Influence of hydrothermal processing on functional properties and grain morphology of finger millet

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Abstract Finger millet was hydrothermally processed followed by decortication. Changes in color, diameter, density, sphericity, thermal and textural characteristics and also some of the functional properties of the millet along with the grain morphology of the kernels after hydrothermal processing and decortication were studied. It was observed that, the millet turned dark after hydrothermal processing and color improved over native millet after decortication. A slight decrease in grain diameter was observed but sphericity of the grains increased on decortication. The soft and fragile endosperm turned into a hard texture and grain hardness increased by about 6 fold. Hydrothermal processing increased solubility and swelling power of the millet at ambient temperature. Pasting profile indicated that, peak viscosity decreased significantly on hydrothermal processing and both hydrothermally processed and decorticated millet exhibited zero breakdown viscosity. Enthalpy was negative for hydrothermally processed millet and positive for decorticated grains. Microscopic studies revealed that the orderly structure of endosperm changed to a coherent mass after hydrothermal processing and the different layers of seed coat get fused with the endosperm.

Keywords Finger millet · Hydrothermal processing · Physical properties · Functional properties · Grain morphology

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Introduction

Finger millet, one of the important minor millets, has unique morphological, textural and nutritional characteristics among cereals. It is a small seeded grain and the kernel is not a true caryopsis but a utricule. The pericarp or so called glume in utricles is not fused to seed coat or testa. Thus, the pericarp is easily removed by rubbing or soaking in water and normally it detaches during threshing. The kernels contain soft endosperm covered by a rigid, dark colored edible seed coat. Removal of seed coat from the kernel is not possible by normal methods. Hence, the millet is pulverized to whole meal and only about 5 % of the seed coat is separated from the flour by sieving, and the sieved flour is used to prepare traditional products. However, the efforts on decortication of the millet indicated that, the grains can be hardened by hydrothermal processing which enables them to withstand the impact during milling (Malleshi 2006). Hydrothermal processing involves steeping the millet to its equilibrium moisture content, steaming at atmospheric or elevated pressure followed by drying. During drying, the gelatinized starch undergoes retrogradation imparting hardness to the kernels (Bhattacharya and Ali 1985). It was reported that, finger millet hardens by 5 fold on hydrothermal processing (Shobana and Malleshi 2007).

In rice, it has been observed that, parboiling changes color of the grain, imparts hardness to the kernels, increases water absorption capacity and also changes viscosity profile including enthalpy values (Bhattacharya and Ali 1985). Parboiled rice becomes glassy, translucent and slightly darker in color compared to its native form. It has been reported that, not only steaming but also steeping and drying cause considerable discoloration to the grain (Kimura et al. 1993). Parboiled grain is more resistant to breakage during abrasive as well as friction

milling than the raw grain. The milling yield increases due to reduced breakage because of healing of cracks in the grain on parboiling. A slight increase in the grain dimensions occur and its packing and flow properties also change (Bhattacharya and Ali 1985). Apart from rice, changes in physicochemical and functional properties of the grain due to hydrothermal treatment have been reported for other cereals such as wheat (Suhasini and Malleshi 1994) and small millets other than finger millet (Kimata et al. 1999). However, information on changes in textural and functional properties including details on grain morphology of finger millet due to hydrothermal processing is limited. One such report was by Shobana and Malleshi (2007), which, deals with some of the functional properties of decorticated finger millet. However, it does not cover detailed information on physical, textural and thermal properties and also the morphological changes of hydrothermally processed finger millet. Hence, studies were undertaken to determine the changes in physical and functional properties and also in the grain morphology of finger millet after hydrothermal processing and decortication.

Materials and methods

Material

A popular high yielding variety of finger millet (GPU 28) was procured from University of Agricultural Sciences, Bangalore, Karnataka. The millet was cleaned to remove immature and damaged grains, deglumed in an Engelberg huller (Sri Ganesha Engineering Works, Chennai, India) and used for the studies.

Hydrothermal processing

About 5 kg of the millet was steeped for about 10 h at 30 °C in excess water. The steeped millet was spread in steel trays (80×40×3 cm) in about 2.5 cm bed thickness and steamed in an autoclave (Krauss Maffee Munchen, Germany) at atmospheric pressure (temperature 98±1 °C) for 30 min. The steamed material was dried in a mechanical drier maintained at 38 °C to 14±1 g/100 g moisture content to prepare hydrothermally processed millet (HM) (Dharmaraj and Malleshi 2011). This was used to prepare decorticated millet.

Decortication

The HM was decorticated in a horizontal carborundum disc mill as per Dharmaraj et al. (2013). The decorticated millet (DM) was separated from broken and seed coat and the weight of each fraction was determined to calculate the yield of decorticated grains. Deglumed native millet (NM), HM and DM were size graded using cereal grader fitted with wire

screens of 1,405 and 1,680 µm openings. The grains of size falling in range of 1,405–1,680 µm were used for the studies on physical parameters and also for light and scanning electron microscopy. Each of the samples was pulverized in a laboratory pulverizer and flour of particle size less than 250 µm was used for determination of functional properties.

Physical properties

Color The color of the grains was measured in accordance with CIE L*, a*, b* color space system (Lab Scan XE Hunter Lab Instruments, Virginia, USA) based on the tristimulus value.

Diameter Diameter of the individual kernels at three major axes, namely, a, b and c ('a' longest intercept, 'b' longest intercept normal to 'a' and, 'c' longest intercept normal to both 'a' and 'b') were measured using a dial caliper (Model 537, Mitutoyo, Japan) to 0.02 mm accuracy. An average value measured from 10 individual kernels was recorded.

Surface area and sphericity The 'a', 'b', and 'c' values representing diameters of the kernel at different axes were determined as described earlier and based on that surface area was calculated (assuming that the grains were almost spherical), using the formula;

$$\text{Surface area, } S = \pi D_g^2,$$

where, D_g is the geometric mean diameter calculated by the relationship;

$$D_g = (abc)^{1/3}.$$

Simultaneously, sphericity of the grains was also determined using the same 'a', 'b' and 'c' values as per the equation (Mohsenin 1996);

$$\text{Sphericity} = \frac{(abc)^{1/3}}{a}$$

An average value for sphericity was calculated based on 10 individual kernels.

Thousand kernels weight, volume and density One thousand grains were counted in a Numigral grain counter (Tecator, Hoganas, Sweden) and their weight and volume was measured. Based on the weight and volume of 1,000 kernels, bulk density was calculated. True density was determined by toluene displacement method using 50 g of sample (Varnamkhasti et al. 2008).

Porosity Porosity of the millet was calculated based on bulk and true density of the grains, by the following relationship;

$$\varepsilon = \left(1 - \rho_b / \rho_t\right) 100$$

where, ε is percentage porosity, ρ_b is bulk density in and ρ_t is true density (Mohsenin 1996).

Hardness The grains were equilibrated to 12 % moisture level by exposing to 64 % relative humidity for 24 h in a desiccator. The individual kernels were compressed with 50 kg load cell at a crosshead speed of 100 mm/min using a food texture analyzer (Stable Microsystem, Model TA-HDi, Surrey, UK). The maximum force required to compress the grains to 80 % of their original size was recorded. The average peak force (N) value from 10 individual kernels was taken as a measure of hardness.

Functional properties

Swelling power and solubility index To 1 g of the sample taken in graduated centrifuge tube, 10 ml of distilled water was added and mixed well, left undisturbed at ambient temperature for 30 min. The contents were centrifuged at $1,750 \times g$ for 25 min. The supernatant was transferred into a pre-weighed petriplate and evaporated to dryness on a water bath to calculate the solubility index. The weight and volume of the wet residue in centrifuge tube was noted to determine the swelling power (Stone and Lorenz 1984). The experiment was repeated at 97 °C.

Viscosity Ten gram of the sample was mixed with 90 ml water at 30 °C (10 % slurry, w/v) and allowed to hydrate for 30 min with occasional stirring. The viscosity was measured using a Brookfield viscometer (Model RV, Brookfield Engineering Inc., Stoughton, USA). Subsequently, the slurry was heated to boiling in a water bath, cooled to 30 °C and the cooked paste viscosity was measured (Brandtzaeg et al. 1981).

Pasting characteristics The slurry (12 %) from each of the samples was progressive heated from 30 °C to 95 °C at 5 °C increase per minute, cooked at 95 °C for 5 min, and cooled to 50 °C at same rate. Changes in the viscosity of the samples were recorded in a Brabender Micro Viscoamylograph (Model No. 803201, Brabender, Duisburg, Germany).

Differential scanning calorimetry (DSC) To 5 mg of the meal, taken in aluminium pan, 20 μ L water was added, the pan was sealed, equilibrated for 2 h and introduced into DSC cell (DSC-30, Mettler Toledo, Zurich, Switzerland). Thermograms were recorded by heating the sample from 25 to 120 °C at a rate of

5 °C/min. The onset, endset, peak temperatures and enthalpy were recorded using STAR^c software.

Light microscopy

The millet kernels were processed for fixing biochemical constituents prior to sectioning (Berlyn and Miksche 1976). The grains were soaked in solution of 0.5 % glutaraldehyde in 0.025 M phosphate buffer (pH 7.0) for 48 h and were dehydrated by successively passing through ethanol-xylene series. The dehydrated grains were infiltrated with paraffin wax and were passed through xylene:ethanol series in ascending order. The grains were cut using a sharp blade and the sections were stained for protein and starch contents with erythrosine (1 g in 100 mL of absolute alcohol) and fast green FCF (0.1 g in 100 mL absolute alcohol) respectively, and viewed under a Phase Contrast Microscope (40X magnification, Olympus, Japan). The selected portions depicting the organization of seed coat, cell walls and starch granules were photographed.

Scanning electron microscopy

The kernels from HM and NM equilibrated to 10 % moisture contents were cut transversely and also longitudinally into two halves using a sharp blade. The cut portions were mounted on metallic stubs with the aid of double-sided scotch tape to expose seed coat and also endosperm portion. The samples were gold coated (about 100 Å) in a KSE 2 AM Evaporation Seevac gold sputter (Polaron SEM Sputter Coating System, Hertfordshire, UK) and scanned in a LEO 435VP scanning electron microscope (Leo Electron Microscopy Limited, Cambridge, UK). The selected portions depicting morphological features of seed coat and endosperm were photographed (Tharanathan and Bhat 1988).

Statistical analysis

The entire experiments were performed with three independent trials, and data are presented as means $\pm$ standard deviation (SD). Data were assessed using single factor ANOVA and means were considered to be statistically significant at $p < 0.05$ using least significant difference.

Results and discussion

Physical properties

The yield of decorticated head grains, broken and seed coat were 65 ± 2.4 , 23.5 ± 1.8 and 11.5 ± 1.2 g/100 g respectively. The L^* , a^* , b^* and ΔE values for color are presented in

Table 1. Drastic differences were observed between the grains and flour of native millet. Compared to grains, flour from NM was lighter in color with higher L^* and lower ΔE values. Redness of the flour was lower than that of grains but yellowness was higher. Hydrothermal processing darkened both grains and flour, which was evident from the decrease in lightness values of grains by 42 % and that of flour by 14 %. In concurrence with this, ΔE values increased by 13 and 35 % for grains and flour samples respectively. A significant decrease in redness by 77 % and yellowness by 89 % was observed for grains. However, a marginal increase in both a^* and b^* values were recorded for the flour.

Decortication of the millet changed color of the grains significantly. The lightness of decorticated grains improved by 2.2 fold over NM grains and by 4 fold compared to HM grains. The flour from DM was also brighter than that from NM and HM which may be due to the removal of seed coat. This was also confirmed by the decrease in ΔE values by 42 % in case of grains and 30 % in case of DM flour compared to that from NM. The redness and yellowness values were decreased by 58 and 76 % in DM grains compared to NM grains. However, compared to HM, DM grains showed an increase in redness by 85 % while its meal exhibited a considerable decrease in redness (61 %). The grains from HM were dark in color and hence redness value was less compared to that from DM. However, the flour from HM is an admixture of seed coat with the endosperm and hence, will be reddish compared to DM flour. The seed coat in HM became dark towards black and hence did not indicate higher redness values unlike the other two samples. The yellowness values indicated by b^* was highest in DM followed by NM and being lowest for HM indicating the total darkness in case of HM. These results indicated that, DM was of light cream in color with a mild yellowish-red look. Even though, hydrothermal processing darkened the millet, decortication brightened it than the NM hence may increase its consumer appeal. The millet significantly undergoes a change in color due to hydrothermal processing turning the grain from brick red to black. This may be mainly due to the nonenzymatic browning reactions of Maillard type (Lamberts et al. 2006), oxidation of polyphenols may be the another reason. Since, decortication involves complete removal of seed coat, DM finally looks more brighter and whiter than NM.

Grain diameter of the millet decreased slightly after hydrothermal processing and decortication (Table 2). Similarly, surface area of the kernels decreased by 3 % after hydrothermal processing and by 16 % after decortication. Hydrothermal processing caused shrinkage of the kernels and decortication further reduced the diameter and surface area of the grain. Sphericity of the millet decreased after hydrothermal processing and significantly improved after decortication. This observation was reflected in bulk density values, which also decreased initially and increased upon decortication. The 1,000 kernel weight of the grains was decreased while, true density and porosity of the millet increased after hydrothermal processing and decortication. During drying the steamed millet, furrows or undulations develop on the surface of the grain, which may be the reason for the decreased sphericity values for HM. This decreased sphericity may result in higher compactness during packing the millet resulting in comparatively lower inter-granular space and therefore decreased bulk density for HM compared to NM. The higher sphericity of the grains after decortication increases the inter-granular space between the grains and therefore bulk density and porosity of the grains increased.

Hardness of the millet increased significantly (6.35 folds) from 37.8 to 234.9 N on hydrothermal treatment and decreased to 161.3 N on decortication (Fig. 1). Significant increase in first peak force from 14 to 40.3 N was observed on hydrothermal treatment which decreased to 34.4 N on decortication (Table 2). The slope of first peak was also high for DM and HM, which indicated that hydrothermal treatment had modified the endosperm texture by removing internal voids and air gaps of the kernel (Raghavendra Rao and Juliano 1970). The force deformation curve for the millet showed two different zones, a sharp initial peak followed by a decrease in force value and again a steep increase. Initial peak force indicated resistance offered by the grain. The second peak indicated the maximum force required by the sample against the applied force, which was generally indicated as grain hardness. Compared to NM, force deformation curve of HM and DM differed totally, the initial peak was not very significant compared to second peak and they look slightly smooth compared to NM, indicating the hard and homogenous endosperm. During steaming, void spaces in

Table 1 L^* , a^* , b^* and ΔE values for color of native, hydrothermally processed and decorticated millet

Sample name		L	a	b	ΔE
Native	Grains	23.8±0.14 ^e	9.1±0.13 ^a	7.3±0.13 ^d	68.1±0.07 ^b
	Whole meal	67.11±0.13 ^b	3.1±0.07 ^c	8.5±0.15 ^c	25.2±0.17 ^c
Hydrothermally treated	Grain	13.7±0.06 ^f	2.1±0.09 ^d	0.8±0.06 ^e	77.0±0.12 ^a
	Whole meal	57.9±0.11 ^c	3.1±0.07 ^c	8.7±0.16 ^c	34.0±0.09 ^d
Decorticated	Grains	53.3±0.16 ^d	3.8±0.03 ^b	12.9±0.11 ^a	39.6±0.17 ^c
	Whole meal	76.3±0.14 ^a	1.2±0.04 ^e	10.8±0.17 ^b	17.8±0.13 ^f

The values are presented as mean ± SD, $n=3$, the mean values with different superscripts in a column differ significantly ($p<0.05$)

Table 2 Physical and functional properties of native, hydrothermally processed and decorticated finger millet

Parameter	Native	Hydrothermally treated	Decorticated
Grain diameter (mm)	1.5±0.42 ^a	1.5±0.31 ^a	1.4±0.31 ^a
Grain surface area (mm ²)	9.2±0.43 ^b	8.9±0.40 ^b	7.5±0.42 ^a
Sphericity	0.93±0.052 ^b	0.89±0.054 ^a	0.97±0.051 ^c
1,000 kernel weight (g)	3.5±0.43 ^b	3.0±0.32 ^a	2.7±0.31 ^a
1,000 kernel volume (g/ml)	4.2±0.23 ^b	4.1±0.21 ^b	3.8±0.20 ^a
Bulk density (g/ml)	0.83±0.051 ^c	0.77±0.053 ^a	0.80±0.051 ^b
True density	1.3±0.20 ^a	1.4±0.21 ^a	1.5±0.22 ^b
Porosity	36±0.5 ^a	43±0.5 ^b	46±0.5 ^b
Textural parameters			
Hardness (N)	38±8.6 ^a	235±8.1 ^c	161±5.0 ^b
First peak force, N	14±4.1 ^a	40±7.1 ^c	34±7.6 ^b
Slope of first peak, N/s	165±10.01 ^a	277±12.5 ^b	265±10.2 ^b
Solubility (g%)			
30 °C	1.0±0.31 ^a	1.6±0.30 ^b	2.9±0.32 ^c
95 °C	1.5±0.40 ^a	3.3±0.21 ^b	3.5±0.12 ^b
Swelling (g%)			
30 °C	85±1.0 ^a	299±2.1 ^b	306±2.3 ^b
95 °C	505±2.2 ^b	494±2.0 ^a	496±2.1 ^a
Viscosity 10 % slurry (cPs)			
Cold paste	—	11±1.0 ^a	22±1.1 ^b
Cooked paste	1717±5.2 ^c	350±3.2 ^a	463±2.0 ^b
Pasting profile			
Peak viscosity (BU)	453±4.2 ^c	84±3.5 ^a	152±2.8 ^b
Hot paste viscosity (BU)	390±4.2 ^c	84±3.5 ^a	152±2.8 ^b
Cold paste viscosity (BU)	576±4.2 ^c	116±4.2 ^a	171±2.8 ^b
Breakdown (BU)	63±2.8	0	0
Setback (BU)	173±2.8 ^c	29±2.8 ^b	15±2.8 ^a
Total set back (BU)	186±4.2 ^c	32±2.8 ^b	19±2.8 ^a
Gelatinization temperature (°C)	72.7±0.28 ^b	81.0±0.42 ^c	68.0±0.14 ^a

The values are presented as mean ± SD, *n*=3, Mean values with different superscripts for a particular row vary significantly (*p*<0.05)

the endosperm get filled by swollen starch granules, protein bodies in the endosperm disintegrate and bind to starch. The cell wall components get compacted and these factors cause hardening of the grain (Bakshi and Singh 1980). Hardness and texture of HM was one of the important parameter, which plays a major role during decortication of the millet (Dharmaraj et al. 2013).

Functional properties

Solubility of the millet increased on hydrothermal processing and decortication. At 30 °C, solubility of DM was highest followed by that of HM and NM. Similar observations were made at 95 °C and there was not much difference between solubility values of DM at these two temperatures. The pregelatinized nature of starch in case of DM may be the reason for this. HM exhibits slightly lower values for solubility than that of DM at lower temperature, which may be

because of presence of seed coat. At 95 °C temperature, there was not much difference between the solubility values of HM and DM. When compared to NM, DM and HM exhibited almost 4 fold higher swelling power at 30 °C, and it remained almost same at 95 °C. However, swelling power of DM and HM at 95 °C were 1.6 times higher than that at 30 °C, while NM exhibited 5.9 fold higher swelling power at 95 °C when compared to that at 30 °C. The native millet contains unprocessed starch, which swells less at lower temperature but swells significantly high at elevated temperature. Whereas, DM and HM contain the gelatinized starch, which swells readily at low temperature and almost remains the same at higher temperature. These observations are in concurrence with that of rice as reported by Unnikrishnan and Bhattacharya (1981).

The cold paste viscosity of DM was 22 cPs and that of HM was negligible (11 cPs), while NM did not show any cold paste viscosity. However, cooked paste viscosity of NM was much higher than that of HM and DM. The pregelatinized

Fig. 1 Force deformation curves of (a) native, (b) hydrothermally processed and (c) decorticated finger millet

nature of starch after hydrothermal treatment may be the reason for this decreased cooked paste viscosity. Pasting profiles of the samples are presented in Fig. 2. Pasting profile of NM was typical like any other cereal starches. The break down in viscosity was 63 BU, set back viscosity was 173

BU and the total set back is 186 BU (Table 2). The paste from HM, however, did not show a significant increase in viscosity until 81 °C when a gradual rise occurred and continued as temperature increased to 95 °C. The peak viscosity reached was 84 BU, which was significantly less than that of NM. The break down viscosity was 0 and the set back and total set back viscosities were 29 and 32 BU respectively. The pasting behavior of DM was also very similar to that of HM, but viscosity started increasing at slightly earlier temperature of 68 °C compared to HM and the peak viscosity attained was 152 BU, which is almost 1.8 times higher than that of HM. The set back and total set back viscosities were significantly less than that of HM. This indicates that the consistency of DM is lower than that of HM. However, the cold paste viscosity of DM was higher than that of the HM.

It was reported for rice that, peak viscosity and the break-down viscosity decrease with the increase in severity of heat treatment (Bhattacharya and Sowbhagya 1979). Due to hydrothermal processing, a significant decrease in peak viscosity was observed and both DM and HM exhibited zero break-down viscosity. It was assumed that break down viscosity indicates the ease with which swollen starch granule disintegrated or in other words the degree of its organization (Bhattacharya and Sowbhagya 1979). Both DM and HM contain pregelatinized starch, which almost look like a homogenous mass with least degree of organization. Peak viscosity is an important characteristic of any starch or flour. The reduced peak viscosity after hydrothermal processing may be due to limited starch swelling and structural disintegration. These observations are in line with the earlier report on hydrothermal treatment to finger millet starch by Adebawale et al. (2005). It was reported by Bhattacharya and Sowbhagya (1979), that the reduction in peak viscosity and cold paste viscosity following modification was a direct result of reorganization within the granule of the modified starches. Hydrothermally modified starches were characterized by an increase in paste stability and gelatinization temperature, regardless of origin. However, DM did not show an increase in gelatinization temperature, in fact it was slightly less (68 °C) than that of NM (72.7 °C), but HM exhibited an increased gelatinisation temperature (81 °C) than NM which may be mainly because of the presence of hydrothermally modified starch along with its seed coat components.

Differential scanning calorigrams

The thermal properties of NM, HM and DM determined by DSC were completely different as NM and DM exhibited endothermic peaks whereas HM showed exothermic peak. The enthalpy for NM and DM were positive (867 and 359 J/g respectively) but it was negative for HM (−3.64 J/g) (Table 3). The ΔH value of DM was comparatively lower than that of the NM. This indicates the presence of partly

Fig. 2 Pasting profiles (a) native, (b) hydrothermally processed and (c) decorticated finger millet

gelatinized starch in DM. Even though, HM also contains partly gelatinized starch, the ΔH value was negative. The positive and negative enthalpy values for NM and HM are unique to the millet as several reports on thermal properties of hydrothermally treated cereals indicate only slight lowering of enthalpy on heating (Ong and Blanshard 1995). It was expected that, seed coat present in HM may contribute an important role in its thermal properties. Hence, to find out the influence of seed coat on enthalpy of the millet, seed coat fractions separated from NM and HM were scanned in DSC. It was observed that, seed coat from both the samples exhibited negative enthalpies (-3.9 J/g). Interestingly, all other thermal properties for seed coat fractions were almost similar to that of HM. Hence, it may be inferred that, since, the energy required to gelatinize the starch in native millet being substantially high, it probably masked the negative enthalpy of seed coat. In the case of HM, since the starch is partially gelatinized, the prominence of negative enthalpy of seed coat causes overall

negative enthalpy to the sample. The drastic difference between the thermal properties of HM and DM is because of the absence of seed coat in the latter.

Light microscopy

Photomicrographs of transverse sections of native millet show the structural features of seed coat and endosperm of NM (Fig. 3a–d). Figure 3a, depicts the millet section stained with fast green FCF wherein multilayered seed coat is clearly seen. Although, seed coat is not stained, its structural features, namely, undulations at outer layer and intactness of the aleurone cells could be observed. Intensely stained aleurone layer revealed that, it is of single layer and well organized (Fig. 3b). Figure 3c and d, depicts the endosperm cells with clearly visible cell wall and well packed hexagonal shaped starch granules. The endosperm cells at peripheral region are lenticular in shape and distinctively different from the polygonal

Table 3 Changes in enthalpies of native, hydrothermally processed and decorticated finger millet as determined by differential scanning calorimetry

Sample ID	Peak type	ΔH (J/g)	Onset temp ($^{\circ}\text{C}$)	Peak temp ($^{\circ}\text{C}$)	Endset temp ($^{\circ}\text{C}$)
Native (NM)	Endo	867.2 ± 2.71^c	50.0 ± 0.04^b	64.2 ± 0.28^b	74.2 ± 0.08^d
Hydrothermally processed (HM)	Exo	-3.6 ± 0.13^a	64.8 ± 0.06^c	67.5 ± 0.07^c	71.4 ± 0.04^b
Decorticated (DM)	Endo	358.3 ± 1.42^b	49.6 ± 0.42^c	57.2 ± 0.14^a	68.7 ± 0.08^a
Seed coat from HM	Exo	-3.9 ± 0.13^a	64.8 ± 0.14^c	67.9 ± 0.27^c	72.3 ± 0.14^c
Seed coat from NM	Exo	-3.9 ± 0.07^a	64.9 ± 0.14^c	67.6 ± 0.14^c	72.1 ± 0.06^c

The values are presented as mean $\pm$ SD, $n=3$, Mean values with different superscripts for a particular column vary significantly ($p < 0.05$)

NM native millet, HM hydrothermally processed millet

Fig. 3 Light microscopic photographs of transverse sections (magnification 40X) **a**) multilayered seed coat; **b**) aleurone layer; **c**) polygonal cells and **d**) lenticular cells of native millet, **e**) disappearance of multilayer in seed coat; **f**) fused seed coat; **g**) mashed polygonal cells; **h**) mashed lenticular cells and **i**) ungelatinized cells near the germ portion of hydrothermally processed finger millet. AL: Aleurone layer, SC: Seed coat, E: Endosperm, SG: Starch granules, CW: Cell wall, G: Germ

shaped cells at the central part of the kernels. Hydrothermal treatment to the millet caused modification of the endosperm along with the seed coat and aleurone layer. Multilayered cellular organization of seed coat changed to an undifferentiated mass (Fig. 3e) and completely fused with the peripheral portion of the endosperm and the aleurone layer gets embedded with the endosperm (Fig. 3f). In the case of endosperm

Fig. 4 Surface topography of native and hydrothermally processed finger millet as observed through scanning electron microscopy **a**) whole grain (40X); **b**) surface undulations in the proximal end (500X); **c**) surface undulations of distal end (500X) and **d**) magnified picture (2 KX) showing the minute pores of the undulations in native millet; **e**) whole grain (40X); **f**) flattened undulations of proximal end (500X); **g**) flattened undulations of distal end (500X) and **h**) prominent undulations near the germ (500X) of hydrothermally processed millet

a **e** **b** **f** **c** **g** **d** **h**

portion, the granular structure of starch changed into a coherent mass, while, the cell walls were still distinctly visible (Fig. 3g and h). However, in the vicinity of the embryo, a few ungelatinized starch granules were still visible (Fig. 3i). It was reported for rice that parboiling changes the orderly polyhedral structure of starch granules into a coherent mass (Raghavendra Rao and Juliano 1970).

Scanning electron microscopy

The changes in surface topography of NM after hydrothermal treatment are depicted in Fig. 4(a–h). The globular shape of kernel changes with an overall shrinkage in size and an increase in visible surface undulations was observed (Fig. 4a & e). A visible crack near the hilum portion was also observed. The surface of NM is not of smooth nature but is made up of several mounds. However, the mounds are prominent in the proximal end (Fig. 4b) with an average diameter of $28.5 \pm 1 \mu\text{m}$. Near the distal end mounds are slightly wider (32 to $38 \mu\text{m}$) and appear stretched (Fig. 4c). Presence of many micro-pores on each of the surface mounds could be seen in a magnified portion (Fig. 4d). Throughout the surface of the grain, presence of minute specks is also observed, which may be the cellulosic protrusions. Due to hydrothermal processing, flattening of these surface mounds was observed (Fig. 4h). However, the

degree of flattening was proportionate (Fig. 4g). The mounds in near to the germ were prominent and largely retained their original shape even after the treatment (Fig. 4h). The reasons for morphological changes during hydrothermal processing may be mainly due to expansion and contraction of the grain during steaming and drying.

Topography of the millet towards its embryo region differs considerably (Fig. 5a). The germ is located in a depression surrounded by a characteristic ridge and a distinct furrow appears towards one side of the germ. Hilum is located adjacent to the germ in a separate but in a somewhat shallow depression. Magnified image of the germ exhibits an intense network structure (Fig. 5b). The endosperm of the millet exhibited two distinct cellular arrangements, one towards the central core and the other towards periphery and most of the starch granules were enclosed by cellular matrix as observed earlier (Dharmaraj et al. 2011). A section of seed coat shown in Fig. 5c reveals that, it is multilayered and is rigidly attached to the endosperm. Hydrothermal processing to the millet imparts considerable changes in the structure of the grain. It was reported that, the endosperm region of HM showed a void space near center, which probably would have occurred during drying the millet (Dharmaraj et al. 2011). In finger millet, hydrothermal processing changed the orderly crystalline arrangement of starch granules and other constituent tissues of

Fig. 5 Scanning electron photographs of native and hydrothermally processed finger millet **a**) surface of germ (100X); **b**) network like structure of germ (500X); **c**) multilayered seed coat (1.5 KX) in native millet, **d**) fused seed coat (1 KX) of hydrothermally processed millet. SC: Seed coat, E: Endosperm

the kernel change into a homogeneous amorphous mass as observed in other cereals (Raghavendra Rao and Juliano 1970). The multilayered seed coat observed in NM undergoes complete transformation by forming undistinguishable mass and seem to fuse with the endosperm (Fig. 5d) and hence the aluerone layer is not distinct. This may occur due to removal of the void spaces present between seed coat and endosperm.

The study indicates that, decortication of finger millet improves its functional properties and thereby the decorticated millet can be easily diversified for different food uses. The drawbacks associated with the seed coat of the finger millet can be largely removed by decortication and the decorticated millet may be conveniently used by a non-traditional consumer also.

Conclusions

The studies reveal that, hydrothermal processing and decortication of finger millet brings in significant changes in the grain. The color of the millet even though darkens after hydrothermal treatment, improves on decortication. Hence, decorticated millet exhibits better consumer appeal compared to native millet. Hardness of the millet increases significantly enabling to prepare decorticated millet. The decorticated millet swells easily and contains lower peak viscosity on cooking and hence may be widely used in different food preparations. Microscopic examinations indicate that on hydrothermal treatment, the endosperm changes into a coherent mass.

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