Characterization of functional, structural and rheological properties of flours from whole grain teff (*Eragrostis tef*) grown in India

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Summary
Ethiopian descendent teff (*Eragrostis tef*) is gaining popularity internationally for its high nutritional value. Current study analysed the chemical composition, functional, pasting, rheological and thermal properties, X-ray diffractiograms as well as microscopic structure of teff flour from grains produced in India marked as sample TFA and TFB. Sample TFB had significantly higher ($p \leq 0.05$) proteins (155.2 g·kg^{-1}) and lipids (25.50 g·kg^{-1}) content and lower moisture (73.40 g·kg^{-1}), carbohydrate (712.08 g·kg^{-1}), crude fibre (12.90 g·kg^{-1}) and ash (20.4 g·kg^{-1}) than sample TFA. Functional properties of the flour samples were found to vary significantly for the samples. Sample TFA had better water absorption, lower gelatinization time and temperature (36.33), higher redness a^* (1.53) and yellowness b^* (13.13) values compared to sample TFB. Sample TFB showed lesser retrogradation tendency and lower lightness L^* value (57.63). The diffractogram revealed that both flours had a typical A-type pattern with higher crystallinity in sample TFB (57.0 %) than sample TFA (50.0 %). The micrographs displayed the presence of compact starch granules with gritty surface packed together with non-starch components including proteins. In conclusion, these results provide useful information for the food industry to develop new teff-based products with desirable nutritional and functional properties.

Keywords
teff flour; chemical composition; functional properties; pasting properties; rheology

Cereals being a food commodity which is easy to handle, have a long shelf life and a distinct flavour makes them a significant part of the human diet since ancient times [1, 2]. Recently, the global market has been subjected to a rise in demand for gluten-free products as the awareness among consumers about celiac and other gluten-related disorders becomes profound [3]. However, he substitution of gluten from food often leads to compromise in not just sensory qualities but also nutritional profile of food products. Since gluten is essential for structural and quality characteristics of the food, the development of gluten-free food products with optimum nutritional, sensory and functional properties becomes a challenge for the food industry [2, 3].

Millets are small-sized seeds that belong to the grass subfamily Panicoideae. Millets are abundant in carbohydrates (60.0–70.0 %), proteins (6.0–19.0 %), dietary fibre (12.0–20.0 %) and minerals (2.0-4.0 %), with a low lipids content (1.5–5.0 %) while containing biologically active substances with antioxidant and antimicrobial activity, which makes them superior to wheat. Being gluten-free, non-acidifying, easily digestible and having a low glycemic index are further advantages of millet grains [1, 4, 5]. Millets are sixth most vital grains nourishing about one-third of the world's population with a production of 2 715 million tons in year 2019 [6]. These attributes of millets have consequently led to diversification in gluten-free food production sources. This has resulted in the diversion of attention towards ancient gluten-free grains with promising nutritional value, including teff.

Teff [*Eragrostis tef* (Zucc.) Trotter] indigenous to Ethiopia, is an ancient cereal crop holding great importance in its native country. Teff grain has been reported as a rich source of carbohydrates and fibre, along with a well-balanced amino acid profile and considerable content of calcium, copper, iron and zinc, when compared to those found in wheat, barley and sorghum, while teff completely lacks gluten proteins [2]. The classi-

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fication of teff cultivars is based on their white or brown colour. Teff grains are rarely classified based on their variety, however, the nutritional and physico-chemical quality of grains and products mase from them are greatly affected by the variety [7]. The flour from teff grains is always made from whole grains, which further improves the nutritional quality of the flour by addition of dietary fibre, starch, proteins and minerals from the bran layer [8]. Teff has been reported to have higher proteins and lipids contents than commonly used cereals [9]. In addition, teff contains slow-release carbohydrates, which makes it suitable for people with type 2 diabetes. It also contains a wide variety of bioactive compounds such as phytosterols, vitamins or phenolic compounds, which are closely associated with beneficial effects on human health [10]. The physico-chemical and nutritional quality of teff flours has been shown to be highly dependent on the variety [3].

Owing to the favourable nutritional profile and ease of cultivation of teff with regards to its climate tolerance, it has been recently introduced to cultivation practices in India. Being a suitable substitute for gluten-free products development, it became important to study the nutritional, functional and rheological properties of flour from teff grains. Therefore, the current study was conducted with the objective to explore these properties of flour from Indian teff and put forth the analysis which can further contribute to selection of suitable processes for product development.

MATERIALS AND METHODS

Materials

Teff (*Eragrostis tef*) grains were procured from two local farmers of Karnataka, India and labelled as TFA (sample A) and TFB (sample B) for analysis. The grains were cleaned and sieved to remove impurities. The cleaned grains were milled by using hammer mill (Scorpio Enterprise, Ahmedabad, India) and passed through a sieve of the mesh size 0.25 mm. The prepared flour was stored in air-tight PET containers under refrigeration conditions until use for a maximum of 14 days. All reagents used in this study were of analytical grade.

Chemical composition

The moisture content was determined by AOAC method 930.15 [11]. The proteins content was determined by AOAC method 984.13 [11] using Biokjel BK06M SMR ALT (Techno Reach, Chennia, India) for digestion and Biokjel Bio Dist F-Est (Techno Reach) for distillation. The crude fibre of the flour samples was determined by AOAC method 991.43 [11] using Fibra Plus FES 6 (Pelican Equipments, Chennai, India). The crude lipids content of samples was determined by AACC method 30.25.01 [12] using Socs Plus SCS 6 (Pelican Equipments). The ash content was determined by AACC method 44.19 [12] using muffle furnace and carbohydrate content by difference.

Falling number

The falling number was determined by using a falling number machine Falling Number 1500 (Perten Instruments, Stockholm, Sweden) by AACC Method 56-81.03 [12]. The flour sample (7.0 g, 14.0 % moisture) was mixed with 25 ml water, shook and placed in the falling number machine for evaluation. The final reading was obtained in seconds which is a sum of 5 s of boiling water treatment, 55 s of stirring and the time taken by the stirrer to fall.

Particle size

The flours' particle size was determined using a laser light diffraction particle size analyser SALD-2300 (Shimadzu, Kyoto, Japan). The method of Vela et al. [3] was used with deionized water and flour dispersion of 10 $g \cdot l^{-1}$, which was added dropwise to the cuvette until the refractive index reached a point between 20 % and 40 %. The percentage of differently sized particles was evaluated and an average particle diameter was calculated as the particle diameter of 50 % (D_{50}) of the normalized particle amount. Additionally, D_{90} (the diameter at which 90 % of the sample is smaller while the remainder is larger) and D_{10} (the diameter at which 10 % of the sample is smaller and the remainder is larger) values were determined.

Colour

The colour characteristics of the flour samples were analysed using a Hunter colorimeter equipped with an optical sensor D25 (Hunter Associates Laboratory, Reston, Virginia, USA). The protocol for the calculation of L^*, a^* and b^* by International Commission on Illumination (CIE) was used, where L^* is lightness, $+a^*$ is redness, $-a^*$ is greenness, $+b^*$ is yellowness and $-b^*$ is blueness [13].

Bulk density and tapped density

The bulk density was measured by the method suggested by Gowthamraj et al. [14] with a slight modification. Sample of 2 g was taken in a 10 ml graduated measuring cylinder and the volume ob-

tained was recorded as initial volume. The sample was tapped on a rubber laden flat surface until no further reduction in volume took place and this volume was recorded as the final volume. The calculation for bulk density (ρ_b) and tapped density (ρ_t) was done by using the following equations and expressed in grams per millilitre.

$$\rho_b = \frac{W_1}{V_1} \quad (1)$$

where W_1 is the weight of sample expressed in grams and V_1 is the initial volume in millilitres.

$$\rho_t = \frac{W_2}{V_2} \quad (2)$$

where W_2 is the weight of sample expressed in grams and V_2 is the final volume in millilitres.

Water absorption capacity

Water absorption capacity (*WAC*) was determined by the method proposed by Wani et al. [1] with slight modification. One gram of each sample was mixed with 10 ml of distilled water and placed in a shaker incubator for 30 min. The samples were then centrifuged in pre-weighed tubes at 3 000 ×*g* for 15 min, the supernatant was removed and lastly the remaining material was weighed. *WAC* is the weight increased by water absorption expressed in percent.

Oil absorption capacity

Oil absorption capacity (*OAC*) was measured in a similar way as *WAC* but water was replaced with 10 ml of refined sunflower oil. *OAC* is the weight increased by oil absorption expressed in percent [1].

Swelling power and solubility

One gram of each sample was dissolved in 30 ml distilled water and heated to 60 °C, 70 °C, 80 °C and 90 °C for 30 min in a shaking water bath. The suspension was cooled to 25 °C and centrifuged in pre-weighed tubes at 3 000 ×*g* for 15 min. The supernatant was collected in a petri dish and dried in a hot air oven at 105 °C for 12 h and weighed next day. Calculation of percent solubility (*SL*) involves comparing the dry mass of soluble compounds in the supernatant to the weight of the initial samples. The paste remaining in the tubes was weighed to calculate the swelling power (*SP*) of the flour samples and expressed in gram per gram [15].

Foaming capacity and foam stability

As per the method suggested by Alemneh et al. [16], the foaming capacity (*FC*) was measured by vigorously shaking 50 ml of 1.0 % flour suspension in a 100 ml volumetric flask for 5 min. The increase in volume of foam after 30 s expresses *FC* of the flour samples.

The volume of foam remaining after resting of 1 h depicts the foam stability (*FS*) and is expressed as the percentage of the initial volume of foam.

$$FS = \frac{V_1 - V_2}{V_1} \times 100 \quad (3)$$

where V_1 is the initial foam volume expressed in millilitres and V_2 is the volume of foam after 1 h expressed in millilitres.

Emulsion capacity

The emulsion properties were studied by taking a homogenized mixture of 1 g flour sample, 10 ml distilled water and 10 ml soybean oil and adding it to a pre-weighed centrifuge tube. The emulsion was then centrifuged at 2 000 ×*g* for 5 min. The ratio of the height of emulsion layer to the total height of the mixture was calculated as emulsion capacity (*EC*) and expressed in percent [17].

Emulsion stability

Emulsion stability (*ES*) was estimated after heating the emulsion contained in a calibrated centrifugation tube at 80 °C for 30 min in a water bath, cooling for 15 min under running tap water to 25 °C followed by centrifugation at 2 000 ×*g* for 15 min. *ES* was calculated as the ratio of the height of emulsified layer post heating to the total height of the mixture and expressed in percent [17].

Pasting properties

The pasting properties of both flour samples were determined using a Rapid Visco Analyzer (RVA) model 3D (Newport Scientific, Warriewood, Australia) as per the Dimri and Singh [13]. Distilled water was added to 3 g of flour sample to make a suspension of 12 % and added to the instrument's aluminium canister and stirred. The programmed heating and cooling cycle of the instrument were used to determine viscosity profiles of the sample with constant paddle rotation speed. The instrument's software was used to measure the peak viscosity (*PV*), trough viscosity (*TV*), final viscosity (*FV*), pasting temperature (*PT*) and pasting time (*Pti*). The viscosities were expressed in centipoise, temperature in degrees Celsius and time in seconds.

Dynamic rheological characteristics

To study the rheological characteristics of flour, the gel prepared in RVA was used and analysed using the instrument MCR 102 (Anton Paar, Graz,

Austria) with a parallel plate geometry as per the method suggested by Mir et al. [18]. Amplitude and frequency tests were carried out to determine the linear viscoelastic region (*LVR*). Values of storage modulus (*G'*), loss modulus (*G''*) as a function of temperature were obtained. After cooling the sample, rheological behaviour was studied by comparing the dependence of *G'* and *G''* with frequency. A frequency sweep at 25 °C was performed and the values of storage modulus and loss modulus were recorded as a function of frequency. The steady shear (shear stress *vs* shear rate) data were obtained over a 0.1–100 s^{-1} shear rate range.

Thermal properties

The thermograms obtained by differential scanning calorimeter DSC 4000 (Perkin Elmer, Waltham, Massachusetts, USA) were used to study the thermal properties of the flour samples. Approximately 10–15 mg of the flour sample hermetically sealed in an aluminium pan were scanned at a temperature ranging from 0 °C to 200 °C at a 10 °C·min^{-1} scanning rate as proposed by Dimri and Singh [13]. Parameters of onset temperature (T_o), peak temperature (T_d), end temperature (T) and enthalpy of gelatinization (ΔH) were obtained from the graphs.

X-ray diffraction patterns

An X-ray diffraction meter D8 Advance DAVINCI (Bruker, Billerica, Massachusetts, USA) operating at a voltage of 45 kV and a current of 40 mA was used for the determination of X-ray diffraction. The diffraction data of flour samples were collected over an angular range of 5° up to 70° (2θ). The percent crystallinity (C) was calculated as per the following formula [19]:

$$C = \frac{P_a}{T_a} \times 100 \quad (4)$$

where P_a represents the area under peaks and T_a is the total area of the curve.

Fourier transform infrared spectroscopy

Structural properties of the flour samples were characterized using Fourier transform infrared (FTIR) spectroscopy obtained by RX I instrument (Perkin-Elmer). Samples were placed on a plate and data were recorded in transmittance mode in a region ranging from 4000 cm^{-1} to 600 cm^{-1} [19].

Scanning electron microscopy

The milled flour morphological properties were analysed by using a scanning electron microscope JSM 6610-LV (JEOL, Akishima, Tokyo, Japan) with 100× magnification. To prepare the sample, double-backed cellophane tape was used to secure the flour to the aluminum stubs and an automatic fine coater JFC-1600 (JEOL) was used to apply a 60 : 40 (w/w) gold-palladium coating during 1 h [19].

Statistical analysis

All measurements were taken in triplicates. Mean and standard deviation of each measured attribute were calculated using IBM SPSS Statistics (IBM, Chicago, Illinois, USA). The *t*-test was used evaluate significance of differences in means at $p \leq 0.05$.

RESULTS AND DISCUSSION

Chemical composition

The chemical composition of the flour samples TFA and TFB are reported in Tab. 1. The proteins and lipids contents in case of TFB was found to be significantly higher ($p \leq 0.05$) than that of TFA. The moisture, carbohydrates, fibre and ash contents were found to be significantly higher in case of TFA than TFB. The differences in chemical composition are known to be mainly due to genetic differences, growing environment and soil conditions [20]. The proteins and carbohydrates contents of both the samples were found to be higher than the values reported in case of Chenopodium album flour by Jan et al. [21], finger millet flour by Gowthamraj et al. [14] and Ethiopian and south African varieties of teff studied by Alemneh et al. [16]. On the other hand, ash, lipids and fibre contents of teff flour were on the lower side. Carbohydrates were the major constituents of the flour samples (Tab. 1) and are known to contribute by 40–80 % to the total energy uptake in human diet while acting as carriers for micronutrients and phytochemicals [22].

Falling number

Falling number is an indicator of viscosity and characterizes the liquefaction degree of the gelatinized water-flour suspension under the influence of temperature and/or enzymes. The falling number was found to be significantly higher ($p \leq 0.05$) for TFA (486 s) when compared to that of TFB (430 s). The values observed were much higher than 250 s, indicating low amylase activity hence lower conversion of starch to saccharides in flour-based fermented products. The results obtained in the current study were lower than those found previously for buckwheat (999 s) but greater than those for millet flour (212 s) and rye flour

Tab. 1. Chemical composition, colour characteristics and particle size distribution of teff flour samples.

Parameter	Teff flour samples	
	TFA	TFB
Chemical composition		
Moisture [g·kg^{-1}]	93.20 ± 0.70 ^{b}	73.40 ± 0.60 ^{a}
Protein [g·kg^{-1}]	135.40 ± 2.70 ^{a}	155.20 ± 1.20 ^{b}
Carbohydrate [g·kg^{-1}]	714.20 ± 4.30 ^{b}	712.08 ± 1.60 ^{a}
Lipid [g·kg^{-1}]	20.60 ± 0.20 ^{a}	25.50 ± 0.50 ^{b}
Crude fibre [g·kg^{-1}]	14.70 ± 0.40 ^{b}	12.90 ± 0.90 ^{a}
Ash [g·kg^{-1}]	21.90 ± 2.00 ^{b}	20.40 ± 0.40 ^{a}
Colour		
Lightness L^*	67.80 ± 1.03 ^{b}	57.63 ± 1.90 ^{a}
Redness a^*	1.53 ± 0.11 ^{b}	1.43 ± 0.20 ^{a}
Yellowness b^*	13.13 ± 0.36 ^{b}	10.96 ± 0.70 ^{a}
Particle size distribution		
D_{10} [μm]	115.80 ^{a}	183.00 ^{b}
D_{50} [μm]	202.32 ^{a}	271.59 ^{b}
D_{90} [μm]	391.51 ^{a}	434.09 ^{b}

All values are mean ± standard deviation (n = 3). Values with different superscript within the same row are significantly different ($p \leq 0.05$).
D_{10}, D_{50}, D_{90} – the diameter at which 10 %, 50 % and 90 % of the sample, respectively is smaller while the remainder is larger.

Tab. 2. Functional properties of teff flour samples.

Parameter	Teff flour samples	
	TFA	TFB
Bulk density [g·ml^{-1}]	0.60 ± 0.01 ^{a}	0.64 ± 0.02 ^{b}
Tapped density [g·ml^{-1}]	0.76 ± 0.01 ^{b}	0.71 ± 0.01 ^{a}
WAC [%]	247.0 ± 1.0 ^{b}	237.7 ± 2.5 ^{a}
OAC [%]	207.0 ± 1.0 ^{a}	212.3 ± 1.5 ^{b}
Foaming capacity [%]	13.6 ± 0.3 ^{b}	7.2 ± 0.3 ^{a}
Foaming stability [%]	75.0 ± 0.9 ^{b}	72.1 ± 1.1 ^{a}
Emulsion capacity [%]	14.9 ± 0.4 ^{a}	36.3 ± 1.0 ^{b}
Emulsion stability [%]	8.2 ± 0.7 ^{a}	19.1 ± 1.4 ^{b}

All values are mean ± standard deviation (n = 3). Values with different superscript within the same row are significantly different ($p \leq 0.05$).
WAC – water absorption capacity, *OAC* – oil absorption capacity.

(95 s) as stated by Berezina et al. [23]. The falling number values determined in the present study were also higher than those previously found for wheat flour (306–337 s) [24].

Particle size

The results determined for particle size distribution are presented in Tab. 1. The median particle size (D_{50}) was found to be significantly higher ($p \leq 0.05$) in case of TFB as compared to TFA. This value is considered best for describing size distribution of flour numerically as it expresses size at which 50 % of the sample is larger while the other half is smaller [25]. The span value (or dispersion) was, however, significantly higher ($p \leq 0.05$) in case of TFA (1.36) than TFB (0.92). The median particle size was higher than that observed by Vela et al. [3] for white and brown teff flour while, the span value or dispersion was stated otherwise. The difference observed may be due to the milling parameters used at the preparation of teff flour.

Colour characteristics

Data on colour characteristics of flour samples are presented in Tab. 1. A significantly lower ($p \leq 0.05$) value of L^* as observed in case of TFB clearly indicated that it had darker colour as compared to TFA. Significantly higher ($p \leq 0.05$) values of a^* and b^* indicated the presence of more redness and yellowness in the case of TFA than in the case of TFB. Comparing the observed values to those reported by Gowthamraj et al. [14] for finger miller flour (L^* of 81.95, a^* of 3.54 and b^* of 11.72), it can be said that teff flour is darker with lower redness and yellowness. The brown colour of teff flour is likely due to the presence of fibre and phytochemicals in higher amount than in cereals such as rice [9].

Bulk density and tapped density

Bulk density and tapped density are important when designing the packaging and product development system for flour. The bulk and tapped density of teff flour are presented in Tab. 2. The sample TFB had significantly higher ($p \leq 0.05$) bulk density than TFA. On the contrary, tapped density was significantly higher ($p \leq 0.05$) in case of TFB as compared to TFA. Bulk density values observed in this study were higher than those reported by Jaddu et al. [26] for little millet (0.47 g·ml^{-1}) and *C. album* (0.56-0.59 g·ml^{-1}) given by Jan et al. [21] but lower that those stated by Ali et al. [27] for pearl millet (1.03 g·ml^{-1}) and soybean flour (1.85 g·ml^{-1}). A higher bulk density is advisable when designing food for infant and convalescent nutrition as higher bulk density reduces the thickness of paste.

Water absorption capacity

WAC directly indicates the maximum amount of water sample can absorb and retain, as this is important for softening and improved digestibility of the product [21]. The results for *WAC* are presented in Tab. 2. TFA with a higher content of carbohydrates had a significantly ($p \leq 0.05$) higher

WAC than TFB. The increase in *WAC* has always been associated with an increase in the amylose leaching and solubility, and with loss of starch crystalline structure. Higher water-absorbing flour was reported to contain more hydrophilic constituents such as polysaccharides (starch), soluble saccharides and proteins, together with lower content hydrophobic components. Since proteins have both hydrophilic and hydrophobic nature, their interactions with water in foods is influenced by their content, degree of interaction with water and conformational characteristics [17]. Overall, both flours had higher *WAC* values as compared to pearl millet (132 %) and *C. album* (229 %), which suggests superior digestibility with potential application in soups and gravies preparation [17, 21, 28].

Oil absorption capacity

Oil and water binding capacities are two vital functional characteristics of flour representing its ability to associate with water/oil under confined conditions [28]. The results for *OAC* are reported in Tab. 2. The study revealed that TFB had significantly higher ($p \leq 0.05$) *OAC* than TFA. The higher value of *OAC* may be accounted to non-polar proteins that form hydrophobic interactions between flour and the hydrocarbon chains present in the oil [17]. The flours with higher *OAC* are potentially useful for retention of flavour, palatability improvement and shelf-life extension of products where in food products, where lipids absorption is desired, particularly bakery products [21].

Swelling power and solubility

Swelling capacity is the increase in volume of the sample on soaking in water [28]. The effect of increasing temperature on the swelling power (*SP*) and solubility (*SL*) is presented in Fig. 1. It can be observed that *SP* and *SL* for both samples increased slightly at 60–70 °C and gradually increased at 70–90 °C. A similar trend in *SP* and *SL* was observed by Kumar et al. [15] on examining proso millet flour, where these values increased gradually when the temperature increased from 60 °C to 90 °C. SP was significantly ($p \leq 0.05$) higher for TFB at 90 °C than for TFA, while at 70 °C and 80 °C, SP values were in the same range for both samples. In the case of flour, several factors such as variety, processing method and particle size significantly affect its *SP* and *SL* [17]. Higher solubility, as seen in case of TFB, may be due to the presence of soluble components including saccharides from starch degradation, proteins and fibre [15].

Foaming capacity and foam stability

Foam is a colloid of gas bubbles trapped in a liquid or solid material, where small gas bubbles are surrounded by a thin liquid or solid film [17]. Foam capacity (*FC*) refers to the amount of interfacial area that can be created by the material while foam stability (*FS*) refers to the ability of the material to stabilize the foam against mechanical and gravitational stresses. The values determined in this study are presented in Tab. 2. *FC* results revealed that the TFA had significantly higher ($p \leq 0.05$) *FC* than TFB. Similarly, *FS* was found to be significantly higher ($p \leq 0.05$) for TFA than TFB.

Emulsion capacity and emulsion stability

The surface-active compounds present in flour, particularly proteins, have the ability to

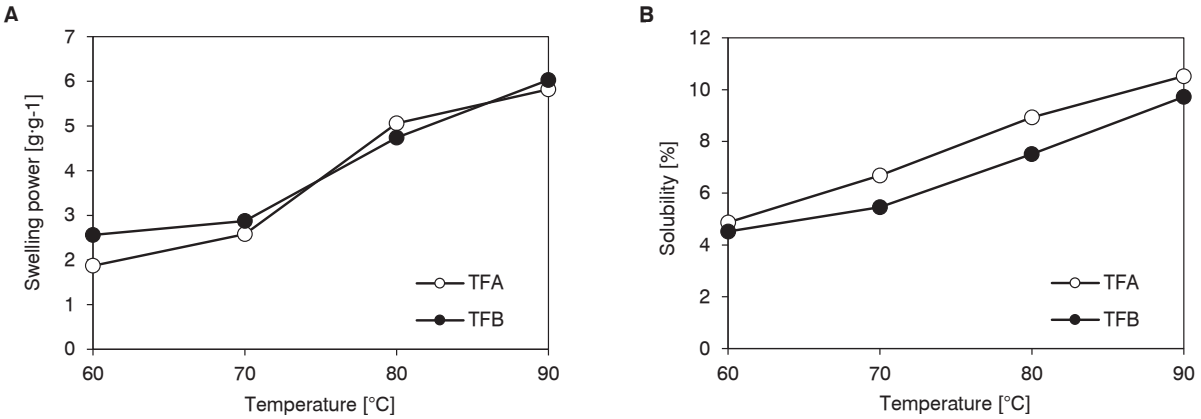

Fig. 1. Swelling power and solubility of teff flour samples.

A – swelling power, B – solubility.

TFA, TFB – teff flour samples.

Tab. 3. Pasting properties and thermal properties of teff flour samples.

Parameter	Teff flour samples	
	TFA	TFB
Pasting properties		
Peak viscosity [cP]	557.33 ± 1.52 b	402.66 ± 1.52 a
Trough viscosity [cP]	525.33 ± 3.51 b	397.33 ± 1.52 a
Final Viscosity [cP]	1 265.33 ± 4.04 b	824.33 ± 2.51 a
Pasting temperature [°C]	91.20 ± 0.10 a	93.70 ± 0.20 b
Pasting time [min]	5.87 ± 0.03 a	6.40 ± 0.01 b
Thermal properties		
Onset temperature [°C]	36.33 ± 0.45 a	36.45 ± 1.52 b
Peak temperature [°C]	86.50 ± 0.36 b	80.60 ± 0.03 a
End temperature [°C]	139.98 ± 0.12 b	132.43 ± 0.51 a
Enthalpy of gelatinization [J·g^{-1}]	300.75 ± 0.84 b	195.11 ± 0.38 a

All values are mean ± standard deviation (n = 3). Values with different superscript within the same row are significantly different ($p \leq 0.05$).

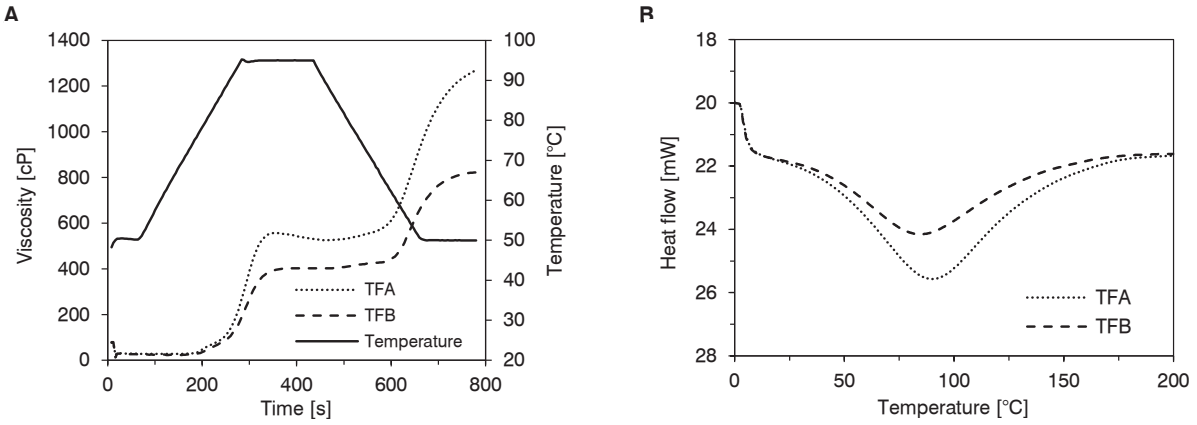

Fig. 2. Viscometric profiles and thermographs of teff flour samples.

A – viscometric profile, B – thermographs.

TFA, TFB – teff flour samples.

form and stabilize emulsion due to the development of electrostatic repulsion with the surface of lipid droplets. Emulsion capacity (*EC*) and emulsion stability (*ES*) results are presented in Tab. 2. The results obtained indicated that TFB had significantly higher ($p \leq 0.05$) *EC* than TFA. Similar trend was observed on comparing *ES* TFB and TFA. Both samples had lower *EC* and *ES* when compared to wheat flour as reported by CHANDRA et al. [17] but higher than that of pearl millet as observed by ALI et al. [27].

Pasting properties

The changes taking place in flour viscosity upon heating are reflected by pasting properties. Rise in temperature causes starch in flour to swell and release amylose along with water from the granules. This results in viscosity increase with temperature. Data on pasting properties of teff flour are presented in Tab. 3 and Fig. 2A. Peak viscosity (*PV*), trough viscosity (*TV*) and final viscosity (*FV*) were established to be significantly higher ($p \leq 0.05$) in case of TFA than in case of TFB. The formation of amylose-protein and amylose-lipid complexes is generally responsible for the increase in viscosity. On the other hand, pasting temperature (*PT*) and pasting time (*Pti*) were significantly higher ($p \leq 0.05$) in case of TFB than in case of TFA. This may be accounted to the higher content of proteins in TFB, which restrict the availability of water for starch by proteins-water interactions and hence limiting the viscosity development [3]. In case of flours, the main component contributing to the development of pasting profiles is the starch present in them even though other components present also contribute to some extent [29]. Altogether, the differences observed were possibly due to the dissimilarity in characteristics

including shape, size and rigidity of particles, amylose, amylopectin and proteins contents, as well as functional properties [15, 30].

Rheological properties

Data on dynamic (storage and loss modulus *vs* angular frequency) and steady (shear stress *vs* shear rate) rheological properties of flour samples are presented in Fig. 3. On increasing the shear rate, an increase in the shear stress was observed for both samples, which is characteristic of the shear thinning behaviour. The steady shear values were lower for TFB than for TFA. The orientation of soluble starches with flow direction and destruction of intermolecular and intramolecular hydrogen bondings of starch with increased shear rate may be accounted for the shear thinning behaviour [31]. Both TFA and TFB exhibited lower values of loss modulus than storage modulus, which depicts the gel to possess weak characteristics or may be similar to solids in structure or show a solid elastic-like behaviour [30]. TFA showed higher storage modulus and loss modulus as compared to TFB. Fig. 3 shows that the difference in the storage modulus values between samples at low frequencies was very small compared to the difference at high frequencies.

Thermal properties

Thermal properties and thermographs are displayed in Tab. 3 and Fig. 2B. The onset temperature denotes the first measurable melting point of the starch granules and was observed to be slightly higher in case of TFB than in case of TFA. The highest energy transfer is indicated by the peak temperature and was found to be significantly higher ($p \leq 0.05$) in TFA as compared to TFB. Differences in starch granule structure and starch granule distribution could lead to variation in the observed gelatinization temperatures. The flour sample TFB has significantly lower ($p \leq 0.05$) enthalpy of gelatinization than TFA. This could be due to effects of non-starch components in the flours, namely proteins and lipids. The presence of proteins and fibre in the flour could decrease the availability of water for starch gelatinization [16].

X-Ray diffraction patterns

Peak intensity is relative to quantity of arranged semi-crystalline structures and/or variations in electron density between crystalline and amorphous lamellae. While the sharp peaks correspond to crystalline region, the diffused peaks correspond to the amorphous region of the flour [28]. The X-ray diffractogram is presented in Fig. 4A. The sample TFA showed peak intensities

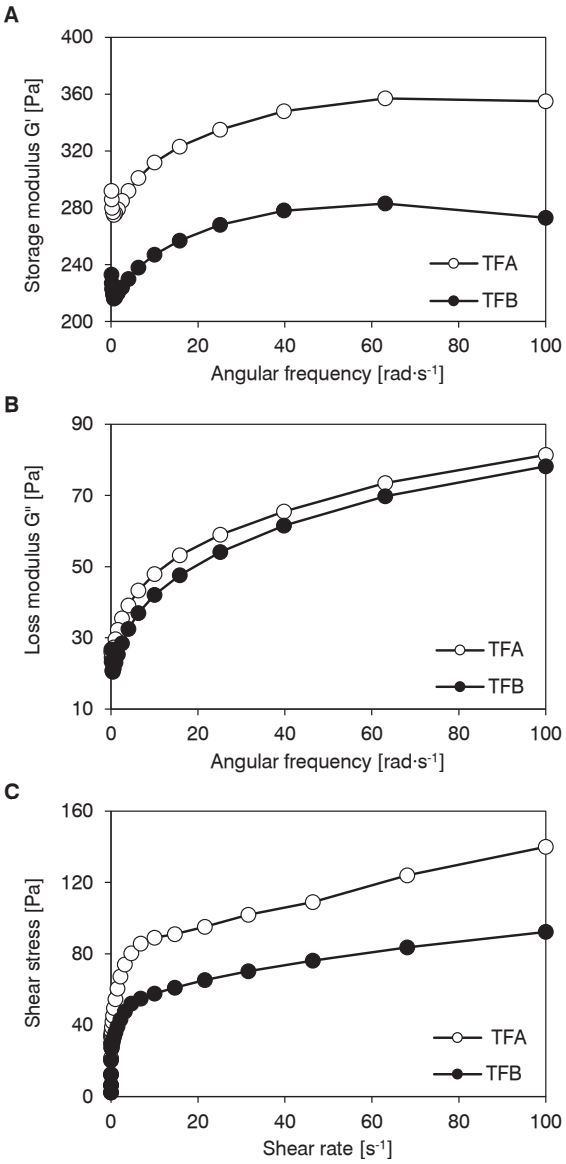

Fig. 3. Storage modulus, loss modulus and shear stress vs shear rate plots of teff flour samples.

A – storage modulus, B – loss modulus, C – shear stress *vs* shear rate plots.
TFA, TFB – teff flour samples.

of 2θ at 15.22°, 17.23°, 18.08°, 23.07° and 26.67°, while similarly TFB showed peaks at 15.22°, 17.41°, 18.10°, 22.99° and 26.87°. This clearly depicted A-type crystallinity for both samples. The typical A-type X-ray pattern for cereal starches is characterized by peaks at 15°, 17°, 18°, 23° and 26° with reflection at 2θ [30]. The percent of crystallinity was significantly higher for TFB than TFA, at 57.0 % and 50.0 %, respectively (data not shown). The crystallinity of samples varies with crystal size and the amount of the crystalline region, which in turn depends on the orientation of amylose as well

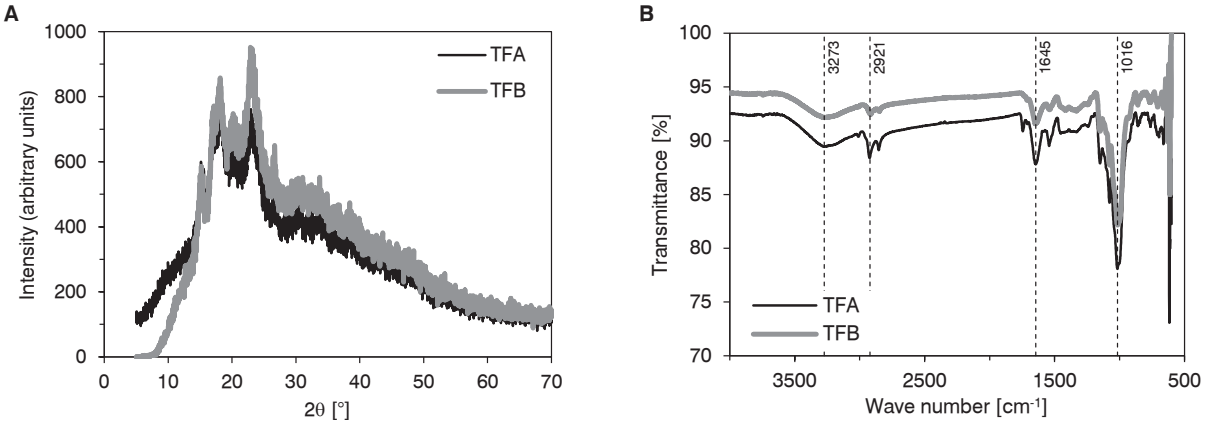

Fig. 4. Diffractograms and FTIR spectra of teff flour samples.

A – diffractograms, B – FTIR spectra.

TFA, TFB – teff flour samples.

as amylopectin and degree of interaction between the two [23]. The lower peak intensities indicate the presence of lower degree of crystallinity. Similar peak intensities of 2θ were observed in case of *C. album* flour by JAN et al. [21], white and brown teff flours by VELA et al. [29], little millet flour by ADEBIYI et al. [28], pearl millet flour by KUMAR et al. [15] and in proso millet flour JADDU et al. [26].

Fourier transform infrared spectra

FTIR spectroscopy is an important quality assessment method conducted to reveal the presence of various chemical functional groups presents in the food material, particularly flour samples in the current study. The FTIR spectra are divided into two parts, specifically, functional group region 4 000–2 000 cm^{-1} and fingerprint region thereafter (2 000–400 cm^{-1}) [32]. FTIR spectra for the flour samples are displayed in Fig. 4B. The peaks in the range of 3 328–3 284 cm^{-1} could be attributed to the O-H bond stretching and were observed at 3 278.50 cm^{-1} and 3 266.82 cm^{-1} for TFA and TFB, respectively. The observed peaks depict better hydrophilic, lipophilic and functional properties in case of TFA than TFB as suggested by ADEBIYI et al. [28]. The asymmetric stretching of the C-H band in the range of 3 000–2 850 cm^{-1} was found at 2 917 cm^{-1} and 2 924 cm^{-1} for sample TFA and TFB, respectively [32]. The vibrations at 1 645.53 cm^{-1} for TFA and at 1 644.84 cm^{-1} for TFB are associated with O-H bending and C=O of amide I band. The intensity at lower wavenumber value was associated with lower crystallinity of the sample TFB, as observed by ADEBIYI et al. [28] in case of pearl millet

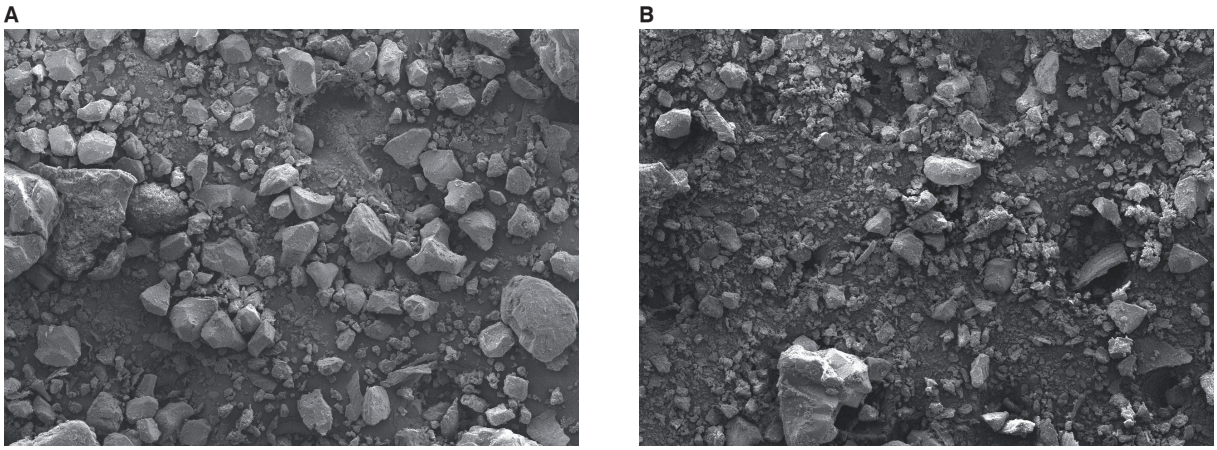

Fig. 5. Micrographs of teff flour samples at 100× magnification.

A – teff flour sample TFA, B – teff flour sample TFB.

flour. The peaks at 1 015.53 cm^{-1} and 1 016.00 cm^{-1} of TFA and TFB, respectively, were assigned to C-O and C-C stretching, as observed for regenerated cellulose film by MOHAMED et al. [33].

Scanning electron microscopy

Images obtained by scanning electron microscopy are presented in Fig. 5. The flour samples present gritty surfaced compact structures of starch granules packed together with non-starch components including proteins, similar as observed by KUMAR et al. [15] and VELA et al. [3]. Similar micrographs showing small, compact and irregular granular structure were obtained in case of pearl millet flour by ADEBIYI et al. [28]. The structural characterization of *C. album* flour by JAN et al. [21] stated a continuous structure with the intact starch granules embedded within a very dense protein matrix.

CONCLUSIONS

The TFA and TFB flours showed significant differences in the proximate composition with higher carbohydrates, crude fibre and ash contents in TFA. Substantial content of proteins was found, ranging from 135 $g \cdot kg^{-1}$ to 155 $g \cdot kg^{-1}$. TFB had lower swelling power and pasting temperature, indicating resistance to swelling and rupturing, while TFA had higher water absorption, lower cooking time (6.40 min) and temperature (93.70 °C). The higher content of starch in TFA could be the reason for higher peak temperature (86.50 °C), end temperature (139.98 °C) and enthalpy (300.75 $J \cdot g^{-1}$). According to the XRD diffractogram, the crystallinity of TFA and TFB were calculated as 57.0 % and 50.0 %, respectively. The microstructure images revealed presence of gritty surfaced compact structures of starch granules. The higher viscosity value suggested that TFA is suitable for food formulations requiring little heating during processing.

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