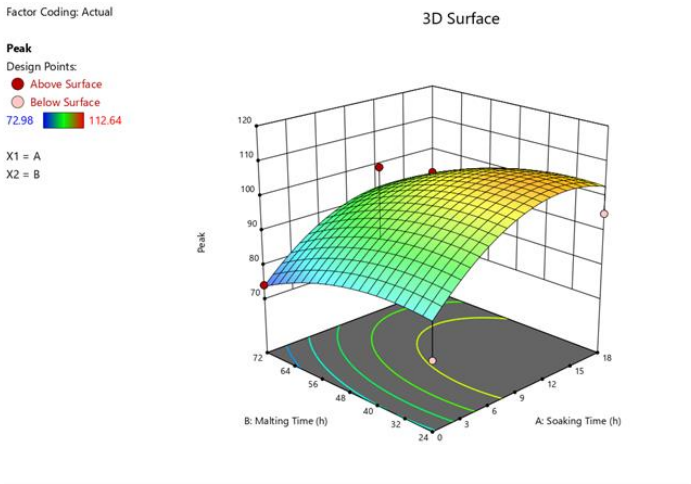
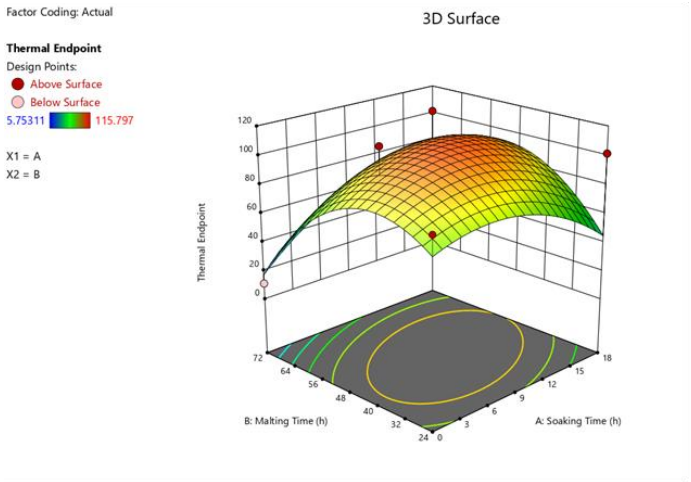
Appendix V. Response surface plots of soaked and malted sorghum (SF) thermal properties (onset, peak, endpoint and enthalpy) temperatures.



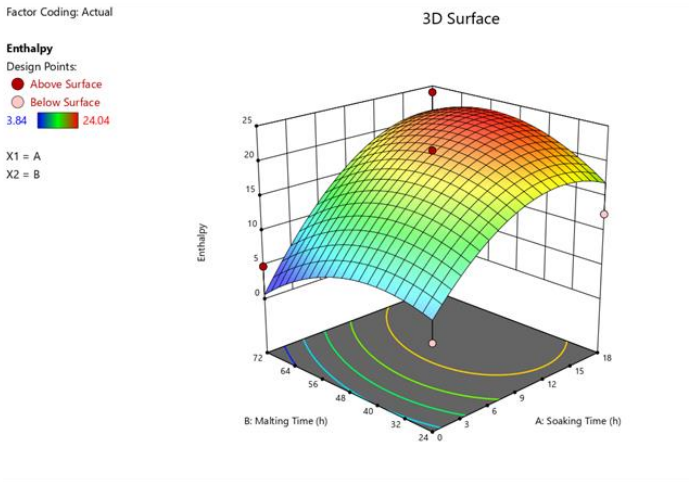
A = Onset



B = Peak



C = Endpoint



D = Enthalpy

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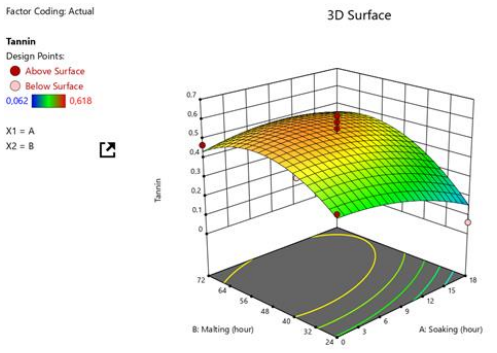
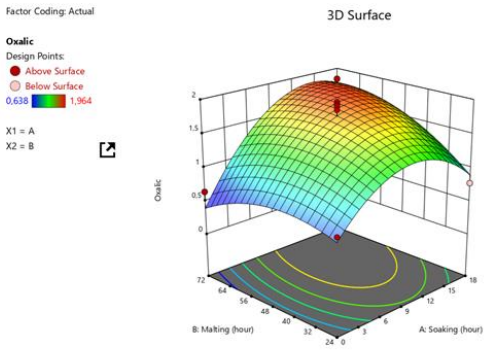
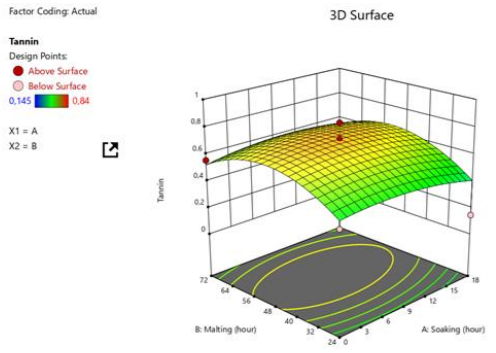
Appendix VI. Response surface plots of soaked and malted light-brown finger millet (A&B), dark-brown finger millet (C&D) and Sorghum flour (E&F) antinutritional properties.



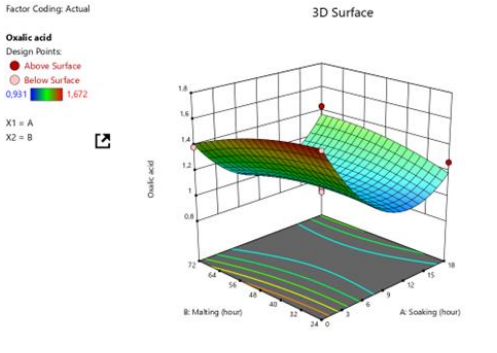
A = Tannin



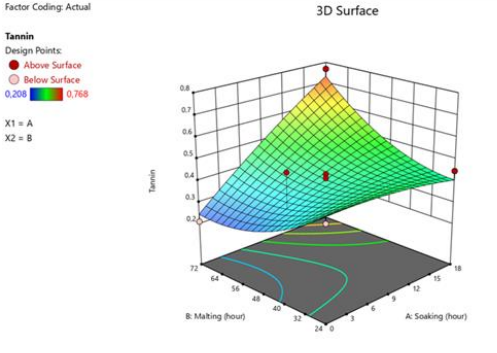
B = Oxalic acid



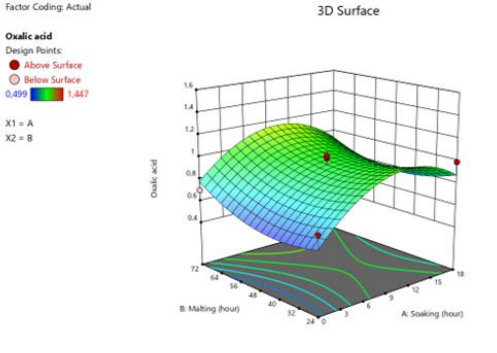
C = Tannin



D = Oxalic acid



E = Tannin



F = Oxalic acid

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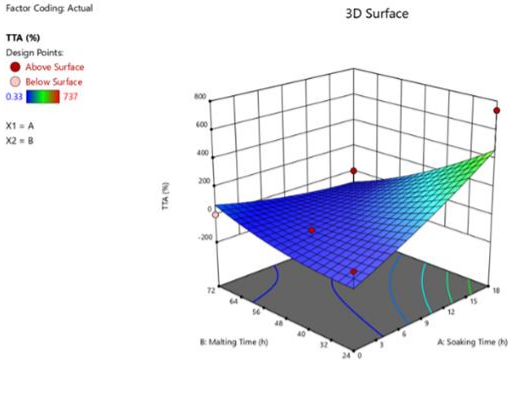
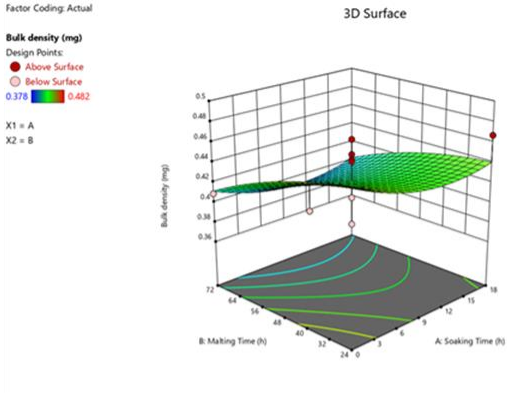
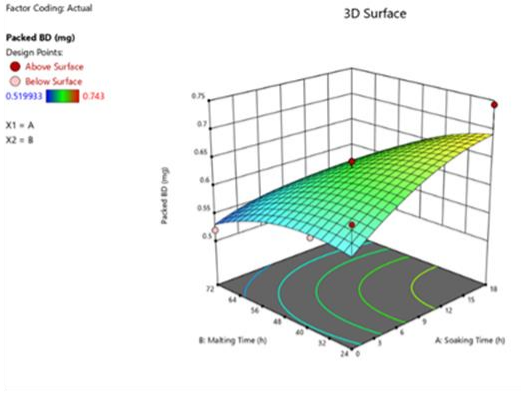
Appendix VII. Response surface plots for the effect of soaking and malting time (h) on functional properties of light-brown finger millet (LBFM). TTA= titratable acid, LBD= loose bulk density, PBD= packed bulk density, OAC= oil absorption capacity and WAC= water absorption capacity.



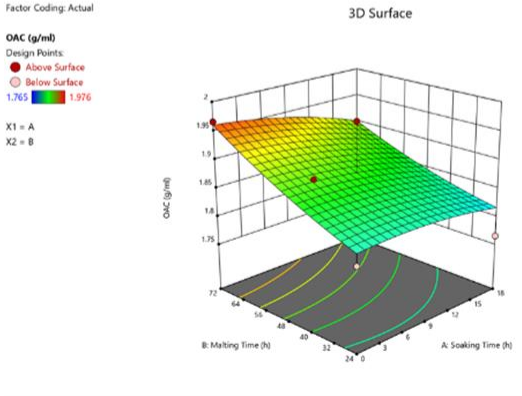
A = TTA



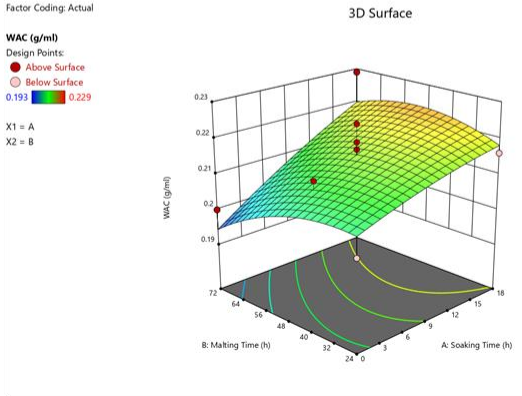
B = LBD



C = PBD



D = OAC



E = WAC

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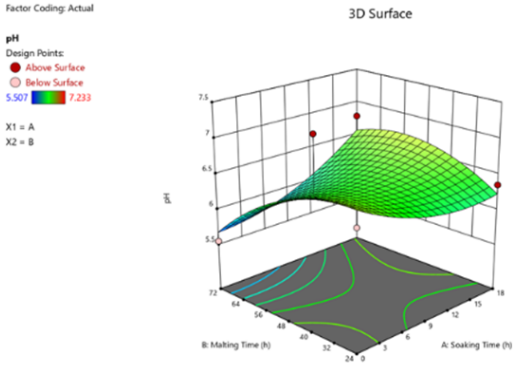
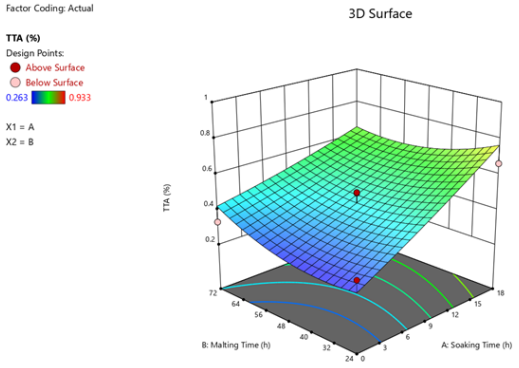
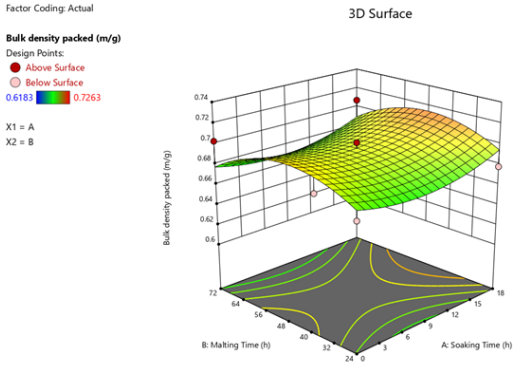
Appendix VIII. Response surface plots for the effect of soaking and malting time (h) on functional properties of dark-brown finger millet (DBFM). TTA= titratable acid, PBD= packed bulk density and WAC= water absorption capacity.



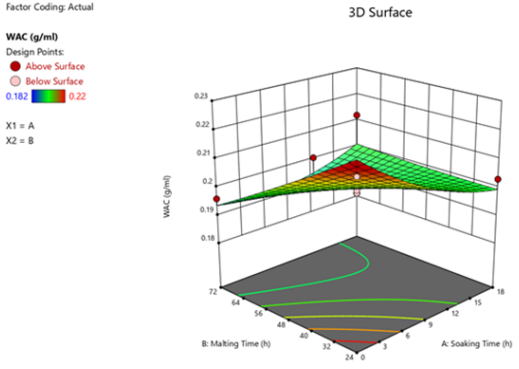
A = pH



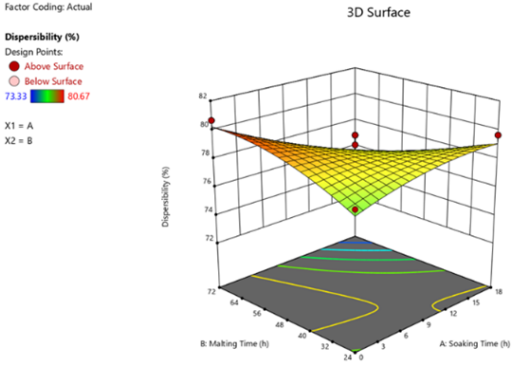
B = TTA



C = PBD



D = WAC



E = Dispersibility

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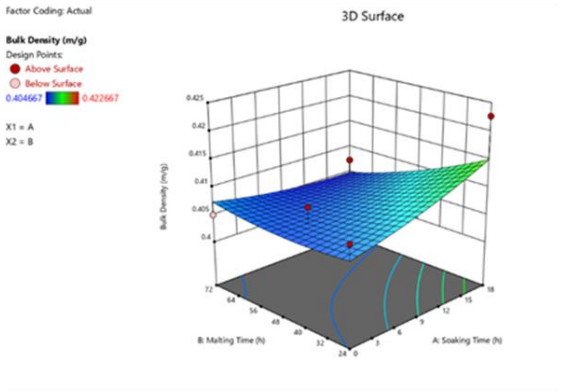
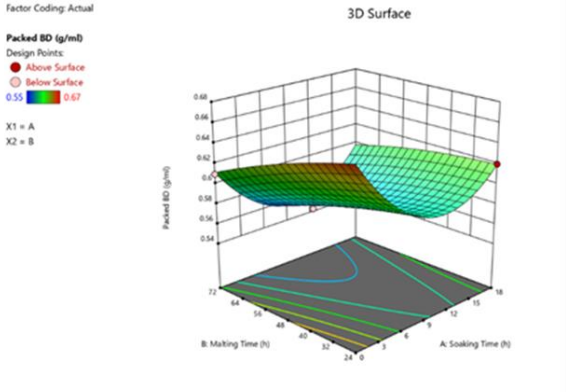
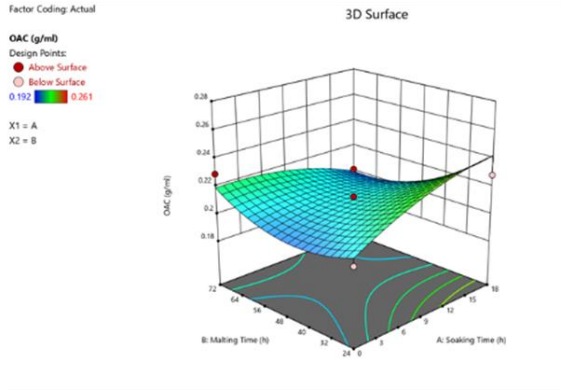
Appendix IX. Response surface plots for the effect of soaking and malting time (h) on functional properties of sorghum (SF). TTA= titratable acid, LBD = loose bulk density, PBD = packed bulk density, OAC = oil absorption capacity and WAC = water absorption capacity.



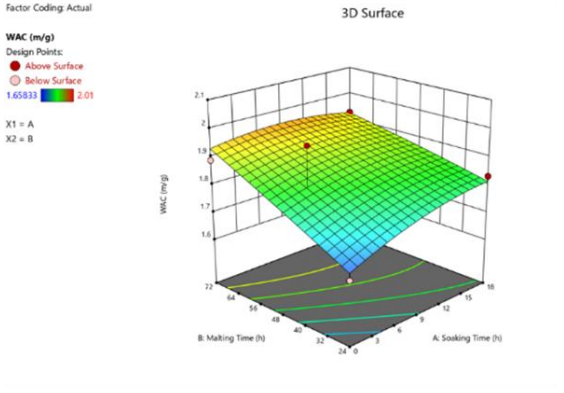
A = LBD



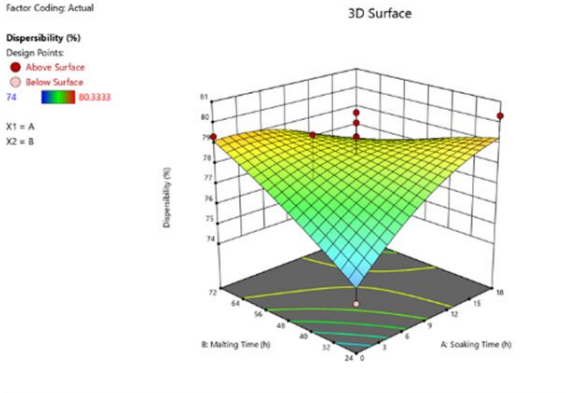
B = PBD



C = OAC



D = WAC



E = Dispersibility

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Appendix X. Level of process variables and value of the quality parameter for thermal properties of soaked and malted finger millet (light-brown) flour

Run	Soaking time (h)	Malting time (h)	Onset (T_0) °c	Peak (T_p)°c	Endpoint (T_e)°c	Enthalpy (J/J)
1	18.00	24.00	110.67 ± 3.42	114.39 ± 3.34	116.90 ± 3.27	8.31 ± 2.86
2	21.73	48.00	99.33 ± 16.52	106.68 ± 11.57	112.25 ± 6.55	26.34 ± 33.60
3	0.00	72.00	76.22 ± 17.21	86.00 ± 15.79	96.76 ± 15.05	12.75 ± 10.34
4	18.00	72.00	109.33 ± 6.10	111.39 ± 6.36	110.29 ± 6.41	3.09 ± 2.67
5	9.00	14.06	96.71 ± 13.16	103.98 ± 13.13	108.79 ± 10.56	25.92 ± 21.46
6	9.00	48.00	72.28 ± 17.64	79.91 ± 20.64	86.16 ± 21.61	12.96 ± 6.15
7	9.00	48.00	72.28 ± 17.64	79.91 ± 20.64	86.16 ± 21.61	12.96 ± 6.15
8	9.00	81.94	101.97 ± 10.86	106.66 ± 8.95	109.33 ± 7.80	10.40 ± 3.23
9	9.00	48.00	72.28 ± 17.64	79.91 ± 20.64	86.16 ± 21.61	12.96 ± 6.15
10	9.00	48.00	72.28 ± 17.64	79.91 ± 20.64	86.16 ± 21.61	12.96 ± 6.15
11	0.00	24.00	87.66 ± 20.86	93.72 ± 18.12	98.27 ± 15.86	12.49 ± 9.49
12	9.00	48.00	72.28 ± 17.64	79.91 ± 20.64	86.16 ± 21.61	12.96 ± 6.15
13	3.73	48.00	97.82 ± 30.20	103.59 ± 24.67	108.80 ± 18.59	9.28 ± 6.27

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Appendix XI. Level of process variables and value of the quality parameter for thermal properties of soaked and malted finger millet (dark-brown) flour

Run	Soaking time (h)	Malting time (h)	Onset (T_0) °c	Peak (T_p)°c	Endpoint (T_e)°c	Enthalpy (J/J)
1	18.00	24.00	109.67 ± 4.16	114.49 ± 3.59	117 ± 3.37	18.08 ± 10.32
2	21.73	48.00	106.60 ± 4.86	112.82 ± 4.35	115 ± 4.02	17.14 ± 9.87
3	0.00	72.00	97.61 ± 8.23	104.76 ± 7.28	109 ± 6.28	20.29 ± 4.17
4	18.00	72.00	103.19 ± 6.24	108.92 ± 4.95	113 ± 4.81	16.85 ± 3.31
5	9.00	14.06	100.26 ± 6.08	106.54 ± 5.44	109 ± 6.15	14.24 ± 6.17
6	9.00	48.00	101.62 ± 0.78	108.15 ± 1.12	113 ± 2.04	22.35 ± 5.33
7	9.00	48.00	101.62 ± 0.78	108.15 ± 1.12	113 ± 2.04	22.35 ± 5.33
8	9.00	81.94	100.80 ± 11.85	105.29 ± 12.26	108 ± 12.48	8.98 ± 6.44
9	9.00	48.00	101.62 ± 0.78	108.15 ± 1.12	113 ± 2.04	22.35 ± 5.33
10	9.00	48.00	101.62 ± 0.78	108.15 ± 1.12	113 ± 2.04	22.35 ± 5.33
11	0.00	24.00	92.05 ± 1 6.49	98.24 ± 14.86	103 ± 15.31	15.61 ± 17.74
12	9.00	48.00	101.62 ± 0.78	108.15 ± 1.12	113 ± 2.04	22.35 ± 5.33
13	3.73	48.00	91.97 ± 3.82	100.53 ± 2.68	106 ± 1.47	15.12 ± 13.43

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Appendix XII. Level of process variables and value of the quality parameter for thermal properties of soaked and malted sorghum flour

Run	Soaking time (h)	Malting time (h)	Onset (T_0) °c	Peak (T_p)°c	Endpoint (T_e)°c	Enthalpy (J/J)
1	18.00	24.00	86.48 ± 15.17	95.14 ± 13.49	101.58 ± 11.71	12.52 ± 11.23
2	21.73	48.00	94.99 ± 21.33	98.69 ± 15.29	103.55 ± 13.34	21.34 ± 18.41
3	0.00	72.00	66.60 ± 10.98	74.05 ± 0.73	82.30 ± 3.27	4.83 ± 3.61
4	18.00	72.00	81.67 ± 10.98	92.83 ± 8.00	101.41 ± 8.45	24.04 ± 20.03
5	9.00	14.06	107.45 ± 5.75	112.64 ± 3.76	116.26 ± 3.45	19.10 ± 13.36
6	9.00	48.00	91.70 ± 20.83	98.61 ± 16.36	104.14 ± 12.43	21.59 ± 16.03
7	9.00	48.00	91.70 ± 20.83	98.61 ± 16.36	104.14 ± 12.43	21.59 ± 16.03
8	9.00	81.94	72.73 ± 8.19	80.70 ± 5.60	86.90 ± 5.43	7.31 ± 4.73
9	9.00	48.00	91.70 ± 20.83	98.61 ± 16.36	104.14 ± 12.43	21.59 ± 16.03
10	9.00	48.00	91.70 ± 20.83	98.61 ± 16.36	104.14 ± 12.43	21.59 ± 16.03
11	0.00	24.00	65.71± 1.58	72.98 ± 2.57	86.15 ± 2.00	3.84 ± 0.51
12	9.00	48.00	91.70 ± 20.83	98.61 ± 16.36	104.14 ± 12.43	21.59 ± 16.03
13	3.73	48.00	109.24 ± 7.52	112.60 ± 5.97	115.80 ± 6.02	11.67 ± 7.14

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Appendix XIII. ANOVA models of the effect of processing on the onset, peak, endpoint and enthalpy of soaked and malted light-brown, dark-brown finger millet and sorghum flours.

Source	Onset (T_0)°c	Peak(T_p)°c	Endpoint (T_e)°c	Enthalpy (J/J)
	P_{-value}	P_{-value}	P_{-value}	P_{-value}
		Light brown FM flour		
Model	0.0747	0.0629	0.0625*	0.8153
X_1	0.1078	0.1206	0.2181	0.8347
X_2	0.8681	0.8054	0.7649	0.2324
X_1X_2	0.6592	0.8124	0.7690	0.7177
X_1^2	0.1932	0.1411	0.0807	0.7319
X_2^2	0.0256*	0.0215*	0.0227*	0.8890
		Dark brown FM flour		
Model	0.0029*	0.0009*	0.0034*	0.1186
X_1	0.0003*	0.0001*	0.0005*	0.9544
X_2	0.9798	0.8603	0.9812	0.6750
X_1X_2	0.0245*	0.0066*	0.0162*	0.3898
X_1^2	0.2854	0.2488	0.0914	0.5244
X_2^2	0.7802	0.3885	0.0618	0.0116*
		Sorghum Flour		
Model	0.2867	0.2117	0.1899	0.0174*
X_1	0.1639	0.0948	0.7699	0.0037*
X_2	0.1663	0.1631	0.5156	0.7318
X_1X_2	0.8213	0.8770	0.3460	0.2427
X_1^2	0.1516	0.0945	0.3111	0.0256*
X_2^2	0.2834	0.3009	0.0316*	0.0370*

*Significant at $p < 0.05$, Non-Significant: X_1 = linear effect of soaking; X_2 = linear effect of malting time; X_1X_2 = interaction of soaking and malting time; X_1^2 = quadratic effect of soaking; X_2^2 = quadratic effect of malting time (h).

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Appendix XIV. Regression models relating response and independent variables for soaked and malted light brown and dark brown finger millet and sorghum flour on onset, peak, endpoint and enthalpy

Response variables	Models	Residual fit at P-value	R^2
	Light brown FM Flour		
Onset (T_0) °c	$+76.27+8.82X_1-0.6682X_2+2.53X_1X_2+7.68X_1^2+11.70X_2^2$	-	0.7032
Peak (T_p)°c	$+83.51+7.37X_1-0.8662X_2+1.18X_1X_2+7.72X_1^2+10.65X_2^2$	-	0.7194
Endpoint (T_e)°c	$+89.38+4.93X_1-0.9197X_2-1.28X_1X_2+8.30X_1^2+9.18X_2^2$	-	0.7200
Enthalpy (J/J)	$+12.43+0.6870X_1-3.36X_2-1.37X_1X_2+1.26X_1^2+0.3975X_2^2$	-	0.2348
	Dark-brown FM Flour		
Onset (T_0) °c	$+100.83+6.25X_1-0.0195X_2-3.01X_1X_2-1.19X_1^2+0.2311X_2^2$	-	0.8911
Peak (T_p)°c	$+107.57+5.44X_1-0.1022X_2-3.02X_1X_2-0.9686X_1^2-0.5494X_2^2$	-	0.9227
Endpoint (T_e)°c	$+112.79+4.72X_1+0.0154X_2-2.83X_1X_2-1.71X_1^2-1.51X_2^2$	-	0.8853
Enthalpy (J/J)	$+21.37-0.0833X_1-0.4986X_2-1.48X_1X_2-1.05X_1^2-4.12X_2^2$	-	0.6538
	Sorghum Flour		
Onset (T_0) °c	$+95.34+8.221X_1-6.63X_2-1.42X_1X_2-9.50X_1^2-5.32X_2^2$	-	0.5264
Peak (T_p)°c	$+101.82+8.86X_1-5.80X_2-0.8450X_1X_2-9.90X_1^2-4.44X_2^2$	-	0.5765
Endpoint (T_e)°c	$+107.17+4.92X_1-8.99X_2+18.75X_1X_2-19.71X_1^2-37.54X_2^2$	<0.0001*	0.5926
Enthalpy (J/J)	$+21.10+7.67X_1-0.5204X_2+2.63X_1X_2-5.67X_1^2-4.00X_2^2$	-	0.8127

*Significant at $p < 0.05$, **Non Significant: X_1 = linear effect of soaking; X_2 = linear effect of malting time; X_1X_2 = interaction of soaking and malting time; X_1^2 = quadratic effect of soaking; X_2^2 = quadratic effect of malting time (h).

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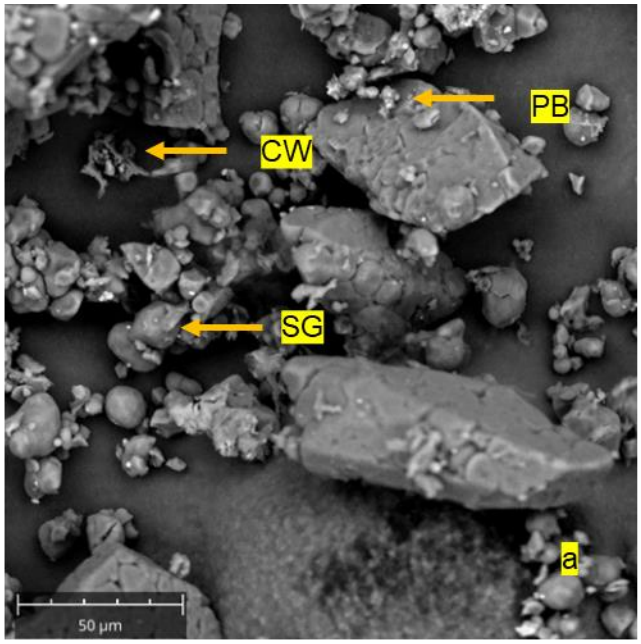
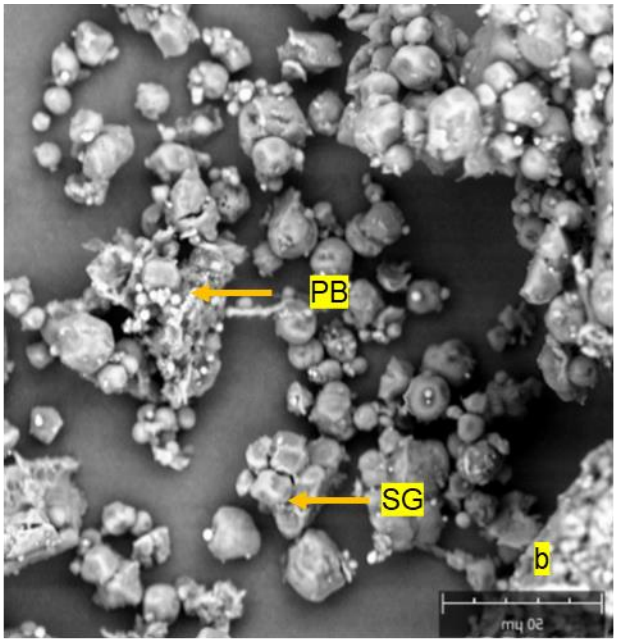
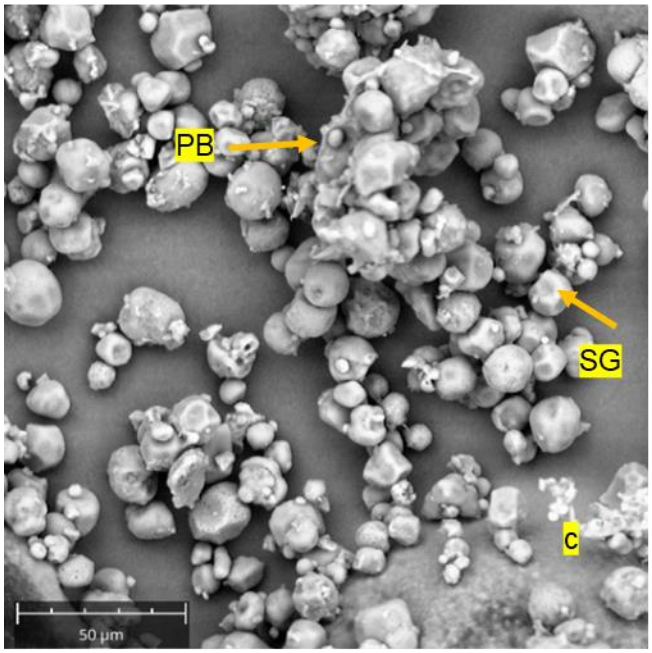
Appendix XVI. Scanning electron Micrographs of soaked and malted light-brown finger millet (LBFM), dark-brown finger millet (DBFM) and sorghum (SF) flour. (a) 18h soaked – 72 h malted DBFM; (b) 18 h soaked – 72 h malted SF; (c) 18 h soaked – 24 h malted SF; (d) 18 h soaked – 72 h malted LBFM; PB= protein bodies; SG= starch granules; CW= cell walls.



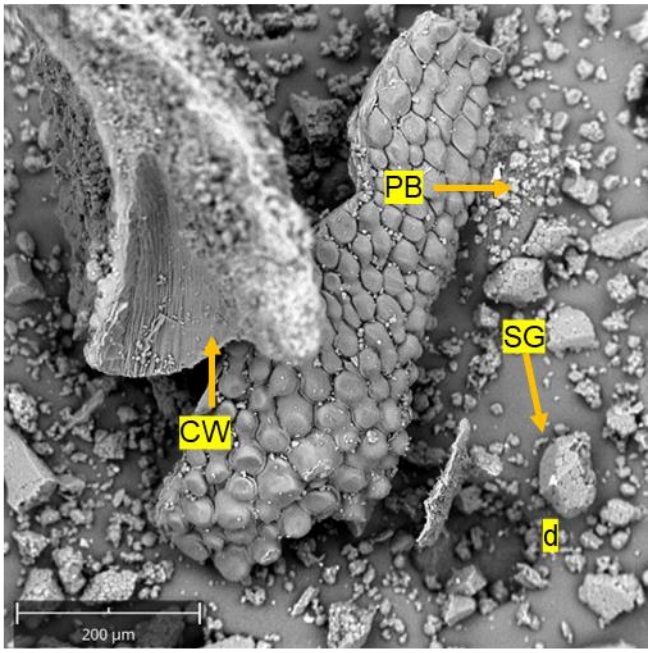
DBFM (18-72)



SF (18-72)



SF (18-24)



LBFM (18-72)

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