TECHNOLOGICAL AND PHYSICO-CHEMICAL CHARACTERISTICS OF HYDROTHERMALLY TREATED FINGER MILLET

A Thesis

Submitted to the

University of Mysore, Mysore

For the award of the degree of

DOCTOR OF PHILOSOPHY

In

FOOD SCIENCE

By

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Dedicated to.....

My husband, who is my support and strength, and my daughter, who is my spirit for the work, my teachers and parents

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DECLARATION

I hereby declare that the thesis entitled **"TECHNOLOGICAL AND PHYSICO-CHEMICAL CHARACTERISTICS OF HYDROTHERMALLY TREATED FINGER MILLET"** submitted to the **University of Mysore, Mysore,** for the award of the degree of **DOCTOR OF PHILOSOPHY in FOOD SCIENCE,** is the result of research work carried out by me at the Department of Grain Science and Technology, under the guidance of **Dr. N. G. MALLESHI,** Scientist and former Head of the Department of Grain Science and Technology, Central Food Technological Research Institute, Mysore - 570020, India, during the period 2003-2009.

I further declare that the results presented in this thesis have not been submitted for the award of any other Degree or Diploma or other similar titles.

(USHAKUMARI S.R.)

Place: Mysore
Date:

Certificate

I, **Ushakumari S.R.,** certify that this thesis is the result of research work done by me under the supervision of **Dr. N.G. Malleshi** at the **Department of Grain Science and Technology, CFTRI**. I am submitting this thesis for possible award of Doctor of Philosophy (Ph. D.) degree in **FOOD SCIENCE** of the University of Mysore.

I further certify that this thesis has not been submitted by me for award of any other degree/diploma of this or any other University.

Signature of Doctoral candidate

Signed by me on

Signature of Guide *Date:*

Date: *Counter signed by*

Signature of Head of the Department

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Ushakumari S.R.

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ABBREVIATIONS

MT	metric tons
mg	milligram
g	gram
kg	kilogram
ha	hectare
MH	million hectares
A^o	angstrom
nm	nanometer
µm	micrometer
mm	millimeter
cm	centimeter
m	meter
ml	milliliter
mm^2	millimeter square
cm^2	centimeter square
sec	seconds
min	minutes
h	hour
%	percent
^oC	degree centigrade
w/v	weight/volume
v/v	volume/volume
ε	porosity
ρ_b	bulk density
ρ_t	true density
cP	centipoise
BU	Brabender units
J/g	Joules/gram
ΔH	change in enthalpy
D_g	geometric mean
N	Newton

FAO	Food and Agricultural Organization
IR	infrared radiation
EC	Enzyme Commission
EMC	equilibrium moisture content
NM	native millet
HTM	hydrothermally treated millet
DHM	dry heat treated millet
DM	decorticated millet
EM	expanded millet
HTST	high temperature and short time
DGS	diethylene glycol succinate
EDTA	ethylenediaminetetraacetic acid
GPC	gel permeation chromatography
DSC	differential scanning calorigram
SEM	scanning electron microscope
L*	lightness
a*	redness
b*	yellowness
ΔE	deviation from the standard
TA	total amylose
SA	soluble amylose
NSP	non starch polysaccharides
Pent/Hex	pentose/hexose
Ara/Xyl	arabinose/xylose
d	lattice spacing
D	crystallite size
<N>	number of unit cells
CCRD	central composite rotatable design
ANOVA	analysis of variance
RH	relative humidity
LDPE	low density polyethylene
FFA	free fatty acids

PUBLICATIONS AND PATENTS EMANATED FROM THE THESIS WORK

Research Papers

1. Ushakumari SR, Rastogi NK and Malleshi NG (2007)
   Optimization of process variables for the preparation of expanded finger millet using response surface methodology.
   Journal of Food Engineering, 82, 35-42.

2. Ushakumari SR, Ravi R and Malleshi NG (2009)
   Functional properties of expanded finger millet.
   International Journal of Food Properties (communicated)

Patents

Malleshi NG and Ushakumari SR
A process for preparation of expanded finger millet
Country; Africa OAPI, No. 13351 dated 29/12/2006 (Granted)
Country: US, No. 2007 0160727 dated 7/12/2007 (Granted)
Country; GB, Application No. 360NF2003/GB (filed)

Posters presented

1. Ushakumari SR, Ravi R and Malleshi NG (2003)
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2. Ushakumari SR, Shobana S and Malleshi NG (2004)
   Functional properties of decorticated finger millet (ragi rice).
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3. Ushakumari SR, Shobana S and Malleshi NG (2004)
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   First National Convention on “Science & Tradition of Food - India’s Heritage of 5000 Years”, July 25- 27, Melukote.

4. Ushakumari SR, Ravi R and Malleshi NG (2006)
   Optimization of process variables for decortication of finger millet through response surface methodology.
   Indian Convention of Food Scientists & Technologists, November 16 - 17, Hyderabad.

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ATTENDANCE CERTIFICATE

This is to certify that **Mrs. Ushakumari S.R.,** Scientist, CFTRI, worked for her Ph. D. thesis entitled "**TECHNOLOGICAL AND PHYSICO-CHEMICAL CHARACTERISTICS OF HYDROTHERMALLY TREATED FINGER MILLET**", during the period January 2003 to November 2009, under my guidance, in the Department of Grain Science and Technology, CFTRI, Mysore.

Place: Mysore
Date:

(N. G. MALLESHI)
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Finger millet (*Eleusine coracana*) or ragi is one of the important minor cereals in Indian subcontinent and also in several of the African countries. The millet kernels are small sized naked caryopsis and comprise of seed coat, germ and endosperm, which form about 13 - 15, 1.5 - 2.5 and 80 - 85% of the grain respectively. The millet contains 6 - 8% protein, 1 - 1.7% fat, 65 - 75% starch, 18 - 20% dietary fiber and 2 - 2.5% minerals. The millet kernels contain soft and fragile endosperm covered by rigidly attached seed coat and get pulverized along with the seed coat whenever efforts were made for its decortication similar to other cereals and millets. In view of this, the millet has never been decorticated and it is invariably pulverized along with the seed coat and the whole meal is used for food preparation. The seed coat is normally of brick red to dark colored and contains polyphenols and pigments, which polymerize and turns dark and unattractive on cooking. Besides, the seed coat imparts characteristic odour and fibrous texture to its foods which affect their sensory qualities. Now a days, a lot of interest is shown by the non-traditional millet consumers in the millet foods due to its health benefits. Hence, need was felt to undertake R&D work to decorticate the millet, which could be cooked in the form of grains similar to rice, so that it would be readily acceptable by the non-traditional millet consumers also.

Among the several methods of cereal processing, hydrothermal treatment or parboiling enhances the grain hardness and improves the milling characteristics. This is true with finger millet also. Recently conducted exploratory research work on the hydrothermal processing of finger millet at CFTRI, Mysore, has shown the promise of adapting this methodology for the millet for its decortication effectively.

Hydrothermal treatment or parboiling of cereals basically involves steeping to hydrate the grains near to their equilibrium moisture content, steaming to gelatinize the starch and dehydrating the same to safe storage moisture level. During parboiling, the grains undergo physicochemical changes leading to improvement in its processing (specifically milling) and nutritional qualities. Normally, in the case of rice, parboiling loosens its husk or seed coat and enables its decortication effectively. Contrary to this, in the case of finger millet, the intactness of the seed coat matter with the

endosperm increases on hydrothermal treatment, rendering the decortication more difficult. The scientific information on the hydrothermal processing of finger millet as well as its decortication and also the effect of these on the nutritional and functional properties including the cooking characteristics are practically nil. Hence, the R&D work was undertaken on “Technological and Physicochemical Characteristics of Hydrothermally Treated Finger Millet” with the following objectives;

1. To study the effect of steeping, steaming and drying conditions (hydrothermal treatment) on the textural and the physicochemical characteristics and also the nutritional qualities of finger millet,

2. To investigate the factors influencing the decortication characteristics of the hydrothermally treated millet and evaluation of the functional properties, nutritional as well as the cooking qualities and the shelf-life of the decorticated millet, and

3. To process the decorticated millet for preparation of value added product, such as expanded millet and evaluation of its quality attributes.

The outcome of the work is presented in the form of a Ph. D. thesis. The thesis comprises of four Chapters; the first Chapter consists of literature review on the nutritional, physicochemical and technological qualities and the food uses of cereals and millets in general and finger millet in particular. The experimental aspect and the results obtained on steeping, steaming and drying the millet and assessment of its quality characteristics are presented in Chapter II, whereas, the factors influencing the decortication of the hydrothermally treated millet and its physicochemical characteristics, cooking qualities and also the information on shelf-life are reported in Chapter III. The details of the processing of decorticated millet for preparation of expanded millet and its functional properties are discussed in Chapter IV. Finally, the references cited in all the Chapters are compiled as a Bibliography section.

The salient features of the experimental work and the results enumerated in the thesis are as follows;

CHAPTER I

INTRODUCTION

The scientific and technological information on the cereals and millets in general and finger millet in particular published in peer reviewed scientific journals, proceedings of the conferences, book chapters and popular articles with respect to production, grain morphology, nutritional composition, processing and food uses are reviewed. Besides, the relevant information on parboiling of rice and other cereals are also suitably discussed. The scope of the work is briefly indicated in this Chapter.

CHAPTER II

PREPARATION AND QUALITY CHARACTERISTICS OF HYDROTHERMALLY TREATED FINGER MILLET

A popularly cultivated finger millet variety (GPU 28) obtained from the University of Agricultural Sciences, Bangalore, India, was used for the studies. The millet was of brick red colored and contained 7.0±0.04% protein, 1.5±0.01% fat, 61.0±0.7% available carbohydrates, 17.1±0.2% dietary fiber and 321±2 mg/100g calcium. The optimum conditions of steeping, steaming and drying to prepare the hydrothermally treated millet (HTM) were standardized, the details of which are as follows;

The kinetics of hydration of the millet was determined by steeping the millet in water maintained at temperature varying from 30 to 70^{o}C with 10^{o}C increment and the time required to attain the equilibrium moisture content (EMC) of the millet, at each of the temperatures was determined. It was observed that, the rate of hydration was positively influenced by the temperature of the steep water and the millet attained its EMC of 35±1%, on steeping for about 10 h at 30^{o}C and only about 1.75 h at 70^{o}C. During steeping, about 0.1% of the solids of the millet leached in to the steep water and the leachets mainly contained low molecular weight sugars, proteins, minerals and polyphenols.

The steeped millet was steamed at atmospheric as well as at elevated pressure up to 35 min and it was observed that steaming the millet for a minimum of 30 min at atmospheric pressure and for 20 min at 1, 17 min at 2, 10 min at 3 and 6 min at 4 kg/cm^2 pressure, respectively, were optimum for complete gelatinization of the starch and transforming the endosperm to homogeneous mass. Steaming for longer than the specified duration caused disintegration of the kernels and oozing of the endosperm matter leading to stickiness and imparting dextrinised aroma to the grains.

The steamed millet was dried at different temperature in a mechanical dryer maintained at 30 - 70^{o}C with about 10^{o}C increment to 14$\pm$1% moisture content and the influence of drying temperature on the quality characteristics, with special reference to the hardness of the hydrothermally treated millet was assessed. Drying the millet at 39$\pm$1^{o}C was identified as optimum drying temperature, as drying at lower than this temperature resulted in development of off flavor and at higher temperatures caused visible fissures and enhanced the friability.

Drying caused considerable changes in the morphological features of the millet, namely, enhanced the hardness of the millet from 37 to 235 N (5 fold), darkened the grains extensively and caused visible surface undulations as well as slight shrinkage in the overall size of the grain. The light as well as the SEM examination of the sections of the HTM showed fusing of the multi-layered seed coat and the aluerone layer into a single entity, cementing the same with the endosperm and flattening of the surface mounds, besides, the loss of the granular structure of the endosperm and the prominent cell walls were distinctly visible. The x-ray diffraction pattern of the hydrothermally treated millet revealed the shift from the semi-crystalline phase of the starch to amorphous form. The thermal properties as recorded by the differential scanning calorimeter indicated the gelatinization of the starch. It also showed negative energy for its enthalpy, which may be due to the seed coat of the HTM.

The gross composition of the millet did not change appreciably but the carbohydrate and protein profiles changed considerably as a result of

hydrothermal treatment. The major changes observed were (1) thermal degradation of starch leading to slight lowering of the amylopectin equivalent portion and increasing the amylose equivalent portion as revealed by the gel permeation chromatography (2) decrease in the extractability of the proteins by about 50% but increasing the prolamin like fraction and lowering the glutelin like fractions of the extracted proteins, and (3) a slight decrease in linoleic acid (3%) and increase in the palmitic acid contents (4%). Hydrothermal treatment resulted in considerable qualitative and quantitative changes in the non-starch polysaccharide (NSP) contents of the millet and prominent among them were; decrease in the cold as well as hot water solubles and also hemicellulose B fractions and, significant increase in the pectic polysaccharides and hemicellulose A fractions. The hydrothermal treatment increased the solubility index and swelling power at ambient temperature and also the cold as well as cooked paste viscosity. Very low peak viscosity (114 BU) and also zero breakdown viscosity were unique to the HTM. The dry heat parboiling of the millet as an alternate to steam treatment was also explored and it was observed that the endosperm modifications during dry heat parboiling resulted in softening of the endosperm instead of hardening as observed in wet heat treated millet.

CHAPTER III

PREPARATION AND QUALITY CHARACTERISTICS OF DECORTICATED FINGER MILLET

The hydrothermally treated millet (HTM) contained the seed coat and was not suitable for cooking. This indicated the need for decortication to improve its culinary properties. The exploratory experiments on the decortication of the HTM in different types of cereal decorticators showed that, horizontal carborundum disc mill was most suitable for the effective decortication. Accordingly, the decortication of the millet was carried out in a lab scale emery disc mill. It was also observed that, incipient moistening of HTM at about 15% moisture content and two stage milling was necessary for decortication of the millet effectively. Accordingly, a protocol for decortication of HTM was standardized, and the yield of decorticated grains, brokens and

the seed coat were, 65, 24 and 11%, respectively. Probably, moistening the seed coat of the HTM reduces the rigidity between the seed coat and the endosperm by denaturing the gummy material and renders it leathery and hence facilitates its separation. The optimization of the parameters influencing the decortication characteristics were also carried out following response surface methodology (RSM) and the yield of decorticated millet was 68% following the optimum conditions determined by the RSM .

The decorticated millet (DM) was of cream color with 0.97 sphericity value and contained about 4.5% protein, 0.8% fat, 10% dietary fiber and 72% starch. The DM contained about 1% minerals out of which calcium was 190 mg/100g. This showed that, separation of the seed coat resulted in loss of protein, fat, dietary fiber and calcium by 36, 48, 42 and 40%, respectively. On the other hand, decortication enhanced carbohydrate as well as protein digestibility of the millet and the bioavailability of calcium and iron by 62 and 46% respectively.

The carbohydrates, proteins and lipid contents and their profiles of the DM were comparable to HTM. However, the differential scanning calorigram of the DM was endothermic which was in contrast to the HTM, which was exothermic. This difference could be due to the absence of the seed coat matter in DM. The X-ray diffraction pattern of the DM was of V type, typical to parboiled cereals.

The decorticated millet cooked to soft edible texture within 5 min by dropping in boiling water and exhibited excellent cooking qualities. The cooked grains retained their discreteness without forming lumps or disintegration. The cooked grains on exposure to the atmosphere for more than half an hour turned slightly brownish and yet retained their soft edible texture and desirable aroma. The moisture content of cooked DM was about 71% and during cooking hardly 4% of the seed matter leached out. The texture profile analysis of the cooked grains was nearly comparable to rice but the adhesiveness was lower than rice. The cooked grains were readily accepted by all age groups with an overall acceptability of 8.0 (like very much) on nine point hedonic scale.

The sorption isotherm studies revealed that, the DM is of very low hygroscopic nature and its critical moisture and humidity were 16.5 and 76%, respectively for safe storage. It was noteworthy that, the DM did not show visible mould infestation even on exposure to 82% humidity for more than 30 days during the sorption isotherm studies. Guided by the sorption studies, the DM was packed in low cost flexible packaging material (LDPE) and stored at accelerated (92±1% RH and 38^{o}C) and ambient (64±1% RH, 25^{o}C) conditions for the storage studies. It was observed that, the product remained acceptable for over 6 months at the ambient and 3 months at accelerated storage conditions (the study period). The changes in the moisture and the free fatty acid (FFA) contents, color and cooking quality as well as the sensory acceptability were evaluated as a function of storage period. There was hardly 1.1% increase in the moisture and 0.05% in FFA contents of the DM even after storage for 3 months at accelerated conditions and the corresponding values were invariably low at ambient storage conditions. The physical features, cooking and sensory qualities of the millet did not change appreciably in both the storage conditions. However, a slight increase in its chewiness was recorded by the panelists for the millet stored for more than 3 months. The studies showed that the shelf-life of DM is more than six months at ambient conditions and can be packed in normal cereal packaging material for its transport and storage.

CHAPTER IV

PREPARATION AND QUALITY CHARACTERISTICS OF EXPANDED FINGER MILLET

Popping or preparation of expanded cereals is one of the traditional technologies for preparation of ready-to-eat products, wherein, the hydrothermally treated and pearled grains are subjected to high temperature short time treatment (HTST). During the process the grains expand uniformly in all directions and hence the shape of expanded cereals resembles the native grains. Since, the expanded cereal is free from the seed coat matter and the cereal undergoes heat treatment twice, namely, during parboiling and also during the HTST, the starch content not only completely gelatinizes but

also undergoes thermal degradation to some extent. Hence, the product exhibits highly desirable functional and sensory characteristics. In view of this, preparation of expanded product from the decorticated millet was explored and its quality characteristics were studied.

The preliminary experiments on the expansion characteristics of the DM indicated that, the moisture content and temperature of heat transfer media and also loosening the rigidity of the endosperm by mechanical impact, play important roles towards expansion of the DM. Accordingly, the influence of each of these parameters on the expansion ratio was studied in detail, and the optimum conditions for preparation of well expanded millet were determined. The results indicated that, the DM equilibrated to 40% moisture content, steamed for about 10 min at atmospheric pressure, deshaped by impacting through the rolls of the heavy duty roller flaker to 0.58 shape factor, dehydrated to about 9% moisture and then subjected to HTST treatment yielded nearly 100% of expanded grains with the expansion ratio of 4.6. Subsequently, these conditions were also confirmed using response surface methodology. The bulk density, sphericity, hardness and overall acceptability of the expanded millet were 0.17 g/ml, 0.90, 5.0 N and 7.2, respectively.

The microscopic examination of the expanded millet indicated the presence of two concentric spheres with an air vacuole in between. It was highly crisp, friable and ready-to-eat product with desirable aroma. The texture profile analysis of the product substantiated these observations. The cold and cooked paste viscosity, solubility index and swelling power of the expanded millet at 30 and 95^{o}C were nearly comparable indicating the fully gelatinized nature of its starch. The carbohydrate profile by gel permeation chromatography indicated the presence of slightly higher proportion of thermally degraded low molecular weight starch components compared to that of native, HTM and DM. The nutritional and functional properties of the expanded millet indicated its suitability for preparation of specialty foods, snacks and also as an adjunct in confectionery.

The relevant references cited in the thesis are compiled in alphabetical order as BIBLIOGRAPHY. The research publications emanated from the thesis work are also appended at the end.

SUMMARY AND CONCLUSIONS

Finger millet is nutritionally superior to many of the major cereals and offers several health benefits. Its culinary uses are limited to flour based products only and its food uses have been confined to traditional users till date. However, very recently, it has been observed that, the hydrothermal treatment to the millet, enhances its hardness and enables its decortication and cooking in the grain form similar to rice. Hence, detailed investigations towards optimizing the hydrothermal processing of the millet and decortication of the same were conducted. Besides, processing of the decorticated millet for preparation of ready-to-eat expanded millet was also explored. The nutritional and functional properties of hydrothermally treated, decorticated and also the expanded millet were studied. The salient features of the outcome of the work are;

- Steeping, steaming and drying are the main unit operations involved in preparation of hydrothermally treated millet. The steeping characteristics of the millet are governed by the temperature of the steep water as the rate of water absorption is rapid at higher and slower at lower temperatures. The millet attains its EMC of 35$\pm$1% after about 10 h of soaking in water maintained at 30^{o}C and within 2 h at 70^{o}C. Hardly 0.1% of the millet solids are leached during steeping.

- The transformation of the endosperm from its highly friable to hard texture (from 37 to 235 N) suitable for decortication was achieved either by steaming the millet for about 30 min at atmospheric pressure or for about 10 min at 3 kg/cm^{2} pressure. Drying the steamed millet beyond 45^{o}C causes fissures and affects its decortication characteristics, whereas, drying the steamed millet at about 40^{o}C transforms the millet to hard and yet slightly mellowable texture and enables decortication effectively.

- The gross nutrient composition of the millet does not change on hydrothermal treatment but it causes considerable changes in its physicochemical characteristics such as, increase in the intensity of the reddish black color, slight reduction in the size with visible undulations, about 5 fold increase in hardness, decrease in the cooked paste viscosity and increase in the hydration capacity etc. Besides, the hydrothermal treatment causes decrease in the protein extractability by 50% and partial degradation of the starch, reduces the water soluble non-starch polysaccharide contents and increases in the alkali soluble non-starch polysaccharides.

- Incipient moist conditioning of the HTM containing 14±1% moisture and two stage decortication facilitated separation of the seed coat with least damage to the endosperm with a yield of about 65% decorticated grains.

- The decorticated millet contains about 4.5% protein, 0.8% fat, 10% dietary fiber, 72% starch and 1% minerals. The bioavailability of its calcium was 62% compared to 30% for the native millet. The DM is a ready-to-cook product and cooks within 5 min to soft edible texture, into discrete grains similar to rice. It may be termed as quick cooking cereal.

- The shelf-life of the decorticated millet packed in low cost cereal packaging material is about 6 months at ambient storage conditions.

- The decorticated millet is amenable for further processing to prepare value added product such as expanded millet. The optimum conditions for preparation of well expanded millet were, equilibrating the DM to about 40% moisture content, steaming the same for about 10 min at atmospheric pressure, deshaping to 0.58 shape factor, dehydrating to about 9% moisture and then subjecting to HTST treatment. The DM expands to 4.5 times of its original volume on subjecting to high temperature short time treatment and yet retains its spherical shape. The expanded millet is of cream color and highly crisp in nature and is

suitable as snack and supplementary food or as an adjunct in confectionery.

From these observations, it could be concluded that, (a) the hydrothermal treatment to finger millet enables its decortication, (b) the decorticated millet is a quick cooking cereal and cooks to discrete grains similar to rice, and (c) the decorticated millet can further be processed for preparation of value added products such as expanded millet. The decorticated millet being ready-to-cook product, has very high potential for its food uses similar to rice and wheat even by the non-traditional millet consumers. The expanded millet being a new generation snack, may find utilization as snacks or as an adjunct in confectionery also.

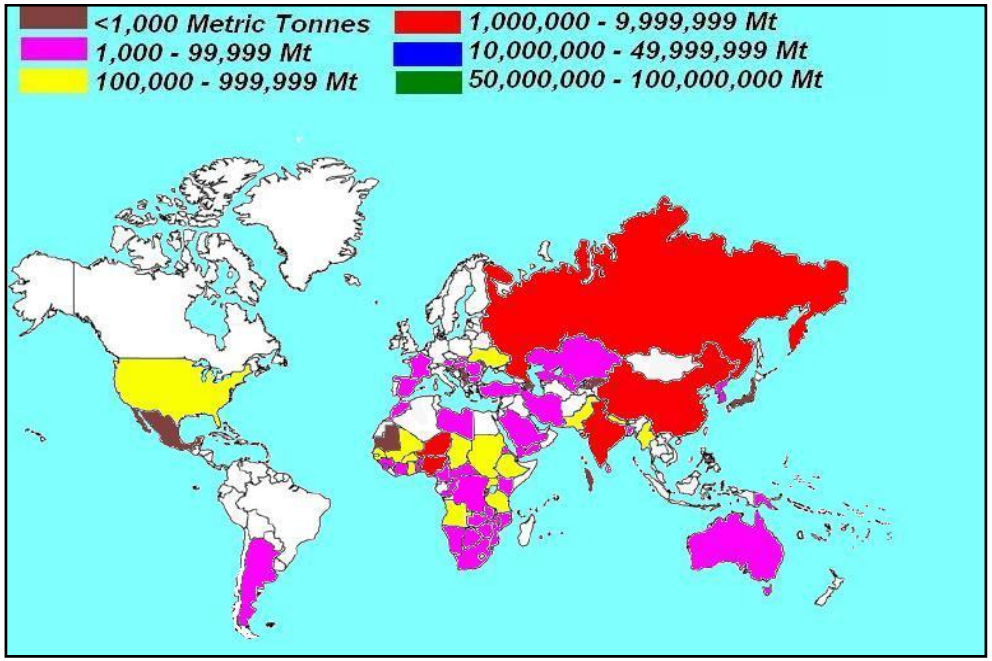
The R & D work presented in the thesis provides an insight of the scientific and technological aspects of hydrothermal processing of finger millet. The physicochemical characteristics of the hydrothermally treated millet and its processing to prepare decorticated and expanded products provide information for diversified utilization and value addition to finger millet. The scientific and technological aspects of the data generated on the millet will add to the database of the millet and may help its processing for value addition including diversified food uses.

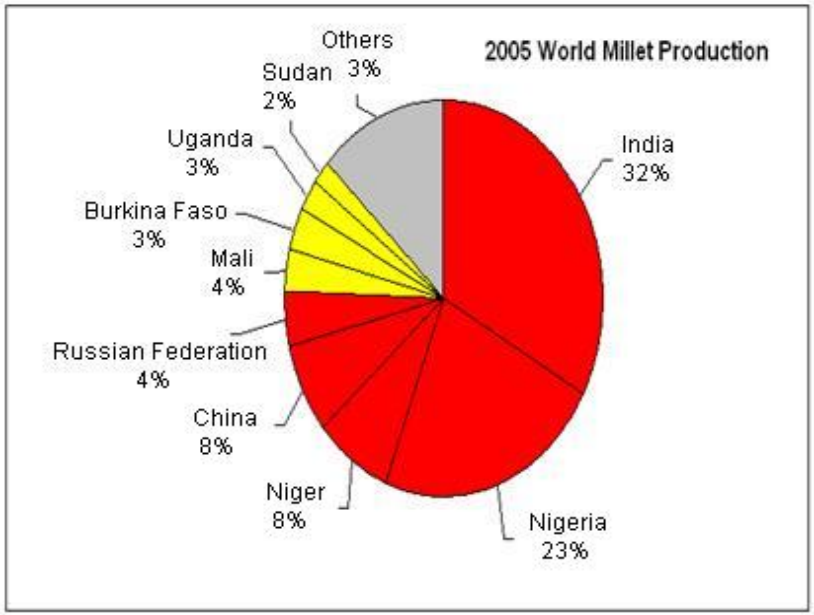
INTRODUCTION

Millet is a generic term used for a heterogeneous group of forage grasses known for their small sized grains widely grown for food and fodder. The millet crops are draught resistant and tolerant to extreme agro-climatic stresses and can be grown on lands where other cereals normally fail to grow. In view of this, millets are valued as potential crops to stretch the availability of food during seasons of monsoon failures or other agro-climatic stresses. But some of the millets are cultivated similar to other cereals in irrigated land also. Millets form the source of carbohydrates and proteins for millions of people mainly in the tropical and subtropical parts of Asia and Africa. Pear millet (*Pennisetum americanum*), Finger millet (*Eleusine coracana*), Proso millet (*Panicum miliaceum*), Foxtail millet (*Setaria italica*), Little millet (*Panicum miliare*), Kodo millet (*Paspalum scrobiculatum*) and Barnyard millet (*Echinochloa frumentacea*) are some of the important millets cultivated in India. Grain Amaranthus (*Amaranthus paniculatus*), Job's tears (*Coix lachryma-jobi*), Fonio (*Digitaria exilis*) and Teff (*Eragrostis tef*) are also categorized as millets or 'pseudo cereals' as they are not cereals in real sense with special reference to their grain morphological features (Hulse et al., 1980).

Millets are mainly cultivated in India, China, Myanmar, North Korea and also Ethiopia, Namibia, Tanzania, Uganda and Zimbabwe are the major producers of the millet in Africa (Figure 1 and Table 1). The total area under the millets in the world is about 33.5 million hectares producing about 35 million tons. India is the largest producer of the millets in the world, with pearl and finger millets making up to 60 and 27% of the total production respectively and the rest being all other small millets (Figure 2).

The world production of finger millet alone is about 4.5 million tons per annum out of which, India produces nearly 55% of the total production (Figure 3). It occupies about 8% of the area under all the millets but accounts for 11% of the millets production. India, Nepal, Sri Lanka, East China and Bangladesh are the Asian countries whereas, Uganda, Kenya, Tanzania, Rwanda, Burundi, Eastern Zaire, Ethiopia, Sudan, Somaliland, Zimbabwe, Malawi,





Source: http://www. gramene.org/species.

Figure 1. Millets growing regions and percentage production of millet in the world

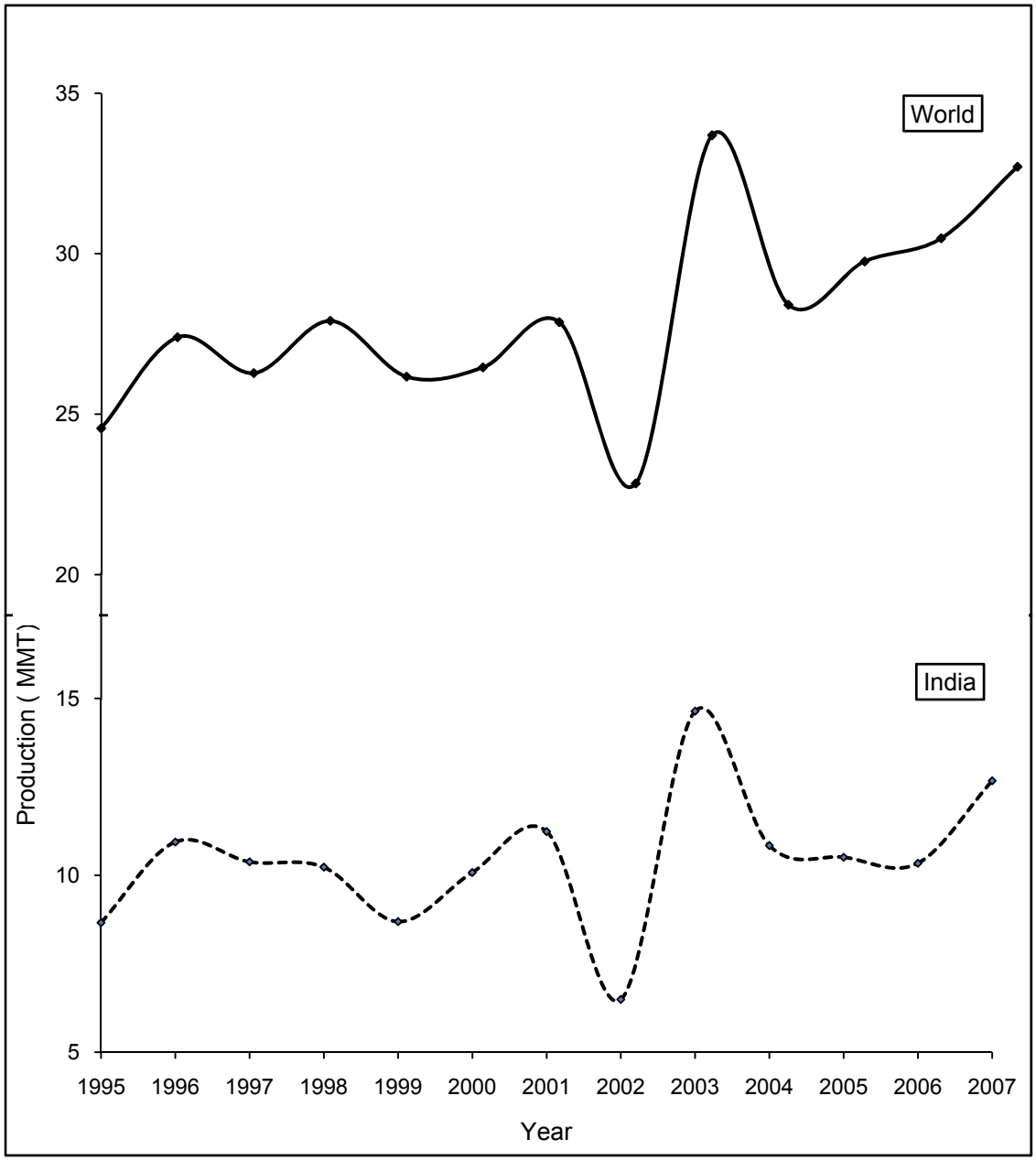
Table 1. Millets producing countries in the world

Country	Area (HA)	Yield (Kg/HA)	Production (MT)
India	11,000,000	8,812	9,000,000
Nigeria	NA	NA	7,964,000
Niger	NA	NA	2,500,000
China	1,070,420	18,225	1,950,800
Burkina Faso	1,500,000	7,158	1,214,419
Russian Federation	500,000	19,500	975,000
Mali	1,245,480	6,544	815,000
Sudan	2,440,000	2,541	620,000
Uganda	390,000	14,974	584,000
Senegal	820,000	5,488	450,000
Chad	706,935	6,083	430,000
Ethiopia	300,000	11,667	350,000
Nepal	NA	NA	288,000
Tanzania	250,000	10,800	270,000
United States of America	250,910	10,350	259,680
Pakistan	NA	NA	180,000
Myanmar	NA	NA	162,000
Ghana	198,000	7,575	150,000
Ukraine	200,000	6,200	124,000
Angola	200,000	5,000	100,000

NA - data not available

HA: hectares, MT: metric tons

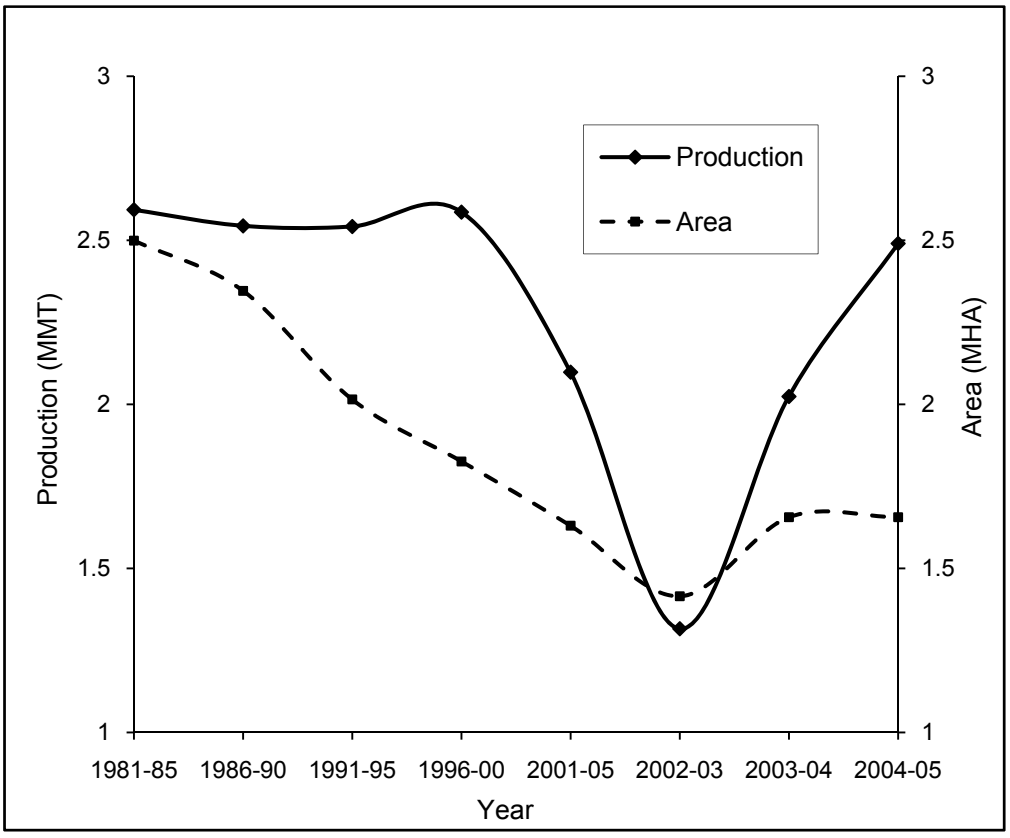
Source: FAO (2007), http://faostat.fao.org



MMT: million metric tons

Source: FAO production yearbook, http://faostat.fao.org/site/339/default.aspx

Figure 2. Production of millets in the world and in India over the years



MMT: million metric tons, MHA: million hectares

Source: Agricultural Marketing, (2006), National Institute of Agricultural Marketing, Jaipur

Figure 3. Production and area under finger millet in India

Zambia and Madagascar are the African countries where finger millet is cultivated prominently.

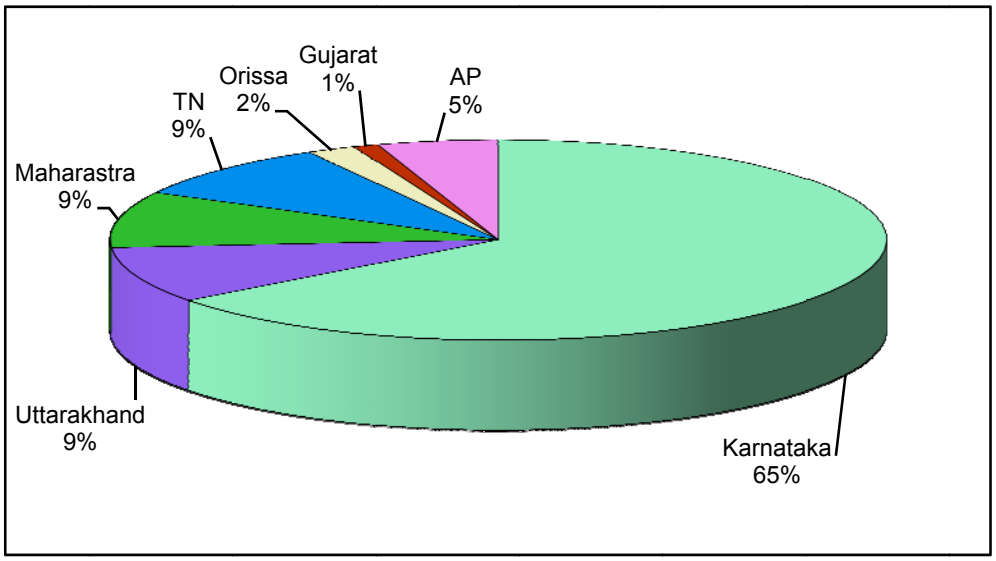
The state of Karnataka in India produces nearly 65% of the Country's production of the millet and the rest is mainly contributed by states of Tamilnadu, Andhra Pradesh, Uttarakhand, Maharastra, Orissa and Gujarat (Figure 4).

The nutritional composition of the millet is not only comparable to the major cereals but also it is superior to many other cereals with respect to several protective nutrients including micronutrients (Hadimani and Malleshi, 1993). Among the small millets, finger millet is an important and nutritionally significant minor cereal.

Finger millet (*Eleusine coracana* L. Gaertn), also known as African millet, commonly called as Ragi, is one of the ancient grains, which is believed to be originated in East Africa and subsequently introduced into India by sea traders around 3000 B.C. (Hilu et al., 1979). The name "ragi" originated from the Sanskrit word "raga" meaning "red". The millet is referred as "Nrutya Kondaka" in Sanskrit literature, means "dancing grain". The typical ear-head of the millet is shown in Figure 5. It is commonly grown for human consumption in India and also in many other arid and semi-arid areas of the world. It can be grown in varying soil and climatic conditions in all most all types of soil including alkaline soils with pH as high as 11 and from sea level to 2500 m altitude and the area of rainfall ranging from 800 to 1200 mm. The millet has outstanding properties as a subsistence food crop and is known as the poor man's food due to its long sustenance. It can be stored safely for many years without infestation even in hot humid areas with marginal storage facilities. The millet grain will retain its viability and quality longer than any other cereal crops. In good climatic conditions, the grain is said to be storable for several decades, thus making it a very important famine reserve food.

1. **Classification**

The most common species of the millet cultivated for food uses, is *Eleusine coracana*, whereas, the other two species, namely, *Eleusine indica* is a wild



Source: Technology for increasing finger millet and other small millets production in India, (2006), AICSMIP, UAS, Bangalore

Figure 4. Percent production of finger millet in different states of India

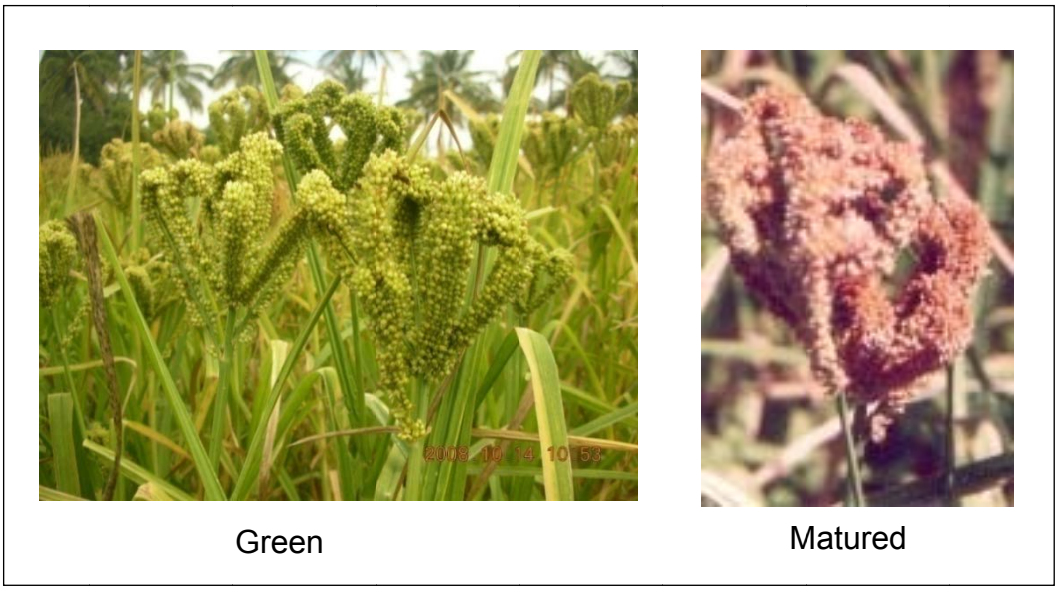


Figure 5. Ear-heads of finger millet

species and *Eleusine africana* is a semi-wild species (Rachie and Peters, 1977). The botanical classification of the millet is as follows;

Kingdom	:	Plantae - Plants
Subkingdom	:	Tracheobionta - Vascular plants
Super division	:	Spermatophyta - Seed plants
Division	:	Magnoliophyta - Flowering plants
Class	:	Liliopsida - Monocotyledons
Subclass	:	Commelinidae
Order	:	Cyperales
Family	:	Poaceae - Grass family
Genus	:	*Eleusine Gaertn*. - Goosegrass
Species	:	*Eleusine coracana* (L.) Gaertn.- Finger millet

2. **Common (Colloquial) names**

Africa	: African finger millet, dagussa, wimbe, osgras
Germany	: Fingerhirse
India	:Ragi, mandua, nagli, ragulu, moothari, nachni, kurukkan, bhav
Nepal	: Kodo
Tanzania	: Mbege, nivegu
Malawi	: Mawere, lipoko, mulimbi, lupodo, malesi
Zambia	: Kambale, lupoko, mawale, bule
Zimbawe	: Rapoko, njera, mazovole, poho
Uganda	: Bulo, otulo
China	: Ts'au-tzu
Thailand	: Phak khouay
International	: Finger millet

(Source: Rachie and Peters, 1977)

3. Grain morphology

Finger millet kernel has distinct morphological features. It is a small seeded grain and the kernel is not a true caryopsis but a utricle. The pericarp or the so called glumes in the utricles is not fused to the seed coat or testa. Thus, the pericarp is easily removed by rubbing or soaking in water and normally it

detaches during threshing.

Wide variations in the color, appearance and size of the millet kernels have been observed among the millet varieties. The color of grains vary from white to orange, deep brown and purple to almost black, but the brick red colored millet is common. However, the colour is confined to the seed coat only, as the endosperm portion of the millet is white similar to rice. The kernels are spherical, globular and oval shaped with size varying in diameter from 1 to1.8 mm with 1000 kernel weight and volume ranging from 1.5 to 3 g and 1.4 to 4.2 ml respectively.

The embryo, endosperm and the seed coat account for about 2, 83 and 15% of the kernel mass respectively. The seed coat contains five layers and is attached tightly to the endosperm (McDonough et al., 1986). The aleurone layer completely encircles the endosperm just beneath the testa and is made up of rectangular cells with thick walls and the cells contain protein, oil, minerals and also enzymes. The endosperm in most of the kernels is of soft and fragile texture and is divided in to three parts namely, the peripheral, corneous and floury endosperm. The floury endosperm comprises 83% of whole grain and contains about 72% of grain protein, 51% of calcium and 86% of phosphorus (Kurien et al., 1959). The protein bodies are distributed throughout the matrix.

The endosperm is mostly filled with starch granules which are spherical in the floury area and polygonal as well as lenticular in the corneous and peripheral endosperm areas (Figure 6). The size of the starch granules ranges from 8 to 21 μm (Wankhede et al., 1979). The protein bodies are generally of smaller size with about 2 μm in diameter. The germ or embryo (270 x 980 μm) of the millet rigidly fixed and located in a slight depression surrounded by a characteristic ridge. The scutellum separates the embryo from the endosperm by the scutellar epithelium.

4. **Chemical composition**

Finger millet also stands unique among cereals because of its excellent nutritional qualities.

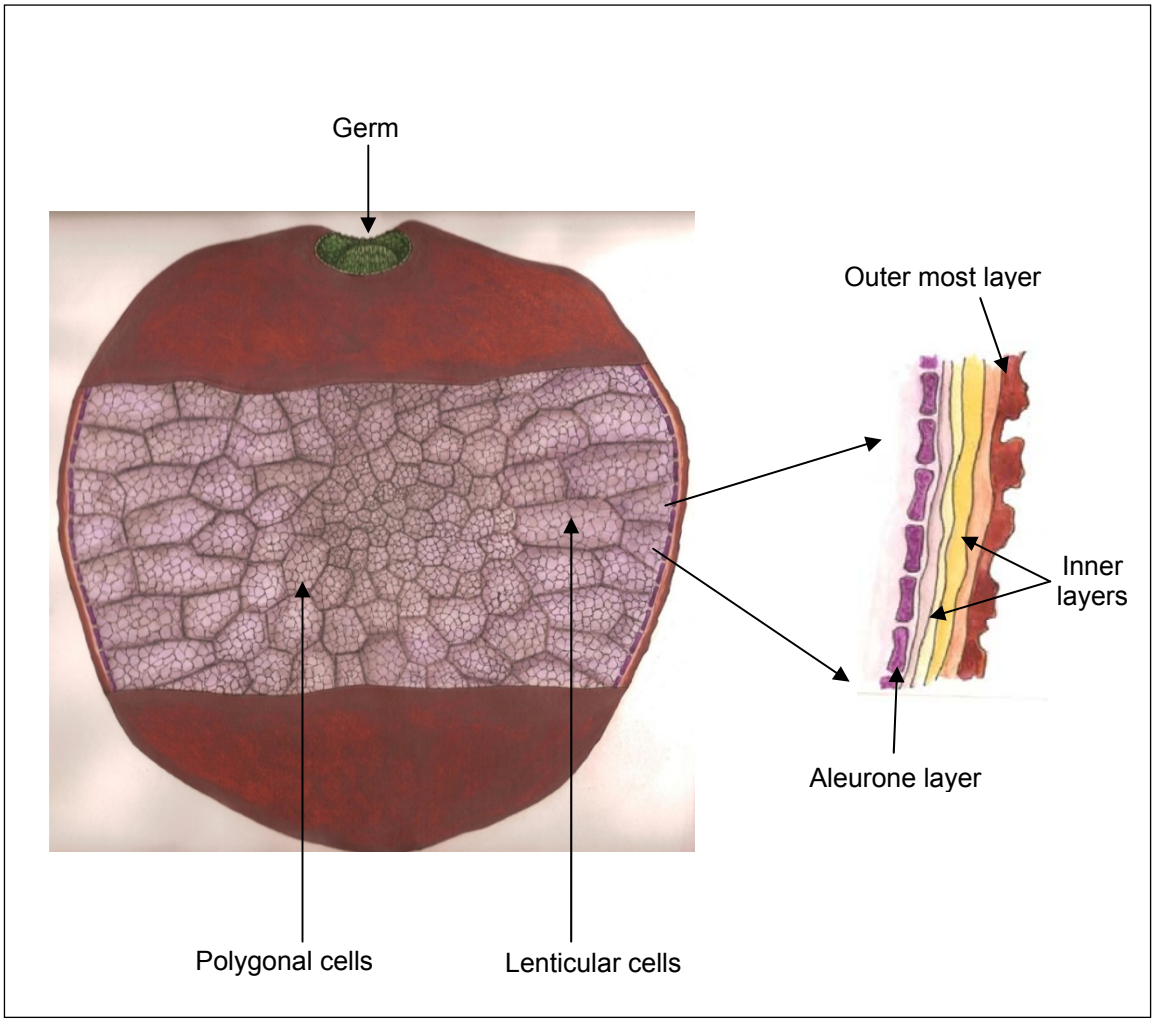


Figure 6. Schematic diagram of finger millet kernel depicting the endosperm and peripheral portions

The millet contains 6 - 8% protein, 1 - 1.7% fat, 65 - 75% starch, 2 - 2.5% minerals and 18 - 20% dietary fiber (Gopalan et al., 2007). The proximate composition of the millet not only compares very well with other cereals and millets (Table 2) but also is superior to wheat, maize, sorghum and rice with regard to dietary fiber, calcium and a few other micronutrient contents.

4.1. Protein

The protein content of the millet normally ranges between 6 - 8% even though varieties as low as 5% and as high as 12% protein have been reported (Hulse et al., 1980). Albumins and globulins constitute 8 - 15% whereas, prolamins with 35 - 50% of the total proteins. The amino acid composition of the millet proteins is of fairly good nutritional value with an average of 2.5% lysine, 1.3% tryptophan, 2.9% methionine, 3.1% threonine, 7.8% leucine and 4.0% isoleucine (Table 3).

The millet proteins are good source of lysine and also contain good amounts of tryptophan, cystine, methionine and tyrosine, which are important for human nutrition (Baptist, 1951). The leucine/isoleucine quotient is about 2, almost equivalent to that of rice and wheat. However, like any other cereal, lysine forms the limiting amino acid in the millet also. The protein efficiency ratio value for the millet protein alone is above 0.95 (Daniel et al., 1974), but on complementing with other vegetable (legumes etc.) as well as animal (milk power etc.) proteins, which are rich source of lysine, the blend forms nutritionally balanced food. Normally, two parts of the millet blended with 1 part of legume forms the product with balanced amino acid profile.

4.2. Lipids

The lipids content of finger millet is hardly 1.5% but they provide invisible fat including some of the essential fatty acids to the consumer. Oleic (49%), linoleic (25%) and palmitic acids (25%) form the predominant fatty acids of the millet lipids. About 72% of the total lipids are present as neutral lipids, 13% as glycolipids and 6% as phospholipids (Mahadevappa and Raina, 1978; Wadikar et al., 2007). Most of the millet lipids are triglycerides and are known to be beneficial to the human gastro-intestinal health, with special reference to minimizing the incidence of duodenal ulcer.

Table 2. Proximate composition of finger millet and a few major cereals (g/100g of edible portion)

	Moisture	Protein	Fat	*Dietary fiber	Carbo-hydrates	Min-erals	Calcium (mg%)	Phos-phorus (mg%)	Iron (mg%)
Finger millet	13.1	7.3	1.3	19.8	72.0	2.7	344	283	3.9
Rice	13.7	6.8	0.5	1.2	78.2	0.6	10	160	0.7
Wheat	12.8	11.8	1.5	12.9	71.2	1.5	41	306	5.3
Maize	14.9	11.1	3.6	10.5	66.2	1.5	10	348	2.3
Sorghum	11.9	10.4	1.9	12.0	72.6	1.6	25	222	4.1
Pearl millet	12.4	11.6	5.0	18.5	67.5	2.3	42	296	8.0
Foxtail millet	11.2	12.3	4.3	14.0	60.9	3.3	31	290	2.8
Little millet	11.5	7.7	4.7	12.2	67.0	1.5	17	220	9.3
Barnyard millet	11.1	11.6	3.9	13.7	74.3	3.7	14	121	5.0
Kodo millet	11.4	8.3	1.4	15.0	65.9	2.6	27	188	0.5

*Source: Gopalan et al. (2007); *Malleshi (2007)*

Table 3. Amino acid composition of finger millet protein and its albumin-globulin, prolamin and glutelin fractions (mg/g total N)

Amino acid	Total protein	Albumin-globulin	Prolamin	Glutelin
Isoleucine	331	205	343	284
Leusine	946	392	859	594
Lysine	217	385	26	425
Methionine	140	Traces	138	81
Cystine	105	13	131	77
Phenylalanine	437	162	554	299
Tyrosine	244	154	313	244
Threonine	361	271	333	273
Valine	521	306	468	407
Arginine	267	539	94	475
Histidine	147	145	127	299
Alanine	549	493	434	403
Aspartate	548	537	295	494
Glutamate	801	739	2047	1312
Glycine	329	392	112	280
Proline	501	272	568	392
Serine	491	364	444	334

Source: Hulse et al. (1980)

The good shelf-life of the millet and its products could also be attributed to its lower levels of fat content.

4.3. Carbohydrates

Free sugars, starch and the non-starchy polysaccharides are the constituents of the millet carbohydrates. Glucose, fructose, maltose and sucrose form the main components of free sugars and they account for 2% of the millet carbohydrates and they are generally present in the bran tissue. They contribute towards the development of aroma during processing, especially during popping and baking. Starch content in the millet ranges from 75 to 80%, and it consists of amylose and amylopectin fractions, normally present in the ratio of 25:75. Unlike rice, there are no reports of very low or very high amylose millet varieties. The millet starch is known to be of slightly higher degree of crystallinity compared to rice starch (Mohan et al., 2005). The non-starch polysaccharides (NSP) of the millet largely consist of cellulose, hemicelluloses and pectinaceous matter. The non-starch polysaccharide content of the millet ranges from 15 to 20% and it forms the major component of the dietary fiber. The cellulose and the hemicelluloses form the major part of insoluble and soluble dietary fiber of the millet respectively (Malleshi et al., 1986).

The slow digesting nature of the millet diet is also attributed to the complex nature of its starch molecules. Many of the starch granules of the millet are compound in nature and are rigid. Probably, because of this, the fragmentation of the granular structure during processing and also digestion by the carbohydrases is of lower order. This contributes towards the nutritional advantages of the millet food in terms of slow digestion and slow release of glucose. The complex nature of its starch also contributes towards the hypoglycemic nature of the millet foods (Lakshmi Kumari and Sumathi, 2002).

4.4. Dietary fiber

The total dietary fiber content of the millet ranges from 17 - 20% and the insoluble dietary fiber forms a major component (15 - 17%), and soluble fiber forms minor component (1 - 2%) of the dietary fiber. Since, the millet foods

are whole meal based, they provide substantial amount of the dietary fiber and add to the bulk of the food.

The dietary fiber has received a lot of attention of food processing scientists because of its health beneficial properties. It offers several benefits with the physiology of the gut namely, easy bowel movement, lowering the absorption of the glucose, regulation of the microflora etc. Since, the dietary fiber is generally unavailable carbohydrates, it does not contribute to the calorie content of the foods. The soluble fiber mostly forms a thin layer over the starchy matter and reduces its accessibility to the digestive enzymes in the GI tract, thereby contributing towards the hypoglycemic nature of the millet foods. The microflora in the colon digests the soluble fiber and release short chain fatty acids which combine with bile acids and prevent their absorption by the system. This phenomenon helps in controlling the excessive cholesterol formation and hence, dietary fiber also acts as a hypocholesterolemic component of the foods. On the contrary, the dietary fiber in the diet beyond certain limit is detrimental because of its chelating nature and thereby reducing the availability of minerals (Maha Lakshmi and Sumathi, 1997).

4.5. Minerals

The millet is exceptionally rich in calcium and contains 300 - 400 mg/100g of calcium, which is about 10 times of that present in rice, wheat and most of the other cereals. Besides, the millet contains 4 - 7 mg% of iron, 270 - 300 mg% phosphorus, 110 - 140 mg% magnesium, 380 - 420 mg% potassium, 4.7 - 5.5 mg% manganese, 1.7 - 2.5 mg% zinc and 140 - 180 mg% selenium (Gopalan et al., 2007).

Probably, due to high calcium and other mineral contents, the millet is considered as a cool food. In addition, this may help in maintaining the acid-base balance and to regulate dehydration and tolerance against thirst. Even though, the mineral content of the millet is comparatively higher compared to other cereals, the bioavailability of mineral is very low because of the presence of higher level of the phytate content. Apart from this, the millet contains relatively higher proportion of oxalic acid (46 mg/100g), which

generally binds with the minerals, reduces their bioavailability and forms oxalate which very often leads to kidney stone (Ravindran, 1991).

4.6. Vitamins

The nutritional qualities of the millet are strengthened by the presence of vitamins. The millet contains 42 μg% of carotene, 0.42 mg% of thiamine, 0.19 mg% of riboflavin, 1.1 mg% of niacin and 18.3 μg% of folic acid.

4.7. Phytochemicals

The millet is known for its therapeutic value because of the presence of several phytochemicals with nutraceutical values. The phytochemicals of the millet include phenolic compounds, phytic acid and flavonoids such as flavones, isoflavones, etc. It contains 0.5 - 2 g% polyphenols and 0.5 - 1.0 g% phytic acid (Ravindran, 1991). Red and brown millet varieties contain high amounts of condensed tannins and polyphenols, which are important phytochemicals with nutraceutical properties. The millet polyphenols are highly complex in nature unlike other polyphenols of plant source. They are sparingly soluble in water, but can be extracted effectively in acidic methanol solvent system. Out of the large number of phenolics present in the millet, gallic acid forms the major constituent of the seed phenolics whereas, the ferulic acid forms the major phenolic of the endosperm cell walls. Nearly 70% of the millet polyphenols are concentrated in its seed coat tissue (Chethan and Malleshi, 2007a). The preliminary investigations on the millet polyphenols towards inhibiting the growth of *Helicobacter pylori* has been highly promising (Malleshi, 2005, Chethan and Malleshi, 2007a). The millet polyphenols are known to contribute towards amelioration of the diabetes related complications (Shobana et al., 2009).

5. Processing and utilization

The major portion of the millet produced is generally used for preparation of traditional foods such as *roti*, *mudde* and *ambli*, but a considerable quantity is also processed to prepare malted and popped millet, and very little is diverted for feed and other uses such as preparation of alcoholic beverages (Marathee,1993).

5.1. Food uses

The millet is normally consumed in the form of flour-based foods such as *roti* (unleavened pancake), *mudde* (stiff porridge or dumpling) and *ambli* (thin porridge). For preparing *roti*, normally the flour is mixed with hot water to partially gelatinize the starch and also to induce the adhesiveness, kneaded into dough, flattened and baked on hot pan by contact heat. For preparation of *mudde*, a small quantity (2 % w/v) of the flour is mixed with water and the slurry is heated to boiling and to that a predetermined quantity of flour is added, and left undisturbed in the form of heap for a few minutes for partial steaming and then it is mixed well with the slurry to a smooth consistency. Finally, it is shaped in to a ball of about 150 g each and consumed along with other adjuncts like *sambar*.

The thin porridge (*ambali*) from the millet is normally a mild fermented product, and is prepared by mixing the millet flour with water containing a small quantity of buttermilk and left overnight and cooked. Mild fermentation of the millet slurry imparts slight sour taste but improves the bioavailability of the minerals. Normally, the millet *porridge* or *ambali* is consumed in summer season because of its soothing effect.

In Africa, the traditional beverage from the millet is lactic acid fermented brew. Similar product is also prepared in the Himalayan region of India and Tibet, Butan and Nepal. For the purpose, the sprouted millet is heated to boiling and allowed to ferment for 2 days after inoculation with special cultures (Bvochora and Zvauya, 2001). This drink is commonly called as *chhang* (Basappa and Venkataramu, 1994). The flour from the millet is used for preparation of Uji (thin porridge) in Kenya and Uganda (Oduori, 1993).

The whole meal from the millet is used for preparation of composite blend with refined wheat flour to prepare gluco biscuits and other bakery products. Up to 20% of the refined wheat could be replaced by the millet flour for the preparation of these products (Selvaraj et al., 2002). It is also used for preparation of various African traditional foods along with teff, maize and barely in many of the African countries.

In recent years, noodles and *papads* based on the millet flour are gaining popularity. The CFTRI process for preparation of noodles involves pretreatment to the millet enabling its cold extrusion and retention of texture of the noodles without fissuring when cooked in water (Sowbhagya and Ali, 2005). *Papad* is a thin crispy Indian wafer sometimes described as a cracker or flatbread and its preparation involves cooking the fine flour in appropriate quantity of water to completely gelatinize the starch, flattening the dough using roller pins to desired circular size and drying (Sila Bhattacharya and Narasimha, 2005). Even though, the millet *papads* appear dark and slightly unappealing, the expansion characteristics of the product are very good and the product on deep oil frying, form crisp product with appealing color. Recently, utilization of the millet for preparation of soup has also been explored. For the purpose, incipient germinated millet is mixed with vegetables, spice and condiments, cooked and roller dried, and subsequently blended with other adjuncts such as milk powder and maltodextrin (Guha and Malleshi, 2006).

The extrusion cooking characteristics of the millet are very poor. However, the meal from the millet can be blended with other cereals and can be extruded in a twin screw or single screw extruder to prepare ready-to-eat products such as snacks and supplementary foods. The refined flour from the millet could be roller-dried to prepare thin wafery ready-to-eat product, which can be used for various specialty food preparations and also as a thickening agent in soups etc.

5.2. Processing

Milling, popping and malting are the popular traditional primary processing technologies applied to the millet extensively. The millet after primary processing could be further processed for preparation of traditional as well as specialty foods and also for use as an ingredient in novel food products. A brief account of these is as follows;

A. Milling

The millet as such is neither a ready-to-eat nor a ready-to-cook cereal. It invariably needs processing for its food uses. Generally, it is pulverized to

flour for preparation of the food products. The millet is cleaned to free from foreign materials such as stones, stalks, chaffs and admixed grains etc and passed through abrasive or friction mills to separate out the glumes or thin pericarp (the non-edible cellulosic tissue) and then pulverized. Similar to most of the cereals and millets, finger millet is not polished to remove the seed coat or husk because of its unique textural features namely, very soft and fragile endosperm with rigidly attached seed coat. Any attempt to dehusk the millet following cereal pearling or decortication methodologies results in pulverization of both the seed coat and the endosperm. Hence, the millet is invariably pulverized along with the seed coat to prepare the whole meal. Normally, it is pulverized in stone mill or iron disc or emery coated disc mills or other types of cereal pulverizers. However, for preparation of the refined flour (the flour almost free from the seed coat matter), the grains are sprayed with 3 - 5 % additional water, tempered for about 10 min, pulverized and sieved to remove the major portion of the seed coat. Moistening and tempering renders the seed coat leathery and as a result, it does not fragment in to finer particles (Malleshi and Desikachar, 1981a), which is separated out by sieving the meal. As on date, the scientific information on the quality criteria of the millet flour suitable for *roti a*nd *mudde* are not well defined. But normally, the finer flour containing about 10% of damaged starch is more suitable for *roti,* whereas, slightly coarse flour is desired for *mudde* (Smitha et al., 2008). The refined flour could be used in bakery and also as a composite flour mix for various food and allied products.

The seed coat, which forms the by-product of the refining process, contains about 700 mg/100g calcium and may serve as a natural source of calcium or as an ingredient for calcium bio-fortification. A composite blend consisting of the millet seed coat and wheat flour has been reported to possess good dough forming and baking characteristics and the biscuits prepared from the composite blend containing about 20% seed coat, exhibited all the desirable quality characteristics for the biscuits and the product was readily accepted (Rateesh et al., 2008).

B. Popping

Popping of finger millet is one of the popular traditional methods and the popped millet flour commonly known, as "*hurrihittu*", is a ready-to-eat product. For preparation of the product, the millet is normally mixed with 3 - 5% additional water or dilute buttermilk to raise the moisture content to about 16%, tempered for 2 - 4 h, and popped by high temperature and short time (HTST) treatment by agitation in sand heated to about 230^{o}C. During popping, the sugars in the aleurone layer react with amino acids leading to Millard reaction and development of highly desirable aroma. When the grain is subjected to HTST treatment, the moisture in the kernel turns into steam, gelatinizes the starch and then explodes (Hoseney et al., 1983). In view of this, the popped millet is a precooked ready-to-eat product and can be used as snack after seasoning with spice and condiments. Also it can be pulverized and mixed with vegetable or animal protein sources such as popped bengal gram, milk powder and oil seeds, and sweetened by jaggery or sugar to prepare a ready-to-eat nutritious supplementary food (Premavalli et al., 2003). Since, popping is a dry process, it is cost effective and the product is almost free from microbial contamination. However, the traditional method of popping wherein hot sand is used as a heat transfer media contaminates the product with minute particles of sand and affects its eating quality. To overcome this drawback, air-popping in a suitable mechanical device has been successfully explored. However, the air popped product normally lacks the characteristic aroma compared to that prepared using sand or other heat transfer media (Malleshi and Desikachar, 1981b). Popped millet can be prepared at household, community or industrial levels. Diversification of the millet in the form of popped food especially for specialty foods and also as adjuncts in brewing offers an advantage because of its ease of preparation, desirable sensory qualities and better shelf-life.

C. Malting

Malting is an *in vivo* biotransformation of viable seeds, which converts the seed into a storehouse of hydrolytic enzymes especially, the amylases. Malting of finger millet is largely practiced for specialty foods and also for preparation of milk based beverages in India and for preparation of local beer

in Africa and also in the Himalayan region. During malting, the bioavailability of proteins, carbohydrates and minerals are enhanced, some of the B-group vitamins are synthesized and the concentration of anti-nutritional factors is considerably reduced. Malted millet is nutritionally superior to the native millet (Malleshi and Desikachar, 1986).

The malting process involves soaking of the viable seeds in water to hydrate and to facilitate germination or sprouting, drying the sprouts, de-rooting or separation of the rootlets and kilning or curing the green malt. Although, all these unit operations influence the quality of the malt, the germination process is the single most important step because, the hydrolytic enzymes developed during germination cause endosperm modification and cause textural and nutritional properties of the seeds. Some of the vitamins are synthesized and the bio-availability of the minerals increases during germination. Kilning imparts characteristic aroma to the malt. The protease and the cell wall degrading enzymes developed during germination partially digest the cell walls and the amylases digest the starch to some extent. Technology for preparation of ragi malt flour almost free from the coarse seed coat, suitable for specialty foods has also been developed at CFTRI (Malleshi et al., 2000). The malt flour being a rich source of amylases, enables to prepare low bulk and calorie dense foods by cooking its aqueous slurry. This has been advantageously utilized for developing various health foods such as, infant food, weaning food, enteral food, milk-based beverages and also confectionary products (Malleshi, 2007). Hence, millet malt is gaining importance as a new ingredient in the food industry.

6. Parboiling

Parboiling is one of the traditional cereal processing methodologies, which involves hydrating the grains fully or partially, steaming or dry heat treating followed by drying. In largely followed conventional method of parboiling, the grains are soaked in water to raise the moisture content near to its maximum absorption capacity or equilibrium moisture content (EMC) or saturation level, the excess water is drained off and steamed at normal atmospheric pressure and dried to safe storage moisture level. Sometimes the grains are soaked to

increase the moisture either to 18 - 22% or to their equilibrium moisture content, and steamed under pressure to prepare pressure parboiled cereals. In the case of dry heat parboiling method, the grains are soaked to the EMC and subjected to conduction heating using hot air or sand or such other heat transfer media (Figure 7). Recently, newer methods of heat transfer have been explored for the preparation of parboiled grains wherein, thermic fluid and Infrared radiation (IR) are used to enable quick conduction of heat (Pillaiyar et al., 1996; Ipsita Das et al., 2009). IR heating involves exposure of the soaked grains to electromagnetic radiation in the wavelength range of 0.8 to 1000 μm. Similarly, microwave heating is also explored wherein, the soaked grains are cooked using a microwave (Mcilroy et al., 1990). However, the quality of the parboiled grains varies depending upon the method of the parboiling and severity of the processing conditions.

It has been well documented that, to prepare the products like expanded and flaked cereals, parboiling technique has been used extensively (Chinnaswamy and Bhattacharya, 1984). Expanded rice is a very popular product in India. Usually dry heat treated paddy, after milling is used for preparation of expanded rice but pressure parboiling is recommended for better expansion of rice (Chinnaswamy and Bhattacharya,1986a). Similar to expanded cereals, flakes are prepared from the parboiled cereals using roller flaker. Flaked cereals are very popular breakfast foods and are generally produced using edge runner or multiple impact flaker from dry heat parboiled rice (Ananthachar et al., 1982).

Parboiling of rice is practiced to a large extent and changes in rice during parboiling of rice has been studied extensively (Bhattacharya and Ali, 1985). Wheat is another cereal which is parboiled and the parboiled wheat is known as bulgur (Suhasini and Malleshi, 1994; Mohapatra and Srinivasa Rao, 2005). The bulgur wheat is mainly used for preparation of popped bulgur, grits, in bakery products, baby food mixes, fortified breakfast cereals and also in food aid programs (Roger, 1970). Both dry and wet heat parboiling methods are followed for the preparation of bulgur. Apart from rice and wheat, there are a few reports available on parboiling of ragi, sorghum and pearl millet.

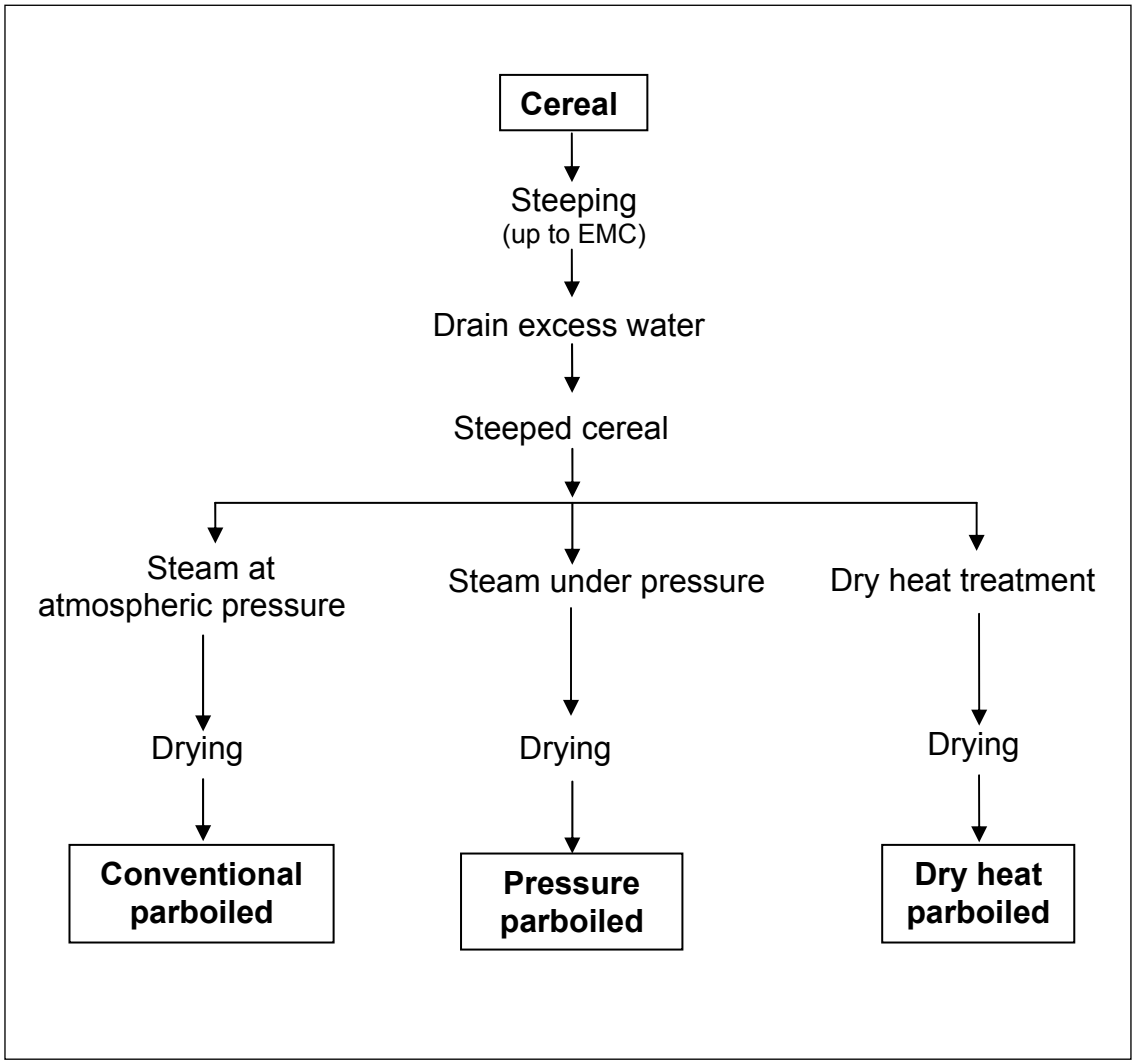


Figure 7. Different methods of parboiling of cereals

The nutritional changes in sorghum and pearl millet due to parboiling were studied by Serna-Saldivar et al. (1994) and reported that, parboiling of sorghum and pearl millet increased the efficiency of removal of germ and pericarp. Young et al., (1993) also studied the changes in the sorghum starch during parboiling and reported that, the starch gelatinization, crystallinity, pasting properties and microstructure were modified during parboiling and as a result, the endosperm texture was strengthened, increasing the decortication yield of parboiled sorghum. Parboiling of small millets other than finger millet was studied by Kimata et al. (1999) and they reported that, the process of parboiling did not affect the nutritive value as well as the amino acid composition of their proteins, but it aided easy dehulling and breakage tolerance in the grains. Wet heat treatment to finger millet improves its culinary properties and enables to prepare the grits as reported by Desikachar (1972). Adebowale et al., (2005) subjected the isolated starch from finger millet to heat moisture treatment and studied the changes in the physicochemical characteristics including X-ray diffraction and thermal properties. The effect of the steam treatment has also been studied on a few other non-cereal starchy foods like arrow root, cassava, tapioca etc to some extent (Raja et al., 1987; Raja and Sindhu, 2000), and the reports indicate that, hydrothermal treatment modified their functional properties namely, increased the EMC and sedimentation volume, improved their paste stability leading to overall improvement in their culinary properties.

The properties of cereals are profoundly influenced by the parboiling conditions. The major biochemical components of the grain, namely, starch, protein and fat in the cellular structure undergo considerable changes in their characteristics during the process. The starch gets gelatinized losing its birefringence as well as the crystallinity and the protein bodies are ruptured and the protein solubility decreases (Raghavendra Rao and Juliano, 1970; Priestley, 1976). As a result of these changes the physicochemical properties of the cereals like viscosity, alkali score, swelling power, solubility, carbohydrate and protein digestibility etc will undergo a drastic change. A part of the gelatinized starch re-associates forming retrograded starch (Ali and Bhattacharya, 1976). However, the contents of starch, protein and fat are not

altered significantly. The fat migrates towards the periphery of the grain and the oil globules in the aleurone layer get disrupted (Sondi et al., 1980). During parboiling, thiamin and such other water soluble vitamins present in the aleurone layer and germ, diffuses into the endosperm and get fixed and due to that, the loss of vitamins during milling is reduced (Padua and Juliano, 1974). The parboiled grain becomes glassy and 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). The grain becomes hard probably, as a result of gelatinization of starch followed by its retrogradation. The parboiled grain is therefore more resistant to breakage during abrasive as well as friction milling than the raw grain. The milling yield of the grain increases due to reduced breakage because of the healing of cracks in the grain on parboiling (Kimata et al., 1999). A slight increase in the grain dimensions has been noticed for rice and as a result of parboiling, its packing and flow properties also change (Bhattacharya and Ali, 1985). The cooking time increases whereas, the stickiness and tenderness of the grain decrease on parboiling compared to the raw milled grain.

Thus, parboiling or hydrothermal treatment to any of the cereals produces profound changes in its physicochemical properties. For rice, they could be summarized as; (1) The raw rice, which is normally opaque changes to rather glassy, translucent and light amber, (2) The hardness of the kernel increases several fold and as a result the milling characteristics improve leading to less breakage and higher yield of the head rice, (3) Enhanced shelf-life, (4) Increase in the level of the oil content of the bran (5) Increased retention of vitamin B_1, (6) Slowing down the rate of hydration at elevated temperature and slightly longer cooking time, and (7) Increased discreteness and chewiness of the cooked grains. The subject matter on parboiling of rice has been reviewed extensively by Bhattacharya and Ali (1985).

The brief description of the parboiling process is as follows; steeping or soaking the grains, which involves immersing the grains in excess water to raise the moisture content to 20 - 40% or till the grains attain their equilibrium

moisture content (EMC). The duration of steeping is normally 10 - 24 h and the rate of hydration is influenced by the temperature of the steep water and is rapid at higher temperatures (Bello et al., 2004). However, the temperature of steep water should be below the gelatinization temperature (70^{o}C) of the cereal starch, otherwise, the grains burst open affecting their quality.

Steaming is the most important unit operation in the hydrothermal treatment wherein the steeped grains are subjected to live steam at atmospheric pressure or at elevated pressures for suitable duration so as to gelatinize the starch, without burst opening of the grains. Normally, steaming time is about 30 min at atmospheric pressure and about 5 - 20 min at elevated pressure. During this treatment the starch undergoes gelatinization, proteins get denatured and cementing of the cell wall components with starch, protein and lipids occur and this culminates in hardening the grain after drying (Nawab and Pandya, 1974).

Dehydration or drying of the steamed material is essential for its safe storage and also for further processing including milling. It is generally done by exposing the steamed material to air heated to about 50^{o}C and also by sun or shade drying. The temperature as well as the rate of drying greatly influences the physical properties and the milling characteristics.

During soaking or steeping the grain, a number of enzymatic changes take place. It has been reported that during steeping a large part of sucrose gets converted into reducing sugars, a small portion of soluble proteins including amino acids and sugars are generally leached out (Anthoni Raj and Singaravadivel, 1980; Ali and Bhattacharya, 1980). Steaming cause major changes in the physicochemical characteristics of the grains. Generally, starch, the main constituent of all the cereals undergoes gelatinization during steaming followed by retrogradation during drying. These changes in the properties of starch play a profound role in the properties of steamed cereal. The A-type X-ray diffractogram of the endosperm changes over to V-type and the starch granules lose their crystallinity and birefringence (Raghavendra Rao and Juliano, 1970). Apart from this, the starch undergoes partial dextrinization and partial enzymatic inter-conversion of amylose and

amylopectin resulting in some changes in their molecular size and weight (Bhattacharya and Ali, 1985). The protein bodies, which occupy the space between the compound starch granules, are ruptured and no longer remain distinct after steaming and the extractability of proteins reduces by 50% and the decrease in the extractability of the protein is directly proportionate to the severity of steaming (Raghavendra Rao and Juliano, 1970). The oil globules present in the aleurone layer and the germ, lose their globular structure and form a thin layer (Mahadevappa and Desikachar, 1968). The ether extractives and the free lipid contents decrease and the bound lipid content increases on hydrothermal treatment (Bhattacharya and Ali, 1985). Almost all the enzymes including lipase are inactivated thereby improving the shelf-life to the product. Browning of the kernels occurs due to Maillard reaction and some of the anti-nutritional factors and heat labile vitamins specially the B-group vitamins get partly destroyed (Padua and Juliano, 1974).

Thus, hydrothermal treatment to the cereals causes significant physicochemical and nutritional changes and these changes influence the quality of the end product. But, as of now, there are no reports available on the parboiling of finger millet to the best of our knowledge except the one by Desikachar (1972), which describes preparation of grits from parboiled finger millet and the other by Shobana and Malleshi (2007), which provides the process details for preparation of decorticated finger millet.

Finger millet kernels are naked caryopsis and are of smaller size compared to rice and many other cereals, contains significant amount of non-starch polysaccharides. It differs from rice with respect to the physicochemical and nutritional characteristics. Unlike rice, the millet contains the husk tissue which is also known to influence the water holding capacity of the kernels. Its seed coat tissue consists of polyphenols and associated pigments, which are known to undergo changes during hydrothermal treatment. In view of this, it was hypothesized that the hydrothermal treatment to the millet and the quality characteristics of the hydrothermally treated millet including its decortication characteristics may differ from that of rice. And apart from this, the hydrothermal treatment to the millet may alter its nutritional and functional

properties. Hence, detailed investigations were conducted on hydrothermal processing of finger millet and its quality characteristics.

Scope of the work

Finger millet has unique morphological, textural and nutritional characteristics among the cereals. The seed coat of the millet is tightly attached to the soft and fragile endosperm and because of this, polishing or decortication of the millet to remove the seed coat has not been successful so far. Cooking the millet similar to rice has not been possible because the seed coat hinders its swelling to soft edible texture and also the seed turns to intense dark color. This limits the usage of the millet only to flour based traditional foods and not in the grain form similar to rice or wheat semolina. In view of these, the millet is always pulverized and the whole flour is used for traditional food preparation and the millet is never cooked in the grain form. But, the products prepared from whole meal millet are dark in color due to polymerization of the phytochemicals present in the seed coat and the products normally exhibit intense characteristic odour. The whole meal based millet products are generally highly chewy and these factors affect the sensory qualities and consumer acceptability. Moreover, the food products based on whole meal happen to be sticky and slimy. Since, the preparation of the traditional products like stiff porridge (*mudde*) or *roti* needs special skills and hence a nontraditional consumer cannot easily switch over to these foods, even though, they desire to consume the millet foods due to its known health benefits. In this direction, efforts were made to improve the processing and culinary characteristics of the millet to obtain the millet product free from the seed coat and which can be cooked similar to rice as discrete grains. The recent research work at CFTRI has shown that the soft texture of millet could be transformed into hard mass by parboiling, thereby enabling to decorticate or debran or polish the same similar to other cereals. The decorticated millet is totally a new and novel product from the millet and the information on its preparation as well as its functional properties is scanty. It was felt that the detailed investigations on the various unit operations involved for preparation of hydrothermally treated millet namely, steeping, steaming, drying and its decortication characteristics for preparation of the decorticated millet were

highly desirable. Besides, generation of the information on the changes in the microstructure as well as nutrient composition as a result of hydrothermal treatment and the functional, culinary and shelf-life of the decorticated millet and its secondary processing for value addition were also highly desirable. Hence, detailed studies were undertaken with reference to optimization of the process parameters for hydrothermal treatment of the millet, decortication of the hydrothermally processed millet and further processing of the decorticated millet for preparation of expanded product. Accordingly, studies were undertaken with the following objectives;

1. To optimize the various process parameters involved in hydrothermal treatment such as steeping, steaming and drying and to study the changes in the textural features of the millet kernel and also in the composition of major nutrients like carbohydrates, proteins and lipids.

2. To study the factors influencing the decortication characteristics of the hydrothermally treated millet and evaluation of the functional, nutritional, culinary and shelf-life of the decorticated millet, and

3. Processing of the decorticated millet for preparation of expanded product and assessment of its quality characteristics.

INTRODUCTION

Finger millet kernel consists of seed coat, germ and endosperm which form 13 - 15, 1.5 - 2.5 and 80 - 85% of the grain, respectively (Hulse et al., 1980). Very often the millet kernels also contain a loosely attached thin pericarp (glumes), a non-edible component. The glumes can be easily removed by rubbing or soaking in water and the deglumed millet forms a fully edible component. The seed coat of the millet comprises of multilayered testa with five distinct layers and beneath which the aleurone layer is located. The one cell aleurone layer surrounds the entire endosperm (McDonough et al., 1986). The seed coat is mostly cellulosic and contains considerable proportion of phytochemicals and polyphenols which impart color to the seed coat. The germ is embedded in a shallow depression of the endosperm. The endosperm of the millet is of soft and highly fragile texture to which the multi-layered seed coat is rigidly attached. Because of these unique textural features, the millet does not withstand the impact and pressure during pearling or decortication and fragments to finer particles along with the seed coat. In view of this, the millet is not at all amenable to polishing or decortication similar to other cereals and millets, and hence decortication of millet has not been possible so far. Cooking the millet in the grain form also has not been possible, because the seed coat hinders swelling of the grain during cooking and prolonged cooking burst opens the kernel exposing the endosperm portion. This leads to highly sticky product which still contains the seed coat and hence is not at all acceptable to the consumer as a food. Thus, the millet is invariably pulverized and used to prepare flour based traditional products such as *roti*, *mudde* and *ambali* (Malleshi, 1989). Now a days, there is increased interest in the millet due to its health benefits, but the unattractive dark color of its foods and the special skills needed to prepare its conventional products, limit its usage by the non-traditional millet consumers. Therefore, it was felt to process the millet to obtain in a form that would be readily acceptable by one and all, similar to rice or wheat.

Parboiling or hydrothermal treatment to the cereals is known to harden the grains and improve their milling efficiency. This is commonly applied to rice worldwide (Bhattacharya and Ali, 1985; Pillaiyar, 1988) and also to wheat

to some extent (Bayram, 2000). There are no reports on parboiling of finger millet except the only one by Desikachar (1972) which indicates that the hydrothermal treatment to the millet enhances its hardness but it does not describe the quality characteristics of the processed millet except indicating its suitability to prepare grits or semolina. The semolina contained the seed coat which limited its common food usage. More recently, a process on preparation of decorticated finger millet has been patented by Malleshi (2006). Although, the patent describes the process of hydrothermal treatment and decortication of the millet, it does not provide detailed information of the various unit operations involved in the hydrothermal treatment to the millet. Further to this, Shobana and Malleshi (2007) conducted preliminary investigations on preparation of decorticated millet and studied some of its functional properties. They observed that, the decorticated millet had all the desirable characteristics for its cooking and consumption similar to rice. However, the article has limited information on the scientific data pertaining to the influence of various unit operations of hydrothermal treatment. The report does not provide in depth information on the decortication characteristics of hydrothermally treated millet and also the physicochemical, functional and textural properties of the decorticated millet.

The hydrothermal treatment to cereals basically involves steeping the grains to their equilibrium moisture content, steaming the steeped grains followed by drying the steamed grains to safe storage moisture level. It has been well documented in the case of rice and wheat that, the quality characteristics of the parboiled grains are largely influenced by these process parameters (Bhattacharya and Ali, 1985; Pillaiyar, 1988; Bayram, 2006). The physicochemical properties, endosperm texture as well as the functional properties of the grains are altered depending upon the severity of processing during hydrothermal treatment. Apart from this, disruption in the organization of the major biochemical constituents of the grain, namely, starch, protein and fat also occur. In the case of rice, it has been reported that the starch gets gelatinized losing its birefringence as well as the crystallinity (Priestley, 1976) and a part of the gelatinized starch re-associates forming retrograded starch (Ali and Bhattacharya, 1976). The total protein content remains almost

unchanged but the protein bodies are ruptured and its solubility decreases (Raghavendra Rao and Juliano, 1970). Although, the total fat content remains unchanged due to parboiling, some portion of the endosperm fat migrates towards the periphery of the grain and the oil globules in the aleurone layer get disrupted (Mahadevappa and Desikachar, 1968; Sondi et al., 1980). The parboiled grain becomes glassy and translucent and darker in color compared to its native form. It has been reported that, not only steaming but also steeping and drying steps cause considerable discoloration to the grain in case of rice (Kimura et al., 1993). Unlike rice and other grains, the millet contains a substantial proportion of non-starch polysaccharides, polyphenols and other phytochemicals which may play a major role in determining the quality characteristics of the hydrothermally treated millet. The millet being a small sized grain with comparatively large surface area may behave differently compared to rice with respect to steeping and drying characteristics. Hence, detailed studies were undertaken for optimizing the various unit operations involved in the hydrothermal treatment and its influence on the physicochemical, textural and nutritional characteristics of the millet.

MATERIALS AND METHODS

1. Materials

A popular high yielding variety of finger millet (GPU 28) was procured from the University of Agricultural Sciences, Bangalore, Karnataka. The millet was cleaned to free from immature as well as damaged grains and also foreign matter using destoner (Sidvin Machineries, Mysore, India) and then deglumed in Engleburg huller (Sri Ganesha Engineering Works, Chennai, India). The deglumed millet was sifted through a screen of 1405 μm pore size to separate the small sized and shriveled grains, and the well filled bold grains which remained as the overtails of the screen forming 85% of the material, was used for the studies.

The chemicals and solvents used were either of analytical or guaranteed reagent grades and were procured from E. Merck, Qualigens, Ranbaxy or Himedia. The enzymes namely, termamyl (E.C. 3.2.1.1), pepsin

(E.C. 3.4.23.1), pancreatin (Lot No. 15H0862) and glucoamylase (E.C. No. 3.2.1.3) were from Sigma Chemicals, USA.

2. Hydrothermal treatment

The process of hydrothermal treatment to the millet involves three important steps namely, steeping, steaming and drying. Since, the quality characteristics of the hydrothermally treated millet is influenced by all these process parameters, experiments were undertaken to optimize each of the process parameters, to prepare the millet, mainly suitable for decortication.

2.1. Steeping

About 250 g of the millet was steeped in excess distilled water at ambient temperature (30^{o}C), and an aliquot (about 10 g) of the steeped sample was withdrawn at appropriate time intervals up to about 24 h, the water adhering to the surface of the kernels was blotted immediately and transferred into pre-weighed aluminum cups and dried in air oven at 105^{o}C for 16 h. The loss in weight was recorded and based on that, the moisture content of the material was calculated (AACC, 2000). The process was repeated by steeping the millet at 40 - 70^{o}C with 10^{o}C increments and the equilibrium moisture content (EMC) of the material steeped at different temperatures was determined. Since, the millet kernels burst opened on steeping in water maintained beyond 70^{o}C, steeping studies were confined up to 70^{o}C only.

One hundred gram of the millet was steeped in 250 ml of distilled water for 10 h at 30^{o}C and filtered using Whatman No. 1 filter paper. The filtrate was concentrated using a flash evaporator (at 40^{o}C), freeze-dried and weighed for quantitative estimation of the solids leached in steep water. The freeze dried sample was also analyzed for its protein, free sugars, amylose and polyphenols contents as described below;

The protein was estimated according to standard AACC (2000) method. The free sugars were extracted by refluxing the freeze dried sample with 70% ethanol (25% w/v) for 3 times successively, the extracts were pooled, concentrated at reduced pressure and temperature (in a flash evaporator) and the total sugar contents was estimated by phenol-sulfuric

acid method (Ford, 1981). The total amylose content of the freeze dried sample was determined following the iodine binding method as per Sowbhagya and Bhattacharya (1971). For assay of the total polyphenols, 1 g of the sample was refluxed with 100 ml of 1% HCl-methanol solvent system for 30 min and the extract was centrifuged. The residue was again refluxed and the process was repeated till the extract tested negative for polyphenols. The supernatants were pooled, concentrated in a flash evaporator and the total volume was noted. An aliquot (1 ml) of the extract was treated with 5 ml of Folin-Ciocalteu's phenol reagent and 10 ml of sodium carbonate solution. The contents were mixed and diluted to 100 ml with distilled water, allowed to stand for 30 min and the absorbance was measured at 760 nm against the reagent blank. Gallic acid (1 mg/ 1 ml) was used as a reference standard (Singleton et al., 1995).

2.2. Steaming

Guided by the experiments on hydration characteristics, the material (batch size of about 5 kg), steeped for about 10 h at 30^{o}C was used for steaming experiments. The steeped material after centrifuging in a basket centrifuge to free it from adhering water was spread in steel trays (80×40×3 cm) in about 1 inch bed thickness (covered by trays to prevent wetting of the grains by the condensed steam) and exposed to live steam (98$\pm$1^{o}C) at atmospheric pressure in an autoclave (Krauss Maffee Munchen, Germany) for different time intervals ranging from 5 to 35 min with 5 min increment at atmospheric pressure. The steaming time was noted when the temperature probe of the autoclave showed 98^{o}C till the steam inlet was stopped. The steeped millet was also steamed at elevated pressure (1- 4 kg/cm^{2}) for 5 to 20 min depending upon the pressure. The steamed material was used for drying studies.

2.3. Drying

For drying studies a mechanical dryer (cross air flow) was used. The preliminary experiments on drying conditions of the material aimed at preparation of the decorticated millet and hence, the observations of the experiments were concentrated not only on the grain morphology but also on

the decortication characteristics of the millet. Based on these experiments, the temperature as well as the rate of drying of the steamed millet was optimized. The material was spread in a bed of about 0.5 cm thickness in the steel trays and exposed to air temperature ranging from 30 - 90^{o}C with 10^{o}C increment, till the moisture dropped to 13$\pm$1%. The examination of the dried millet for the physical features such as formation of fissures, deformation in shape, variations in size, shape and color, clearly indicated that drying the millet at 39$\pm$2^{o}C was most appropriate with respect to the various quality attributes suitable for decortication. Accordingly, the millet (in 1 kg batches) steamed for different steaming time and pressure, was dehydrated at 39$\pm$2^{o}C to about 14% moisture content and used for evaluation of the influence of steaming time on its quality characteristics. The drying kinetics was also determined by dehydrating the steamed millet at 39$\pm$2^{o}C up to 6% moisture content.

3. Influence of steaming time on the quality characteristics of the millet

To study the influence of steaming time on some of the quality parameters of the millet, the millet steeped to its EMC steamed at atmospheric pressure for 5 - 35 min with 5 min interval and dried at 39$\pm$2^{o}C was used. The samples thus prepared were examined for the color, grain diameter, hardness and hydration kinetics and also their whole meals (less than 250 µm) prepared by pulverizing the samples in a laboratory flour mill (Universal Engineering Works, Mysore, India) were used for the determination of the viscosity. Further, the meals were defatted using petroleum either (60 - 80^{o}C) and their total and soluble amylose contents were estimated. Parallely, the native millet was also analyzed for all these parameters. In addition to this, the millet steamed for varying pressure was also evaluated for its hardness. The average values for all these parameters (except for color and hydration kinetics) were analyzed statistically by Duncan's multiple range test (Snedecor and Cochran, 1962).

3.1. Color

The color indices of the grains in terms of CIE Lab scales namely, L*, a*, b* attributes and also the ΔE values (the deviation from the standard taken as 100% reflectance) were recorded in a Hunterlab color measuring system (Labscan XE, Reston, Virginia).

3.2. Diameter

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

3.3. Hardness

The grains were equilibrated to 12% moisture level by exposing to 64% relative humidity for 24 h in a desiccator and 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) and 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.

3.4. Viscosity

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

3.5. The **hydration kinetics** of the samples was determined as explained for that of the native millet whereas, the soluble and total amylose contents were determined as per Sowbhagya and Bhattacharya (1971).

The quality parameters of the millet, steamed for different duration indicate that, the duration of steaming influences not only the hardness but also the other quality parameters which indicate the severity of heat treatment in one way or the other. In view of this, the steaming the millet for 30 min was identified as the optimum steaming time. Accordingly, the millet steeped for 10 h at ambient temperature, steamed for 30 min at atmospheric pressure and dried at 39$\pm$2^{o}C to 14$\pm$1% moisture content was prepared on semi-pilot scale

and utilized for further studies. The millet thus prepared was designated as **hydrothermally treated millet (HTM)**, and the notation HTM has been used throughout the forgoing text. Figure 8 presents the flow chart for the preparation of the hydrothermally treated millet.

4. Quality characteristics of hydrothermally treated millet (HTM)

The important physical characteristics of HTM namely, color, grain diameter, sphericity, surface area, 1000 kernel weight as well as volume, bulk density, true density, porosity, hardness and hydration characteristics were determined as described briefly in the subsequent pages.

The kernels were processed for fixation of the biochemical components for the microscopic examination and examined for some of the morphological features in a light microscope as well as in a scanning electron microscope.

The HTM was pulverized in a laboratory flour mill to particle size less than 250 μm and the whole meal used for the determination of some of its functional properties such as viscosity, solubility, swelling power and pasting profile. The thermal properties of the HTM were determined in a differential scanning calorimeter whereas, crystallinity of the starch *in situ* was measured by X-ray diffraction. The meal was defatted and used for the determination of nutrient contents as well as the carbohydrate, protein and lipid profiles. Simultaneously, all these parameters were determined for the native millet (NM) also.

4.1. Physical properties

A. The color, diameter and hardness of the HTM were determined as explained earlier.

B. Surface area and sphericity

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

Surface area, $S = \pi D_g^2$

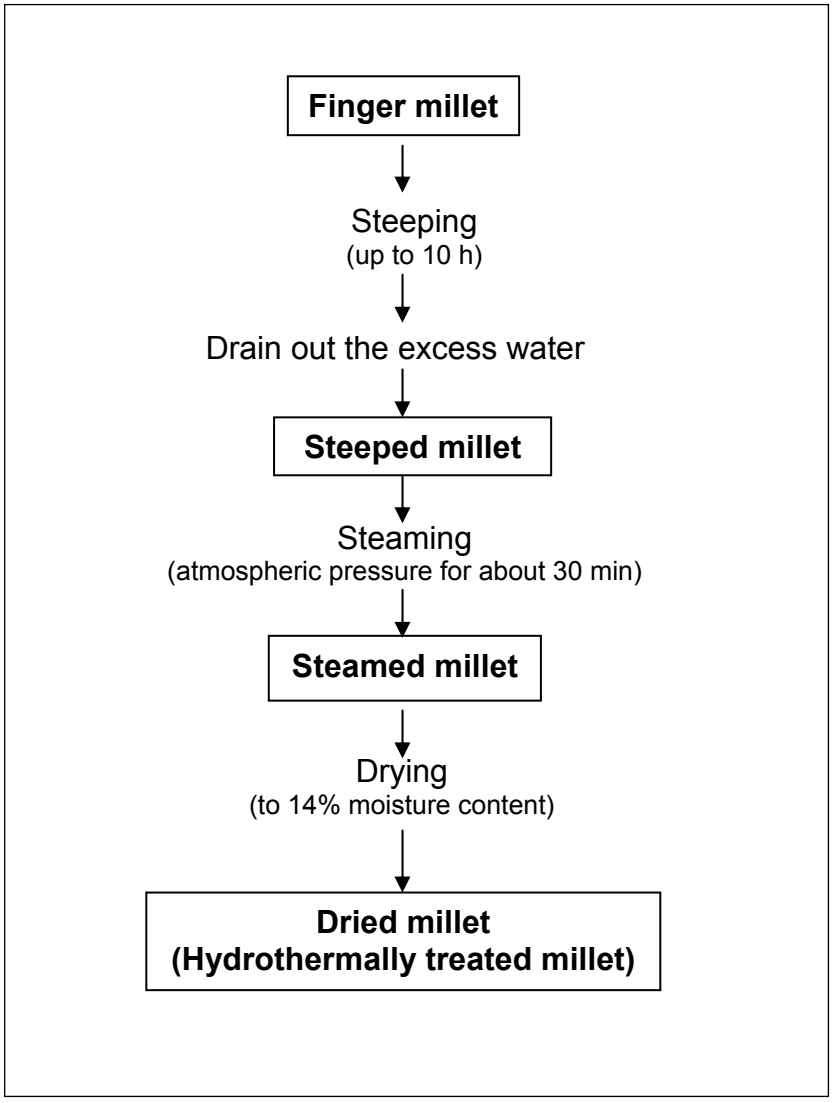


Figure 8. Flow chart for the preparation of hydrothermally treated finger millet

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

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

Simultaneously, the 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 the sphericity was calculated based on 10 individual kernels.

C. Thousand kernel weight, volume and density

One thousand grains were counted in a Numigral grain counter (Tecator, Hoganas, Sweden) and their weight as well as the apparent volume was measured. The volume was recorded in a 5 ml measuring cylinder. The average of three independent determinations was recorded.

Based on the weight and volume of the 1000 kernels, the apparent density was calculated. However, the true density was determined by toluene displacement method using 50 g the sample (Varnamkhasti et al., 2008).

D. Porosity

The porosity of the millet was calculated based on the apparent and the true density of the grains, by the following relationship;

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

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

4.2. Nutrient composition

A. Moisture, **fat**, **protein** and **ash** contents of the millet meal were determined according to AACC (2000) methods and the **soluble**, **insoluble** and **total dietary fiber** contents were determined by the method of Asp et al. (1983). The ash content was dissolved in dilute HCl and the solution was used for estimation of calcium by precipitating as calcium oxalate (AOAC, 2000), whereas copper, zinc and iron contents were estimated by atomic

absorption spectroscopy (AOAC, 2000).

B. Protein digestibility

To 1 g each of the samples 15 ml of 0.1N HCl containing 15 mg of pepsin was added and incubated at 37^{o}C for 3 h. The contents were neutralized with 0.2N NaOH and to that 7.5 ml of phosphate buffer (0.05M, pH 8) containing 4 mg of pancreatin was added. The reaction mixture was incubated at 37^{o}C for 24 h (Mouliswar et al., 1993), made up to 50 ml with distilled water and centrifuged at 1650×g for 20 min. An aliquot of the supernatant was analyzed for its protein content following Lowry's method (Schacterle and Pollack, 1973).

C. Carbohydrate digestibility

The samples (100 mg) were mixed with 10 ml water containing 0.1 ml of termamyl and heated in a boiling water bath for 15 min. To the contents, 15 mg of pepsin in 15 ml of 0.2M glycine - HCl buffer (pH 2) was added and incubated at 37^{o}C for 2 h, neutralized with 0.2 N NaOH and to that 15 ml of 0.05M phosphate buffer (pH 6.8) containing15 mg of pancreatin was added and incubated at 37^{o}C for 2 h. The pH of the reaction mixture was then lowered to 4.5 using dilute acetic acid to which 15 ml of 0.05M acetate buffer containing 15 mg of glucoamylase was added and incubated for 2 h at 55^{o} C. The glucose released was estimated using the dinitrosalicylic acid reagent (Ngo Som et al., 1992).

4.3. Carbohydrate profile

A. Free sugars

Twenty gram each of the samples mixed with 70% ethanol (25% w/v) was refluxed for about 2 h, cooled to room temperature and centrifuged. The extraction was repeated with the residue till the extract tested negative for sugars. The extracts were pooled and freed from the colored matter as well as the non-sugar constituents by passing through dowex (H^{+}) and dowex (OH^{-}) resins successively and concentrated under vacuum. The total sugar contents of the extract were determined by phenol sulphuric acid method (Ford, 1981).

To identify the component sugars, 10 - 20 μl of diluted sugar solution (extract) was fractionated by high performance liquid chromatography

(Shimadzu LC- 8A liquid chromatogram fitted with a aminopropyl column of 25 cm length 4.6 mm diameter and equipped with a CBM-8A system controller, SPD-M8 AVP photo diode array detector and a software class 8A), using water-acetonitrile (25:75) as mobile phase at a flow rate of 1.5 ml/min and the eluted constituent sugars were identified using glucose, fructose, galactose, maltose, sucrose, xylose, arabinose, ribose, mannose and lactose standards.

B. Starch

The total and soluble amylose contents of the HTM and NM were determined as per Sowbhagya and Bhattacharya (1971) and the starch was fractionated following gel permeation chromatographic methodology. To 50 mg of the defatted sample, 4 ml of 90% dimethyl sulphoxide was added, the contents were boiled in a water bath for 15 min, centrifuged, and an aliquot of the supernatant containing 10 mg carbohydrates was fractionated by ascending chromatography on a Sepharose CL-2B (Pharmacia Fine Chemicals, Sweden) column (1.6 $\times$ 60 cm) using a peristaltic pump, at a flow rate of 15 ml h^{-1}. The carbohydrates were eluted with double-distilled water containing 0.02% sodium azide and 3 ml aliquots of the eluent was collected in tubes numbering 50 (Chinnaswamy and Bhattacharya, 1986b) and the carbohydrate content was estimated using the phenol-sulphuric acid method (Ford, 1981).

C. Non-starch polysaccharides

The residue from the free sugar extraction (23.5 g) was used for isolation of non-starch polysaccharide (NSP) fractions. The procedure followed for the isolation of the different fractions is presented in Figure 9.

The residue after extraction of free sugar was mixed with 200 ml of distilled water, the contents were stirred for 2 h at room temperature and centrifuged. The process was repeated thrice and the extracts were pooled, dialyzed, concentrated in a rotary flash evaporator and freeze dried in a Virtis Lyophilizer, and weighed to determine **cold water soluble NSP** contents.

The residue obtained after the cold-water soluble NSP extraction was suspended in about 100 ml water and the slurry was cooked to gelatinize the starch.

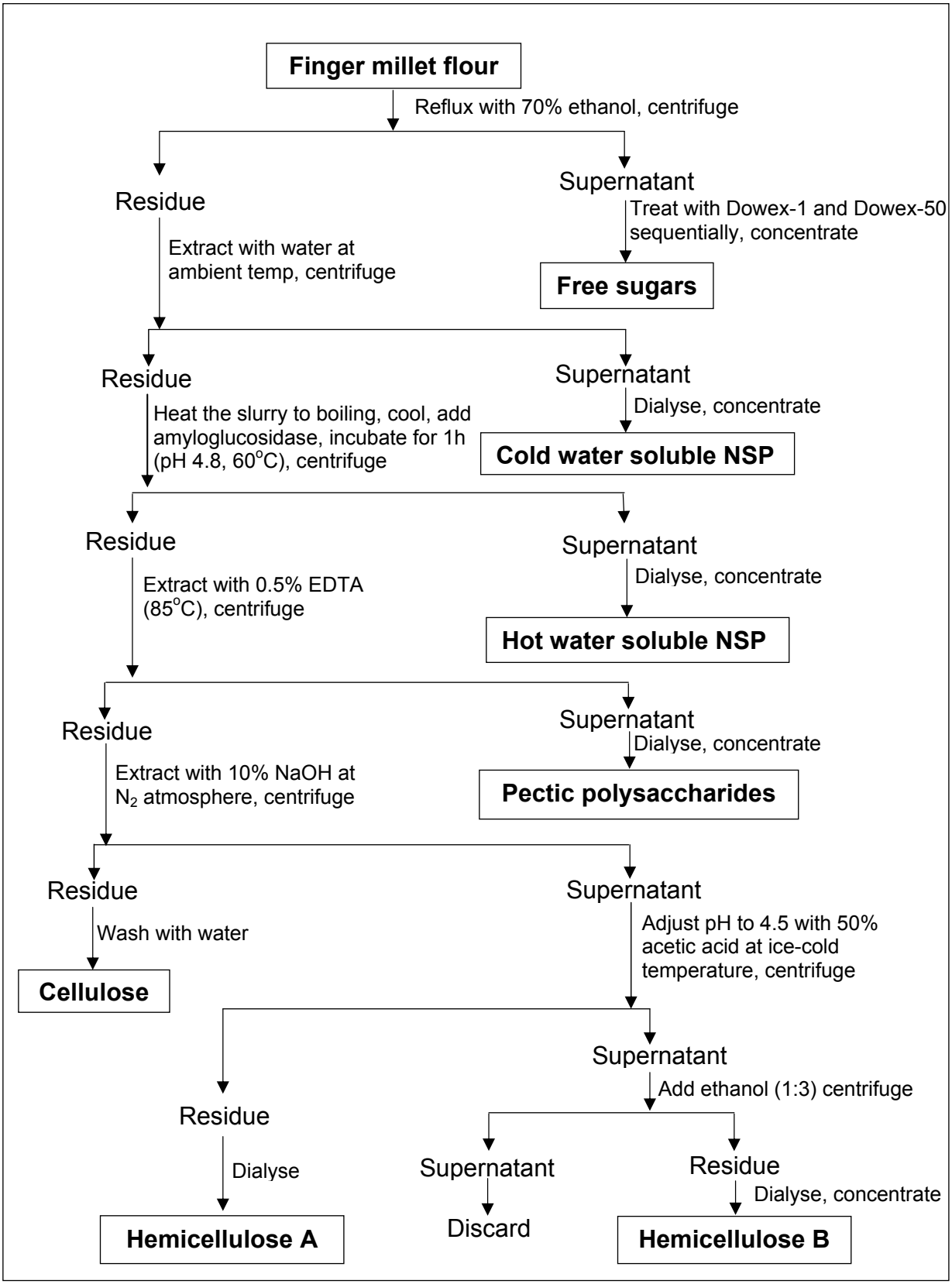


Figure 9. Flow chart for isolation of non-starch polysaccharides

One hundred ml of 0.05M acetate buffer (pH 4.8) containing 500 mg amyloglucosidase was added to the gelatinized slurry and incubated at 60^{o}C for starch hydrolysis. After completion of the starch hydrolysis, the contents were centrifuged and the centrifugate was dialyzed, concentrated and lyophilized and the **hot water soluble NSP** content was noted.

The residue from hot-water soluble NSP was extracted successively thrice with 0.5% ethylene diamine tetraacetic acid (EDTA) (100 - 150 ml) at 80^{o}C for 2 h, the extract was centrifuged, dialysed, concentrated and freeze dried for determination of **pectic polysaccharide** contents.

To the residue, 10% NaOH solution was added drop-by-drop under nitrogen atmosphere and stirred for 4 h and centrifuged. The supernatant was used for the isolation of hemicellulose A and hemicellulose B fractions whereas the residue formed the cellulose.

The pH of the supernatant was adjusted to 4.5 with 50% acetic acid at ice-cold temperature and the precipitated **hemicellulose A** was separated by centrifugation, dialyzed and freeze-dried. To the centrifugate, 3 volume of ethanol was added and the precipitated **hemicellulose B** fraction was collected by centrifugation. It was dialyzed and freeze dried.

The residue from hemicellulose extraction was washed repeatedly with water, the washings were discarded and the residue was freeze dried to get **cellulose** fraction.

The isolated polysaccharide fractions (5 mg) were suspended in 0.3 ml of water, to that 0.7 ml of conc. H_2SO_4 was added at ice-cold temperature and allowed to stand for 30 min. The contents were diluted with water (6.1 ml) to bring down the acid concentration to 8% and refluxed in water bath for 10 - 12 h after which the volume of the hydrolysate was made up to 20 ml and used to estimate total carbohydrates, uronic acid and also for preparation of alditol acetate derivatives. To an aliquot of hydrolysate (containing 5 to 50 μg of uronic acid), 3.0 ml of conc. H_2SO_4 was added drop wise at ice-cold temperature. The contents were boiled in water bath for 20 min, cooled to

room temperature and to that 0.1 ml of 0.1% alcoholic carbazole reagent was added. The reaction mixture was kept in dark for 2 h and the absorbance measured at 530 nm to estimate the **Uronic acid** content (Knutson and Jeanes, 1968).

The hydrolysates were neutralized with $BaCO_3$ and filtered. The filtrate was treated with amberlite resin to remove excess barium ions and then it was concentrated in a flash evaporator. To the concentrate taken in a stoppered test tube, 0.2 ml of inositol (5 mg/ml), 0.5 ml of 0.1 M Na_2CO_3 and 1 g sodium borohydride were added. After about 8 h standing, excess borohydride was destroyed by adding 2 N acetic acid drop wise and the boric acid formed was removed by co-distillation with methanol. The resulting glycerols were acetylated with pyridine in presence of acetic anhydride (0.5 ml, 1:1, v/v) in boiling water bath for 2 h to prepare alditol acetate derivatives. Excess reagents from the derivatives were removed by successive evaporations with water and toluene (Sawardekar et al., 1965). The alditol acetate derivatives were dissolved in chloroform and the component sugars were separated by gas liquid chromatography and the component sugars were identified using the standard sugars.

4.4. Protein fractionation

Five gram of the defatted meal was extracted with 15 ml of the solvents as indicated below sequentially (Youssef, 1998). In each case the samples, as well as the residues were extracted for 1 h with continuous stirring followed by centrifugation at 4300×g for 20 min (Figure 10). The protein contents of the fractions were estimated as per Lowry's method (Schacterle and Pollack, 1973) and their relative proportions were calculated.

1. Distilled water (Fraction I, contains albumins)
2. 5% NaCl (Fraction II, contains globulins)
3. 60% tertiary butanol containing 0.1% guanidine hydrochloride (Fraction III, contains prolamins)
4. 60% tertiary butanol containing 1% guanidine hydrochloride and 0.6M mercaptoethanol (Fraction IV, contains prolamin like proteins)

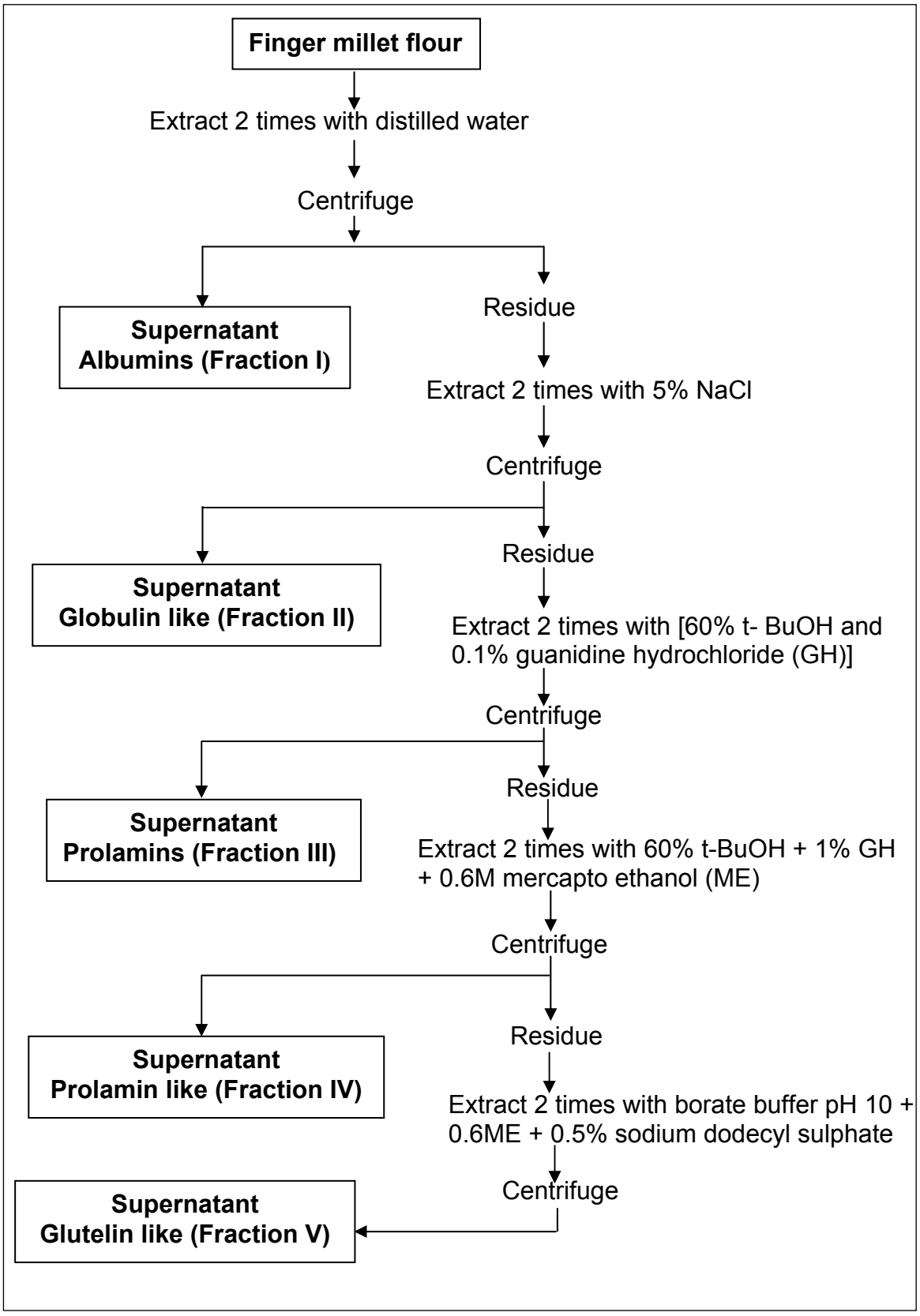


Figure 10. Flow chart for isolation of protein fractions

5. Borate buffer (pH 10) with 0.6M mercaptoethanol and 0.5M sodium dodecyl sulphate (Fraction V, contains glutelin like proteins).

The total proteins of the HTM were also fractionated through SDS-PAGE electrophoresis. For the purpose, 50 mg the defatted sample was extracted with 300 µl of extractant containing 4% SDS, 2M urea and 5% of 2-mercaptoethanol, for 1 h followed by centrifugation at 4300×g. An aliquot of the extract was fractionated using SDS-PAGE electrophoresis (Mini-Slab Gel, Balaji Scientific Services, Chennai, India) at a constant voltage of 50 V for 3 h (Table 4) and the individual protein bands were compared with that of the protein standards.

Table 4. Composition of SDS-PAGE stacking and resolving gels

	Stacking gel (5%)	Resolving gel (12%)
Acrylamide (ml)	0.83	4.0
Running/stacking buffer (ml)	1.25	2.5
Water (ml)	2.835	3.2
APS (µl)	30	60
TEMED (µl)	10	10
SDS (µl)	100	100

APS: Ammonium per sulphate
TEMED: N,N,N,N, Tetra methyl ethylene diamine
SDS: Sodium dodecyl sulphate

4.5. Fatty acids profile

The fat content of the meal was extracted with petroleum ether (60 - 80^{o}C) and to 40 mg of extracted fat, 1 ml of dichloromethane / benzene followed by 2 ml of 1% sodium methoxide solution (1 g sodium dissolved in 100 ml of anhydrous methanol) were added. The contents were heated to 50^{o}C for 10 min, cooled and mixed with 0.1 ml of glacial acetic acid, 5 ml of distilled water and 15 ml of petroleum ether (40 - 60^{o}C), sequentially, and the fatty acid contents of the organic layer were fractionated by gas chromatography (Model

GC-15A, Shimadzu Corporation, Kyoto, Japan) using a 15% diethylene glycol succinate (DGS) column (Krishnamurthy et al., 1983).

4.6. Functional properties

A. The viscosity and hydration kinetics of the HTM were determined as explained earlier, whereas, swelling power, solubility index and pasting profiles were studied as described below.

B. Swelling power and solubility Index

To 1g of the meal taken in graduated centrifuge tubes, 10 ml of distilled water was added and boiled for 30 min in a water bath with occasional stirring and the contents were centrifuged at 1750×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. Subsequently, the weight and volume of the wet residue in the centrifuge tube was noted to determine the swelling power according to Stone and Lorenz (1984).

C. Pasting characteristics

A 15% (w/v) slurry of the flour taken in the bowl of the amylograph was heated progressively from 30 to 92^{o}C at 7.5^{o}C increase per minute, maintained at 92^{o}C for 1 min and cooled to 50^{o}C at the same rate and the changes in the viscosity was recorded in a Brabender Viscoamylograph (Model No. 803202, Brabender, Duisburg, Germany).

4.7. Thermal properties of the starch

To 5 mg of the sample taken in aluminium crucibles, 20 μL water was added, mixed well, the crucibles were sealed, equilibrated for 2 h and scanned in a differential scanning calorimeter (821^{e} Mettler Toledo, Greifefsee, Switzerland) to record the calorigrams. The thermal transition of the starch content of the sample in terms of onset and peak temperature and also the end point of gelatinization were recorded from the calorigrams.

4.8. X-ray diffractogram

The whole meal was packed in rectangular glass crucibles and exposed to X-ray beam generated by X-ray diffractometer (MiniFlex – II, Desktop X-ray diffractometer, Japan) equipped with a θ-θ goniometer at 25 mA and 30 KV,

with Cu kα filtered radiation. The scanning range for 2θ was set to 6 - 45° to cover all the significant diffraction peaks of crystallites with a scan speed of 3° per min. The microstructural parameters of starch in the millet were computed from the X-ray diffraction pattern by a single order method based on Warren-Averbach Fourier theory (Warren and Averbach, 1952). For this purpose, a known analytical function for crystal size distribution was used (Somashekarappa et al., 1999). The isolated starch from the native millet was taken as a reference sample for the studies.

4.9. Degree of gelatinization

The degree of gelatinization of the starch content was determined by amylose-iodine complex method. To 200 mg of the defatted sample taken in a test tube, 98 ml of water was added and treated with 2 ml of 10M KOH solution and the contents were gently agitated for 5 min. The slurry was centrifuged and 1 ml of the supernatant was treated with 0.4 ml of 0.5 M HCl and made up to 10 ml with water and to that 0.1 ml of iodine reagent was added and the absorbance (A) was read at 600 nm. In a separate experiment, 200 mg of the defatted sample taken in a test tube, 5 ml of 10M KOH solution was added and the contents were agitated gently followed by centrifugation. To 1 ml of the supernatant, 1.0 ml of 0.5M HCl was added, the volume was made up to 10 ml with water and to that 0.1 ml of iodine reagent was added and the color developed was measured (B). The ratio of the absorbance (A/B) obtained from each sample was proportional to the degree of gelatinization (Birch and Priestley, 1973).

4.10. Microscopic examination

A. Light microscopy

The millet kernels were processed for fixing the biochemical constituents prior to sectioning (Berlyn and Miksche, 1976). The grains were soaked in solution of 0.5% glutaraldehyde in 0.025M phosphate buffer (pH 7.0) for 48 h with two changes of 24 h each. The glutaraldehyde treated grains were dehydrated by successively passing through ethanol series and subsequently by ethanol-xylene series as shown in the flow diagram (Figure 11). The dehydrated grains were infiltrated with paraffin wax and then suspended in xylene.

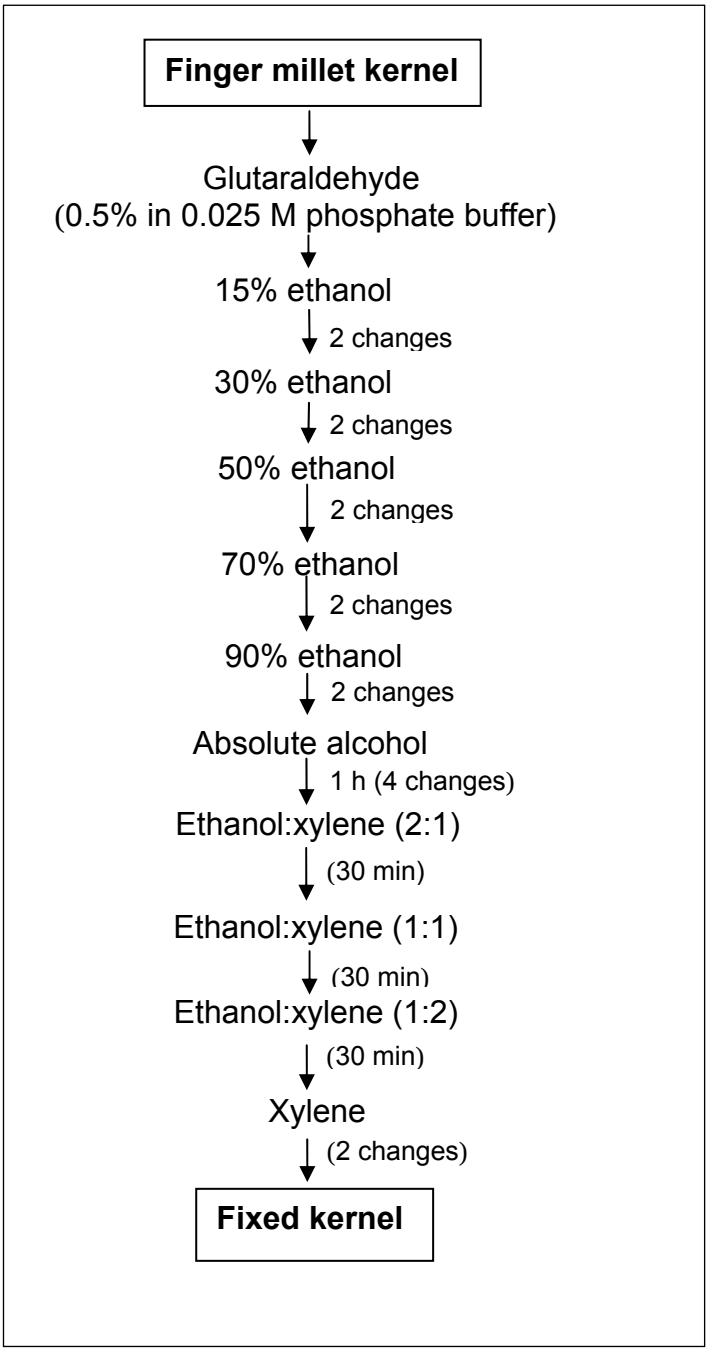


Figure 11. Flow diagram showing various steps followed for fixation of millet kernels for microscopy

To that, scrapings of wax was added till the xylene was saturated with paraffin wax and the contents were left overnight at room temperature and incubated at 58^{o}C. The melted wax was decanted and replenished with fresh wax and the process was repeated (4 to 5 times) till the material was free from xylene. The grains were then embedded in a mixture of paraffin wax and bees wax (95:5) to make the blocks. The blocks were cut open to expose the grains, soaked in 20% aqueous glycerol for 24 h at 4^{o}C and the thin sections (about 7 μm) were taken. The sections were suspended in xylene to dewax and were passed through xylene:ethanol series followed by ethanol series in ascending order as shown in the flow chart (Figure 11). Subsequently, some of the sections were stained for protein and starch contents with erythrosine and fast green FCF respectively, and viewed under light microscope for examining the organization of the cell walls and the starch granules.

B. Scanning electron microscopy

The kernels from HTM and NM equilibrated to 10% moisture contents were used for microscopic examination of the cellular organization of the endosperm as well as the aleurone tissue, for the granular organization of the starch in the cells and also for the morphological features of the surface of the kernel using scanning electron microscope. The grains were cut transversely and also longitudinally into two halves using a sharp blade. The cut portions were mounted on the metallic stubs with the aid of double-sided scotch tape to expose the seed coat and also the endosperm portion. The samples were gold coated (about 100 A^{o}) in a KSE 2AM 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) and the selected portions depicting morphological features of the seed coat and also the endosperm were selectively photographed (Meek, 1976).

5. Dry heat parboiling

Dry heat parboiling of rice is practiced widely. The process involves agitation of the steeped cereal in hot sand. This is relatively simple method and requires lower capital investment compared to steam parboiling. Hence, the

feasibility of adapting this method for the millet was also explored. For the purpose, the millet steeped to the EMC was blotted to remove the surface moisture content and then dropped in sand (material to sand ratio used was 1:8) heated to 110 to 180^{o}C with 10^{o}C increment, agitated continuously for 30 to 120 sec depending upon the temperature. The grains were separated immediately by sieving off the sand. The dry heat treated (DHT) millet in each case were examined critically for the translucency and gelatinization of starch and based on that, the sample treated at a temperature of 150^{o}C for 30 sec was taken for evaluation of some of its physical properties and also for its decortication characteristics.

RESULTS AND DISCUSSIONS

1. Hydrothermal treatment

The main process variables involved in the hydrothermal treatment of the millet namely, steeping, steaming and drying are independent of each other but the overall quality characteristics of the product depends on all these. Hence, a brief account of each one of these on the quality characteristics of the hydrothermally treated millet is discussed below.

1.1. Steeping

The hydration characteristics of the millet steeped at different temperatures indicated that the rate of hydration is temperature dependent and increases with the increase in temperature of steep water. Higher the temperature of the steep water, not only the rate of water absorption was rapid but also the hydration capacity of the millet was slightly higher. During the initial stages of soaking, a steep rise up to about 25% in the moisture content of the millet was observed which subsequently slowed down till the millet attained the equilibrium moisture content (EMC). The EMC of the millet was 35% at 30^{o}C and it increased to 36, 37 and 38% at 50, 60 and 70^{o}C, respectively (Figure 12). While the duration of steeping for attaining EMC was about 10 h at 30^{o}C but it reduced to 7, 5, 2.5 and 1.75 h, at 40, 50, 60 and 70^{o}C, respectively. The increase in the rate of hydration at higher temperature could be due to the solubilization of some of the seed coat constituents leading to opening up of the pores thereby facilitating easy water penetration into the grain.

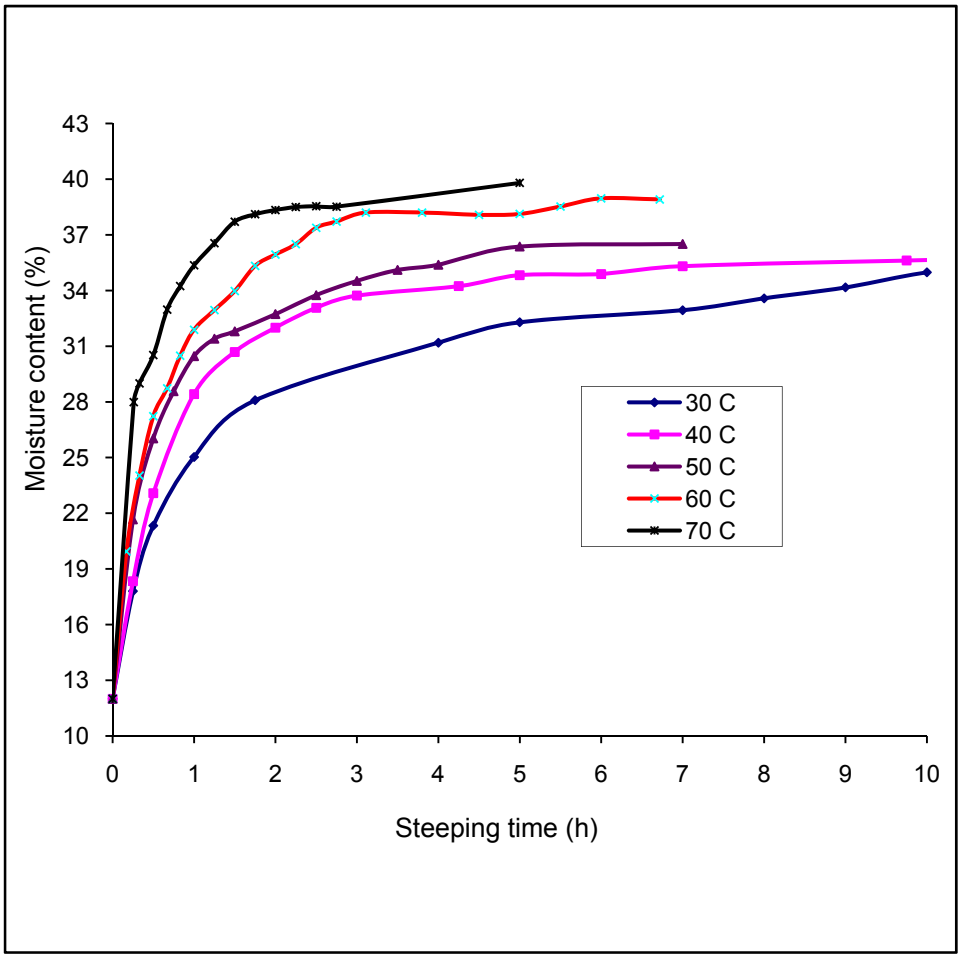


Figure 12. Hydration kinetics of native finger millet steeped at different temperatures

It could be also due to the disruption of hydrogen bonds and weakening of the micellar structure of starch granules thereby enhancing the hydration capacity (Maskan, 2002; Thakur and Gupta, 2006). In addition to these, the water holding capacity increases due to partial gelatinization of starch granules, especially the smaller sized granules at 50 to 70^{o}C.

Absorption of water by the cereal grains can be regarded as a process of diffusion (Bandopadhyay and Ghose, 1965). Due to the moisture gradient between the surface and the inner portion of the grain, the moisture diffusion into the grain takes place. This gradient is low at lower temperature and appreciable only at high temperatures (Becker, 1959; Bhattacharya and Subba Rao, 1966). The rate of moisture transfer into the grain is directly proportional to the difference between the saturation moisture content, M_s, and moisture content of the grain at any given time, M, and is termed as the moisture driving potential (M_s-M). For a constant value of M_s, an increase in moisture content, reduced the potential (M_s-M), resulting in a lower moisture uptake at later stages of hydration (Deshpande et al., 1994).

The increase in the moisture content of the grains on steeping is due to filling up of the void spaces of the endosperm and also due to absorption of water by cell walls, starch and protein contents of the grain. Even though, proteins form a smaller component in cereals, it also absorbs a substantial proportion of water (Mayer and Polja, 1975) along with starch. The other components such as mucilages, cellulose and pectic substances also contribute to the phenomenon. Thus, the total water absorbed by the millet will be the additive of the water absorbed by starch, protein, non-starch polysaccharides and also the water molecules entrapped between the layers of seed coat and also in the voids between the seed coat and the endosperm.

A. Leaching loss

During steeping, some of the water-soluble constituents of the millet such as sugars, soluble starch, amino acids, proteins and polyphenols as well as pigments and minerals leach out in the steep water. Total leaching loss of the millet after soaking for about 10 h at ambient temperature was hardly 0.1% and the leachets mainly contained free sugars (62.15$\pm$1.0%), amylose

(24.37±0.4%), protein (7.7±0.3%) and polyphenols (5.78±0.2%) (Table 5). Anthoni Raj and Singaravadivel (1980) and also Ali and Bhattacharya (1980) reported sugars, amino acids and phenolic compounds as the main constituents of the leachets in case of rice. Besides these, the water-soluble vitamins, minerals and phytochemicals normally leach out into the steep water. Generally, steeping at elevated temperature causes excessive solubilization of the seed coat matter of cereals facilitating leaching of the nutrients and the same could be expected in the case of the millet also.

Table 5. Composition of leachets (g/100g)

Amylose	24.37±0.4
Proteins	7.70±0.3
Total sugars	62.15±1.0
Polyphenols	5.78±0.2

1.2. Steaming

Steaming is the most important unit operation of hydrothermal treatment as the major changes with respect to the physicochemical properties of the millet including the endosperm modification take place during steaming. The most important among them is the gelatinization of starch (Bhattacharya and Ali, 1985). The starch granules of the steeped grains start swelling as the temperature increases and the amylopectin component of the starch, containing more number of hydrophilic groups, absorbs more water, resulting in swelling of the granules. As gelatinization proceeds, the granules get ruptured, facilitating melting of the starch crystallites leading to a total change in the endosperm to a homogeneous mass. Apart from this, the protein bodies normally get denatured, the oil globules get ruptured and polyphenols undergo partial hydrolysis and some of them bind with starch and proteins. These changes lead to cementing of the cellular components on drying or dehydration and thereby hardening it. Browning of the endosperm occurs due to Maillard reaction. Due to these changes, the grain assumes special physical properties such as plasticity, translucency etc (Otegbayo et al., 2001). However, the seed coat of the millet hinders swelling of the endosperm to its full capacity even though it undergoes gelatinization. The millet on

steaming swells slightly and looks translucent and slightly bulged as compared to the native millet. Since, steaming is the most important unit operation of hydrothermal treatment to the millet, wherein most of the physicochemical changes occur, the various physicochemical changes that take place during steaming the millet have been discussed in detail in the forgoing text separately.

1.3. Drying

The steamed millet contains about 36% moisture and hence it is necessary to dry it to safe storage moisture level (12 - 14%). Hence, drying is very important processing step in the hydrothermal treatment and it also influences the physicochemical properties of the millet to a large extent. The drying conditions caused visible changes on the morphological features of the millet besides on its overall quality attributes. The rate of drying at the ambient ($30\pm1^{o}C$) temperature was slow and the material exhibited undesirable smell, probably due to microbial growth. On the other hand, drying at temperature higher than $50^{o}C$ caused rapid dehydration but at the same time it caused visible crack formation as well as excessive physical deformation. Generally, development of cracks or fissures in cereals is common phenomenon whenever the grains are dried at temperature higher than $60^{o}C$ (Cnossen, et al., 2003). Rapid drying produces a steep moisture gradient in the grain as the moisture from the surface evaporates at a faster rate and in turn the moisture from the interior portion migrates to the peripheral portion of the grain. Because of this, the inner portion of the grain contracts and the peripheral portion expands, and the stress and strain thus created causes moisture gradient leading to formation of fissures in the grain (Kunze, 2001). The fissures develop into visible cracks shortly after drying. Apart from this, the grains normally undergo bulging or swelling during steaming, get contracted during drying leading to undulations which is shown by the visible surface deformation. However, the extent of the deformation is largely dependent on the temperature of drying, it is low at lower temperature and severe at higher temperature. Hence, to avoid the formation of fissures and also the severe deformation, drying at slightly higher than ambient but lower than $50^{o}C$, is highly desirable. Probably because of this, shade drying is followed for

steamed paddy and in the case of sun drying or hot air drying, the semidried material (about 18% moisture content) is heaped for equilibration of moisture in the grain before it is finally dried to safe storage moisture level (Bhattacharya and Indudhara Swamy, 1967).

The dehydration characteristics of the steamed millet presented in Figure 13, reveals that, the loss in moisture content of the millet was rapid in the initial 2 h of drying and slowed down in later stages. Like any other cereals, the drying curve is asymptotic and the grain reached the moisture content of about 5% after 3 h of drying at 39±1°C under the experimental conditions.

Drying of the grain can be treated as a mass transfer. Normally the loss of moisture in the grain held by starchy endosperm and the seed coat, is a function of time (Igathinathane and Chattopadhyay, 1999). Moisture gradient causes differential stress inside the kernel, which if sufficiently large, causes fissures in the kernel (Cnossen, et al., 2003).

2. Influence of steaming time on quality characteristics of the millet

Steaming significantly influences the endosperm characteristics of cereals and hence, the influence of steaming conditions with special reference to the steaming time on some of the quality characteristics of the millet was determined. For the purpose, the millet steeped for 10 h at ambient conditions was steamed for 5 to 35 min at atmospheric pressure, dried at 40±2°C to 14±1% moisture level. The samples were evaluated for color, hardness, viscosity, total and soluble amylose contents as well as the hydration characteristics. In addition to this, the millet steamed for varying steam pressure from 1 to 4 kg/cm^2 and dried under similar conditions to 14±1% level was evaluated for its grain hardness. Steaming the millet beyond 4 kg/cm^2 caused disintegration of grains and hence the steam pressure was limited to 4 kg/cm^2 only.

The **color** of the cereal grain is one of the important parameter which reflects the type of processing that it has undergone. The color of the millet was recorded in terms of the L*, a*, b* indices and the ΔE values. The 'L*'

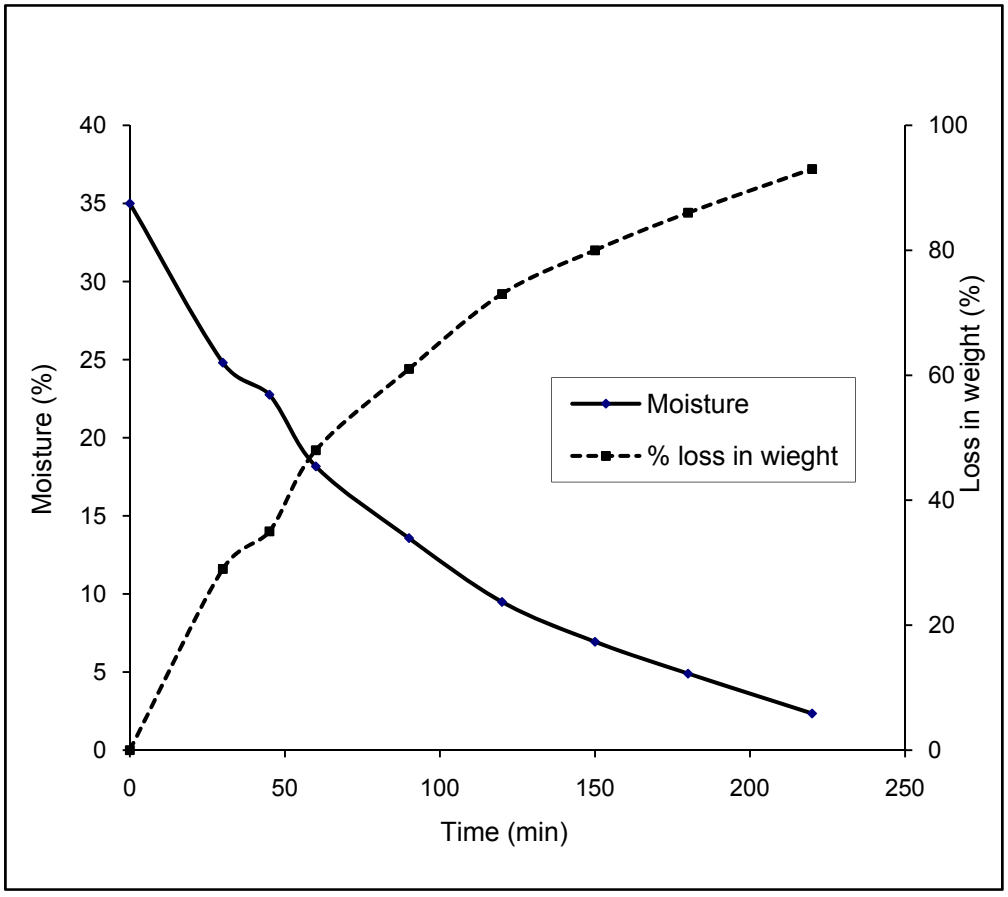


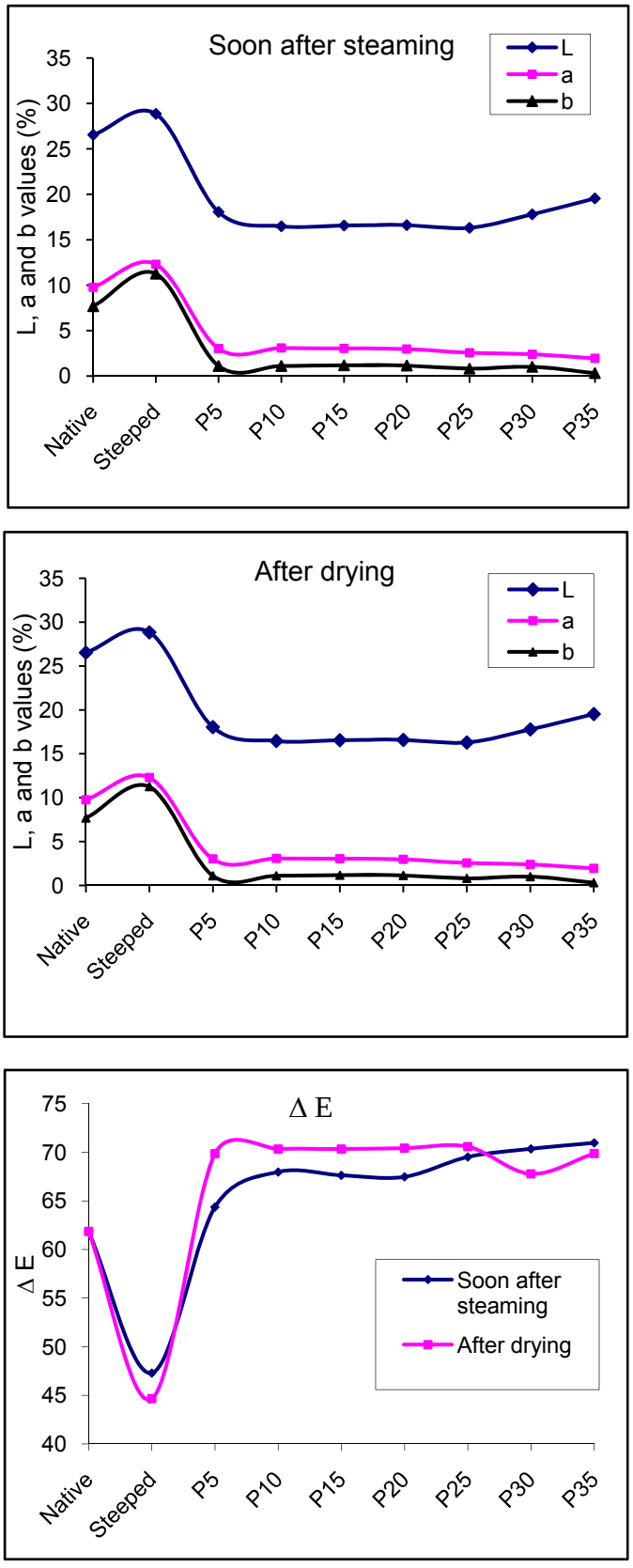
Figure 13. Dehydration characteristics of steamed finger millet

values represent lightness, positive and negative values for 'a*' represent redness and greenness, and likewise, positive and negative values for 'b*' represent yellowness and blueness respectively. The ΔE represents deviation in the color values of the test material from the standard, the absolute white taken as 100 (Krishna Murthy and Kantha, 2005). In the present study no negative values for a* and b* indices were observed for the native, steamed as well as the dried millet.

The changes in the intensities of color indices of the millet from native to steeped, steeped to steamed and steamed to dried state presented in the Figure 14, clearly bring out the fact that the major changes in the color of the millet occurs during steaming as well as during drying. The color of the millet became light on steeping as indicated by the changes in L*, a* and b* values from 31, 11 and 12 to 44, 7.5 and 7.2, on steeping. This is also reflected by the decrease in the ΔE values from 61.8 to 47.3. The change in the color of the steeped grains could be due to the removal of the adhering dirt and also solubilization of some of the pigments of the seed coat during steeping the millet. Lamberts et al. (2006) also reported similar information with respect to the color during steeping of the brown rice. They recorded 13% decrease in the yellowness values of the flour from brown rice to the flour prepared from steeped and freeze dried brown rice.

As mentioned earlier, steaming and drying caused considerable changes in the color indices of the millet. The maximum change in the color occurs within the initial 5 min of steaming and probably, darkening of the millet initiates soon after exposing the material to live steam. This was clear from the decreased lightness values from 31 to 14.8, redness from 9.8 to 5.5 and yellowness from 7.7 to 3.1, respectively that occurred within 5 min, which did not change appreciably on steaming the millet for longer period (Figure 14). However, only the yellowness values decreased from 3.1 to 2.4 on extending the steaming time from 5 to 35 min.

On the other hand, drying the steamed millet caused considerable changes in all the color indices, as the L*, a* and b* values of the steamed millet changed from 14.8 to 16.1, 5.5 to 3.0 and 3.1 to 1.1, respectively, on



P5 - P35: millet steamed from 5 to 35 min

Figure 14. Influence of steaming time on the color indices of steamed and dried finger millet

drying. However, the color of the steamed millet varied depending up on the steaming conditions, as the intensity of the darkness increased with the duration of steaming. This was evident from the increase in lightness (16.1 to 19.5) values and decrease in redness (3.0 to 1.9) and yellowness (1.1 to 0.32) values.

The overall difference in the color of the grain recorded in terms of ΔE, increased significantly (from 65.4 to 76.3) soon after steaming and exhibited a marginal increase (from 76.3 to 77.5) as the steaming time increased. However, on drying the steamed millet, a slight decrease in the ΔE values (76.3 to 72.8) was observed. The changes in the color of the millet from the native to steeped, steeped to steamed and steamed to dried millet is illustrated in the Figure 15.

The color indices of the flours from 5 min steamed and dried millet (P5) as well as the NM are indicated in Figure 16. The noteworthy features of the changes in the color of the millet on hydrothermal treatment observed in the present study are; the difference in the ΔE values between the grain and the meal from both the NM and P5 is 40. Likewise, the difference between ΔE values of P5 and NM in their grain as well as in the meal form is 7.4. This clearly shows that drastic difference exists between the color of the endosperm and the seed coat, as it is well known that in the case of the millet, the seed coat is colored whereas its endosperm is white. Steaming causes a proportionate increase in the darkness of both the seed coat and the endosperm of the millet.

A negative correlation has been reported between the severity of parboiling and the color of the grains in the case of rice. According to Pillaiyar and Mohandoss (1981a), among all the color indices, lightness was the best indicator of discoloration, which was mainly affected by the temperature and the duration of steaming. Kimura et al. (1993) also reported that higher the steam pressure or longer the steaming time, lower were the lightness values for rice. Or in other words, the color of the rice changes to light yellow or amber after parboiling.

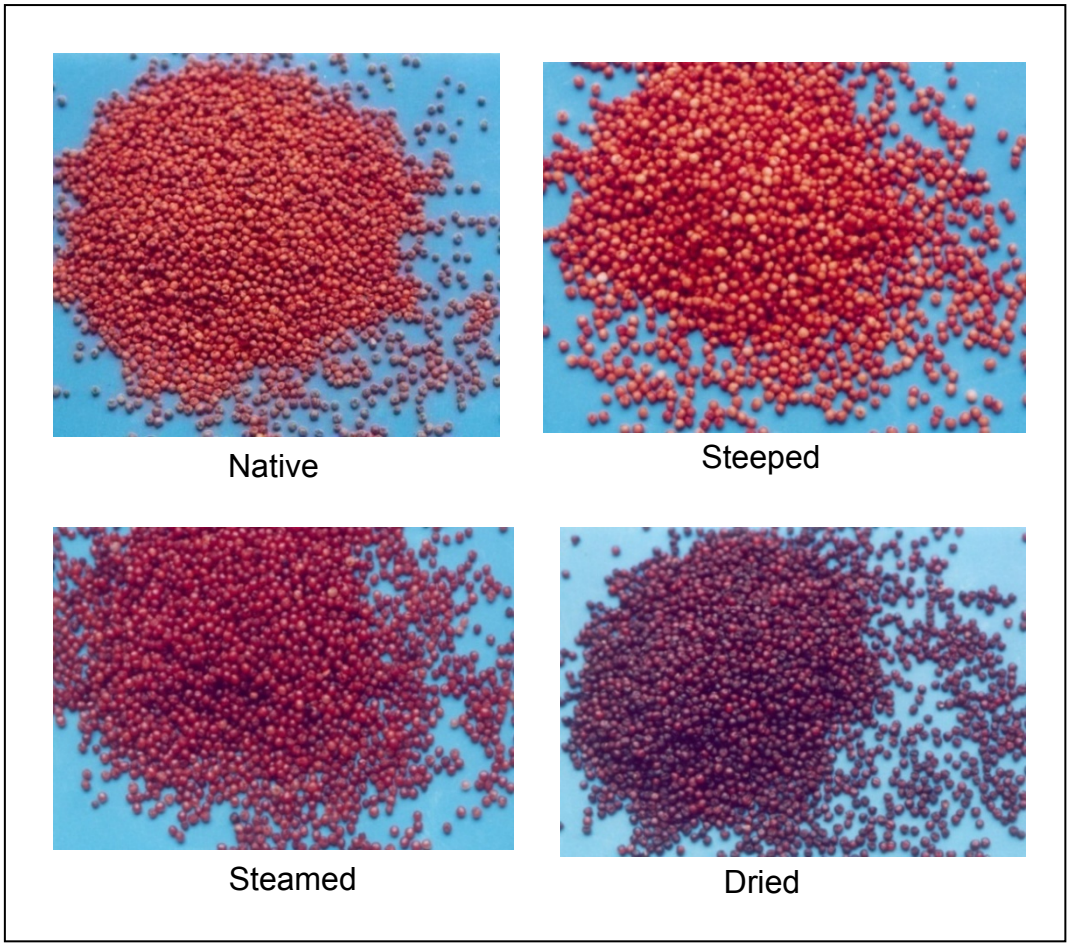
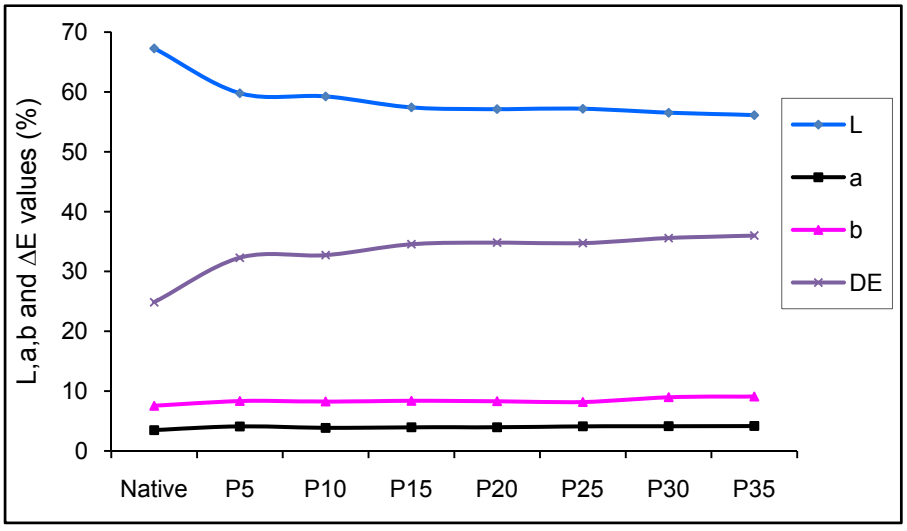


Figure 15. The color of finger millet kernels at different stages of hydrothermal treatment



P5- P35: millet steamed from 5 to 35 min

Figure 16. Influence of the steaming time on the color indices of finger millet flour

Darkening of the millet seed coat on hydrothermal treatment is mainly due to the polymerization of the polyphenols and pigments present in the seed coat. On the other hand, browning of the endosperm is mainly due to the non-enzymatic browning reaction of the endosperm constituents and also diffusion of pigments and the polyphenols from the seed coat. There are at least two pathways through which browning takes place namely, Maillard and caramelization pathways. Both pathways involve sugars as the main substrates (Horrobin et al., 2003). The reducing sugars and amino acids present in the millet thus may involve in these browning reactions leading to the dark color of the millet after hydrothermal treatment. Diffusion of the pigments into the endosperm during soaking has been reported for rice also (Islam et al., 2004; Lamberts et al., 2006).

The **hardness** of the millet also increased significantly as the duration of steaming increased up to 35 min. It increased by about 3.3 fold (37 to 123 N) within the initial 5 min of steaming, which further increased to 235 N (6 fold) when the steaming time extended up to 30 min and subsequently, there was no substantial increase. However, extending the steaming time beyond 35 min was not followed as some of the grain burst opened and a portion of the endosperm was exuded. From Table 6, it could be observed that steaming for 5 min caused sharp increase in hardness and beyond that, the increase in hardness was gradual. During steaming, the void spaces in the endosperm get filled by the swollen starch granules, the protein bodies in the endosperm disintegrate and bind to the starch and the cell wall components get compacted and these factors cause hardening of the grain (Nawab and Pandya, 1974; Bakshi and Singh, 1980).

The increase in hardness of rice due to the increase in the duration of steaming has been reported by Pillaiyar and Mohandoss (1981a). They reported 1.1 to 2 fold increase in the hardness of rice as the temperature and duration of steaming increased. Normally, with the increase in the severity of the steaming conditions, the hardness of the grain increases to certain extent and beyond that, a part of the endosperm is exuded out. This destroys the integrity of the kernel and thereby decreases the hardness. Hence, normally

Table 6. Influence of steaming time on some of the quality characteristics of finger millet

	Hardness (N)	Diameter (mm)	Cooked paste viscosity (cP)	Total amylose (g%)	Soluble amylose (g%)	TA/SA
Native	37^{a}	1.48^{e}	415^{h}	16.7^{a}	11.0^{d}	1.52^{a}
P 5	123^{b}	1.38^{d}	182^{g}	18.4^{bcd}	10.5^{cd}	1.75^{b}
P10	145^{c}	1.35^{c}	167^{f}	18.5^{bcd}	10.5^{cd}	1.76^{c}
P15	152^{d}	1.34^{bc}	156^{e}	18.7^{bcd}	10.1^{bcd}	1.85^{c}
P20	165^{e}	1.34^{bc}	152^{d}	18.7^{bcd}	9.8^{bcd}	1.91^{d}
P25	189^{e}	1.28^{a}	138^{c}	19.1^{d}	9.6^{abc}	1.99^{e}
P30	235^{g}	1.27^{a}	133^{b}	19.0^{d}	8.7^{a}	2.18^{f}
P35	235^{g}	1.28^{a}	131^{a}	19.0^{d}	8.6^{a}	2.21^{g}

Values in the same column with different superscripts differ significantly ($P \leq 0.5$) according to Duncan's multiple range test (DMRT)

P5-P35: steamed from 5 to 35 min

TA: total amylose; SA: soluble amylose

during parboiling of cereals, steaming time is limited not only to gelatinize the starch but also to retain the integrity of the grain which otherwise will have adverse effect on milling qualities and its food value. The increase in the hardness of the grain due to steaming has advantage with respect to several technological and functional qualities of the cereals, especially minimizing the breakage of the kernels during milling.

Steaming followed by drying the millet slightly reduced the overall size of the grain which is evident from the decrease in grain **diameter** from 1.48 to 1.38 mm. The diameter further decreased to 1.28 mm as the steaming time increased from 5 to 25 min and thereafter remained constant up to 35 min (Table 6). Even though, the millet kernels appear to be bulged soon after steaming, drying exerts shrinkage in the size of the grain. This may be due to removal of the moisture from the grain leading to shrinkage of the different tissues during drying. It may be recalled here that air vents which exist between the endosperm and the seed coat get filled by the expanded endosperm on steaming and this causes slight bulging of the kernel. However, on drying, the seed coat matter collapses and adheres to the shrunken endosperm. This not only leads to the overall reduction in the size but also to the formation of undulations.

The steaming time also exerted considerable influence on the cooked paste **viscosity** of the millet. The viscosity of 10% slurry of the NM was 415 cP, whereas that from the millet steamed for 5 min was 182 cP, indicating 56% reduction. Steaming the millet up to 30 min decreased the viscosity to 131 cP and extending the steaming time beyond 30 min did not show any significant decrease in the viscosity (Table 6).

The decrease in the viscosity of the millet as a result of hydrothermal treatment could be due to the physicochemical changes its endosperm constituents undergo. The starch being the major constituent of the endosperm, the changes in its characteristics will have major influence on the variations in the viscosity of the millet. During steaming and drying, the starch undergoes gelatinization as well as retrogradation. Since, the retrograded starch is known to swell to a lesser extent than its native starch, viscosity of

the steamed and dried material will be normally lower than its native starch. Besides this, the particle size of the flour from the steamed and dried millet being slightly coarser compared to the particle size of the native millet, it absorbs lower level of moisture at the post-gelatinization temperature and exhibits reduced swelling power. This factor also could be one of the reasons for the lower cooked paste viscosity of the steamed and dried millet. In case of rice also Unnikrishnan and Bhattacharya, (1981) observed that the swelling power is altered by parboiling and the swelling power of the parboiled rice flour at 70^{o}C and above temperature is lower than the raw rice.

The fundamental changes during hydrothermal treatment are; the gelatinization of the starch and also complexing of the amylose component with lipids and proteins and in view of this, the **solubility of the amylose** is altered. Steaming the millet for 5 min increased its total amylose content from 16.7 to 18.4% and extending the steaming time up to 35 min did not show any noticeable changes in its content. However, the solubility of the amylose decreased from 11 to 8.6% as the duration of steaming increased from 5 to 35 min (Table 6).

The cleavage of some of long chain branches of amylopectin may occur during hydrothermal treatment leading to the changes in the amylose contents. The complexing of the amylose with lipids and proteins will also add to this factor. While the first factor results in the increased measure of apparent amylose, the second factor decreased the soluble amylose. The gelatinization of the millet during steaming followed by the retrogradation of amylose component during drying may be the reason for the decrease in the soluble portion. This could be clearly observed from the gradual increase in the ratio of total to soluble amylose content from 1.52 to 2.21 (Table 6) with the increase in the steaming time. In case of rice also it has been reported that parboiling does not alter the overall content of its amylose but enhances its solubility (Ali and Bhattacharya, 1972).

Similar to the other parameters described earlier, steaming the millet for about 5 min brought out major changes in its hydration characteristics also. The EMC of the millet which was 35% in its native stage changed to

42% on steaming for 5 min (Figure 17). But the EMC was also dependent on the temperature of the steep water, as it was 42% at 30^{o}C and it increased to 43 and 44% at 60 and 70^{o}C, respectively. It was also observed that the kernels started burst opening and lost their integrity on steeping beyond 9, 1.5, and 0.67 h at 30, 60 and 70^{o}C, respectively. Kernel disintegration occurs at all the temperatures of the steeping, but the disintegration occurs at much longer time at lower temperature compared to that at higher temperatures. The rate of hydration of the millet steamed for longer time was also followed similar trend except for the millet steamed for 20 min, which exhibited slightly higher moisture content than the other samples at any given point. This peculiar behavior of the millet was confirmed by determining the EMC for all the samples separately, by steeping at 30^{o}C and noticed that the EMC of the millet increased gradually as the steaming time increased up to 20 min and subsequently, a slight decreased was observed (Figure 18). This could be due to the proportionate increase in the degree of starch gelatinization up to 20 min of steaming and followed by a slight thermal degradation of the gelatinized starch, as the steaming time increased. However, the hydration kinetics of the millet steamed for 10, 15, 25 and 35 min were intermediate to that of the millet steamed for 5 and 20 min.

The rate of hydration of the millet steamed for different duration at 60^{o}C showed almost similar trend (Figure 19). However, the hydration kinetics of the millet steamed for 20 and 30 min were overlapped on each other. The rate of hydration at 70^{o}C was also followed similar trend except for the millet steamed for 30 min, which exhibited slightly lower rate of hydration than the other samples (Figure 20). However, the moisture content of the millet at any given point was higher for the higher temperature of steeping, irrespective of the steaming time of the millet. This is clearly indicated in Figure 21, which shows the differences in the rate of hydration recorded in terms of moisture content of the sample at intermediate stage of steeping time (40 min). A significant difference could be seen in the moisture content of all the samples steeped at 30^{o}C when compared that at 60^{o}C. However, there was no appreciable difference between the samples steeped at 60 and 70^{o}C.

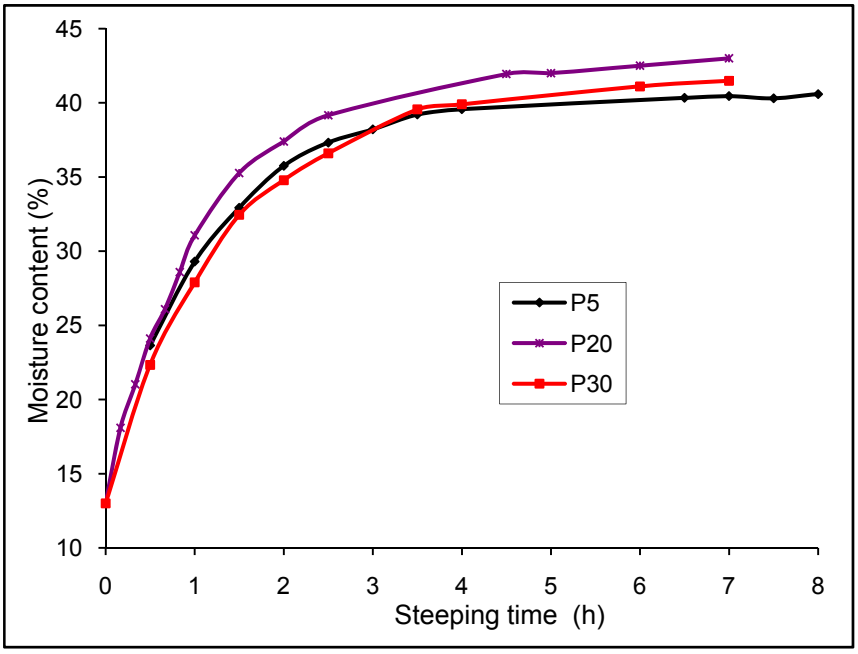
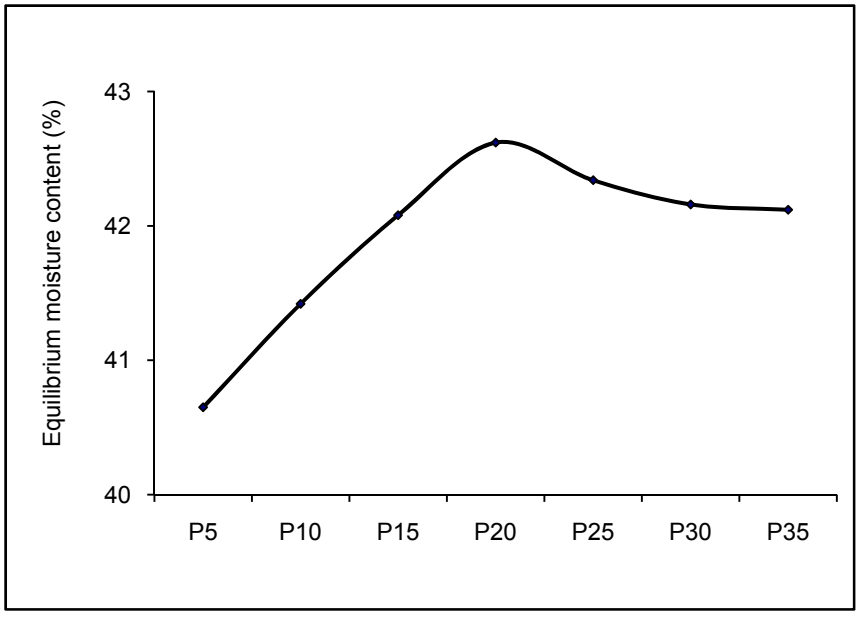


Figure 17. Influence of steaming time on the hydration kinetics of finger millet at 30°C



P5-P35: Steamed from 5 to 35 min

Figure 18. Influence of steaming time on the equilibrium moisture content of finger millet at 30°C

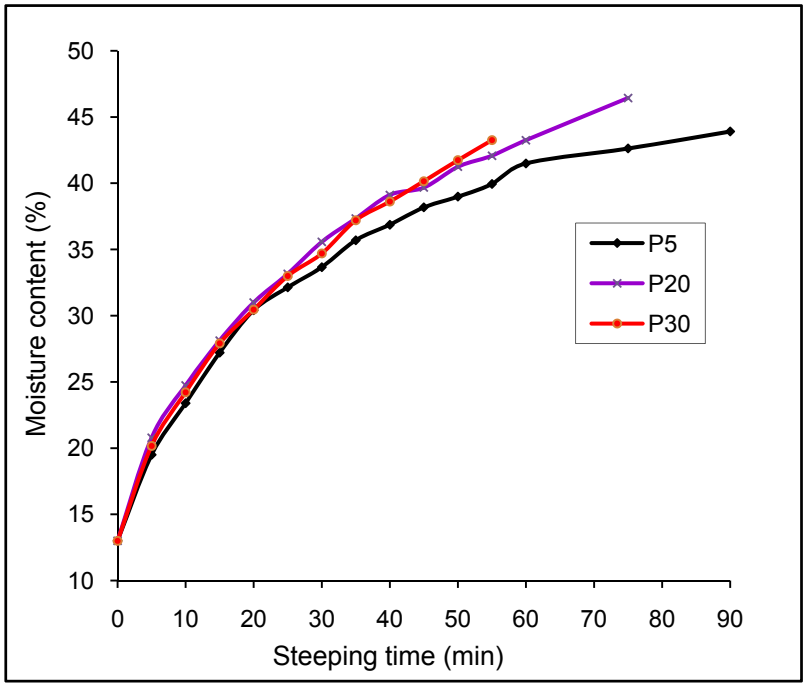


Figure 19. Hydration kinetics of finger millet steamed for different duration at 60°C

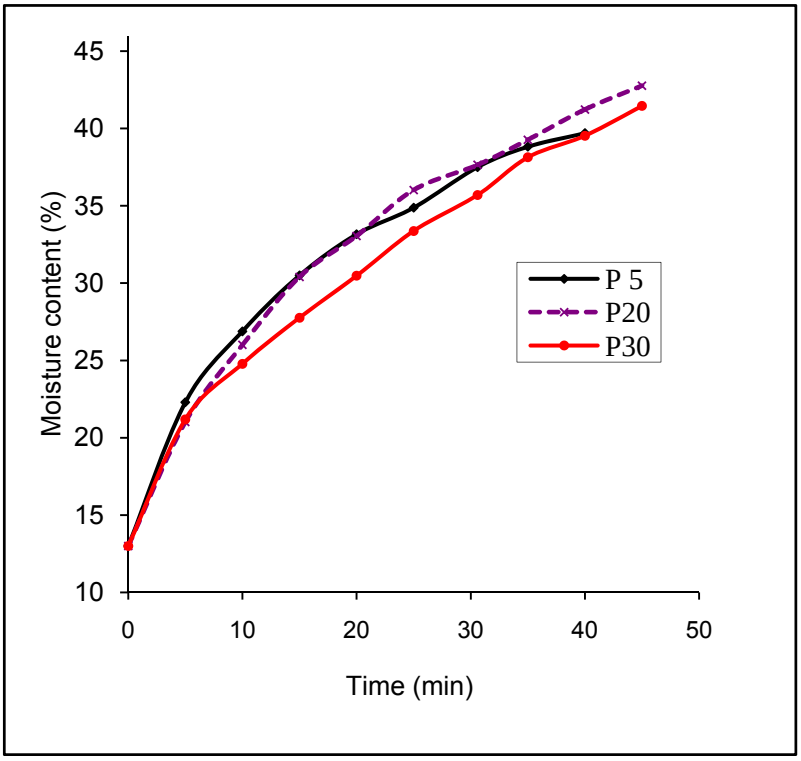
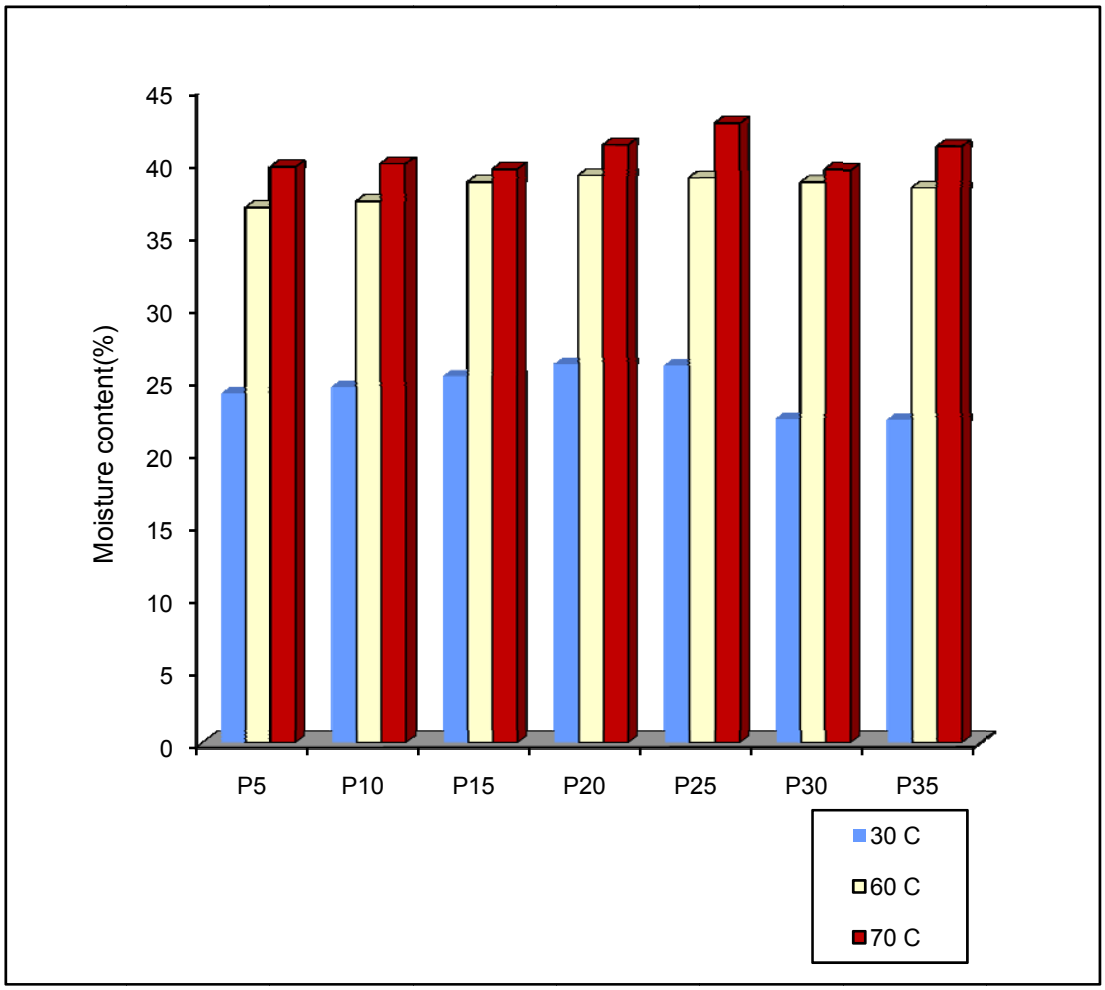


Figure 20. Influence of steaming time on the hydration kinetics of finger millet at 70°C



P5 - P35: steamed from 5 to 35 min

Figure 21. Moisture content of finger millet steamed for varying time after steeping for 40 min at different temperatures

The hydration characteristics of the parboiled rice studied by several workers clearly reveal that, the kinetics of hydration is largely dependent on the severity of parboiling and also it has been reported that, the EMC of parboiled rice is higher at lower temperature of steeping (30^{o}C) and is lower at higher temperature of steeping (80^{o}C). Ali and Bhattacharya (1972) in their studies on hydration and amylose solubility behavior of parboiled rice, reported that, the rate of hydration of rice at temperatures above the gelatinization point decreases on parboiling, the extent of decrease being again proportional to the severity of treatment. Unlike rice, in the case of millet, the rate of hydration and the EMCs increased with the increase in the temperature of the steep water but did not follow any particular trend as the duration of the steaming increased.

The steamed millet contains gelatinized starch and denatured protein and its water holding capacity is normally higher than NM. However, its hydration capacity increases as the temperature of the steep water increases. Hence, steeping the grains at higher temperature for longer duration probably, imbibes more and more water and as a result, swelling of the endosperm occurs. This exerts pressure on the seed coat, which gives up beyond certain level. The seed coat of the millet normally consists of non-starch polysaccharides, proteins, lipids and phytochemicals. Out of these, the non-starch polysaccharides normally absorb higher levels of water during steeping the millet and may swell further. During this process, some of the water soluble components from the seed coat, especially the pectin and hemicelluloses may lose their gummy nature and hence the seed coat as a tissue, loses its strength, leading to burst opening during steeping. It was also noticed that, the leachets including colored pigments were negligible during steeping irrespective of the severity of steaming. Normally, the native millet on steeping to its EMC swells up to 20% of its original volume, but contrary to this, the steamed millet swells by only about 10% and the kernels which were shrunken did not regain the original size completely.

The effect of **pressure steaming** on the hardness of the grain was positive to certain extent namely about 20, 17, 10 and 6 min at 1, 2, 3 and

4 kg/cm^2 pressure, respectively. As mentioned earlier, steaming beyond 4 kg/cm^2 pressure was not feasible because the grains lost their integrity and part of the endosperm exuded out. The millet steamed under pressure was slightly harder than that steamed at atmospheric pressure (Figure 22). Hence, to obtain the hydrothermally treated millet suitable for decortication, the following conditions were found optimum, either 30 min steaming at atmospheric pressure or 20 min at 1 kg/cm^2 or 17 min at 2 kg/cm^2 or 10 min at 3 kg/cm^2 or 6 min at kg/cm^2. The influence of steam pressure on the various quality parameters of the millet along with the hardness have been discussed in detail in Chapter III, wherein, the various factors influencing the decortication characteristics of the millet have been focused. However, for all practical purpose, steaming at atmospheric pressure is more feasible, which can be carried out at household or cottage level using the existing facilities. Hence, for the further studies, the millet steamed at atmospheric pressure was considered.

The most important quality characteristic of the millet on hydrothermal treatment is the grain hardness that enables decortication of the millet. The changes in hardness, grain diameter, viscosity, total and soluble amylose contents were not significant beyond 30 min of steaming. The preliminary studies on decortication characteristics of the millet steamed for different time indicated that, enhancing the grain hardness up to 235 N was highly desirable. Thus, from the above observations on color, hardness, hydration characteristics, viscosity and grain diameter of the steamed millet, it was inferred that steaming the millet at atmospheric pressure for 30 min was optimum to transform the soft and fragile nature of the endosperm of the millet into a rigid mass, suitable for preparation of decorticated millet. In view of this, further studies on the quality characteristics of the hydrothermally treated millet were concentrated only on the millet **steamed for 30 min** (denoted as **HTM** in the forgoing text).

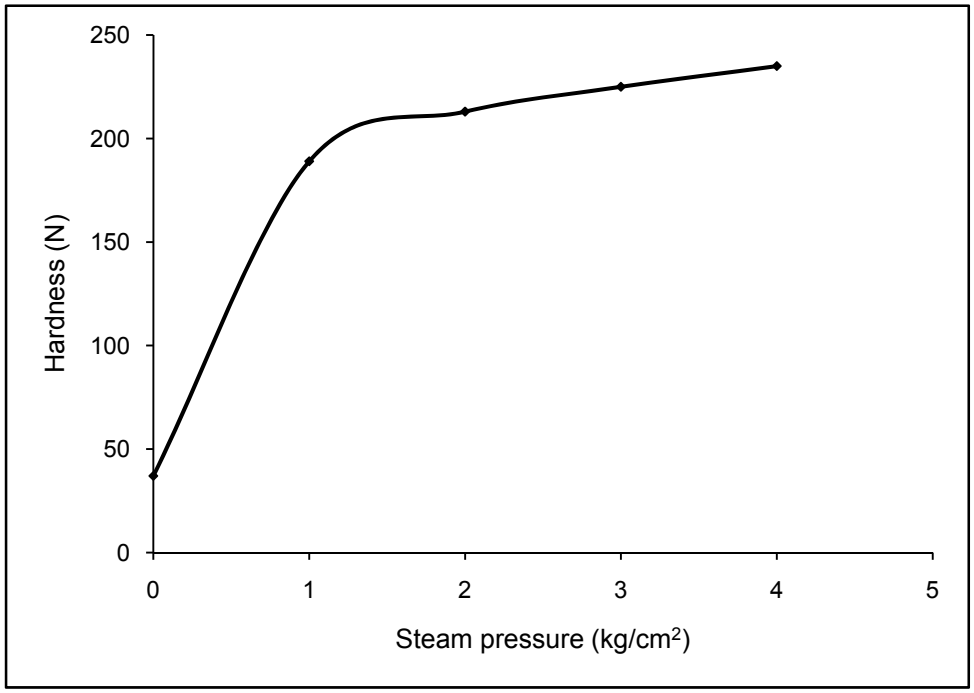


Figure 22. Effect of steam pressure on the hardness of finger millet

3. Quality characteristics of the hydrothermally treated millet (HTM)

3.1. Physical properties

A. Color

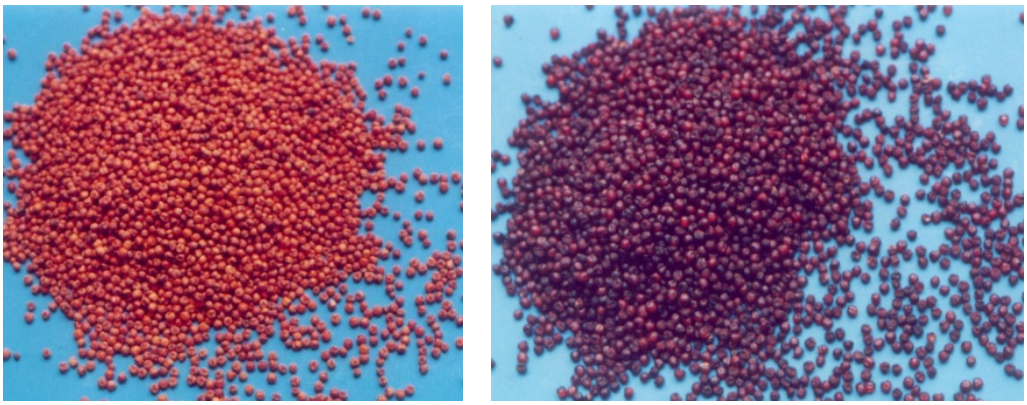
The HTM was of dark brown color with lightness (L*), redness (a*) and yellowness (b*) values of 13.8, 2.1 and 0.8, as against 23.8, 9.1 and 7.3 for that of NM, respectively (Table 7). The color of the grain recorded in terms of the ΔE values was 77 for HTM and 68 for NM revealing the intense dark dolor of the HTM. The L*, a* and b* values for the meal from HTM were 57.9, 3.13 and 8.66, while the corresponding values for the meal from the NM was 67.1, 3.09 and 8.45, respectively. The ΔE value for the meal from HTM (34) was also significantly higher than the NM (25). From these observations it may be noted that, darkening of the millet is not only confined to the seed coat but also to the endosperm (Figure 23). The difference between the lightness values of HTM grains and its meal was 44 whereas the corresponding values for NM grain and its meal was also about 44. Likewise, the difference in the lightness values of the HTM and NM grains was 10 units, almost comparable to their corresponding meals (9.2). Interestingly, the difference in ΔE values of the HTM grains and its flour (43) was same as that of NM grains and its flour (43). Similarly, the difference between the ΔE values of the HTM and NM grains was 8.99 and that of the HTM and NM meals was 8.83. It may be recalled here that, the differences in the color of the NM and HTM as well as that between the grains and flours of HTM and NM were 40 and 7.3, respectively, for the sample steamed for 5 min and the similar trend was observed even for sample steamed for 30 min. These observations show that the changes in color of the endosperm as well as the seed coat matter increased in concurrence with the steaming time. The results indicate that the relative difference between the color of the seed coat and the endosperm of the native millet is proportional to steaming, but the degree of darkening depends upon the steaming time.

B. Grain diameter, sphericity, density and porosity

Some of the important physical parameters of HTM and NM are presented in Table 8. The grain diameter of the HTM (1.46 mm) was slightly lower than that of NM (1.48 mm) and in concurrence with that, the surface area of the NM

Table 7. Color indices of native and hydrothermally treated finger millet

Colour	Native		Hydrothermally treated	
	Grains	Whole meal	Grains	Whole meal
L*	23.75±0.07	67.11±0.1	13.73±0.07	57.91±0.1
a*	9.09±0.07	3.09±0.07	2.07±0.07	3.13±0.02
b*	7.33±0.05	8.45±0.02	0.80±0.01	8.66±0.1
ΔE	68.05±0.1	25.19±0.07	77.04±0.1	34.02±0.07



NM HTM

Figure 23. Photograph of native and hydrothermally treated finger millet grains

Table 8. Some of the physical properties of the native and hydrothermally treated finger millet

Parameter	Native	Hydrothermally treated	Percentage change
Grain diameter (mm)	1.48±0.02	1.46±0.04	(-) 1.4
Grain surface area (mm^2)	9.24±0.10	8.92±0.20	(-) 3.5
Sphericity	0.93±0.03	0.89±0.05	(-) 4.3
1000 kernel weight (g)	3.49±0.05	2.71±0.07	(-) 22.0
1000 kernel volume (g/ml)	4.20±0.07	4.10±0.10	(-) 2.4
Bulk density (g/ml)	0.83±0.01	0.77±0.03	(-) 7.2
True density	1.31±0.04	1.35±0.03	3.0
Porosity	36.00±2.00	43.00±3.00	19.4
Hardness (N)	37.00±5.00	235.00±8.10	535.0

kernels also decreased from 9.24 to 8.92 mm^2 on processing. These changes are mostly due to shrinkage in the size of the kernels. The sphericity and the bulk density of the millet decreased after hydrothermal treatment from 0.93 and 0.83 g/ml to 0.89 and 0.77 g/ml, respectively, whereas, the true density and porosity values increased slightly (from 1.31 to 1.35 g/ml and from 36.3 to 43.0) after hydrothermal treatment.

The hydrothermal treatment to the millet caused flattening of the surface mounds on the surface of the millet resulting in furrows and undulations. Increased undulations of the kernels as a result of hydrothermal treatment reduce the compactness on packing the millet and this increases inter-granular space resulting in lower apparent bulk density for HTM compared to that of NM. This also explains the higher values of the porosity observed for the HTM than that of NM, which is the ratio of the inter-granular void space and volume of the grains in bulk pack (Mohsenin, 1996). Similar to these observations, Reddy and Chakraverty (2004) also reported that the bulk density decreases while the true density and porosity of the paddy increases on parboiling.

C. Textural parameters

The force deformation curves (FDC) of NM and HTM are presented in Figure 24. From the FDC, the maximum force, the number of major peaks, first peak force and the initial slope of the linear portion of the curve were quantified according to Murthy and Bhattacharya (1998). The major peak in the FDC indicates the maximum force required to break the kernel, which generally represents the grain hardness. This force is about 6.35 times higher for HTM than NM, as the hardness of the HTM was 235 N against 37 N for NM. This shows that, hydrothermal treatment enhances the hardness of the millet by several folds. The FDC for the NM exhibited two prominent peaks with a larger number of small sized multiple peaks. The first peak indicates the initial resistance (14 N) offered by the grain against the applied force whereas, the second peak is the total resistance offered by the grain. The smaller multiple peaks could be due to the friable texture of the millet endosperm.

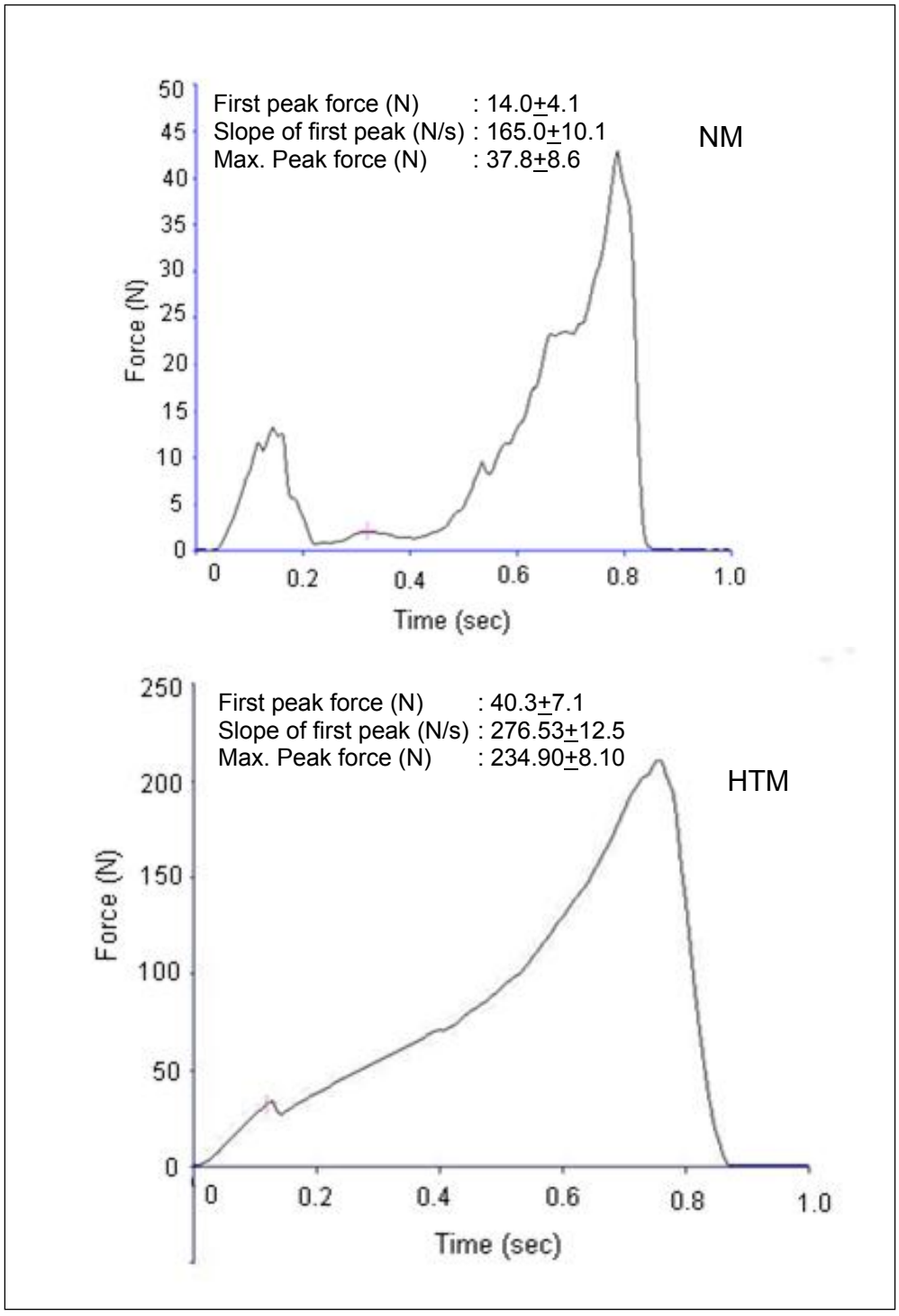


Figure 24. Force deformation curve of native and hydrothermally treated finger millet

The FDC of HTM also showed two peaks but it was conspicuous with respect to the absence of small sized multiple peaks as observed in the case of NM. Or in other words, the smooth curve of the HTM reveals its homogeneity in the endosperm. The significant difference between the ratio of first and second peak of NM (2.5) and HTM (5.9) could be due to the rigidity of the seed coat of HTM as compared to the mutlilayers in case of NM. This is also reflected by the significantly higher value for the slope of HTM (276 N) compared to that of NM (165 N).

From the force deformation curves it could be inferred that, the millet undergoes considerable physical transformation and textural modification during hydrothermal treatment leading to about 6 fold increase in the hardness. Probably, this textural modification enables decortication of the millet which otherwise gets pulverized during milling. It may be noted here that, the increase in the hardness of the millet as a result of hydrothermal treatment is much higher than that reported for rice, as several reports on rice indicate hardly 1.5 to 2 fold increase in the hardness (Pillaiyar and Mohandoss, 1981a; Islam et al., 2004).

The increase in the hardness as a result of hydrothermal treatment is observed for all the cereals and this property helps in minimizing the breakage during milling which is more relevant to rice, as the milling of rice always aims at higher yield of head grains. However, in case of wheat, the soft wheat is bulgurized to enhance its hardness (Sarita et al., 2007), specifically to prepare higher yield of grits which is used for the preparation of soya fortified bulgur wheat (Hayta et al., 2003) for nutrition intervention programs.

3.2. Nutrient composition

The hydrothermal treatment did not cause significant changes in the nutrient contents of the millet (Table 9). The net protein content of the HTM remained almost the same (6.9%) but the ether extractives and also the soluble fiber contents decreased slightly (from 1.54 to 1.16% and from 1.4 to 0.85%, respectively). However, the total dietary fiber content, which is one of the important biochemical constituents of the millet that offers several health benefits, did not undergo quantitative changes as a result of hydrothermal

Table 9. Nutrient composition of native and hydrothermally treated finger millet

	Native	Hydrothermally treated
Moisture (g%)	11.1±0.07	11.1±0.07
Protein (g%)	7.0±0.04	6.9±0.03
Ether extractives (g%)	1.5±0.01	1.2±0.01
Available carbohydrates (g%)	61.0±0.70	62.0±0.50
Total amylose	16.7±0.20	19.1±0.30
Soluble amylose	11.0±0.10	9.7±0.10
Dietary Fiber (g%)		
Soluble	1.4±0.07	0.9±0.01
Insoluble	15.7±0.10	16.0±0.07
Total	17.1±0.20	16.9±0.10
Minerals (mg%)	2.0± 0.02	1.6±0.03
Calcium (mg%)	321.0±2.00	315.0±2.00
Iron (mg%)	6.0±0.10	6.0±0. 07
Copper (mg%)	1.6±0.05	1.2±0.08
Zinc	2.1±0.04	2.1±0.07
Carbohydrate digestibility (%)	61.0±1.00	73.0±2.00
Protein digestibility (%)	79.0±1.00	91.0±2.00

treatment. A slight decrease in the extractable fat may be due to its complexing with the amylose component of the millet starch. A slight variability in the content of some the nutrients could be due to loss of the nutrients during steeping.

A. Carbohydrate digestibility

The hydrothermal processing of the millet enhanced its carbohydrate digestibility by about 12% over its native counterpart (Table 9). Pregelatinization of the starch due to the hydrothermal treatment backed up by the loss of granular rigidity could be the reason for the increase in the carbohydrate digestibility. Besides, a slight decrease in the polyphenol contents could have contributed for the increase in the digestibility, as the millet polyphenols are known to inhibit its carbohydrases (Thompson and Yoon, 1984). It has been reported by Holm and Bjorck (1988), that an increased availability for enzymatic hydrolysis is closely related to the loss of the orderly crystalline structure within the endosperm due to processing.

B. Protein digestibility

Similar to the carbohydrate digestibility, the protein digestibility of HTM (91%) was higher than that of NM (79%). The hydrolysis of protein-polyphenols complex and protein denaturation during hydrothermal treatment besides, degradation of tannins (Ramachandra et al., 1977) on wet heat treatment may be the reason for the increased digestibility of the HTM proteins. Even though, the millet contains hardly 7% proteins, it provides considerable quantity of dietary protein to its consumers due to the quantity of its intake. In the case of the millet, prolamin protein forms the major storage protein and its biological value is relatively lower. But the higher degree of protein digestibility of the HTM may slightly compensate the drawback associated with the prolamins and the HTM may offer better biological value to its foods.

The growth promoting quality of the parboiled cereals has been studied by several workers and according to Serna-Saldivar et al. (1994), the protein efficiency ratio (PER) of the normal sorghum decreases slightly whereas, that of high lysine sorghum remains unchanged on parboiling. Similarly, in case of pearl millet also, the same workers observed slightly lower values for PER on

parboiling. On the contrary, Bender (1978) reported slight increase in the PER values of rice on parboiling.

The hydrothermal treatment did not cause significant alterations in carbohydrate contents of the millet but it induced qualitative changes in the carbohydrate constituents. Accordingly, the changes in the free sugar, starch and the non-starch polysaccharides are discussed below;

3.3. Carbohydrates

A. Free sugars

The major sugars identified in the NM and HTM were glucose, sucrose, fructose and maltose and traces of ribose. The contents of these sugars decreased from 1.10 to 0.71% after hydrothermal treatment (Table 10). The decrease could be due to leaching during steeping and also due to their interaction with the free amino acids due to Maillard reaction during steaming and drying.

B. Starch

The hydrothermal treatment not only altered the ratio of amylose to amylopectin equivalents of the millet but also changed the composition of its amylose slightly. The total amylose content increased from 16.7 to 19.1% but the soluble amylose content decreased from 11 to 9.7%. These changes in the composition of amylose may be due to the retrogradation of the soluble amylose after hydrothermal treatment. In the case of rice also about 6% decrease in the soluble amylose content as a result of parboiling has been reported by Ali and Bhattacharya, (1972). However, the increase in apparent amylose content may be attributed to the cleavage of long chain branches of the amylopectin. It is now well established that, part of amylose in starch exists in a bound form with polar lipids, either as inclusion compounds or linked through hydrogen bonding. Furthermore, the dissociation and reaggregation of amylose chains results in the alteration in the molecular conformation, leading to enhancement of the helical form and thereby lowering the solubility of amylose (Raja and Sindhu, 2000).

Table 10. Free sugar contents (70% aqueous ethanol extracts) of native and hydrothermally treated finger millet (g/100g)

	Native	Hydrothermally treated
Glucose	0.387±0.05	0.298±0.07
Fructose	0.105±0.04	0.044±0.006
Maltose	0.157±0.02	0.134±0.04
Sucrose	0.225±0.03	0.107±0.05
Ribose	0. 086±0.05	ND
Others	0.125±0.06	0.127±0.08
Total	1.085±0.04	0.710±0.06

ND: not detected

The changes in the starch profile were further confirmed by its fractionation by gel permeation chromatography. The chromatograms clearly indicate two fractions, Fraction I, normally representing the larger molecules of starch namely, amylopectin and Fraction II, representing the amylose equivalent part of the starch (Ramesh et al., 1999). The Fraction I, gets eluted at void volume and the Fraction II, enters the gel and gets eluted over a longer elution time. Hydrothermal treatment to native millet caused a slight broadening of the Fraction II. The carbohydrate content of Fraction I in NM was about 61% and that of Fraction II was about 39%, but in the case of HTM, a decrease in the Fraction I (52%) and a proportionate increase in the Fraction II (48%) were observed (Figure 25). Thus, it can be inferred that, nearly 9% of the higher molecular weight carbohydrates, namely, the amylopectin equivalent portion was partially degraded to the amylose equivalents. This is in line with the general observations made by several researchers in the thermally processed cereal carbohydrates. However, the extent of degradation depends upon the severity of the heat treatment (Mahanta and Bhattacharya, 1989).

C. Non-starch polysaccharides (NSP)

Apart from starch and free sugars, the non-starch polysaccharide constituents

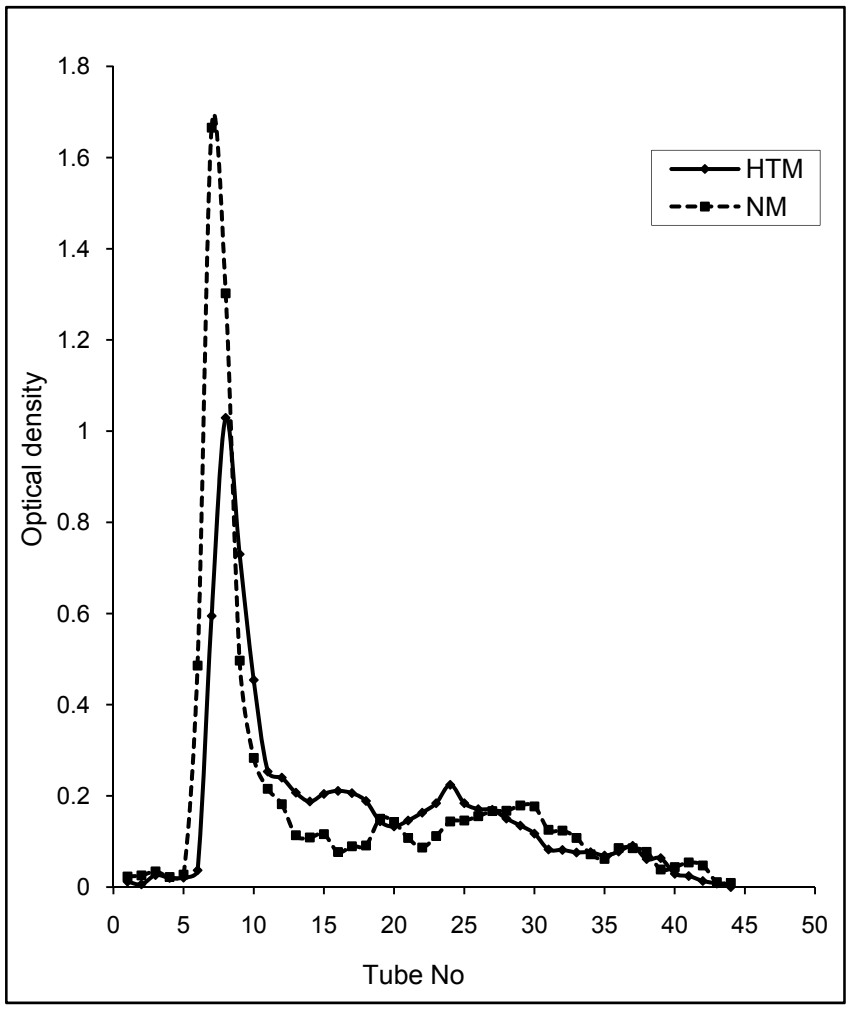


Figure 25. Carbohydrate profiles of native and hydrothermally treated finger millet

also underwent considerable changes in their composition but their content remained almost unchanged, as total NSP content of NM was 20.27% and that of HTM was 20.11% (Table 11).

The cold-water and the hot-water solubles as well as the hemicellulose B fractions of NSP decreased from 2.0, 2.9, 1.53% to 1.57, 0.99 and 0.9%, respectively after hydrothermal treatment whereas, the pectic polysaccharides, the hemicellulose A and also the cellulose fractions increased from 0.9, 0.94, 12.41% to 1.92, 1.38 and 13.35%, respectively. Arabinose, xylose, mannose, glucose and fructose were identified as the major monosaccharides in all the NSP fractions.

The major constituents in cold-water solubles in both NM and HTM were mannose and ribose, but hydrothermal treatment slightly decreased the mannose content (91.7 to 81.9%) and increased the ribose content (1.66 to 8.9%) of this fraction. On the contrary, in the case of hot-water soluble fractions, mannose, ribose and xylose were major sugars and hydrothermal treatment increased the ribose (4.1 to 9.9%) and arabinose (0.9 to 10.8%) contents but decreased xylose (3.2 to 1.4%) content.

The hydrothermal treatment also slightly altered the ratio of pentoses to hexoses of the pectic polysaccharides of the millet. Mannose was the major sugar (88.6%) in the NM with traces of pentoses, but in the case of HTM, fructose was the major sugar (84.6%) with traces of arabinose and xylose.

Similar to pectic polysaccharides, the major sugar in the hemicelluloses A fraction of NM was mannose and the hydrothermal treatment decreased its content by 5% and increased the ribose content by about 2.5%. Unlike hemicellulose A fraction, the constituent sugars in hemicellulose B fraction of the NM were arabinose (21.2%), xylose (24.7%) and fructose (39.1%) with traces of ribose. The HTM exhibited a slight decrease in the arabinose (20.2%), xylose (20.3%) and fructose (29.2%) contents and a proportionate increase in the ribose (8.1%) content. The major sugar in the cellulosic fraction of NM was mannose (80.2%) but in HTM, it was fructose (86.5%).

Table 11. Yield and composition of non-starch polysaccharide fractions of native and hydrothermally treated finger millet (g/100g)

	Cold water soluble		Hot water soluble		Pectic polysaccharides		Hemi cellulose A		Hemi cellulose B		Cellulose	
	NM	HTM	NM	HTM	NM	HTM	NM	HTM	NM	HTM	NM	HTM
Yield	2.0±0.04	1.6±0.05	2.9±0.07	0.99±0.04	0.9±0.07	1.92±0.01	0.94±0.01	1.38±0.02	1.53±0.02	0.9±0.04	12.41±0.08	13.4±0.1
Uronic acid	5.3±0.09	7.83±0.03	9.75±0.1	9.34±0.1	7.32±0.1	8.37±0.1	7.82±0.01	11.8±0.2	7.47±0.01	10.4±0.1	8.79±0.2	7.94±0.03
Constituent sugars (%)												
Ribose	1.66±0.03	8.87±0.04	4.11±0.01	9.9±0.1	0.78±0.02	0.99±0.06	0.78±0.01	3.25±0.1	5.6±0.2	8.1±0.1	4.21±0.1	2.28±0.01
Arabinose	0.17±0.01	0.51±0.01	0.93±0.02	10.8±0.1	1.00±0.1	1.98±0.02	0.77±0.01		21.2±0.8	20.2±0.3	-	0.79±0.02
Xylose	1.02±0.02		3.22±0.03	1.38±0.01	0.98±0.01	3.5±0.07	0.69±0.01	0.37±0.03	24.7±0.5	20.3±0.4	2.48±0.09	0.49±0.02
Mannose	91.7±0.6	81.9±0.5	78.3±0.2	-	88.6±0.1		88.9±0.1	84.0±0.1	-	-	80.2±0.1	
Galactose	-	0.29±0.01	1.41±0.01	-	-	0.42±0.02	-	-	-	-	2.9±0.1	0.94±0.02
Glucose	-	-	1.41±0.03	50.32±0.2	-		-	-	-	-	-	-
Sucrose	-	-	1.64±0.04	0.27±0.01	-		1.05±0.04	-	1.29±0.04	2.1±0.1	-	0.78±0.04
Fructose	-	-		17.98±0.2	-	84.6±0.6	-	0.41±0.01	39.1±0.3	29.2±0.3	-	86.5±0.1
Maltose	0.13±0.02	0.65±0.01	0.66±0.04		-	0.18±0.02	-	0.17±0.01	0.29±0.03	-	1.39±0.01	0.76±0.03
Pent/Hex	0.03±0.01	0.11±0.01	0.1±0.01	0.32±0.01	0.03±0.01	0.08±0.01	0.02±0.01	0.4±0.01	1.26±0.01	1.55±0.01	0.08±0.01	0.04±0.01
Ara/Xyl	0.17±0.01	-	0.29±0.01	7.83±0.01	1.02±0.01	0.57±0.01	1.12±0.01	-	0.86±0.01	1.0±0.01	-	1.61±0.01

Pent: Pentose, Hex: Hexose, Ara: Arabinose, Xyl: Xylose

In general, the major changes in the NSP fractions of the millet as a result of hydrothermal treatment could be summarized as follows; the arabinose to xylose ratio decreased in cold water solubles, pectic polysaccharides and hemicelluloses A fractions, but it increased in hot water soluble, hemicellulose B and cellulosic fractions.

It has been reported by Malleshi et al. (1986) that, pentoses are the major constituent sugars in both cold and hot water soluble fractions of NSP of the native finger millet. In contrast to that, Subba Rao et al. (2004) reported that hexoses form the main sugars in water soluble NSP fraction of finger millet, besides, pentoses form the main sugars in hemicellulose B fraction of the millet. The qualitative and quantitative changes observed in the individual NSP fractions of the HTM could be due to the heat-moisture treatment to the millet. The seed coat and the cell walls form the most of the NSP constituents of the millet and they also undergo changes along with the other major biochemical components during hydrothermal treatment. During steeping, a small portion of the water soluble constituents of the cell walls may have leached out and subsequently, during steaming a kind of thermal degradation or fragmentation of cell wall material may occur due to expansion and contraction of the endosperm. In view of this, the water soluble as well as the alkali soluble constituents of NSP may undergo qualitative and quantitative changes during hydrothermal treatment to the millet.

3.4. Proteins

Similar to carbohydrates, the millet proteins also undergo considerable changes during hydrothermal treatment. The NM contained glutelin like (41%) and prolamin like proteins (28%) as major protein fractions followed by prolamins (19%), albumins (8%) and globulins (4%). After hydrothermal treatment, the protein extractability decreased from 94 to 56% and it contained 32% glutelin like and 45% prolamin like fractions followed by 9% prolamins, 8% globulins and 6% albumins (Table 12).

The hydrothermal treatment to the millet causes slight transformation in its proteins which not only decreases its total extractability to 54% but also altered the composition of the constituent fractions. The prominent changes in

Table 12. Protein fractions of native and hydrothermally treated finger millet (g/100g)

Protein Fractions	Native	Hydrothermally treated
Albumins	0.54±0.10 (8.14)	0.23±0.08 (5.89)
Globulins	0.27±0.07 (4.07)	0.30±0.04 (7.69)
Prolamins	1.26±0.20 (19.0)	0.35±0.06 (8.97)
Prolamin-like	1.83±0.10 (27.60)	1.76±0.20 (45.12)
Glutelin-like	2.73±0.15 (41.17)	1.26±0.18 (32.30)
Total	6.63±0.14 (99.98)	3.9±0.15 (99.97)
Percentage extraction	94.00±0.5	56.00±0.8

Values in the parenthesis indicate the percentage

the component proteins were; the increase in globulins and prolamin like fractions by 89 and 63%, and decrease in albumins, prolamins and glutelin like fractions by 28, 53 and 22%, respectively. This may be due to denaturing of protein bodies and possible formation of protein-starch and protein-polyphenols complexes. In the case of rice also it has been reported that, parboiling decreases the extractability of the proteins in general and 45% of the globulins fraction in particular (Kamini Devi et al., 1997). The composition of constituent proteins in the NM observed in the present study is nearly comparable to that reported by Ramachandra et al. (1978) for finger millet proteins.

The proteins of the NM and HTM fractionated by the SDS-PAGE electrophoresis are presented in Figure 26. The protein bands were of 14 - 97 kDa in NM, which remained almost same in HTM except for the decrease in their intensity. This may be due to the decreased extractability of the total proteins as a result of hydrothermal treatment.

3.5. Fat

The hydrothermal treatment to the millet caused only marginal changes in its fatty acid contents. The elution profiles of the fatty acids of both NM and HTM presented in the Figure 27, clearly indicate the separation of the constituent

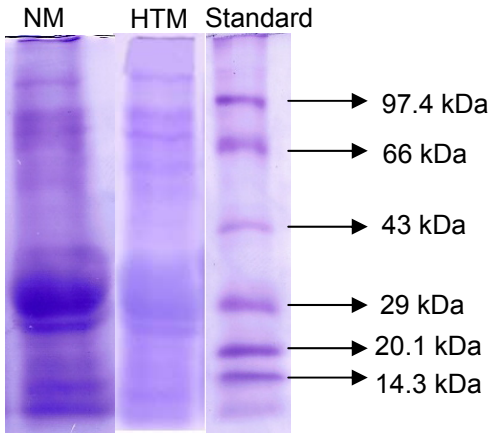


Figure 26. Fractionation of proteins of native and hydrothermally treated finger millet through SDS -PAGE

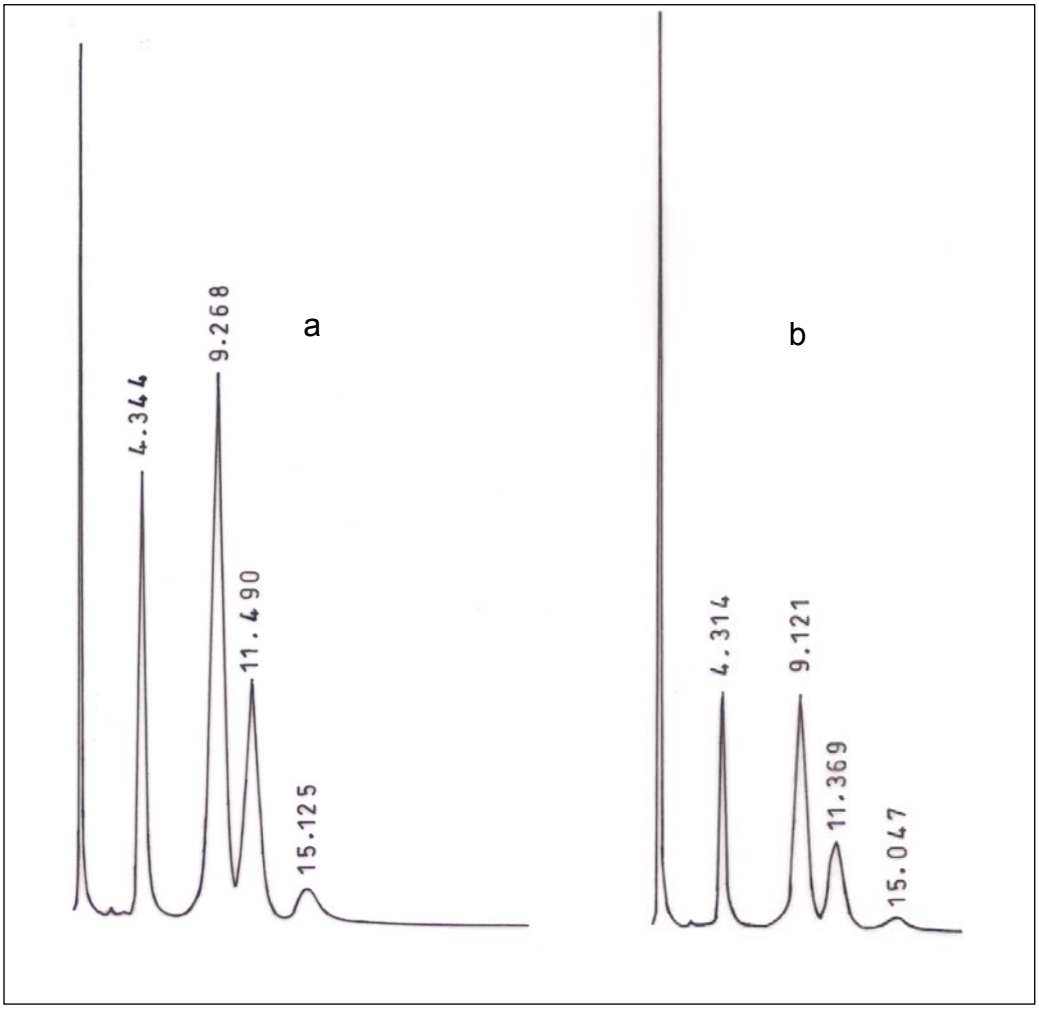


Figure 27. Fatty acids profiles of native (a) and hydrothermally treated (b) finger millet

fatty acids thereby enabling identification of the constituent fatty acids easily. Oleic (51%), palmitic (20%) and linoleic acids (24%) identified as the main fatty acids in NM and similar pattern was observed in HTM except for a slight decrease in the linoleic (12%) and a slight increase in the palmitic (18%) acid contents (Table 13). The extractability of the free lipids decreased marginally and a slight increase in the extractability of the bound lipids occurred. The fatty acid profile of the NM in the present study is comparable to the profile of the millet in the data base for cereals (AOCS, 1990). The millet is a poor source of dietary lipids, even then, its lipids play an important role in the diet of the millet consumers, as nearly 50% of lipids are in the unsaturated form. The decrease in the unsaturated fatty acid contents as a result of hydrothermal treatment to the millet may be due to complexing of amylose specifically with linoleic acid (Karkalas et al., 1995). This leads to a slight (*per se*) increase in the palmitic acid, the saturated fatty acid of the millet. Thus, due to the hydrothermal treatment, the unsaturated fatty acid contents decrease resulting in an increase in the saturated fatty acids, but the extent of these changes in finger millet is marginal.

Table 13. Fatty acids profile of native and hydrothermally treated finger millet (%)

Fatty acid	Native	Hydrothermally treated
Palmitic (16:0)	20.25±0.50	23.99±0.8
Stearic (18:0)	ND	2.23±0.1
Oleic (18:1)	51.13±1.0	50.99±2.2
Linoleic (18:2)	24.42±0.8	21.38±0.9
Linolenic (18:3)	4.07±0.1	3.64±0.2
Free lipids	1.46±0.1	1.41±0.2
Bound lipids	0.90±0.1	0.94±0.2

ND - not detected

3.6. Functional properties

A. Viscosity

The differences in viscosity values of NM and HTM at 10% slurry concentration, was negligible at ambient temperature but the difference was considerable after cooking the paste. In fact, the cold paste viscosity of the NM was too low to record by the Brookfield viscometer and that of HTM was hardly 10 cP, which could be measured by the instrument. The viscosity of the uncooked millet flour could not be recorded by the instrument as the raw starch at ambient condition swells very little, whereas, the pregelatinized starch of the HTM swells to some extent and its viscosity could be recorded. On the other hand, the cooked paste viscosity of the NM was several folds higher (1717 cP) than that of the HTM (350 cP) (Table 14). This is because the starch in NM expands by several folds on cooking resulting in an enormous increase in the viscosity, but in the case of HTM, the swelling of the granules is slightly restricted because of the changes it has undergone during hydrothermal treatment (mostly retrogradation).

In the case of rice also, Unnikrishnan and Bhattacharya (1983), observed negligible viscosity for the normal parboiled rice at 30^{o}C and higher levels of the viscosity as the temperature increases. They also reported that, the viscosity depends on the severity of the parboiling. The characteristic behavior of the HTM with respect to its lower cooked paste viscosity shows its suitability for preparation of low bulk and calorie dense foods.

B. Solubility index and swelling power

The solubility and swelling power of the millet exhibited noticeable changes due to the hydrothermal treatment but the values for both the parameters were temperature dependent. The solubility values of the HTM at 30^{o}C (1.6%) and 90^{o}C (3.3%) were higher than that of the NM (1.0 and 2.9%, respectively). But, the swelling power of HTM (299%) was nearly 3.5 fold higher than that of the NM (85%) at 30^{o}C whereas it was nearly comparable at 95^{o}C (505% for NM and 494% for HTM). The swelling power of HTM at 95^{o}C was 1.6 times higher than the swelling power at 30^{o}C, but in the case of NM it was 5.9 times (Table 14).

Table 14. Functional properties of native and hydrothermally treated finger millet

Parameter	Native	Hydrothermally treated
Viscosity 10% slurry (cP)	*	11±1.0
Cold paste	1717±5.0	350±3.0
Cooked paste		
Solubility (g%)		
30 °C	1.0±0.07	1.6±0.1
95 °C	2.9±0.1	3.3±0.2
Swelling (g%)		
30 °C	85±1.5	299±1.8
95 °C	505±3.1	494±4.2
Peak viscosity (BU)	534±2.4	114±1.9
Trough viscosity (BU)	384±2.0	114±1.5
Final viscosity (BU)	817±3.2	164±1.8
Breakdown viscosity (BU)	149±1.7	0
Setback viscosity (BU)	391±2.9	50±1.4
Pasting temperature (°C)	74.9±1.0	86.3±1.0

**Too low to record in the Brookfield viscometer*

The native starch in NM does not appreciably swell at lower temperature but it swells significantly at elevated (beyond 70^{o}C) temperature. The swelling power in the case of HTM is lower even though it contained gelatinized starch because the starch has undergone retrogradation related changes, rendering it less susceptible to swelling as a function of heat. In the case of parboiled rice also, it was reported that, the swelling power at ambient temperature was about 425% which increased to 900% at 95^{o}C (Unnikrishnan and Bhattacharya, 1981) showing about 2 fold increase on heating.

C. Hydration kinetics

Figure 28, shows the changes in the moisture content of the HTM on steeping at different temperatures, which shows that, the rate of hydration as well as the EMC of the millet increased with increase in temperature of the steep water. The millet attained 41% moisture content after steeping for 6, 1.75, 1.3, 0.8 and 0.75 h at 30, 40, 50, 60 and 70^{o}C, respectively. The influence of temperature of steep water on the EMC of the millet has been explained earlier also, wherein, the rate of hydration as influenced by the steeping conditions as well as the temperature of steep water, have been discussed explicitly.

D. Pasting characteristics

The pasting profiles of both the NM and HTM presented in Figure 29 clearly indicate that, the amylograms of the HTM is completely different from NM in terms of increase in gelatinization temperature, lower peak viscosity, zero breakdown and also lower setback viscosity. The interesting observation in the pasting profile of HTM is the sharp increase in the viscosity only after 86^{o}C unlike the NM, which was at 74.9^{o}C. The peak viscosity of HTM was 114 BU which was 5 times lower to that of NM (534 BU).

The trough, final and setback viscosity for HTM and NM were 114, 164, 50 BU and 384, 817, 391 BU, respectively, (Table 14) indicating relatively lower values for HTM for all the indices of the amylograms. The negligible difference between the values of peak and trough viscosity for the HTM reveals that the starch in HTM does not undergo disintegration during cooking phase unlike the starch of the NM, which exhibits a breakdown viscosity of

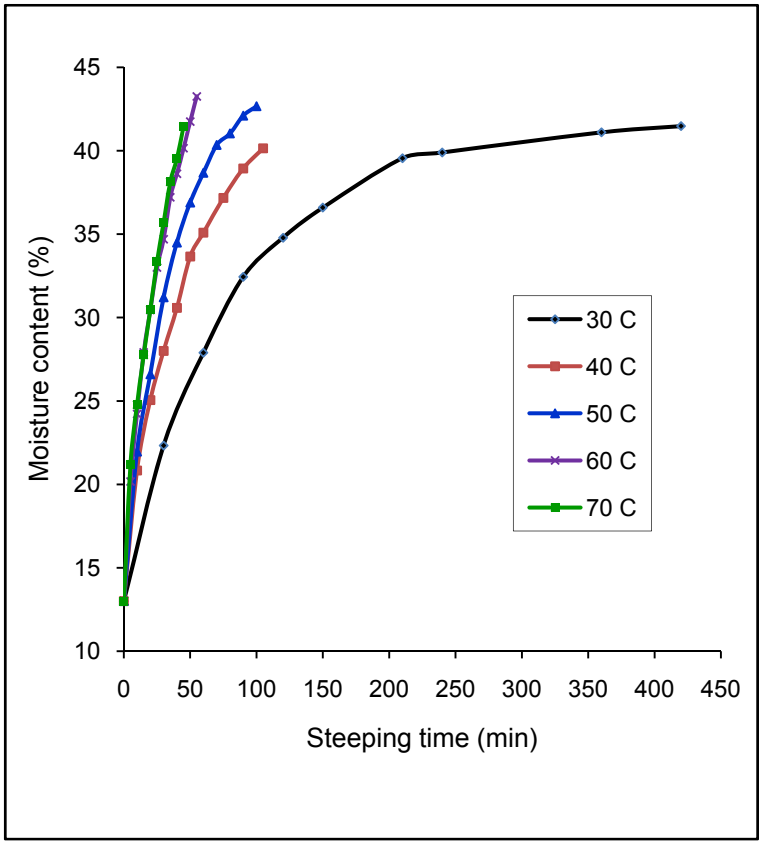


Figure 28. Hydration kinetics of hydrothermally treated finger millet steeped at different temperatures

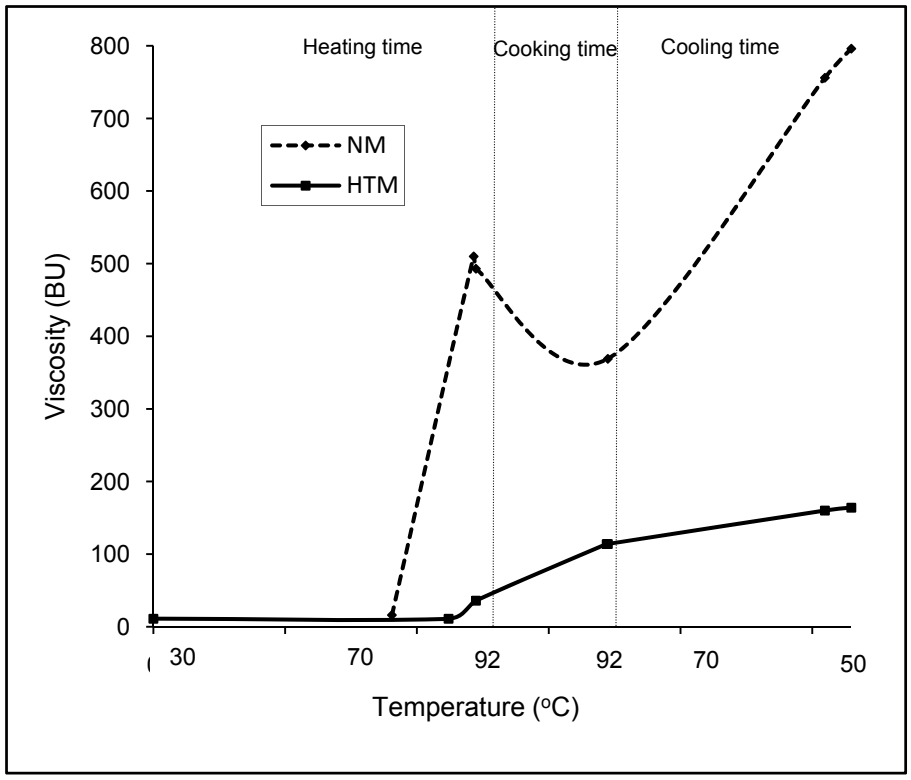


Figure 29. Pasting profiles of native and hydrothermally treated finger millet

149 BU. This shows that the native starch granules undergo shear thinning during cooking. The HTM also exhibited significantly low peak viscosity and zero breakdown viscosity.

The viscosity parameters of the HTM were lower than that of NM, except the gelatinization temperature. The increase in the gelatinization temperature may be due to the presence of a few ungelatinized starch granules which might have got embedded in the gelatinized mass, and start swelling only after they were released as a result of loosening the endosperm cellular matrix. Hence, this phenomenon of increasing the viscosity occurs at temperature beyond 86^{o}C. Peak viscosity is an important characteristic feature of any starch or cereal flours as it indicates the swelling ability of the starch on cooking in water. However, the viscosity is normally dependent not only on the concentration of solids but also on the nature of the cereals. Hence, the lower peak viscosity of hydrothermally treated millet may be due to the limited swelling ability of its starch as a result of structural modification that take place on wet-heat treatment.

Adebowale et al. (2005) studied the changes in the viscosity patterns of the isolated starch from finger millet, mixed with different levels of water, in a Rapid Visco Analyser and reported that, heating the starch with 30% moisture content at 100^{o}C in an air oven for 16 h, in a sealed glass container reduced its peak viscosity from 387 to 296 RVU (23%). However, in the present study, the HTM did not show any peak viscosity and its maximum viscosity was nearly 79% lower than the NM. In the case of rice also it has been reported that, the peak viscosity of parboiled rice is lower than the raw rice and the reduction in the viscosity depends on the severity of the parboiling conditions (Bhattacharya and Sowbhagya, 1979). The reduction in peak viscosity and cold paste viscosity of rice on parboiling is a direct result of reorganization of the constituent molecules of its modified starch. Heat moisture modified starches were characterized by an increase in paste stability as well as the gelatinization temperature, regardless of the origin of starch (Bhattacharya and Sowbhagya, 1979).

Schoch and Maywald (1968) classified viscosity patterns of cereals from Brabender amylograph as follows: Type A, high swelling starches which show a high pasting peak followed by rapid and major thinning during cooking; Type B, moderate swelling starches which show lower peak viscosity and much less thinning; Type C, restricted swelling starches which show no specific pasting peak and the viscosity remains constant or increases during cooking and Type D, highly restricted swelling starches, that do not swell sufficiently to give a viscous paste when cooked at normal concentrations. The heat moisture treated starches fall in the category of Type C, thus, HTM exhibited Type C pattern.

3.7. Differential scanning calorigrams

The thermal properties of the HTM and NM determined in terms of calorigrams were completely different as the NM exhibited endothermic peak where as the HTM showed exothermic peak. The enthalpy for NM was positive (867 J/g) but it was negative for HTM (-3.64J/g). Considerably lower values for the onset, peak and endset temperature were also observed for HTM compared to NM (Table 15). The positive and negative enthalpy values for NM and HTM are unique to the millet as several reports on the calorigrams of hydrothermally treated cereals indicate only slight lowering of the enthalpy on heating (Ong and Blanshard, 1995). It was expected that, the seed coat present in the HTM may play an important role in its thermal properties. Hence, to find out the influence of the seed coat on the enthalpy of the millet, the seed coat matter separated from NM and HTM were also scanned in DSC and it was repeatedly observed that the seed coat matter from both the samples exhibited negative enthalpies (-3.9 J/g). Hence, it may be inferred that the energy required to gelatinize the starch in the native millet being substantially high, it probably masked the negative enthalpy of the seed coat, but in the case of the HTM, since the starch is partially gelatinized, the prominence of the negative enthalpy of the seed coat causes overall negative enthalpy to the sample. Or in other words, the net energy required to gelatinize the starch in NM is positive whereas that in HTM is negative. Similar observation was made in the case of brown rice also by Mohan et al. (unpublished data).

Table 15. DSC characteristics of native and hydrothermally treated finger millet

Sample	Peak type	ΔH (J/g)	Onset temp (^oC)	Peak temp (^oC)	Endset temp (^oC)
Native	Endo	867.17	50.03	64.20	74.19
Hydrothermally treated	Exo	-3.64	64.83	67.47	71.42
Seed coat of HTM	Exo	-3.88	64.84	67.9	72.26
Seed coat of NM	Exo	-3.93	64.88	67.62	72.05

Average of two independent determinations

The peak temperature for HTM was 67^{o}C, slightly higher than that of NM (64^{o}C). The reasons for this could be the hydrothermal treatment and annealing of starch as a result of the soaking followed by partial gelatinization during parboiling (Marshall et al., 1993). The relatively higher peak temperature (by about 3^o) observed for the HTM compared to NM is in concurrence with the higher gelatinization temperature recorded for the HTM in the pasting profile.

3.8. X-ray diffractogram

The X-ray diffractograms of the whole meals from NM and HTM as well as the isolated starch from the native millet are presented in Figure 30 and the corresponding microstructural parameters are presented in Table 16. The diffraction patterns of the NM is comparable with a triplet pattern observed for the isolated starch at 2θ of 15, 17 and 23^o indicating the A type pattern for the millet starch. The diffraction peaks of the HTM were invariably small and of lower area compared to that of NM. This shows that the starch in HTM is largely of amorphous nature with very little crystallinity. The HTM exhibited diffused peak only at 19.8^o of 2θ and the absence of peaks at 15 and 17^o are conspicuous. The peak at 2θ of 20^o is commonly observed in the case of parboiled cereals similar to what has been observed in the present study.

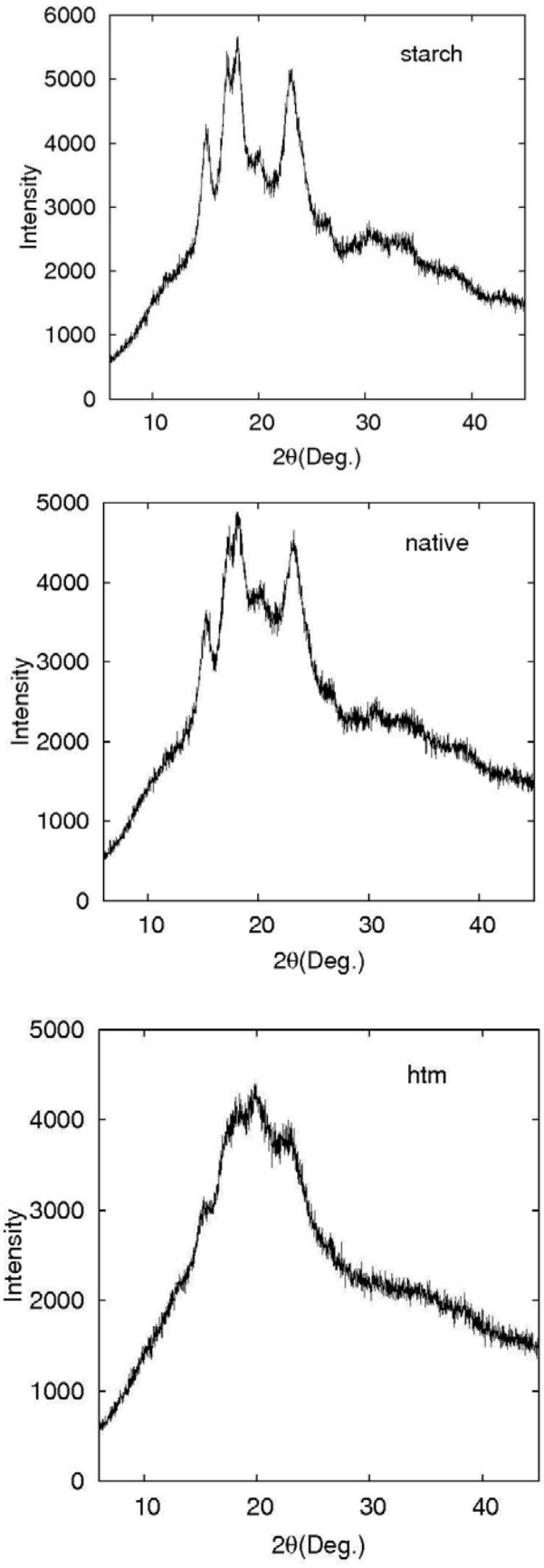


Figure 30. X-ray diffractogram of isolated starch, native and hydrothermally treated finger millet

Table 16. Microstructural parameters of native and hydrothermally treated finger millet using exponential distribution function.

2θ (degree)	'd' (Å)	<N>	P	'g' (%)	Δ (%)	D = N.d (Å)
			Starch			
15.10	5.86	9.35	8.42	0.2	4.09	54.8
17.61	5.04	5.79	4.92	0.3	4.50	29.2
23.04	3.86	9.29	8.34	0.2	4.12	35.9
			Native			
15.30	5.79	8.08	7.29	0.1	4.02	46.8
17.86	4.97	4.95	4.18	0.2	4.78	24.6
23.15	3.84	7.48	6.73	0.1	4.22	28.7
			Hydrothermally treated			
19.81	4.48	1.75	1.37	0.1	2.57	07.8

According to diffraction theory, the intensity of the peak depends on the amount of orderly semicrystalline structures and/or on the differences in electron density between the amorphous and crystalline lamellae (Feigin and Svergun, 1987) and therefore the sharp peaks can be directly correlated to crystalline region and the diffused peaks to amorphous region of the millet.

The HTM showed slightly lower values for the lattice spacing (d), number of unit cells in a particular direction of reflection (N) and crystal size (D) compared to NM. The intrinsic strain (g in %) reveals that the HTM exhibits isotropic strain behavior compared to that of NM, which was anisotrpic. The 'Δ' indicates the goodness of the fit of experimental profiles and the reliability of the microstructural parameters given in Table 16.

Hoover and Vasanthan (1994), subjected starches of different origins to heat-moisture treatment and studied the X-ray diffraction patterns and observed that, the treatment induced changes not only in the crystalline regions but also in amorphous regions of all the starches irrespective of their

origin. They also noticed decrease in the intensities of the peaks as the severity of heat treatment increased. The decreased intensity of the peaks on treatment may either be due to crystallite disruption or reorientation of the double helics forming the crystalline array due to the hydrothermal treatment that gelatinizes its starch. Native cereal starch granules display quite complex structure with several levels of organization, normally linear amylose being amorphous and amylopectin being semicrystalline (Lopez-Rubio et al., 2007), but processing the cereals generally disrupts the crystallinity of its starch and parboiling normally transforms the crystalline structure to amorphous one. Parboiling also causes a perceptible shift in the crystalline phases of the granule of the native starch including all microstructural parameters. It was reported that V-type X ray pattern occurs during parboiling of rice as a consequence of amylose-lipid complex (Priestley, 1976). Parboiled rice exhibits either V type or mixed A and V type X-ray pattern (Ong and Blanshard, 1995), probably due to the presence of both ungelatinized and gelatinized starch or also may be due to the recrystallization of the starch. However, in the case of the millet, only a single peak at 2θ of 19.8^{o} was observed after hydrothermal treatment and no mixed type patterns were recorded. Thus, it may be concluded that almost all the starch present in the millet has undergone gelatinization during the treatment under the experimental conditions.

The absence of recrystallization of the starch in the HTM could be the special features of the millet starch. It may be opt to state here that, Singh et al. (2006), who studied the nature of crystallinity in native and acid modified starches, reported relatively higher degree of crystallinity in finger millet starch (30%) compared to other cereal starches. Similarly, Mohan et al. (2005) reported that, the crystallinity of finger millet starch (30%) was considerably higher than the rice starch (22%). Mahanta et al. (1989) studied the starch crystallinity in rice subjected to different degree of parboiling and observed the shift from A to V or A to mixed type X-ray pattern depending upon the severity of parboiling. They also observed comparatively low degree of crystallinity in all the samples.

3.9. Degree of gelatinization

The degree of gelatinization is defined as the ratio of gelatinized starch to total starch content in a product. It is calculated from spectrophotometric measurement of the starch-iodine complex formed in aqueous suspension of samples before and after the complete solubilization of the starch in alkali (Wootton et al., 1971). The degree of gelatinization of starch in HTM was found to be 65% as against only 2% for NM. This is an apparent value and may not represent the true degree of gelatinization. Normally, whenever, the starch is cooked in sufficient water, 100% gelatinization occurs. But, only 65% gelatinization of HTM starch could be due to the hydration of the millet to only 35% moisture content prior to steaming. The limited water and also the compact form of the grain or the environment of the starch in the endosperm does not allow the grains to swell to their full capacity on heating.

According to Stapley et al. (1998), whenever, the starch is heated in sufficient water, it undergoes glass transition followed by melting of starch crystallites as the temperature increases. The degree of gelatinization of starch in any food plays an important role with respect to the end uses of the product. Normally, whenever the food grain is cooked, most of its starch content is gelatinized, which facilitates the rapid digestion. However, the degree of gelatinization is dependent on the processing conditions and subsequently influences the carbohydrate digestibility of the foods. Among the common methods of cereal processing, cooking the flour as well as dehulled grains in excess water, extrusion cooking and roller drying generally cause, complete gelatinization of the starch whereas, *roti* or *chapathi* making gelatinizes the starch partially.

3.10. Microscopic studies

A. Light microscopy

The photomicrographs of the transverse sections of the native millet show the structural features of the seed coat and the endosperm of NM (Figures 31a-d). Figure 31a, depicts the millet section stained with fast green FCF wherein the multilayered seed coat is clearly seen. Figures 31b, 31c and 31d show the sections stained with erythrosine for localizing the cell walls and proteins.

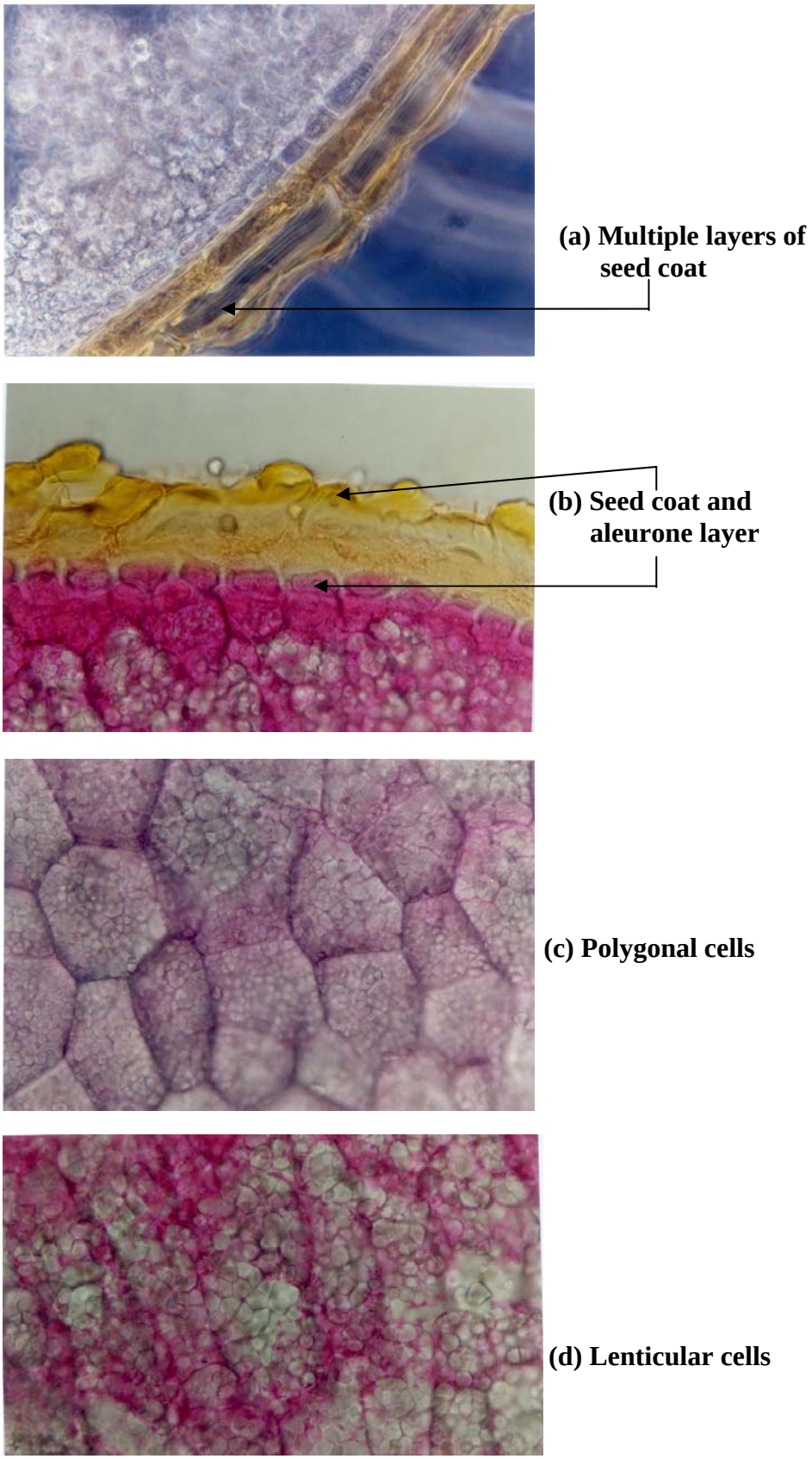


Figure 31. Light microscopic photographs of transverse sections of native finger millet

Although, the seed coat is not stained, its structural features, namely the undulations at outer layer and intactness with the aleurone cells could be observed (Figure 31a). The intensely stained aleurone layer reveals that it is of single cell structure and well organized (Figure 31b). Figure 31c, depicts the organization of the cellular matter with the endosperm with clearly visible cell boundaries and well packed starch granules at the central part of the endosperm. On the other hand, Figure 31d, shows the reorientation of the granules compacted in the lenticular cells towards the peripheral end and this is distinctively different than the polygonal cells present at the central part of the kernels.

The hydrothermal treatment to the millet not only caused endosperm modification but also changed the texture of the seed coat and the aleurone tissues. The multilayered cellular organization of the seed coat observed in the native millet changed to unilayer (Figure 32a) and completely fused with the peripheral portion of the endosperm (Figure 32b). The unicellular aleurone tissue also undergoes transformation to a homogeneous mass and gets embedded with the endosperm. On the other hand, in the case of endosperm portion, the granular structure of the starch changes in to a coherent mass and yet exhibits the cell walls prominently (Figure 32c and 32d). However, in the vicinity of embryo, the changes in the cellular matrix are minimum besides, it contained a few ungelatinized starch granules (Figure 32e). This showed that, the hydrothermal treatment modified both the seed coat as well as the endosperm texture of the millet. The embryo portion of the cereals normally consists of free sugars, lipids, NSP, protein bodies and also vitamins and minerals, and hence the starch granules in that region are fully embedded by the dense population of other biochemical constituents. In view of this, the probability of the textural changes in the embryo and its surrounding region is minimum.

Mahadevappa and Desikachar (1968) microscopically examined the status of the lipids and proteins in the native and parboiled rice and reported the presence of disrupted oil globules and disintegrated protein bodies.

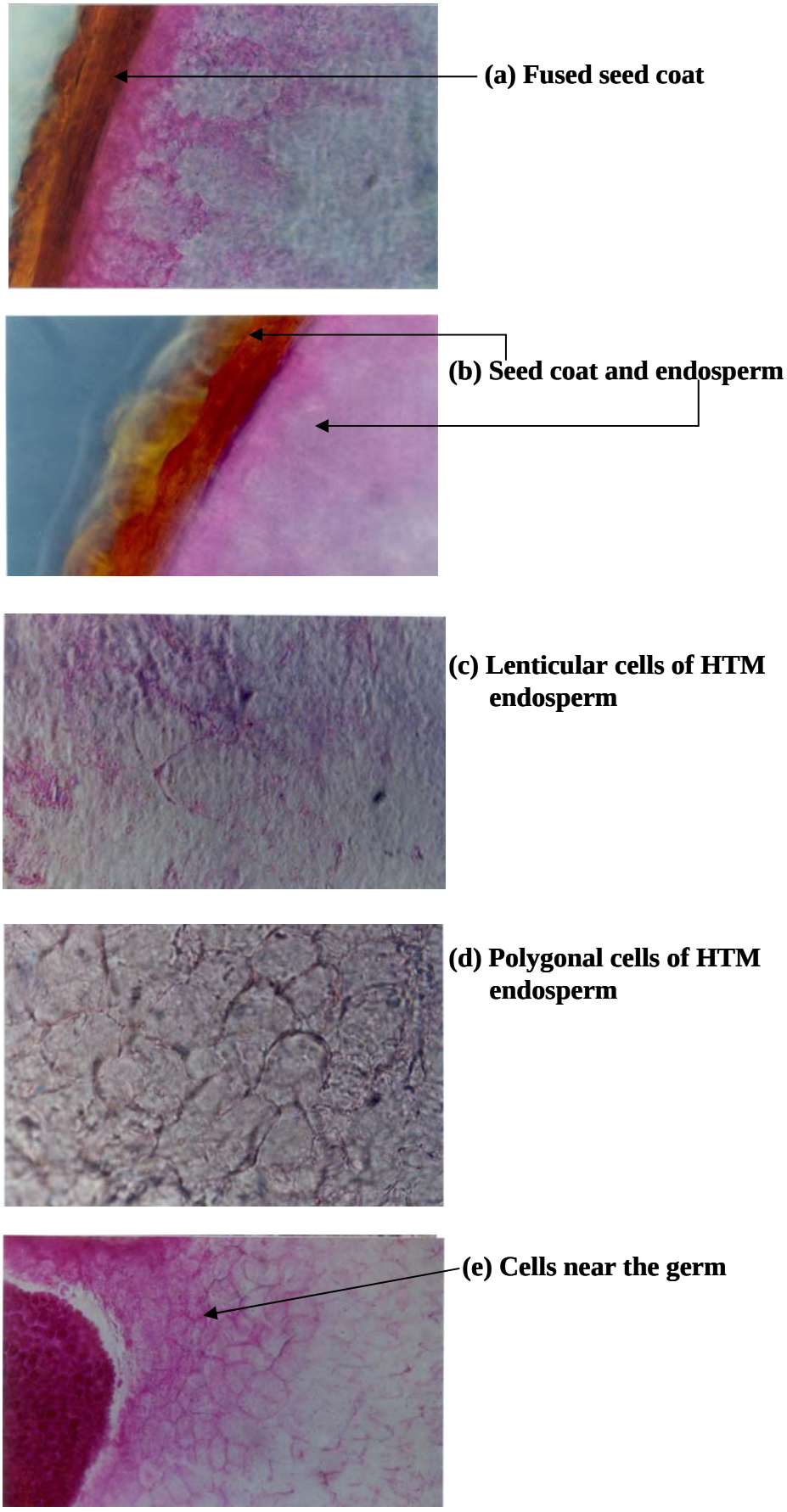
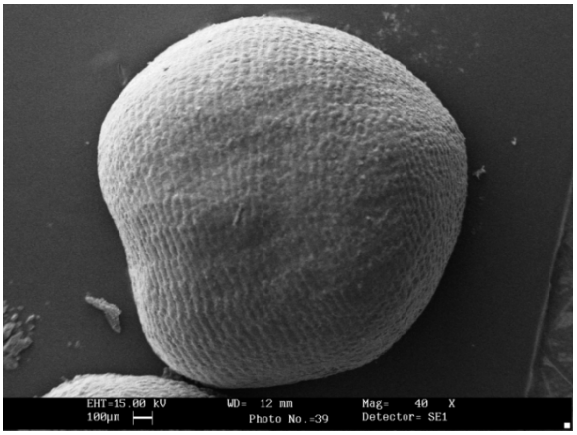


Figure 32. Light microscopic photographs of transverse sections of hydrothermally treated finger millet

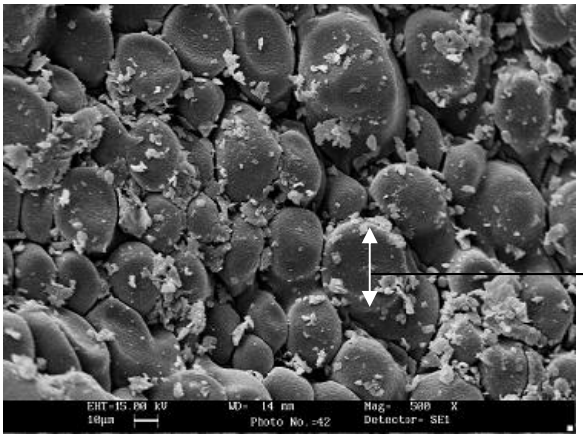
Raghavendra Rao and Juliano (1970) also conducted the histological examination of the parboiled rice and observed that, the orderly polyhedral structure of the starch granules of rice changed into a coherent mass. They also observed that the protein bodies were no longer distinct in parboiled rice.

B. Scanning electron microscopy

The scanning electron micrographs of the surface topography of the NM are depicted in Figures 33a to 33d. From the Figure 33a, it could be observed that, the millet kernel is of globular shape with a small depression near the embryo. The surface of the millet is not of smooth nature but is made up of several mounds. However, the mounds are prominent near the embryo (Figure 33b) and their average diameter is 28.5$\pm$1 μm. The surface mounds are slightly wider (32 to 38 μm) and appear stretched towards the other side of the kernel (Figure 33c). The presence of many micro-pores on each of the surface mounds could be seen in a magnified portion of the surface (Figure 33d). Throughout the surface of the grain, the presences of minute specks are also observed, which may be the cellulosic protrusions. The topography of the millet towards its embryo portion differs considerably with the other part of the grain (Figure 34a).The germ is located in a depression surrounded by a characteristic ridge and a distinct furrow appears towards one side of the germ. The hilum is located adjacent to the germ in a separate but in a somewhat shallow depression. The magnified image of the germ exhibits an intense network structure (Figure 34b). Figure 34c, illustrates the overall view of the transverse section of the endosperm with two distinctly different cellular arrangements, one towards the central core and the other towards the periphery. Most of the granules in the core portion of the kernel are pentagonal with a few granules being spherical and hexagonal shapes whereas, those at the periphery appeared to be lenticular. This aspect of the microstructure of the kernel could be more clearly seen in Figures 31c and 31d. A section of the seed coat shown in Figure 34d reveals that, it is made up of multilayer with an average thickness of 18$\pm$1μm. The Figure also indicates that, the seed coat is rigidly attached to the endosperm. The transverse section of the endosperm (Figure 34e) indicates that, most of the starch granules are enclosed by the cellular matrix.

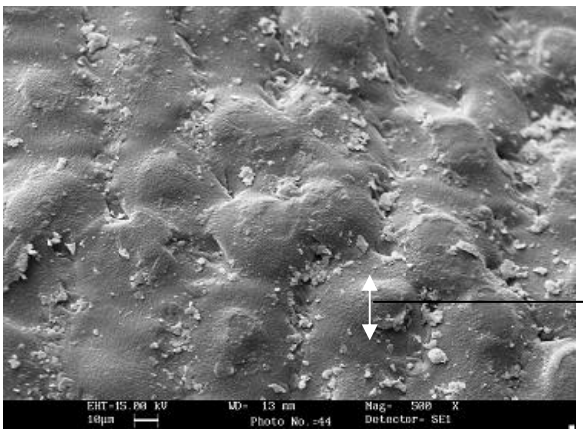


(a) Whole kernel (40 X)



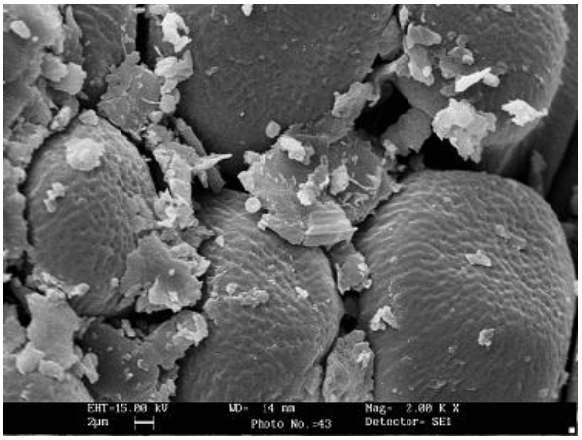
(b) Surface mounds near the germ portion (500 X)

Average diameter 28.47 µ



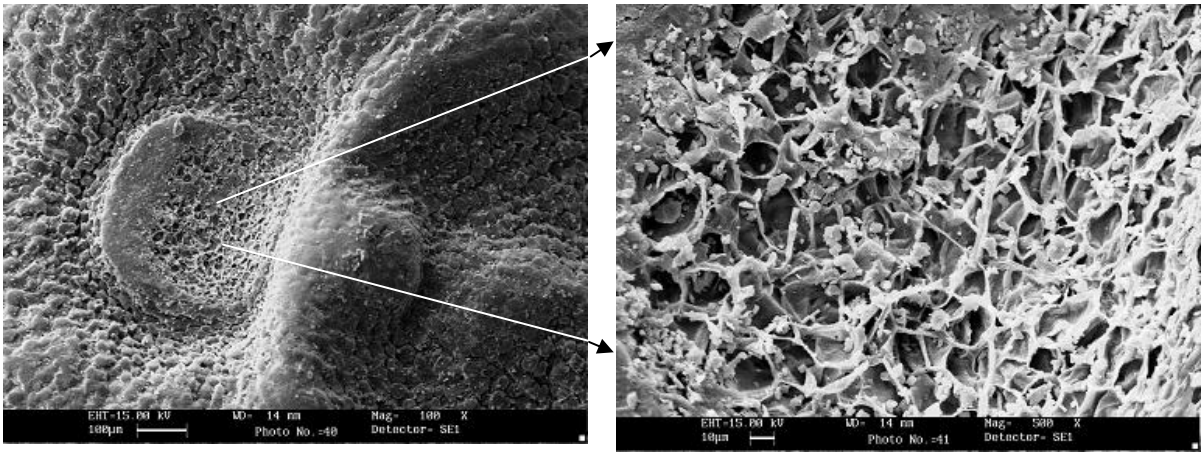
(c) Surface mounds on dorsal portion (500

Average diameter 35.4 µ



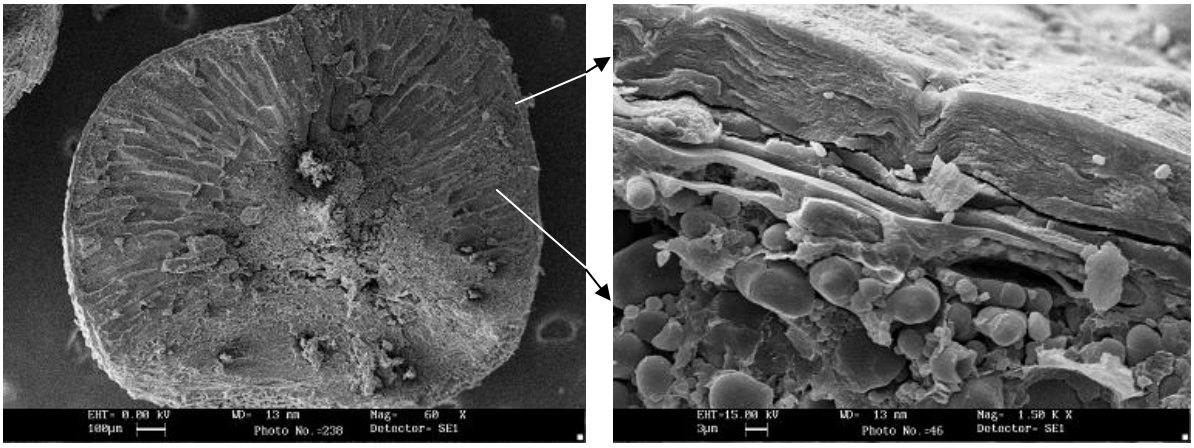
(d) Micro-pores on the surface mounds (2.00 KX)

Figure 33. Topography of native finger millet kernel as seen through scanning electron microscope



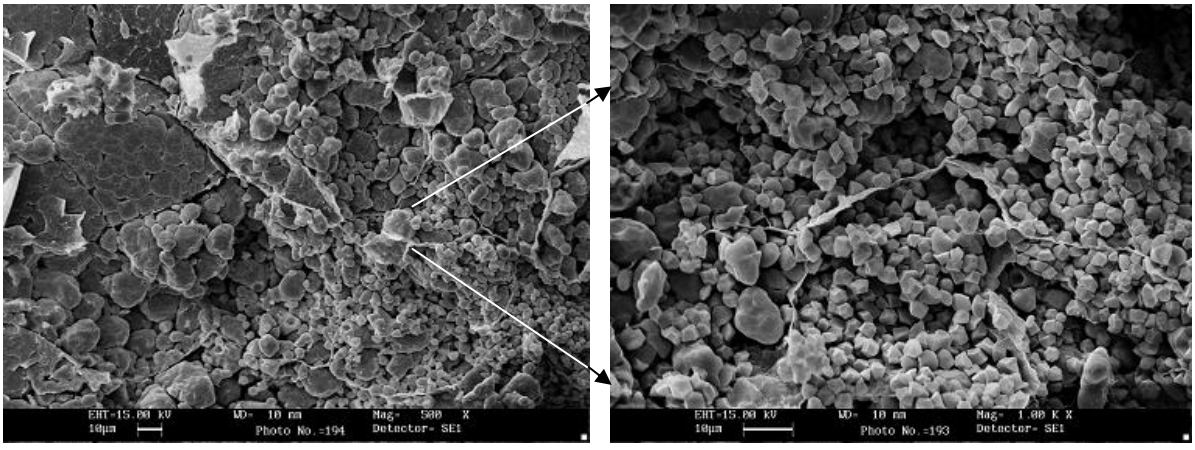
(a) Germ portion (100 X)

(b) Germ portion (500 X)



(c) Transverse section - over all view (50 X)

(d) Seed coat and adjacent endosperm (1.5 X)



(e) Clusters of starch granules (500 X)

(f) Starch granules (1.00 KX)

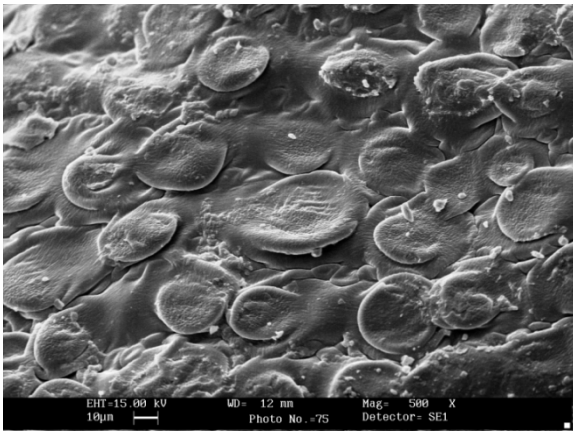
Figure 34. Scanning electron photomicrographs of germ surface and the transverse sections of native finger millet

The magnified image of the same (Figure 34f) clearly brings out the enclosure of the starch granules by the papery thin cell walls. The protein bodies in the millet endosperm are of tiny size with hardly 2-3μm thickness, and are attached to endoplasmic reticulum, besides sitting on the surface of the starch granules.

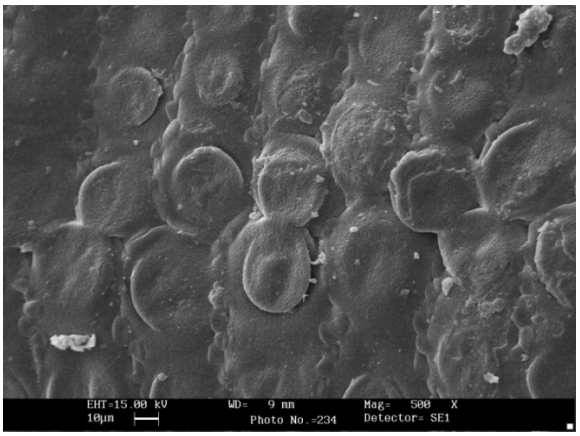
The hydrothermal treatment to the millet caused considerable changes in the morphological features of the grain and prominent among them are shrinkage in its overall size and increased visible undulations (Figure 35a), and also a visible crack near the hilum portion. The reasons for the morphological changes during hydrothermal treatment are mainly due to expansion and contraction of the grain during steaming and drying. The reasons for these changes have been elaborated earlier. The changes in the surface morphology are prominent (Figure 35b and 35c) throughout the grain except for the embryo region as mounds adjacent to the embryo region largely retained their original shape (Figure 35d) in contrast to flattening of the mounds in other part of the surface of the kernel.

The endosperm section of HTM illustrated in Figure 36a shows a void space near the center, which probably would have occurred during drying the millet. Even though, the endosperm appeared to be a homogenous mass (Figure 36b), the identity of the cells with distinct cell boundaries could still be seen whereas, the portion of seed coat fused with the endosperm is clearly visible in Figure 36c. However, a small number of granules could still be seen just beneath the seed coat. The multilayered seed coat observed in the NM undergoes complete transformation by forming a unilayer and getting fused with endosperm. This may occur due to the removal of the void spaces present between the seed coat and the endosperm. Normally, the seed coat is made up of non-starch polysaccharides complexed with cellular proteins. These constituents absorb considerably higher proportion of water and some of their soluble components ooze out during steaming filling the voids, which on drying contract and cement not only among its layers but also along with the endosperm.

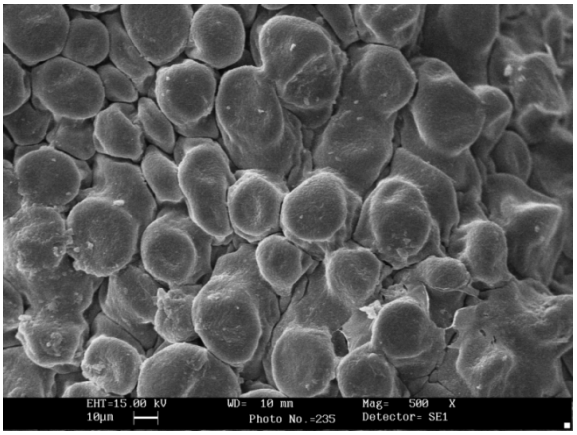
(a) Whole grain (40 X)



(b) Flattened mounds – adjacent to the germ portion (500 X)

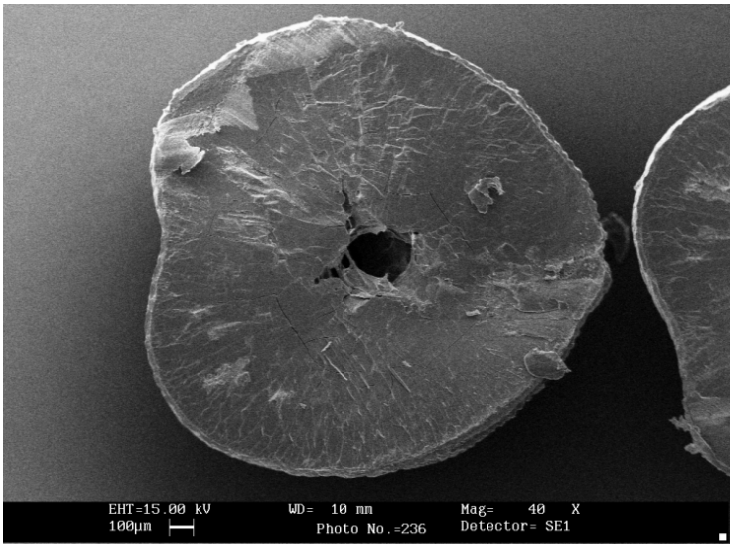


(c) Flattened mounds on dorsal portion (500 X)

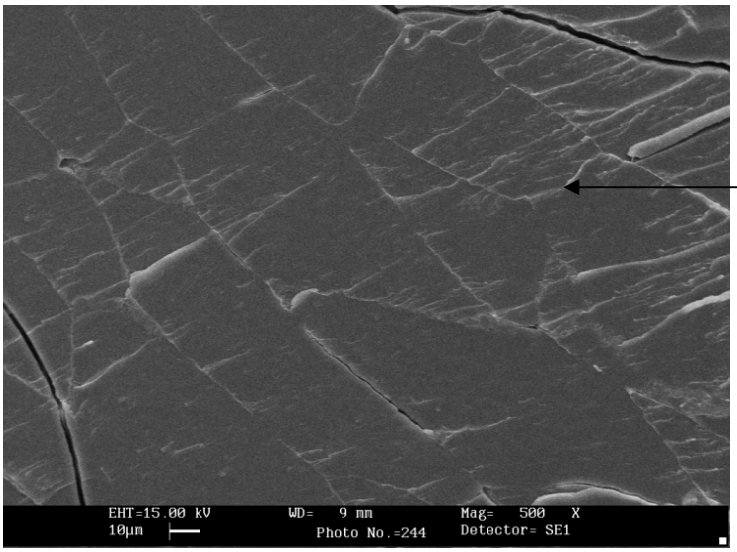


(d) Slightly flattened mounds over the germ (500 X)

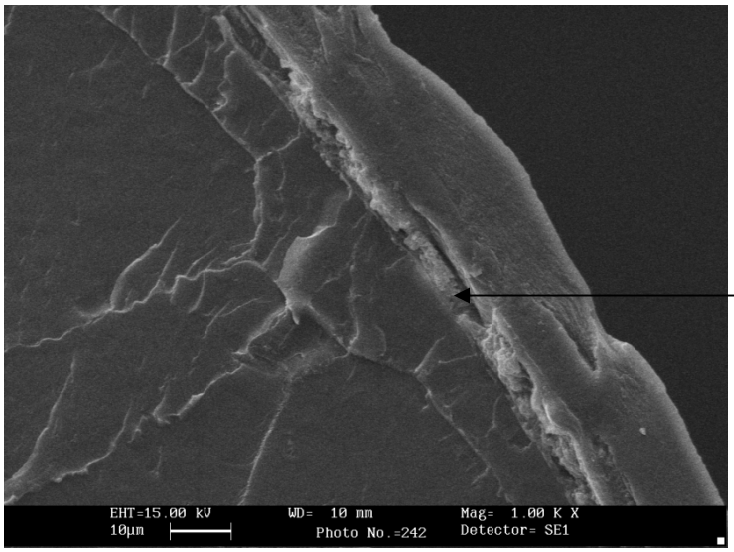
Figure 35. Topography of hydrothermally treated finger millet as seen through scanning electron microscope



(a) Transverse section - over all view (40 X)



(b) Cell boundaries in the HTM endosperm (500 X)



(c) Fused seed coat with endosperm (1.00 KX)

Figure 36. Scanning electron photomicrographs of transverse sections of hydrothermally treated finger millet

The endosperm constituents namely, starch granules, cell walls, protein bodies and other constituents completely lose their morphological features and change to a coherent mass or in other words, the orderly crystalline arrangement of the starch granules and other constituent tissues of the seed change into a homogeneous amorphous mass.

The microscopic examination of NM and HTM clearly brought out the visible changes the kernels undergo during hydrothermal treatment. Some of the observations made under this section help to explain the processing characteristics of the millet with special reference to its milling. The reason for the utilization of the millet in the flour form only and not in the decorticated form can be explained from these microscopic observations. The granular as well as the cellular organization of the endosperm indicate that, the major portion of it is of floury texture and the seed coat is attached to the endosperm rigidly. Hence, even the slightest abrasion or friction pulverizes the endosperm and also fragments the seed coat. On the other hand, the microscopic examination of the HTM clearly shows that, the entire endosperm undergoes transformation into a rigid mass and also the multilayered seed coat changes to unilayer on hydrothermal treatment, and yet the seed coat attaches to the endosperm rigidly. Hence, the endosperm of the hydrothermally processed millet withstands the mechanical impact without easily fragmenting under the normal conditions of decortication. However, separation of the seed coat from the endosperm is not easy because of its intactness with the endosperm. In view of this, the HTM needs moist conditioning as pretreatment for its decortication. This aspect has been elaborated in the next Chapter.

4. Dry heat parboiling

Some of the quality characteristics of the dry heat treated millet (DHM) prepared by exposing the steeped millet to sand heated to different temperatures and time are presented in Table 17. The observations presented in Table reveal that, the millet needs to be mixed with the heat transfer media maintained at about 150^{o}C for about 30 sec to gelatinize its starch, without causing any damage to the seed coat. Exposing the steeped

Table 17. Visible observations of dry heat treated finger millet prepared under different conditions of temperature and time

Temperature (˚C)	Time (sec)	Observations
100	120	Not translucent
-do-	180	Not translucent, brittle
110	60	Not translucent
-do-	120	Not translucent, brittle
120	60	Not uniformly translucent
-do-	90	Not uniformly translucent
-do-	120	Brittle
130	60	Not uniformly translucent
-do-	90	translucent
-do-	120	Slightly brittle
140	30	Not uniformly translucent
-do-	60	translucent and mellowable
-do-	90	Brittle
150	30	translucent and mellowable
-do-	60	Slightly brittle
160	30	translucent and mellowable
-do-	60	Slightly brittle
170	30	translucent and mellowable
180	30	Slightly brittle

millet to the heat transfer media of less than 150^{o}C, not only results in lower degree of gelatinization but requires longer period of contact. This imparts brittle texture to the grain whereas, mixing the steeped millet to the heat transfer media at temperatures higher than 160^{o}C causes surface charring and slight parching of the grains. In view of this, the millet steeped for about 10 h and agitated in sand heated to 150$\pm$2^{o}C for 30$\pm$5 sec was found most optimum for preparation of DHM. Accordingly, the DHM was prepared at semi-pilot scale and evaluated for some of its physicochemical characteristics.

The DHM was darker than the NM but lighter than the HTM as evident from the L* (19.3), a* (8.5), b* (6.6) and ΔE (72.3) values for color (Table 18). It was slightly bulged with a grain diameter of 1.8 mm and surface area of 9.87 mm^2 which are slightly higher than the corresponding values for HTM (1.46 mm and 8.92 mm^2). The thousand kernel weight and volume of the DHM were 3.2 g and 4.4 ml respectively, as against 2.7 and 4.1 for HTM. The bulk and true density values of DHM were slightly lower (0.73 and 1.23 g/ml) than the HTM (0.77 and 1.35 g/ml). The hardness of DHM (18N) was also considerably lower than that of the HTM (230N) as well as the NM (37N). This could be due to the instant drying of the millet during the heat treatment, leading to sudden decrease in the moisture content. This may not facilitate retrogradation of the starch and as a result the hardening of the endosperm does not take place. The preliminary studies on the decortication characteristics of the DHM were very poor, as almost all the grains fragmented in to grits during milling. Since, the main objective of the study was to prepare the HTM suitable for preparation of decorticated millet, further studies on DHM was not undertaken.

Dry heat parboiling of cereals is no doubt simple and an economical process and is extensively practiced for rice even now. But, the preliminary experiments on the decortication characteristics of DHM were not at all promising as a slightest impact caused breakage of the grain leading to pulverization of the endosperm and seed coat. However, detail investigations on the various factors influencing the endosperm texture of the millet needs to be carried out, to make it a viable process for millet.

Table 18. Some of the quality characteristics of dry heat treated finger millet

Parameter	Hydrothermally treated	Dry heat treated
Color		
L*	13.73±0.07	19.26±0.09
a*	2.07±0.07	8.50±0.08
b*	0.80±0.01	6.56±0.05
ΔE	77.04±0.10	72.29±0.20
Diameter (mm)	1.46±0.04	1.80±0.06
Surface area (mm^2)	8.92±0.20	9.87±0.10
Sphericity	0.89±0.05	0.91±0.05
1000 kernel weight (g)	2.71±0.07	2.73±0.03
1000 kernel volume (ml)	4.10±0.10	4.40±0.12
Bulk density (g/ml)	0.77±0.03	0.73±0.04
True density (g/ml)	1.35±0.03	1.23±0.02
Hardness (N)	235.00±3.00	20.00±5.00

Summary and Conclusions

Hydrothermal treatment to the millet involves steeping, steaming and drying. The steeping characteristics of the millet depend on temperature of the steep water and the rate of hydration is rapid at elevated temperatures. The equilibrium moisture content of the millet (EMC) is 35±1% and the millet attained its EMC on steeping for about 10 h at 30°C and about 2 h at 70°C. Steeping the millet beyond 70°C caused burst opening of the kernel.

It was observed that, steaming the millet either at atmospheric pressure for 30 min or at 4 kg/cm^2 for 6 min was optimum. Steaming the millet for more than 35 min at atmospheric pressure and for more than 6 min beyond 4 kg/cm^2 pressure damaged the kernel integrity leading to exuding the part of the endosperm. Drying the steamed millet caused surface undulations and slight deformation of the kernel. Drying the millet at 39±1°C was optimum as drying lower than this temperature resulted in development of off flavor and at higher temperature, caused visible fissures in the grain besides enhancing its friability.

Hydrothermal treatment did not change the gross nutrient content of the millet but it caused considerable changes in its carbohydrate and protein profiles. It caused slight thermal degradation of starch as well as the prolamin proteins. The total extractability of the proteins was decreased by about 50%. However, hydrothermal treatment did not alter the fatty acid profile of the millet significantly.

Hydrothermal treatment darkened the kernels, increased the grain hardness by 5 to 6 fold. It reduced the cooked paste viscosity but increased the hydration capacity of the millet. The thermal properties and the crystalline nature of the starch were also altered by the hydrothermal treatment, as indicated by the negative enthalpy by the differential scanning calorigram and shift in crystalline pattern of the starch from A to V-type as revealed by the X-ray studies. The endosperm of the hydrothermally treated millet was homogeneous coherent mass as revealed by the microscopic examination.

From the above observations it may be concluded that, the optimum conditions for preparation of hydrothermally treated millet are, raising the moisture content of the millet to 35±1%, by steeping at ambient or at elevated temperatures (<70^{o}C), steaming for about 30 min at atmospheric pressure or for about 6 min at 4 kg pressure and drying at about 40^{o}C to safe storage moisture level. Hydrothermal treatment to the millet alters its physicochemical characteristics including enhancing its hardness by 5 fold, reducing the protein extractability by about 50% and slightly degrading the amylopectin component of its starch.

INTRODUCTION

Decortication or pearling or milling of cereals is normally carried out to separate out the seed coat from the endosperm without causing damage to the kernel. But in the case of wheat, maize, sorghum and millets, decortication is not common and even if the grains are decorticated, generally they are further size graded into grits, semolina or flour. In the case of cereal processing, the terms decortication, pearling, polishing and also milling are used in synonyms. Decortication is mainly a physical process, and it is generally ruled by the principles of friction, abrasion, shear or impact and sometimes the combination of two or more of these principles. In case of those grains having husk as a distinct entity such as rice, oats, barley etc., impact or compression shear is applied to remove the outer layers of the kernel. But in case of wheat and sorghum wherein, the seed coat mainly comprises of the testa and aleurone layers, normally the principles of friction and abrasion are used to separate out the seed coat. However, it is well known that the grain moisture content and the status of the endosperm with respect to its fragility, play a very important role during decortication of cereals (Bhattacharya and Indudhara Swamy, 1967). In the case of rice, the bran layer is rather loosely attached to the endosperm and it detaches easily during milling. But in the case of wheat and sorghum incipient moist-conditioning is known to facilitate removal of the bran as the treatment not only loosens the intactness of the bran with the endosperm, but also makes it leathery and hinders its fragmentation (Tkac, 1992). In the case of HTM, decortication mainly refers to detaching the seed coat and to obtain the endosperm in intact form. The HTM, as described in Chapter II, contains the seed coat which is rigidly attached to the endosperm unlike in parboiled rice, wherein the husk is loosely attached. In view of this, either friction or abrasion or synergy of both was explored to detach the seed coat. Hence, the influence of the grain moisture content and also the incipient moist-conditioning on milling qualities of the HTM was also investigated.

The seed coat content in HTM forms almost 13 - 15% of the total kernel mass, which is known to contain a good amount of protein, fat, dietary fiber and micronutrients. Thus, removal of the seed coat not only leads to loss

of the seed matter but also in the loss in some of the nutrients from the millet. However, the seed coat of the millet is also known to contain some of the antinutritional factors and its separation may improve the digestibility and bioavailability of the other nutrients.

As mentioned earlier, the food uses of the millet are mainly confined to the meal based products because decortication was unheard in case of finger millet so far. Hence, the decorticated millet is a new generation product from the millet. Since, it is essentially a parboiled millet, the physicochemical and nutritional characteristics of the decorticated millet are largely influenced by the preprocessing conditions of the millet to prepare HTM, namely, steeping, steaming and drying conditions. Parboiled rice is known for some of its textural and nutritional benefits over raw rice because, the physicochemical as well as the biochemical changes that take place during parboiling influence its nutritional and also the culinary properties. The most important advantage associated with the culinary characteristics of the parboiled rice is, its discreteness on cooking (Kato et al., 1983). Apart from this, it has been well established that parboiled rice exhibits better storage properties and shelf-life mainly due to the increase in the hardness and inactivation of the lipase (Anthoni Raj and Singaravadivel, 1982). This may hold good with decorticated millet because of its hard texture and inactivation of lipase, but the extremely good storage properties of the finger millet which is attributed to its polyphenols rich and tough seed coat content, may not hold good for decorticated millet also since it is devoid of the seed coat. In view of this, the storage property of the decorticated millet may differ extensively than its native millet. As expected, the main food use for the decorticated millet would be cooking it in the form of discrete grains. The scientific information on this aspect of the millet would be totally new information and hence the various aspects of the millet with respect to its cooking characteristics and texture of the cooked millet including its sensory acceptability were of paramount importance. It is expected that, the decorticated millet may exhibit quality characteristics similar to parboiled rice. However, the nature of carbohydrates as well as proteins besides, the non-starch polysaccharide contents in the endosperm of the millet are different than rice. Apart from this, normally the

embryo is detached during milling of rice but in the case of millet since the embryo is placed in a shallow depression, its separation normally may not occur during decortication. Besides, the possibility of diversified uses for the decorticated millet for conventional and novel food products, which are generally prepared from rice and wheat, was also explored.

It has been explained earlier that, the primary objective of the hydrothermal treatment to the millet was to enhance its hardness to enable its decortication and hence the important factors influencing the hardness of the HTM were investigated. Apart from the hardness, the other physical properties of the HTM such as shape, size, surface area, volume, porosity etc which are known to influence the decortication characteristics of the millet were also studied.

Hence, detailed investigations were undertaken to study the decortication characteristics of the millet and the physicochemical properties and also the cooking qualities as well as the shelf-life of the decorticated millet.

MATERIALS AND METHODS

1. Materials

The hydrothermally treated millet (HTM) prepared on pilot scale as described earlier was size graded using the cereal grader fitted with the wire mesh screens of 1680 and 1405 μm openings and the grains of size falling in the range of '-1680+1405' μm were used for the studies.

2. Decortication

2.1. The mill

The preliminary experiments on the decortication of HTM using different abrasive and friction type cereal milling machinery, namely, Engleburg huller (Sri Ganesha Engineering Works, Chennai, India), McGill miller (HT McGill, Houston, Texas, USA), vertical cone polisher (Dahanu Industrial Works, Thane, India), horizontal carborundum disc mill (Millone, Radhika Industries, Rajkoat, India) and the barely pearler (Satake Engineering Co Ltd.,

Hiroshima, Japan) were conducted. It was observed that, the horizontal carborundum disc mill was most suitable for the decortication of the HTM effectively. Accordingly, for the studies on decortication of the millet horizontal carborundum disc mill was used. The mill comprises of two horizontal discs of about 18.5 cm diameter. The upper disc is stationery while the bottom disc is attached to a motor which rotates at 960 rpm. The clearance between the discs can be adjusted to different levels. The feed hopper is placed at the centre of the top plate. The mill basically works on the principles of abrasion and friction.

The various factors that influence the decortication characteristics such as the moisture content of the HTM, incipient moist-conditioning of the grains prior to decortication, the feed rate and the clearance between the discs were studied to optimize the decortication characteristics so as to get maximum yield of decorticated head grains.

To optimize the feed rate and the clearance between the plates of the carborandum discs of the mill, the decortication experiments were conducted using the HTM of about 14% moisture content. From the preliminary experiments, it was observed that the feed rate of 1kg/h and the clearance of 1.3 mm between the discs of the mill were optimum and hence, the same conditions were used throughout the decortication studies. Further, it was also noticed that, instead of single stage milling, 2 stage milling was desirable to minimize the breakage as well as for the effective removal of the seed coat.

2.2. Moisture content of HTM

Normally, the moisture content of the cereals largely influences their decortication characteristics in terms of degree of decortication and also the yield of the decorticated head grains. Accordingly, the HTM in a batch size of 100 g each, equilibrated to different moisture levels ranging from 6 - 21% moisture contents, was used for decortication experiments. The millet after the first pass was sifted through a sieve of 1003 μm followed by a sieve of 600 μm openings and all the three fractions were collected separately. The "+1003" μm fraction was termed as head grains; "-1003+600" μm as brokens

and "-600" μm as the seed coat or husk. The partially decorticated head grains were again decorticated in the same setup, and the decorticated head grains, brokens and seed coat were separated. The brokens and the seed coat matter from both the passes were pooled. The grains that were almost free from the seed coat (> 90%) were considered as decorticated grains. All the three milling fractions were equilibrated to 12% moisture content, weighed and the yield of head grains and other fractions were calculated using the following relation;

$$\text{a) Yield of head grains (\%)} = \frac{\text{Weight of head grains}}{\text{(Weight of head grains + brokens+ husk)}} \times 100$$

$$\text{b) Yield of brokens (\%)} = \frac{\text{Weight of brokens}}{\text{(Weight of head grains + brokens+ husk)}} \times 100$$

$$\text{c) Yield of seed coat (\%)} = \frac{\text{Weight of seed coat}}{\text{(Weight of head grains + brokens+ husk)}} \times 100$$

2.3. Influence of incipient moist-conditioning

The experiments on the influence of the moisture content on the yield of head grains indicated that, the millet at 15±1% moisture level was more suitable for decortication and accordingly, the HTM equilibrated to 15±1% moisture level in 100 g batches, was sprayed with 1 - 7% additional water with 1% increment and tempered for 10 min and decorticated as described above. The head grains from the first stage of milling were again mixed with 1 - 6% additional water, with 1% increment, equilibrated and again milled in the same set up. The milling fractions (head grains, brokens and the seed coat) were equilibrated and weighed to determine the milling yield. Based on these experiments, a decortication protocol was developed (Figure 37).

3. Influence of steaming conditions

Steaming plays very important role on the endosperm modifications as well as the overall quality characteristics of HTM. Among the various physicochemical characteristics of HTM, hardness is the single most parameter that influences the decortication properties. Hence, experiments were carried out to study

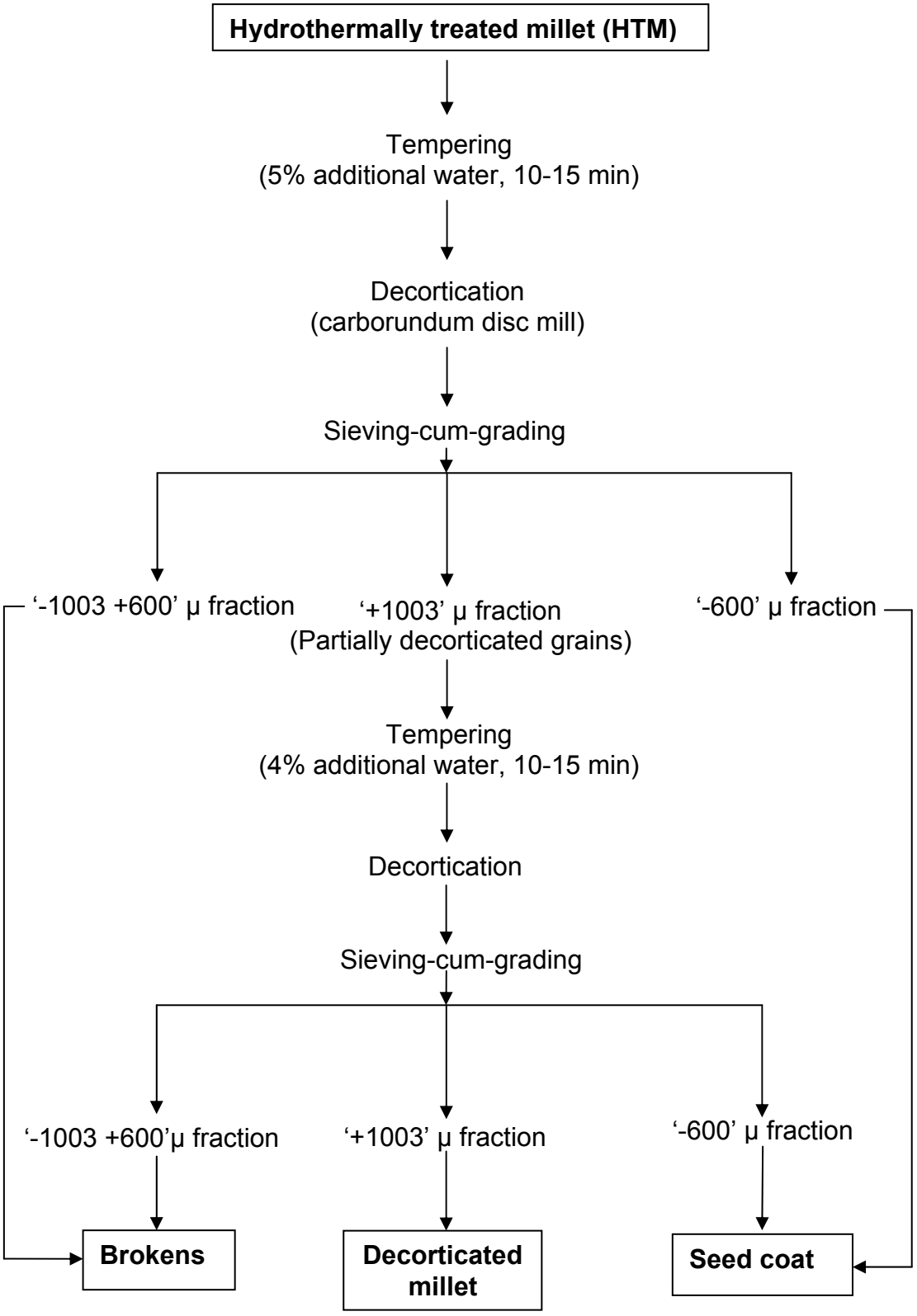


Figure 37. Flow chart for the preparation of decorticated finger millet

the influence of steaming conditions like, the steaming time and steam pressure on the hardness of the steamed and dried millet and assessing their decortication characteristics. For the purpose, a preliminary experiment was conducted prior to response surface methodology wherein, the millet steeped to the EMC, was steamed at atmospheric pressure from 5 to 35 min with 5 min increment as described earlier. Subsequently, in another set of experiments, the steeped millet was steamed at 1, 2 and 3 kg/cm^2 pressure for 30 min and at 4 kg/cm^2 pressure for 15 min. In all the cases, the steamed millet was dried at 40$\pm$1^{o}C to 14$\pm$1% moisture content and denoted as 'steamed and dried millet' (SDM). The hardness of all the samples was determined using a texture analyzer as described earlier. Further to that, an experiment was designed using response surface methodology mainly to find out the most suitable conditions of steaming that produces the millet with desirable level of hardness, which on decortication yields maximum percentage of decorticated head grains. The responses studied were mainly hardness and milling yield. In addition to this, a few other physical parameters of SDM such as porosity, density and also the hydration capacity were included as part of the responses.

3.1. Response surface methodology

A two variable, five level central composite rotatable (CCRD) experimental design was employed (Myers, 1971). The two independent variables were the steaming time and steaming pressure. The complete experimental design is shown in Table 19 with coded (X_1) as well as actual (X_2) levels of independent variables. The experimental design included star points and five centre points. The treatment schedule for CCRD is shown in Table 20. All experiments were carried out in a randomized order to minimize any effect of extraneous factors on the responses. The responses studied were the milling yield, hardness, porosity, water absorption, equilibrium moisture content, color, 1000 kernel weight, bulk density and true density. The coefficients of the response function, their statistical significance and processing conditions were evaluated. Coefficients of the model given in the equation were evaluated by regression analysis and tested for their significance. The insignificant coefficients were eliminated based on the p values and the final equation for

Table 19. Variables and their levels for Central Composite Rotatable Design (CCRD)

Parameters	Levels		
	-1	0	+1
X1	0	8.562158	35
X2	0	4.734572	4

Table 20. Treatment schedule for CCRD

Sl. No.	Steaming time (min)	Steam pressure (kg/cm^2)
1	5.12	0.59
2	5.12	3.41
3	29.88	0.59
4	29.88	3.41
5	0.00	2.00
6	35.00	2.00
7	17.50	0.00
8	17.50	4.00
9	17.50	2.00
10	17.50	2.00
11	17.50	2.00
12	17.50	2.00

the prediction of the responses was obtained. The analysis of variance (ANOVA) is indicated in the Table 21.

A. Optimization

According to the canonical analysis described by Myers (1971), the stationary points were located for the corresponding responses. The data were analyzed by multiple regressions to fit the following second order (quadratic) polynomial model;

$$y = \beta_0 + \sum_{i=1}^{2} \beta_i X_i + \sum_{i=1}^{2} \beta_{ii} x_i^2 + \sum_{i=1}^{2} \beta_{ij} x_i x_j$$

wherein, y is the predicted response, $ß_0$, $ß_i$, $ß_{ii}$, and $ß_{ij}$ are constant regression coefficients of the model. X_i and X_j are the independent factors. The effect of individual linear, quadratic and interaction terms was determined (Khuri and Cornell, 1987). The significance of all the terms in the polynomial was judged by F test and p values whereas, the multiple correlation coefficient (R) was calculated by probability levels. To visualize the relationships between the responses and independent factors, a software "Statistica" (version 5, StatSoft, Tulsa, OK) was used and the results were expressed graphically by generating response surfaces.

B. Responses

The responses namely, hardness, porosity, color, 1000 kernel weight, apparent density and true density and also the water absorption capacity as well as the equilibrium moisture content were determined as described earlier (Chapter II). The yield of the decorticated grains was determined as explained earlier.

Guided by the RSM studies, the millet steeped for 10 h and steamed at 3 kg/cm^2 pressure for 10 min and dried at 40$\pm$2^{o}C was prepared on pilot scale and was decorticated using pilot scale carborundum disc mill following the protocol developed for decortication.

The decorticated millet (DM) prepared was used for determination of the physical properties and cooking qualities and also for the storage studies.

Table 21. Analysis of variance for the fitted second order polynomial model as per CCRD

	Sum of squares			
	Hardness	Milling yield	Water absorption	Porosity
Steaming time (L)	3348.37	120.19	155.94	52.49
Steaming time (Q)	1448.94	877.93	50.91	291.45
Steam pressure (L)	2436.87	1082.20	998.43	100.44
Steam pressure (Q)	206.49	160.86	62.02	141.71
1L by 2L	3369.22	460.32	0.00	61.23
Error	12207.97	2590.88	1147.94	653.11
Total SS	22858.30	5178.60	2396.44	1233.48
Regression Coefficients				
Mean/Interc.	176.92	-14.86	41.57	44.96
Steaming time (L)	5.11	4.22	-0.29	1.30
Steaming time (Q)	-0.10	-0.08	0.02	-0.04
Steam pressure (L)	28.11	29.03	1.65	2.99
Steam pressure (Q)	-2.84	-2.51	1.56	-2.36
1L by 2L	-1.66	-0.61	0.00	0.22

The DM was pulverized in a laboratory pulverizer to prepare meal of particle size less than -250 μm and analyzed for its nutrient composition. The meal was also used for the determination of its carbohydrate, protein and lipid profiles besides, for evaluation of some of the functional and thermal properties, and also for its X-ray diffraction as explained earlier.

4. Physicochemical properties

4.1. The physicochemical properties such as color, grain diameter, bulk density, 1000 kernel weight as well as volume, grain hardness, hydration characteristics, viscosity, solubility index and swelling power and the nutrient composition of the DM were determined as described earlier (Chapter II). The carbohydrate, protein and fatty acid profiles, carbohydrate and protein digestibility, total and soluble amylose content, thermal properties (DSC calorigram) and the X-ray diffraction pattern of the DM were also studied following appropriate methodologies as described for that of the HTM in Chapter II.

The native millet is known to contain considerable levels of phytochemicals with neutraceutical ability and among them polyphenols and phytic acid are prominent. Both of these are known to be concentrated in the seed coat matter (Chethan and Malleshi, 2007b) and some portion of the polyphenols from the seed coat migrates towards the endosperm during hydrothermal treatment (Shobana, 2009). Hence, the polyphenols and phytic acid contents of the DM were assayed.

4.2. Polyphenols

The polyphenols content of the DM was determined as per the procedure of Singleton et al. (1995) as described earlier (Chapter II).

4.3. Phytic acid

The phytic acid content was determined using the Megazyme kit (K-PHYT 05/07,Megazyme, Ireland). Accordingly, about 1g of the meal is extracted with 20 ml of hydrochloric acid (0.66M) for 3 h at room temperature with constant stirring and 1 ml of the extract was taken and centrifuged for 10 min at 11,300×g and the supernatant was neutralized with 0.5 ml of NaOH (0.75M).

To 0.05 ml of the neutralized extract, 0.60 ml distilled water was added followed by addition of 0.2 ml of sodium acetate buffer (0.2M, pH 5.5) and 0.02 ml of phytase. The mixture was incubated at 40^{o}C for 10 min and to that 0.2 ml of glycine buffer (0.4M, pH 10.4) containing 0.02 mL of alkaline phosphatase was added. The mixture was again incubated at 40^{o}C for 15 min and the reaction was stopped by the addition of 0.3 ml of 50% trichloroacetic acid. The contents were centrifuged at 11,300×g for 10 min and to 1 ml of the centrifugate, 0.5 ml of color reagent (5 parts of 10% ascorbic acid in 1M sulphuric acid and 1 part of 5% ammonium molybdate) was added and the optical density was measured at 655 nm against a standard phosphorus solution to determine the **total phosphorus content**. Simultaneously, the **free phosphorus** was determined by mixing 0.05 ml of the neutralized extract with 0.2 ml of sodium acetate buffer and 0.62 ml of distilled water followed by incubating at 40^{o}C for 10 min. To the reaction mixture, 0.02 ml of distilled water and 0.2 ml of glycine buffer was added and incubated at 40^{o}C for 15 min followed by the addition of 50% trichloroacetic acid. The contents were centrifuged at 11,300×g for 10 min to 1 ml of the centrifugate and 0.5 ml of color reagent was added and the absorbance was measured at 655 nm. Parallely, the optical density (OD) for the standard was recorded using the standard solution supplied along with the kit. The phosphorus and phytic acid contents were calculated as;

$$\text{Phosphorus (g/100g)} = \text{OD for standard} \times 0.1112 \times \Delta A_{\text{phosphorus}}$$

where;

$\Delta A_{\text{phosphorus}}$ = Difference between the total phosphorus and the free phosphorus

$$\text{Phytic acid (g/100g)} = \frac{\text{Phosphorus}}{0.282}$$

4.4. Bioavailable calcium and iron

The millet is known for its high calcium content and nearly 40% of it is concentrated in the seed coat matter. Moreover, the millet also contains considerable amount of phytic acid, which is known to combine with calcium and other minerals and reduce their bioavailability. But most of the phytic acid

is located in the seed coat of the millet and hence separation of the seed coat by decortication is expected to enhance the bioavailability of minerals in the DM. In view of this, the bioavailability of calcium and iron of the DM were determined.

Bioavailable calcium and iron were analyzed by the method of equilibrium dialysis (Miller et al., 1981). In brief, the meal of NM and DM were first subjected to simulated gastrointestinal digestion by adjusting the pH to 2.0, followed by addition of pepsin (3 ml of 16% pepsin in 0.2M HCl) and incubation in a shaker water bath at 37^{o}C for 2 h. Then the digest was frozen for 90 min to stop the reaction. The frozen digest was thawed and an aliquot of the digest (20 ml) was tested for its titrable acidity by adding 5 ml of pancreatin-bile extract mixture (4 g of pancreatin and 25 g bile extract in 1 L of 0.1M $NaHCO_3$) against 0.2M NaOH until a pH 7.5 was attained.

The remaining digest was transferred into the dialysis tubes (molecular cut-off 10 kDa) and subjected to simulated intestinal digestion by placing the dialysis tubes in Erlenmeyer flasks containing 25 ml $NaHCO_3$ (equivalent to moles of NaOH determined by titratable acidity). The flasks along with the tubes were incubated in a shaker water bath at 37^{o}C for 30 min (until the pH of the solution in the flask changes to 5.0), and to the contents of the flask, pancreatin-bile extract mixture was added and shaken for another 2 h (until the pH reached 7.0). The dialysate from the tube was carefully transferred to graduated tube and the volume was measured and its calcium and iron contents were estimated by Atomic Absorption Spectroscopic method (Suma et al., 2007).

4.5. Solid loss and swelling power at different temperatures

To 5 gram of DM taken in graduated centrifuge tubes, 60 ml of distilled water was added, left for 2 h in a water bath maintained at 30^{o}C, the contents were centrifuged at 1750×g for 20 min. The total volume of the supernatant was noted and an aliquot (10 ml) was transferred into a pre-weighed petriplate and evaporated to dryness to estimate the amount of solids leached. The residue in the centrifuge tube was weighed and dried. From the weight of the sample

in wet as well as in dry conditions, the swelling power and the water uptake were calculated. The experiment was repeated at higher temperatures up to 90^{o}C with an increment of 10^{o}C.

5. Cooking qualities of the decorticated millet

5.1. Determination of cooking time

About 10 g of the DM taken in a wire mesh gadget was immersed in boiling water (70 ml), one or two representative grains from the lot was taken out every minute and pressed between two glass slides and the spreadability as well as the translucency of the spread was observed. Cooking was considered optimum when the spread no longer exhibited opaqueness or uncooked flour particles and the time taken to attain this state was considered as the cooking time.

5.2. Water uptake, swelling power and solid loss

A known quantity (10 g) of DM taken in a perforated metallic jar was cooked by immersing in boiling water (70 ml) for the predetermined cooking time, the cooked grains were removed and the adherings were washed with minimum water into the same container and the total volume was noted. An aliquot (10 ml) of the residual water, taken in a pre-weighed petriplate, was evaporated to dryness using a boiling water bath and finally dried in air oven at 50^{o}C to constant weight to determine the solid loss. The cooked grains were also weighed and dried to determine the swelling power and water uptake during cooking.

An aliquot (1ml) of the residual liquid was diluted with 25 ml of distilled water followed by the addition of 2 ml of 0.2% iodine. The total volume was made up to 100 ml and the absorbance was measured at 630 nm (Sowbhagya and Bhattacharya, 1971), to calculate the **amylose** content in the residual liquid.

5.3. Texture profile analysis (TPA)

The cooked grains were equilibrated to room temperature in a closed container and their texture profiles were measured in a universal texture analyzer (Stable Microsystems, model TA – HDi, Surrey, UK). The force

required to compress a single grain to cause 75% deformation was recorded at a crosshead speed of 100 mm/min with 50 kg load cell. The hardness, springiness, adhesiveness, chewiness, cohesiveness and gumminess were measured from the texture profile (Krishna Murthy and Kantha, 2003). An average value for 10 grains was calculated to report the texture profile.

5.4. Sensory analysis

About 100 g of the DM was cooked in 250 ml of water for the optimum time so that all the water was absorbed and evaluated for its sensory attributes while it was warm. The sensory evaluation was done following quantitative descriptive analysis method (Chapman et al., 2001). Evaluations were carried out under the fluorescent light at 25$\pm$2^{o}C with 64% RH. For the purpose, the cooked millet was served without adding any adjuncts, to a group of trained panelists (n=10) and their evaluation of the product for appearance, flavor, mouth feel and discreetness on a structured line scale marked with 10 points were recorded. However, for evaluating the overall quality of the product, the panelists were asked to mark on a 9 point hedonic scale which was anchored at extremely dislike (1), neither dislike nor like (5) and like extremely (9). The sensory scores for each attribute were tabulated and the mean score were calculated. These mean scores represent the panel's judgment about the sensory quality of the samples. Subsequently, the cooked millet was also served to some of the non-traditional millet consumers along with *sambar*, the traditional spicy adjunct normally used along with rice, and their opinion with respect to overall acceptability of the product as a substitute to rice, was obtained.

6. Storage studies

6.1. Sorption behavior

For studying the sorption isotherm, 5 g of the DM taken in duplicate pertriplates was exposed to different relative humidity (RH) ranging from 11 to 92%, built up in desiccators using appropriate saturated salt solutions (Rockland, 1960) (Table 22). The desiccators were kept in a room maintained at 27^{o}C. The samples were weighed periodically at every 2 - 3 days till they attained constant weight or onset of mould growth, whichever occurred

earlier. About 100 g of the DM taken in a petriplate were also exposed to different humidity along with the other samples in all the desiccators. These samples were used for examining the influence of the RH on some of the quality characteristics namely, color, free fatty acid contents (FFA) (AOAC, 2000) and cooking qualities. The samples were examined for the total plate count according to Vanderzant and Splittstoesser (1992) in the terminal stages of the sorption studies.

Table 22. Saturated salt solutions and their relative humidity (RH)

Salt	RH%
Lithium chloride (LiCl)	11
Potassium acetate (CH_3COOK)	22
Magnesium chloride ($MgCl_2$)	32
Potassium carbonate (K_2CO_3)	44
Sodium bromide (NaBr)	56
Sodium nitrite ($NaNO_2$)	64
Sodium chloride (NaCl)	75
Potassium chromate (K_2CrO_4)	86
Potassium nitrate (KNO_3)	92

6.2. Shelf-life studies

The sorption isotherm revealed that, the decorticated millet was comparable to other milled cereals with respect to the hygroscopic nature. It was also noticed that the DM retained its physical and sensory qualities without any visible mould growth even at 86% RH on exposure to about 75 days. Hence, a low-density polypropylene (gauze 350 μm) was identified as packaging material for the storage studies. Accordingly, 250 g of freshly prepared DM was packed in LDPE pouches (water vapor transmission rate 4.31 at 92% RH at 38^{o}C) in unit of size 10×15 cm (l×b). The pouches were sealed and stored at ambient (27^{o}C, 64% RH) and accelerated (38^{o}C, 92% RH) storage conditions. The pouches were withdrawn from accelerated conditions periodically for once in 15 days for accelerated and once in a month for ambient storage conditions, and analyzed for moisture, free fatty acids and

color and also the samples were cooked and the sensory acceptability of the cooked millet was assessed as described earlier.

RESULTS AND DISCUSSIONS

1.1. Decortication characteristics

The decortication characteristics of the hydrothermally treated millet were influenced by the moisture content of the material and also by the moist-conditioning treatment. The HTM at different moisture levels was subjected to decortication and it was observed that the millet with moisture content less than 12% resulted in considerable breakage of the kernels without peeling of the seed coat. But as the moisture content of the DM increased up to 15%, the yield of decorticated millet improved and beyond that breakage as well as deshaping of the kernels occurred (Figure 38). Under the experimental conditions, the millet with about 15% moisture content exhibited maximum yield of the decorticated grains (45%). However, it was observed that, moist-conditioning improved the decortication characteristics of the millet. Accordingly, to enhance the milling yield, moist conditioning of the millet was explored at each stage of milling. It could be inferred from the Table 23 that, the yield of the head grains varied as a function of added moisture. The yield increased from 56.3 to 85.3% as the percentage of added water increased from 1 to 5 and after that it tended to decrease slightly with a marginal increase in the brokens. The highest yield of 85.3% was obtained for the HTM with 5% added water. Accordingly, the millet equilibrated to 15% moisture content was sprayed with 5% additional moisture and decorticated. Subsequently, the partially milled head grains again tempered with 1 - 6% additional water and decorticated. It was observed that, the yield of the decorticated grains increased (50 to 64.6%) as the percentage of added water increased from 1 to 4 and thereafter the yield started declining. Thus, the HTM with 15% moisture content was tempered with 5% added water at I stage milling, followed by tempering with 4% water in the II stage, resulted in a milling yield of 64.6% (Table 23). Thus, under the experimental conditions of milling, the yield of head grains, brokens and the seed coat fractions were 65, 28 and 6.8%, respectively. The proportion of these milling fractions remained almost constant even during the semi-pilot scale milling of the millet.

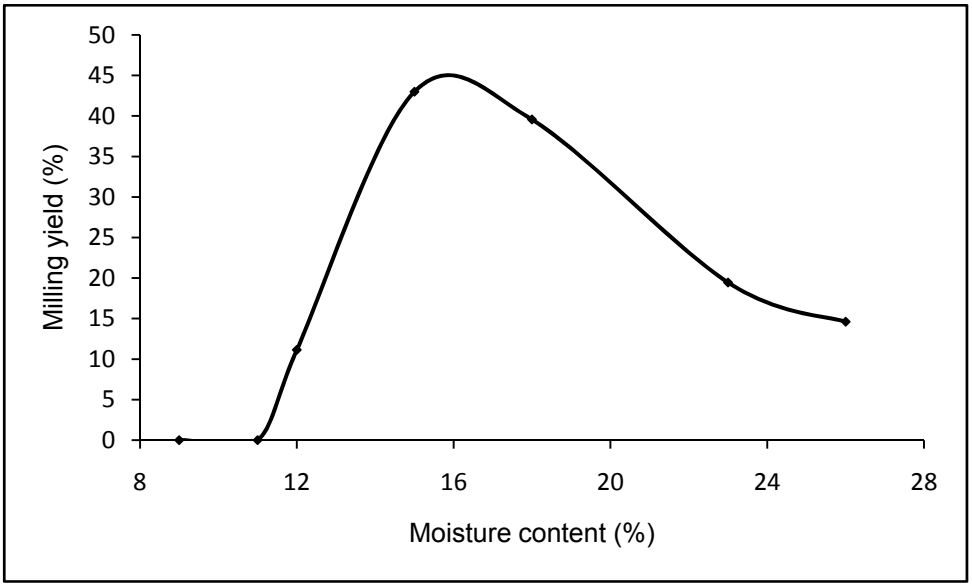


Figure 38. Yield of head grains as a function of the grain moisture content (without moist conditioning)

Table 23. Yield of milling fractions as influenced by the moist conditioning

Added moisture (%)	Head grains (%)	Brokens (%)	Seed coat (%)
	I Stage		
1	56.3[a]	39.4[f]	4.3[a]
2	60.0[b]	35.2[e]	4.8[ab]
3	69.0[c]	25.4[d]	5.6[b]
4	75.7[d]	15.5[c]	8.8[cd]
*5	*85.3[e]	[(i)]5.7[a]	[(ii)]9.0[d]
6	85.2[e]	6.9[b]	7.9[c]
	II Stage		
1	50.0[a]	30.7[c]	4.6[a]
2	55.2[b]	24.8[d]	5.3[ab]
3	60.4[c]	18.9[c]	6.0[bcd]
4	64.6[c]	[(iii)]13.9[a]	[(iv)]6.8[d]
5	62.3[d]	16.6[b]	6.4[cd]
Milling yield	64.6	[(v)]19.6	[(vi)]15.8

** taken for II stage milling*

v = *(i) + (iii)*

vi = (ii) + (iv)

Values in the same column with different superscripts differ significantly (P≤ 0.5) according to Duncan's multiple range test (DMRT)

The effect of grain moisture content on the milling yield has been well documented in case of rice. Generally, at low moisture content the grains are brittle and will not withstand the milling impact resulting in the breakage whereas, at high moisture content the grains are soft and get fragmented decreasing the total head grain yield (Bhattacharya and Indudhara Swamy, 1967). In the case of finger millet also, Shobana and Malleshi (2007) reported that, tempering with 6% additional water improved the decortication characteristics. Incipient moist conditioning softens the seed coat rendering it slightly leathery and hence gets easily scrapped between the carborundum discs of the mill. Moist-conditioning the millet beyond 5% at I stage and 4% at II stage milling again rendered to millet too soft and caused deshaping leading to decrease in the milling yield.

1.2 Response surface methodology

In any experiment, when many factors and interactions affect the desired responses, (RSM) is an effective tool for optimizing the process variables and to identify suitable conditions for preparing the product of desired quality characteristics. The RSM is a statistical method that uses quantitative data from an appropriate experimental design to determine and to simultaneously solve multivariate equation. It generally involves an experimental design such as Central Composite Rotatable Design (CCRD) to fit a second order polynomial by a least squares technique (Hunter, 1959). To determine the interrelationship among the test variables and also to describe the combined effect of all the test variables in the response, suitable equation is used (Rastogi et al., 1998). Thus, the effect of the steaming time and steam pressure on the milling yield of the HTM was optimized using response surface methodology. For the purpose, the hardness of the kernels was considered as a primary factor. A preliminary experiment on the influence of steaming time and steam pressure on hardness of HTM is illustrated in the Figure 39, which clearly indicates that, as the steam pressure and the steaming time increases, the hardness of the kernels increases proportionally to certain extent. With the increase in the severity of steaming, the hardness increases up to a certain point, beyond which it decreases because the grain loses its integrity. Steaming beyond 35 min at atmospheric pressure and more

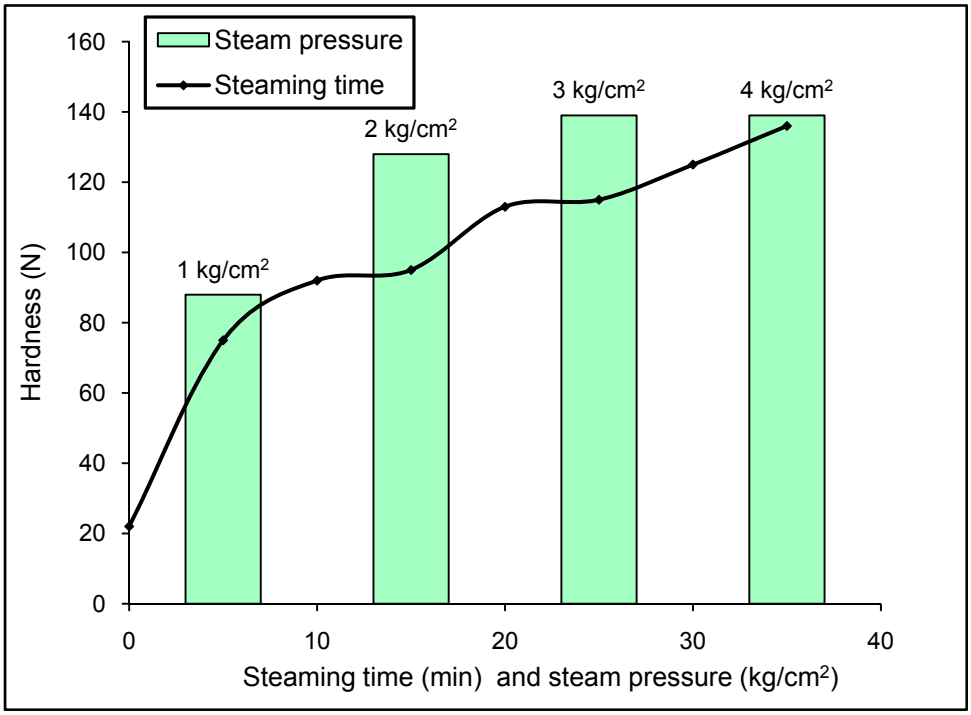


Figure 39. Hardness of finger millet steamed for varying pressure and time

than 15 min at about 4 kg pressure caused disintegration and exuding the part of the endosperm in gummy form. These observations were utilized for designing the experiments on CCRD to optimize the steaming conditions of the millet.

A. Responses

a. Hardness

As indicated earlier, the steaming time and steam pressure profoundly influenced the hardness of the millet (Figure 40a). The relationship between the hardness and steaming time found to be linear as the hardness of the millet increased with the increase in steaming time, whereas, the effect of steam pressure on hardness was quadratic. Steaming at high pressure (3.41 kg/cm^2) for a few minutes increased the hardness to 235 N and prolonged steaming beyond 15 min at this pressure caused exuding part of the endosperm and resulted in decreased hardness (76.3 N) of the kernels. Thus, the effect of severity of steaming on hardness was positive up to a certain extent and was negative thereafter. Thus, the combined effect of steaming time and steam pressure on hardness was dependent on the duration of steaming. Similar observation was made for rice by Islam et al., (2004), wherein, rice was parboiled at two different temperatures (90 and 100^oC) at varying steaming time (5 to 60 min) and reported that steaming the rice at 100^oC over 20 min decreased its hardness. Similar observations were also made by Biswas and Juliano (1988) on parboiling of rice and they reported that, steaming at 1.5 kg/cm^2 pressure for 10 min resulted in exuding part of the endosperm.

b. Milling yield

Similar to hardness, the milling yield also varied significantly with steaming time and steam pressure. With the increase in steaming time, the milling yield increased to certain extent and thereafter the increase was marginal. But, the steam pressure after certain threshold limit caused detrimental effect on milling yield. With the increase in steam pressure the milling yield increased proportionally to a certain extent and thereafter, it decreased exponentially (Figure 40b). This may be due to the loss of kernel integrity, which decreases

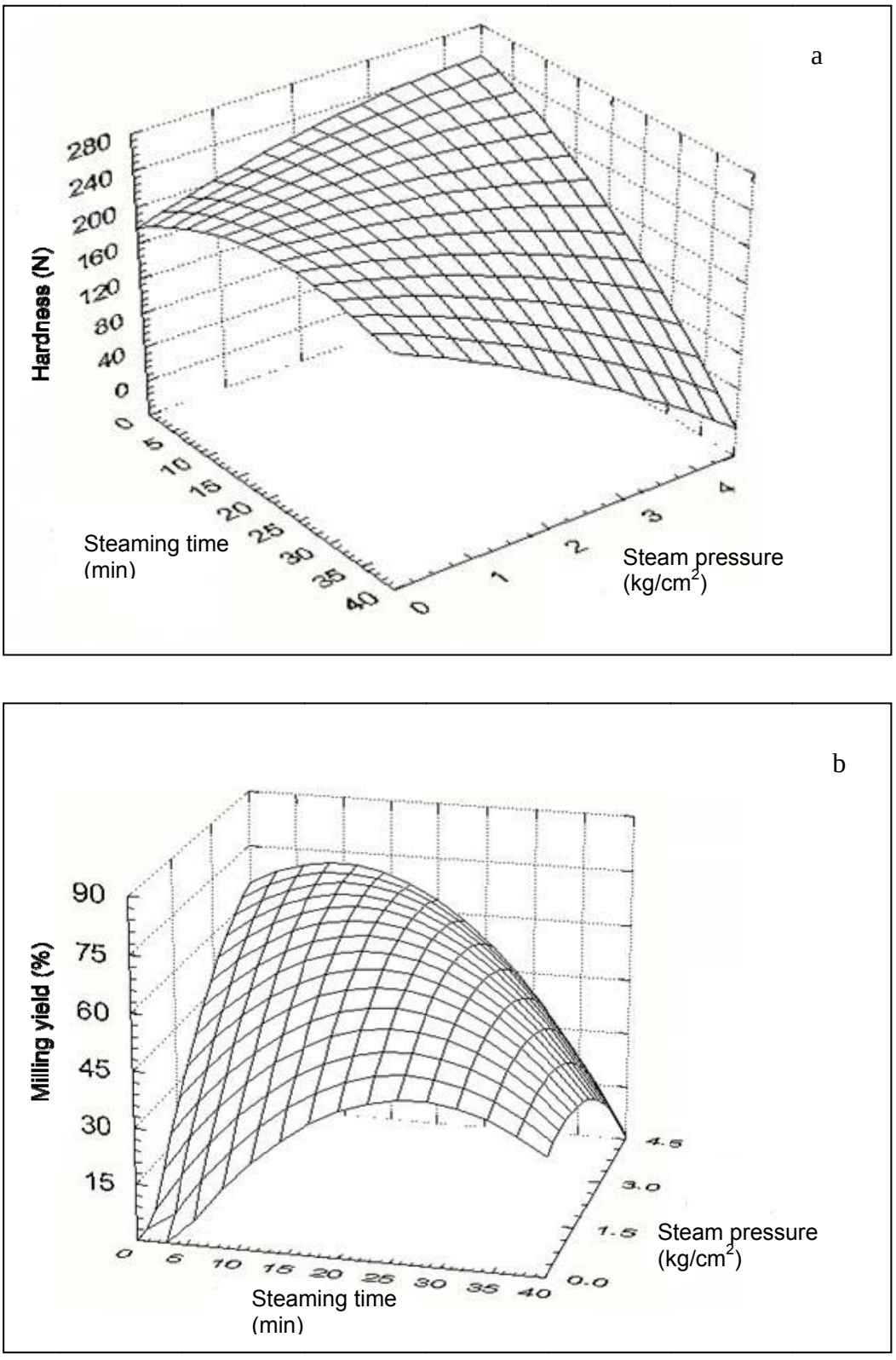


Figure 40 (a). Effect of steam pressure and steaming time on hardness (a) and milling yield (b)

the grain hardness and thereby reducing the milling yield. However, at steaming time of 17.5 min and steam pressure of 3.2 kg/cm^2, the milling yield was maximum (68%), which could be considered as optimum under the experimental conditions.

c. Porosity

The influence of steam pressure on porosity of the millet was higher compared to that of steaming time (Figure 41a). The porosity of the millet varied from 37 to 41 depending upon the severity of the steaming conditions. The decrease in the porosity may be due to the sealing of the air vents and voids present in the endosperm and also between the endosperm and the seed coat resulting in the increased compactness on hydrothermal treatment. However, steaming at higher pressure (3.41kg/cm^2) for longer time (29.88 min) resulted in increased porosity values (43), probably, because of the opening of the kernel and loss of endosperm constituents. Normally, cereals have compact endosperm but the compactness depends upon the ratio of the hard to soft endosperm. Generally, the soft endosperm contain free space or voids whereas, the hard endosperm comprises highly compact texture. However, in case of hydrothermally treated millet, even though the voids were filled up by expanded or gelatinized starchy material, drying conditions of the gelatinized material, induced porosity to some extent. As expected, higher the porosity of the grain, lesser will be the hardness and such grains become highly susceptible to breakage during milling.

d. Water absorption capacity and equilibrium moisture content

The water absorption capacity of the millet varied from 39 to 82.21%, the lowest being for the mildly steamed sample and the highest for the severely steamed millet. Unlike, hardness, milling yield and porosity of the millet, which exhibited a quadratic behavior, there was near linear relationship between water absorption capacity and the severity of the steaming conditions (Figure 41b). The water holding capacity of the steamed millet mainly depends on the status of the starch and as the degree of gelatinization increases, its water holding capacity increases. However, beyond a certain point of steaming time, under normal as well as under pressure steaming, the starch

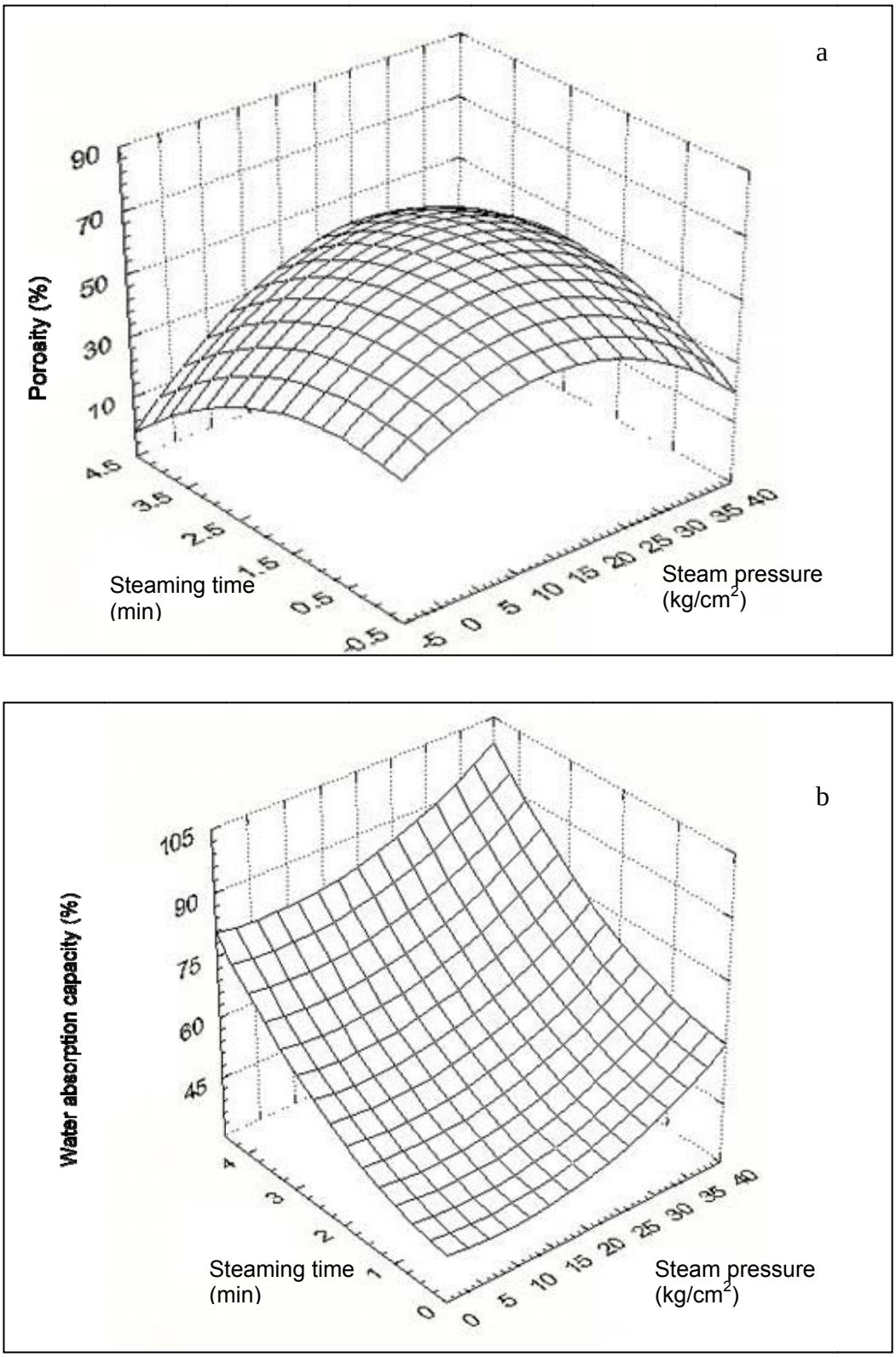


Figure 41. Effect of steaming time and steam pressure on porosity (a) and water absorption capacity (b)

undergoes partial dextrinization. The dextrinized starch is also known to absorb higher proportion of water than the normal starch and hence, the millet steamed under severe conditions continuous to hold increased proportion of water. However, the extent of increase in water holding capacity was higher for pressure steamed millet compared to millet steamed at normal conditions.

Similar to water absorption capacity of the millet, the equilibrium moisture content (EMC) also reveals the severity of parboiling. The EMC of the millet varied from 40 to 57% depending upon the severity of the hydrothermal treatment.

e. Color

The color values recorded in terms of ΔE as a function of steaming time and steam pressure are presented in Table 24. The least change in color (ΔE=48) was observed for the millet steamed at 2 kg/cm^2 pressure for 0 minute (0 minute means, the time at which the pressure gauge in the autoclave just attains 2 kg/cm^2). The maximum value for ΔE (58) was showed by the millet steamed for 29.88 min at 3.41 kg/cm^2. This shows that both duration of steaming as well as the steam pressure influence the color of the millet i.e., steaming the millet at higher pressure for longer period increased the intensity of dark color.

f. Thousand kernel weight and density

The steaming time and steam pressure did not exert any specific influence on the 1000 kernel weight as the values of the millet prepared under different steaming conditions varied from 3.3 to 3.5 g. In other words, the real mass of the kernels remained almost unaltered. However, the apparent density of the kernels varied from 0.73 to 0.84 g/ml with the steaming conditions. Similar to apparent density, the true density of the millet also varied marginally (1.27 to 1.39) with the increase in the steam pressure and steaming time (Table 24).

For optimization of steaming conditions, only four parameters namely the hardness, milling yield, porosity and water absorption capacity of the steamed millet were considered. From the regression calculations of the response surface methodology, the optimum steaming time and the

Table 24. Experimental Design for CCRD and the measured responses

Sl No.	X1	X2	Hardness (N)	Milling yield (g%)	Porosity	Water absorption capacity (%)	EMC (%)	1000 kernel Weight (g)	Apparent density (g/ml)	True density (g/ml)	Color (∆E)
1	5.12	0.59	256	39	38	47	42	3.5	0.83	1.34	47
2	5.12	3.41	235	77	41	82	55	3.5	0.79	1.33	55
3	29.88	0.59	213	66	38	51	44	3.5	0.83	1.34	50
4	29.88	3.41	76	61	43	87	57	3.4	0.73	1.30	58
5	00.00	2.0	187	16	40	39	39	3.5	0.81	1.34	46
6	35.00	2.00	214	31	40	58	47	3.5	0.80	1.33	53
7	17.50	0.00	213	16	40	43	41	3.3	0.84	1.39	47
8	17.50	4.00	225	58	41	56	47	3.3	0.75	1.27	56
9	17.50	2.00	225	78	37	60	48	3.4	0.83	1.38	54
10	17.50	2.00	200	63	40	46	43	3.3	0.83	1.31	51
11	17.50	2.00	227	43	40	52	44	3.5	0.80	1.32	49
12	17.50	2.00	240	65	38	48	43	3.5	0.83	1.34	51

pressure predicted was 10 min and 3.2 kg/cm^2 respectively. Accordingly, the predicted values for the yield of the decorticated grains, hardness, porosity and water absorption capacity were 68.33%, 63.43%, 52.23 and 204.01 N respectively. The predicted conditions were verified and confirmed by conducting experiments under these conditions. The differences between actual and predicted values were not statistically significant ($p<0.05$).

Subsequently, the millet was processed to prepare the decorticated millet on pilot scale following the optimum conditions for steaming time and pressure. The millet steeped at ambient conditions for 10 h, steamed at 3.2 kg pressure for 10 min, dried at 40$\pm$2^{o}C to 14$\pm$1% moisture and then milled as described earlier. The yield of the decorticated grains was 68$\pm$1% which was well within the range of the predicted value.

The DM was freed from the brokens and the adhering bran by aspirator cum grader and the cleaned material was used for the determination of physicochemical properties, cooking qualities and shelf-life studies.

2. Physical properties

The decorticated grains were of light cream color, near spherical shape, opaque and exhibited desirable consumer appeal (Figure 42). Table 25 presents the L*, a*, b* and ΔE values for DM and HTM. The lightness value (L*) of DM was significantly high (53.32) compared to that of the HTM (13.73). Similar observations were made for the redness and yellowness values also, which increased from 2.07 and 0.8 to 3.82 and 12.87, respectively, after decortication. This indicated that, the DM was of slightly reddish cream in color (ΔE= 39.93). The change in color of the endosperm from milky white to mild reddish cream may be due to the inward movement of the pigments and polyphenols and also due to Maillard reaction during the hydrothermal treatment. Even though, the hydrothermal treatment darkened the millet, decortication improved its color and overall appearance also.

The disadvantage of darkening of the millet due to hydrothermal treatment has been overcome by decortication, as the ΔE values for the DM was lower

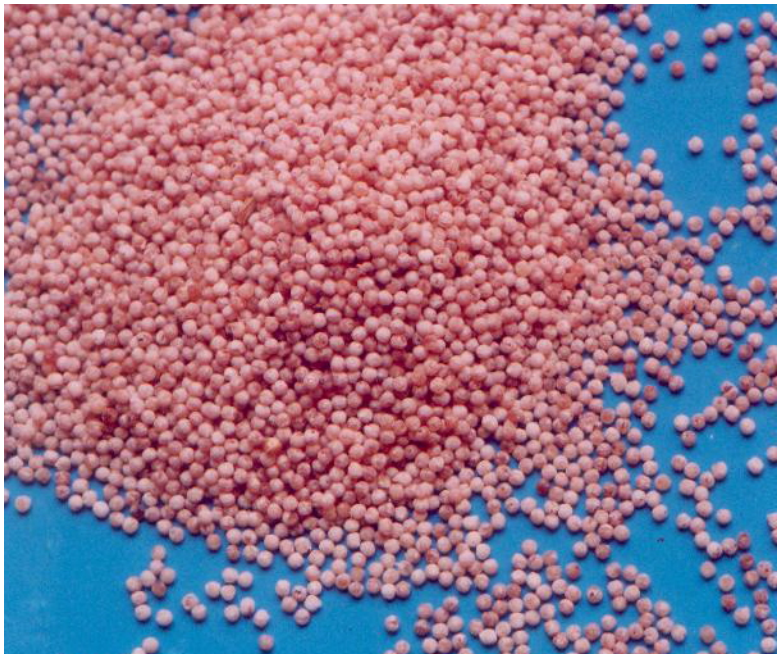


Figure 42. Decorticated finger millet grains

Table 25. Color indices of the grains and meals of hydrothermally treated and decorticated finger millet

Colour	Hydrothermally treated		Decorticated	
	Grains	Whole meal	Grains	Whole meal
L*	13.73±0.07	57.91±0.10	53.32±0.2	76.31±0.10
a*	2.07±0.07	3.13±0.02	3.82±0.06	1.23±0.03
b*	0.80±0.01	8.66±0.10	12.87±0.06	10.82±0.04
ΔE	77.04±0.1	34.02±0.07	39.63±0.20	17.76±0.10

than the NM (∆E=68). This was true even after pulverizing the DM to prepare the meal as it was of light color (∆E= 17.76) than the NM (∆E=25). This was also substantiated from the L*(76.31), a*(1.23) and b* (10.82) values of the DM.

The color of the finger millet has been one of the main hindrances for its acceptability, especially by the non-traditional millet consumers. Normally, when the native millet is pulverized, the seed coat particles contribute for the redness of the meal even though the millet endosperm is of white color and further when the native millet meal is cooked, the product formed is of intense dark color making it largely unattractive. Decortication involves complete removal of the seed coat and the DM finally looks brighter and whiter than the native millet. Even though, the endosperm undergoes slight discoloration after hydrothermal treatment, the flour from the DM was even whiter than the native millet.

Unlike parboiled rice, the grains of DM were not of glassy and translucent in appearance and rather looked opaque, which may be because of the incipient surface popping during milling. The milling parameters namely, the moisture content of the grain, the feed rate, the residence time of the grains between the emery discs and also the number of passes in the mill, influenced the final appearance of the product. The millet decorticated with very low residence time in the mill and higher number of passes, looked translucent and glassy, whereas those with higher residence time and lower number of passes looked opaque and whiter.

The physical parameters of DM and HTM are presented in Table 26. The grain diameter of the DM (1.43 mm) was slightly less than that of HTM (1.46 mm). Hydrothermal treatment to the millet caused shrinkage in the size of the kernels, which may be the reason for the decrease in grain diameter. In addition to this, decortication also caused reduction in the diameter because of the removal of the seed coat. Reduction in the size resulted in lowering the surface area of the grain from 8.92 to 7.75 mm^2. The 1000 kernel weight of the DM (2.95 g) was slightly higher than that of HTM (2.71 g), whereas the

Table 26. Physical and functional properties of hydrothermally treated and decorticated finger millet

Parameter	Hydrothermally treated	Decorticated
Grain diameter (mm)	1.46±0.04	1.43±0.02
Grain surface area (mm^2)	8.92±0.20	7.47±0.12
Sphericity	0.89±0.05	0.97±0.02
1000 kernel weight (g)	2.71±0.07	2.95±0.04
1000 kernel volume (g/ml)	4.1±0.10	3.8±0.06
Bulk density (g/ml)	0.77±0.03	0.796±0.01
True density	1.35±0.03	1.47±0.01
Porosity	43.00±3.00	46.00±1.5
Hardness		
Slope of first peak (N/s)	276.53±12.5	264.7±10.2
First peak force (N)	40.3±7.10	34.4±7.6
Max. Peak force (N)	235±8.10	161±5.00
Viscosity 10% slurry (cP)		
Cold paste	11±0.7	22±0.40
Cooked paste	350±3	463±1.00
Solubility index (g%)		
30 ^oC	1.6±0.1	2.9±0.1
95 ^oC	3.3±0.2	3.5±0.1
Swelling power (g%)		
30 ^oC	299±1.8	306 ±1.2
95 ^oC	494±4.2	496±2.5

1000 kernel volume of DM (3.8 ml) was slightly lower than that of the HTM (4.1 ml) and this increased the apparent (1.355 g/ml) as well as the true density (1.47 g/ml) of the millet on decortication. The increase in the density of the millet resulted in the increase in porosity values from 43 to 46 on decortication. The sphericity value changed from 0.89 to 0.97 probably due to removal of the undulations during decortication.

The hardness of DM (161 N) as recorded by the force-deformation curve, was slightly lower than the HTM (243 N) but was significantly higher than NM (43 N). However, not much difference was observed in the first peak force (34 and 40N) as well as the initial slope of the first peak (264 and 276 N/s) between the DM and the HTM. As explained earlier, during processing of the millet for preparation of HTM, the hardness of the grains increased by several folds, but a slight reduction in the hardness observed for DM could be due to the separation of the seed coat. However, the similarity of the profiles of the force deformation curves between DM and HTM indicates that, decortication did not affect the endosperm texture with respect to its hardness (Figure 43).

3. Functional properties

The solubility of the meal from the DM was 2.9% at ambient (30^{o}C) and 3.5% at elevated (95^{o}C) temperature. But the swelling power increased significantly from 306 to 496% at 95^{o}C. The reason for the increased swelling power at elevated temperature could be due to gelatinization of some of the ungelatinized or partially gelatinized granules in the DM. The solubility index of the DM was higher (2.9%) than the HTM (1.6%) at 30^{o}C but the values were comparable at 95^{o}C. The values for swelling power were also comparable at both the temperatures (Table 26).

The cold paste viscosity of the DM was 22 cP and it increased to 463 cP on cooking. The measurable level of the viscosity for the DM even at ambient temperature indicates the presence of pregelatinized starch but the significant increase in the viscosity on cooking is probably due to gelatinization of the ungelatinized as well as the partially gelatinized starch

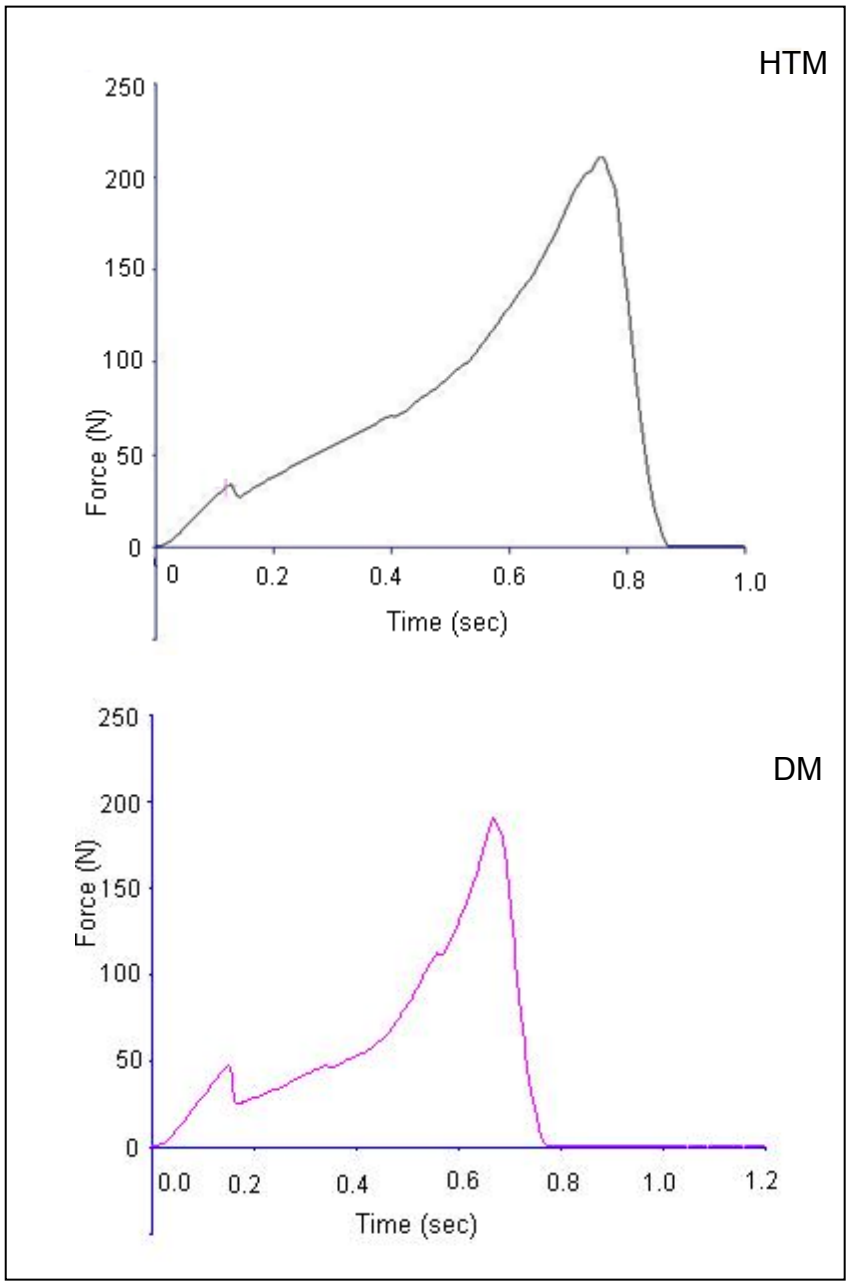


Figure 43. Force deformation curves of hydrothermally treated and decorticated finger millet

granules present in the DM. This observation corroborates with that made on the swelling power of DM. The pasting behavior of the DM recorded in the form of viscograms was also very similar to that of the HTM, except for the temperature at which the viscosity begins to increase, as it is considerably lower for DM (69^{o}C) compared to HTM (86^{o}C) (Figure 44). The viscosity of DM also increases continuously with the increase in the temperature and exhibited no breakdown in the viscosity similar to HTM. However, the viscosity of DM at any given temperature was considerably higher than that of the HTM (Table 27).

The viscogram clearly indicates that the DM contains a small proportion of ungelatinized starch, which swells at about 70^{o}C temperature leading to a slight increase in its viscosity beyond 70^{o}C temperature. No significant increase in the viscosity on heating the slurry at higher temperature shows that the major portion of the starch in the DM is pregelatinized and hence exhibits no breakdown in the viscosity which normally occurs in all the starches isolated from cereals. The pregelatinized nature of the DM starch is also reflected by the marginal increase in the viscosity on cooling the slurry. However, the significant difference between the temperature of increase in initial viscosity of DM and HTM could be due to the resistance offered by the seed coat matter for swelling. The difference in the viscosity values of DM and HTM at each stage could be due to the difference in the starch content between DM (73%) and HTM (65%).

The hydration curve for DM shows an initial rapid hydration phase up to the moisture level of 65% followed by a slow and steady increase in the second phase till it attained its equilibrium moisture content of 72%. The EMC values for the DM were 72, 80, 83, 85 and 87%, at 30, 40, 50, 60 and 70^{o}C, respectively (Figure 45). This shows that, with the increase in temperature of the steep water, the EMC of the millet increased and also the time taken to attain the EMC was shorter. However, at all the temperatures of steeping, the EMC of the DM was higher than that of the HTM. The removal of the seed coat and thereby the increased starch content of the DM may be the reason for this.

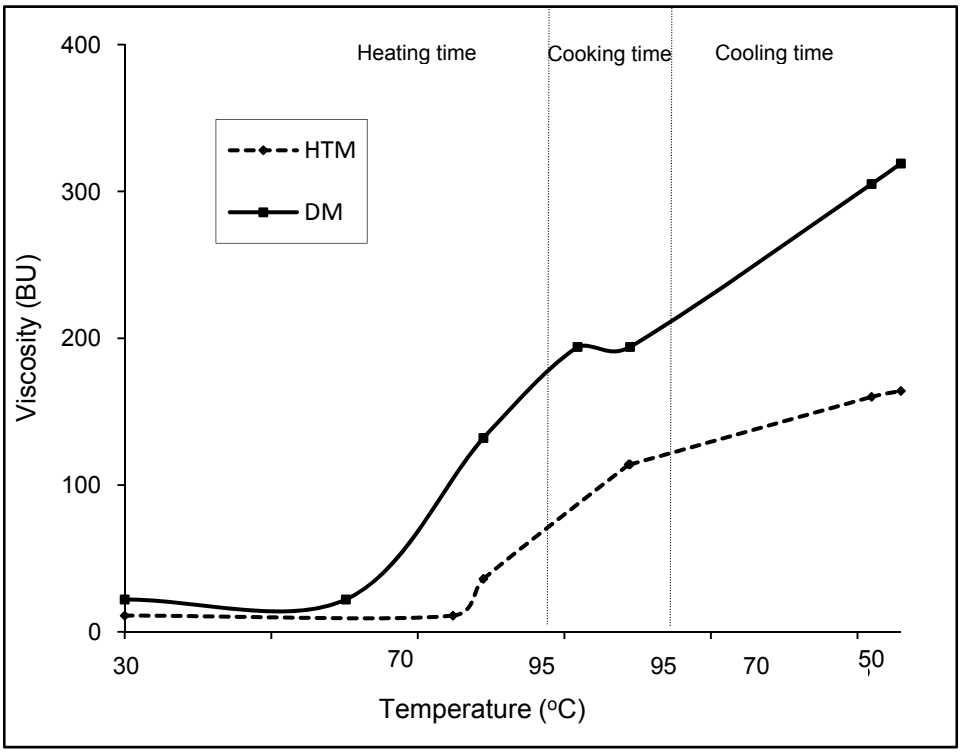


Figure 44. Pasting profiles of hydrothermally treated and decorticated finger millet

Table 27. Pasting properties of hydrothermally treated and decorticated finger millet*

Parameter	Hydrothermally treated	Decorticated
Peak viscosity (BU)	114	194
Trough viscosity (BU)	114	194
Final viscosity (BU)	164	319
Breakdown (BU)	0	0
Setback (BU)	50	109
Pasting temperature (^{o}C)	86.3	69.3

** average of two independent determinations*

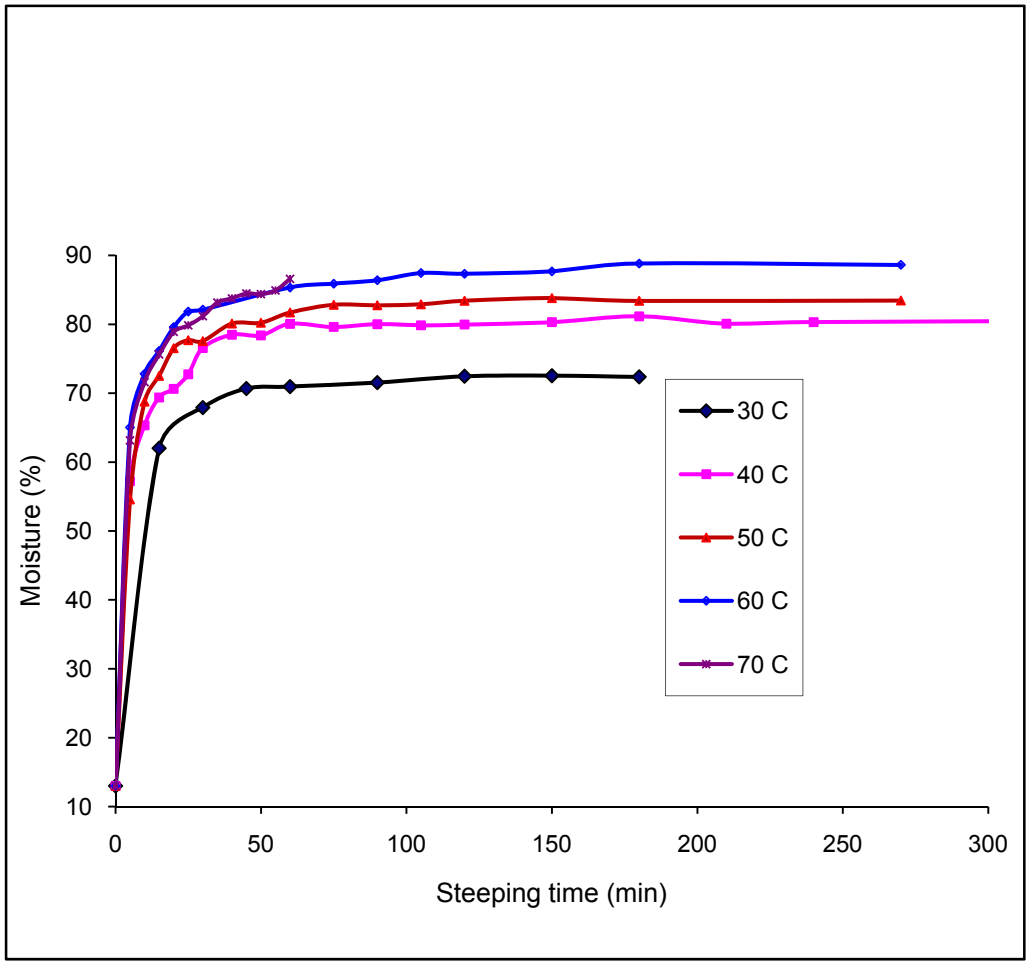


Figure 45. Hydration kinetics of decorticated finger millet at different steeping temperatures

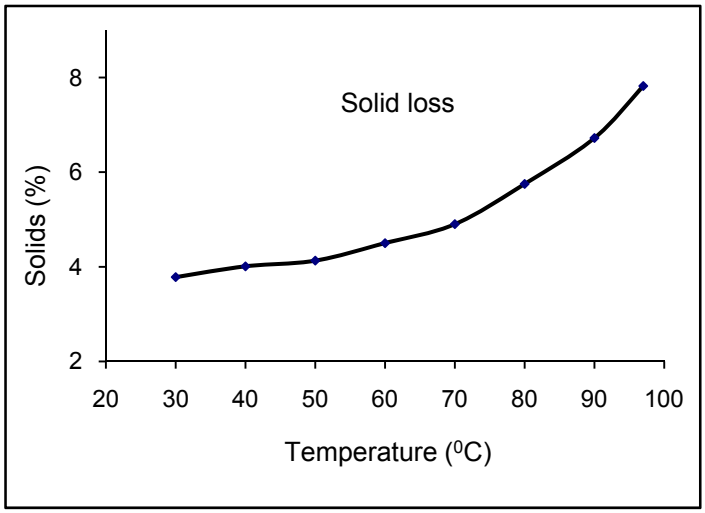
The solid loss, swelling power and the moisture uptake of the DM at different temperatures is presented in Figure 46. As the temperature increased from 30 to 95^{o}C, the solid loss and swelling power of DM increased from 3.8 to 7.8% and 343 to 634% respectively. This also resulted in a proportionate increase in the moisture uptake by the grains.

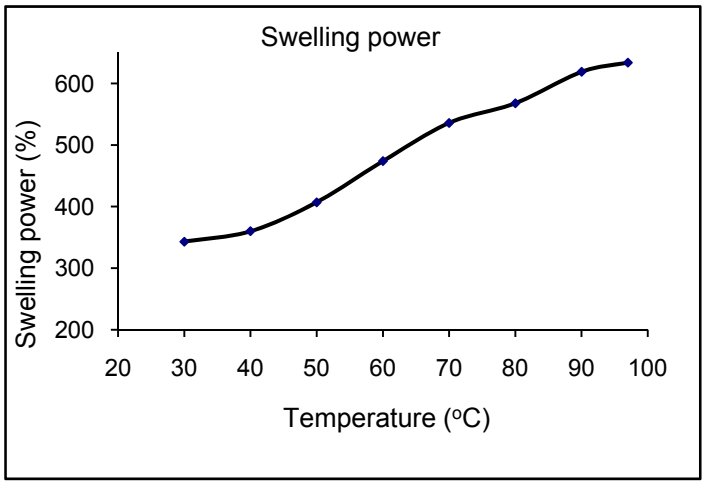
From the Table 28, it could be seen that there was a drastic difference in the enthalpy of DM and HTM. The enthalpy of HTM was -3.6 J/g and that of DM was 359 J/g. Similarly, the onset and peak temperatures for DM were lower than HTM by 15 and 10^{o}C respectively. However, there was not much difference between the endset temperature values between the DM and HTM. In the case of rice also, it has been reported that, parboiling reduces the enthalpy and the related temperature parameters compared to its raw counterpart (Ong and Blanshard, 1995). The drastic difference between the thermal energies of HTM and DM is because of the absence of the seed coat in the latter.

The X-ray diffractogram of DM and HTM are similar and also the values for the microstrucural parameters are nearly the same (Figure 47). However, the percentage of crystalline matter in the DM is slightly higher than HTM. The X-ray diffractograms and microstructural parameters are totally dependent on the nature of starch present in the cereals and in the current study, the basic material being the hydrothermally treated millet, the only difference between DM and HTM is the removal of seed coat. Since, the seed coat is mainly non-starch material, it may not affect the X-ray diffractogram. But the increase in the crystallinity is because of the increased level of starch content in DM compared to HTM.

4. Nutrient composition

Hydrothermal treatment did not cause any significant change in the nutrient content of the millet as indicated earlier, but decortication reduced most of the nutrients except for its starch content (Table 29). The protein content of the millet decreased by 37% (from 7.0 to 4.4%) and the ether extractives by 33% (from 1.16% to 0.77%), ash content from 1.63 to 1.0% and the total dietary fiber content from 17 to 10% after decortication.





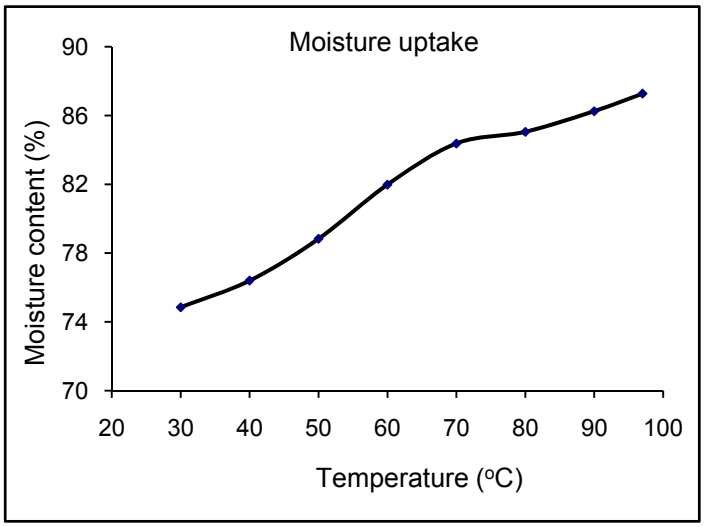
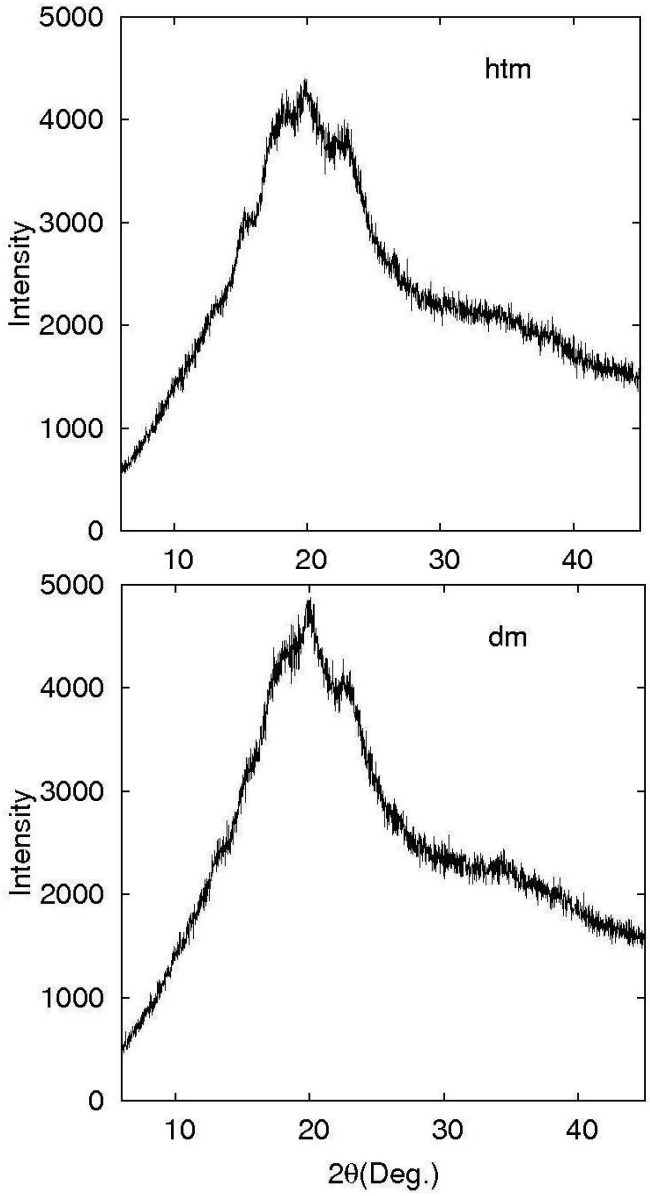


Figure 46. Solid loss, swelling power and moisture uptake of decorticated finger millet at different temperatures

Table 28. The DSC characteristics of hydrothermally treated and decorticated finger millet*

Parameter	Hydrothermally treated	Decorticated Millet
Peak type	Exo	Endo
ΔH (J/g)	-3.64	358.26
Onset temp (^{o}C)	64.83	49.60
Peak temp (^{o} C)	67.47	57.21
Endset temp (^{o} C)	71.42	68.73

**average of two independent determinations*



Parameter	Hydrothermally treated	Decorticated millet
2θ in Deg	19.81	19.81
'd' in Å	4.48	4.48
<N>	1.75	1.78
P	1.37	1.39
g' (%)	0.1	0.1
Δ (%)	2.57	2.51
D = N.d in Å	07.84	07.97

Figure 47. X-ray diffractogram of hydrothermally treated and decorticated finger millet

Table 29. Nutrient composition of hydrothermally treated and decorticated finger millet

	Hydrothermally treated	Decorticated
Moisture (g%)	11.06±0.07	10.46±0.05
Ether extractives (g%)	1.16±0.01	0.77±0.01
Protein (g%)	6.90±0.03	4.43±0.02
Carbohydrates (g%)	62.00±0.70	73.00±0.50
Total amylose (g%)	19.10±0.14	18.60±0.12
Soluble amylose (g%)	9.70±0.13	8.30±0.11
Dietary Fiber (g%)		
Soluble	0.85±0.02	2.30±0.01
Insoluble	16.00±0.07	7.80±0.06
Total	16.85±0.10	10.10±0.10
Minerals (mg%)	1.63±0.04	1.00±0.03
Calcium (mg%)	315.00±2.00	190.00±2.50
Iron (mg%)	6.00±0.10	3.15±0.10
Copper (mg%)	1.20±0.07	1.18±0.06
Zinc (mg%)	2.15±0.05	1.85±0.07
Carbohydrate digestibility (%)	73.00±1.50	78.00±1.20
Protein digestibility (%)	91.00±1.40	98.00±1.10
Polyphenols (g%)	ND	0.52±0.02
Phytic acid (g%)	ND	0.36±0.01
Bioavailable calcium (%)	ND	62.00±1.50
Bioavailable iron (%)	ND	46.00±1.40

ND – not determined

The process also caused reduction in the calcium content of the millet from 320 to 190 mg/100g (by 40%) and iron content from 5 to 3 mg%. However, there was only a marginal decrease in copper and zinc content of the millet due to decortication. On the other hand, the total available carbohydrates (starch and free sugars) of DM are significantly higher (73%) than HTM (62%), which is mainly due to the removal of the cellulosic seed coat matter. Moreover, the decortication significantly increased the soluble fiber content by 170% (from 0.85 to 2.3%). The decrease in some of the nutrient contents of the DM is mainly due to removal of the seed coat matter as it could be seen from Table 30 that, the seed coat contains significant proportion of protein (9.5%), ether extractives (3.7%), dietary fiber (46%) and calcium (860 mg/100g).

Earlier studies by Kurien et al. (1959) on distribution of the calcium in seed coat and endosperm and also by Malleshi and Desikachar (1981a), with respect to the nutrient composition of the refined flour and seed coat, clearly indicated that, the seed coat of the millet contains nearly 30% of the major nutrients and is a good source of insoluble fiber.

Although the decorticated millet contains lower levels of nutrients than its native as well hydrothermally treated counter parts, the bioavailability of the nutrients including the carbohydrate and protein digestibility were considerably higher. The carbohydrate and protein digestibility of the DM were 78 and 98% respectively. The starch may undergo thermal degradation and proteins get denatured during hydrothermal treatment besides, the removal of the seed coat may increase their availability for enzymatic digestion.

The bioavailability of the calcium in the NM is hardly 30%. In the case of DM it was almost increased by 2 fold (62%) which amounts to nearly 120 mg/100g of the millet. Similarly, the bioavailability of iron is also increased to 46% compared to NM which contained hardly 10% bioavailable iron. Further to this, the increase in soluble dietary fiber and the presence of nearly 10% dietary fiber in the DM definitely contribute for its health benefits. Separation of the seed coat lowers the phytic acid and polyphenol contents of the millet from 1.15 and 1.9 % to 0.34 and 0.5%, respectively which in turn benefits by

Table 30. Composition of seed coat of hydrothermally treated finger millet (g/100g)

Moisture	11.18±0.07
Fat	3.71±0.06
Protein	9.45±0.04
Carbohydrates	18.82±0.80
Dietary fiber	
Soluble fiber	1.83±0.02
Insoluble fiber	44.59±1.20
Total	46.42±1.50
Minerals	4.83±0.07
Calcium (mg%)	864.00±5.40
Polyphenols	7.50±1.20
Phytic acid	1.22±0.07

enhancing the bioavailability of minerals. In view of this, the DM can form a very good dietary component for all age groups because of its superior nutrient contents compared to milled rice as well as other refined cereals.

5. Carbohydrates

A. Free sugars and starch

The free sugars content of the DM was 0.7% nearly the same as that of HTM. The major constituent sugars namely, the glucose, fructose, maltose and sucrose and their contents remained almost same in both DM and HTM (Table 31).

Decortication slightly decreased the total as well as the soluble amylose contents of the millet from 19.1 and 9.7% to 18.63 and 8.2%, respectively. Slightly lower values of total as well as the soluble amylose content could be due to separation of a portion of the peripheral endosperm on decortication.

It may be observed from the Figure 48 that, Fraction I being mainly the amylopectin equivalent, decreased on decortication and a considerable increase in Fraction II was observed. This is evident from the total proportion of the carbohydrates under Fraction I which decreased from 52 to 41% and

Table 31. Component sugar contents (70% aqueous ethanol extracts) of hydrothermally treated and decorticated finger millet (g/100g)

	Hydrothermally treated	Decorticated
Glucose	0.298±0.02	0.243±0.02
Fructose	0.044±0.003	0.052±0.003
Maltose	0.134±0.003	0.086±0.003
Sucrose	0.107±0.004	0.059±0.003
Ribose	-	-
Others	0.127±0.004	0.255±0.004
Total	0.710±0.01	0.695±0.01

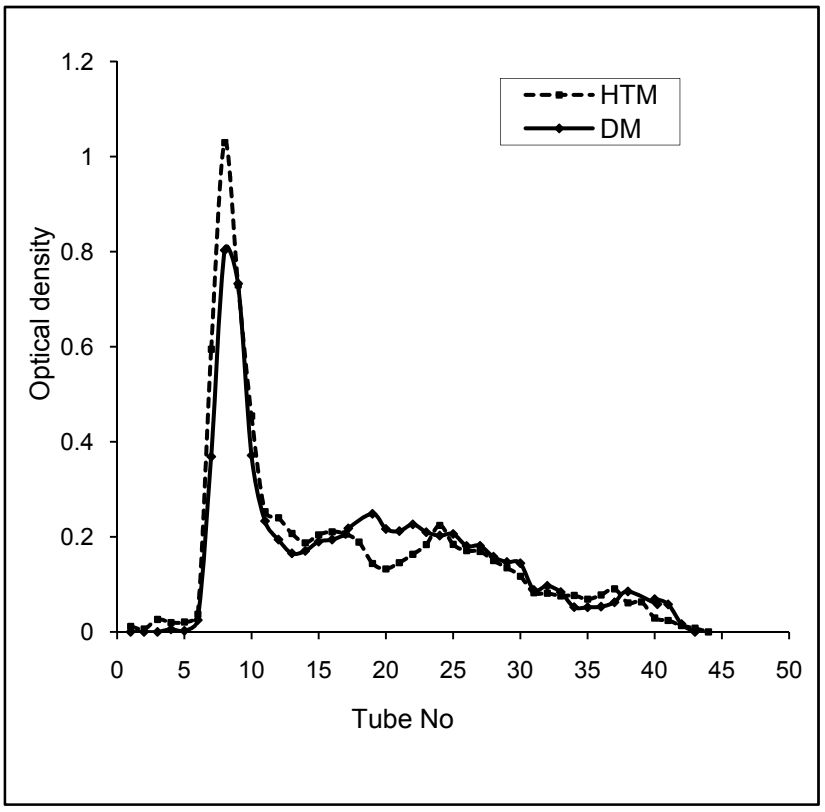


Figure 48. Carbohydrate profiles of hydrothermally treated and decorticated finger millet

that under the Fraction II increased from 48% to 59% on decortication.

B. Non-starch polysaccharides (NSP)

Decortication caused qualitative as well as quantitative changes in all the NSP fractions mainly because of separation of the cellulose rich seed coat matter from the HTM (Table 32). The notable changes in the NSP constituents as a result decortication were, slight increase in the cold-water solubles (from 1.57% to 1.99%) and a significant increase in the hot-water solubles (from 0.99% to 3.6%). Apart from this, both hemicelluloses A as well as B fractions decreased from 1.38 and 0.9 to 1.13 and 0.5% respectively. The pectic polysaccharides content also decreased slightly from 1.92 to 1.01%. As expected, a considerable decrease in the cellulosic fraction was recorded in DM (8.94%) compared to HTM (13.35%).

There were no significant changes in the component sugars of the cold water soluble NSP due to decortication whereas, it caused considerable changes in the constituent sugars of hot water soluble fraction of the NSP namely, complete absence of glucose and occurrence of mannose besides, a slight reduction in ribose (from 9.9 to 3.51%) and arabinose (from 10.8 to 0.11%) contents.

The major constituent sugar in pectic polysaccharides was fructose (84.56%) in HTM but it was mannose (75.53%) in DM with traces of sucrose (7.16%), xylose (2.03%), arabinose (2.37%) and ribose (3.48%). However, the major sugar in hemicellulose A fraction was fructose (82.3%) whereas, that in the case of hemicellulose B fraction were fructose (31.2%), mannose (19.9%) and arabinose (19.8%) with traces of ribose and sucrose. Glucose (86.7%) was the main constituent sugar of cellulose fraction.

The changes in the content of the NSP fractions as a result of decortication are not only due to separation of the seed coat matter but also due to the changes in the constituent sugars of the NSP fractions during hydrothermal treatment. Generally, the pentosans namely, hemicelluloses and also the pectinaceous matter with cell wall proteins are the main non- starch component of the endosperm.

Table 32. Yield and composition of non-starch polysaccharide fractions of hydrothermally treated and decorticated finger millet

	Cold water soluble		Hot water soluble		Pectic polysaccharides		Hemicellulose A		Hemicellulose B		Cellulose	
	HTM	DM	HTM	DM	HTM	DM	HTM	DM	HTM	DM	HTM	DM
Yield	1.6±0.05	1.99±0.05	0.99±0.04	3.6±0.04	1.92±0.01	1.01±0.01	1.38±0.02	1.13±0.03	0.9±0.04	0.5±0.03	13.4±0.1	8.94±0.1
Uronic acid	7.83±0.03	15.7±0.02	9.34±0.1	8.61±0.1	8.37±0.1	9.42±0.1	11.8±0.2	10.47±0.2	10.4±0.1	12.7±0.1	7.94±0.03	6.81±0.1
Constituent sugars (%)												
Ribose	8.87±0.04	8.87±0.04	9.9±0.1	3.51±0.1	0.99±0.06	3.48±0.1	3.25±0.1	3.36±0.1	8.1±0.1	8.6±0.1	2.28±0.01	2.16±0.01
Arabinose	0.51±0.01	0.61±0.01	10.8±0.1	0.11±0.01	1.98±0.02	2.37±0.02		1.78±0.1	20.2±0.3	19.8±0.2	0.79±0.02	0.8±0.01
Xylose		-	1.38±0.01	0.58±0.01	3.5±0.07	2.03±0.02	0.37±0.03	0.81±0.01	20.3±0.4	19.9±0.3	0.49±0.02	1.22±0.02
Mannose	81.9±0.5	80.9±0.5	-	84.9±0.5		75.5±0.5	84.0±0.1	-	-	-		-
Galactose	0.29±0.01	0.3±0.01	-	-	0.42±0.02	-	-	-	-	-	0.94±0.02	0.68±0.01
Glucose	-	-	50.3±0.2	-		-	-	-	-	-	-	87.2±0.5
Sucrose	-	-	0.27±0.01	-		7.16±0.02	-	1.1±0.02	2.1±0.1	2.8±0.1	0.78±0.04	1.15±0.02
Fructose	-	-	18.0±0.02	-	84.6±0.6	-	0.41±0.01	82.4±0.5	29.2±0.3	31.2±0.2	86.5±0.1	-
Maltose	0.65±0.01	0.7±0.01		-	0.18±0.02	-	0.17±0.01	0.18±0.01	-	-	0.76±0.03	-
Pent/Hex	0.11±0.01	0.11±0.01	0.32±0.01	0.04±0.01	0.08±0.01	0.1±0.01	0.4±0.01	0.07±0.01	1.6±0.01	1.4±0.01	0.04±0.01	0.05±0.01
Ara/Xyl	-	-	7.83±0.01	0.19±0.1	0.57±0.01	1.17±0.01	-	2.2±0.01	1.0±0.1	1.0±0.01	1.61±0.01	0.66±0.01

Separation of the seed coat, mainly the cellulosic fraction, results in proportionate increase in the content of non-cellulosic NSP fractions in the DM. This is also reflected by the increased level of soluble dietary fiber content in DM compared to HTM.

6. Proteins

Decortication of HTM slightly lowered the protein content and also altered its composition. The slight increase in salt soluble proteins (7.69 to 9.57%) as a result of decortication is favorable with respect the protein quality of the millet even though the water soluble proteins (albumins) content remained the same. However, a slight increase in the prolamins and prolamin-like proteins from 8.97 to 9.85% and 45.12 to 48.45%, respectively (Table 33) could be due to the increase in their extractability in DM compared to HTM.

Electrophoretic pattern of DM in comparison with HTM indicates that, protein bands above 30 kDa are either diminished or completely absent and higher intensity of bands in the molecular range of 14 to 30 kDa were prominent. This may be due to the molecular degradation of proteins in the DM and also due to the separation of the seed coat (Figure 49). Reza et al. (2005) also reported the decrease in the total number of bands and their intensity in parboiled and milled rice when compared to its raw counterpart.

7. Fatty acids profile

The fatty acids profile of DM was almost similar to that of HTM, but for a marginal decrease in linoleic acid content (from 21 to 20%) and a slight increase in the palmitic acid content (from 23 to 26%). The free lipid content of the HTM decreased from 1.4 to 0.75% as a result of decortication without affecting the content of the bound lipids (Table 34 and Figure 50).

8. Cooking qualities

The time taken by the millet to cook to soft edible texture was hardly 6 min when dropped in excess boiling water as indicated by the translucent spread when pressed between the glass slides (Figure 51). The DM cooked in the form of discrete grains is shown in Figure 52. During cooking, the grains remained in fluidized state indicating that they retain their discreetness even

Table 33. Protein fractions of hydrothermally treated and decorticated finger millet (g/100g of sample)

Fractions	Hydrothermally treated	Decorticated
Albumins	0.23±0.06 (5.89)	0.20±0.08 (5.63)
Globulins	0.30±0.03 (7.69)	0.34±0.06(9.57)
Prolamins	0.35±0.04 (8.97)	0.35±0.07 (9.85)
Prolamins-like	1.76±0.10(45.12)	1.72±0.14 (48.45)
Glutelins-like	1.26±0.21(32.30)	0.94±0.09 (26.47)
Total	3.90±0.32 (99.97)	3.55±0.41 (99.97)
Percentage extraction	56.00±1.20	82.00±1.90

Values in the parenthesis indicate the percentage

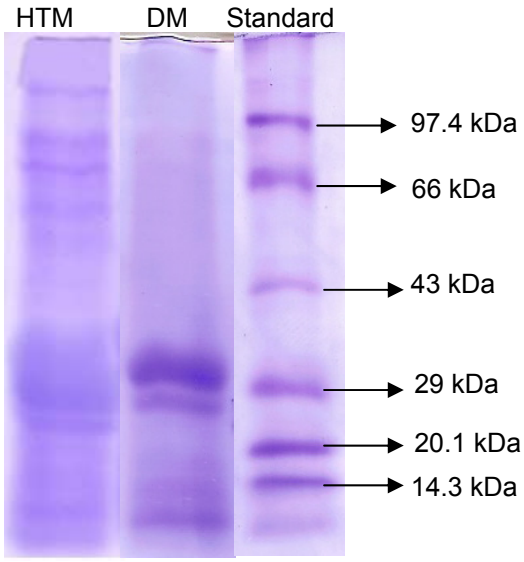


Figure 49. Fractionation of proteins of hydrothermally treated and decorticated finger millet through SDS - PAGE

Table 34. Fatty acids profiles of hydrothermally treated and decorticated finger millet

Fatty acid	Hydrothermally treated	Decorticated
Palmitic16:0	23.99±0.03	26.18±0.03
Stearic 18:0	2.23±0.1	0.12±0.02
Oleic18:1	50.99±0.5	50.43±0.4
Linoleic18:2	21.38±0.2	20.26±0.2
Linolenic18:3	3.64±0.1	2.6±0.1
Free lipids	1.41±0.1	0.75±0.1
Bound lipids	0.94±0.02	0.918±0.03

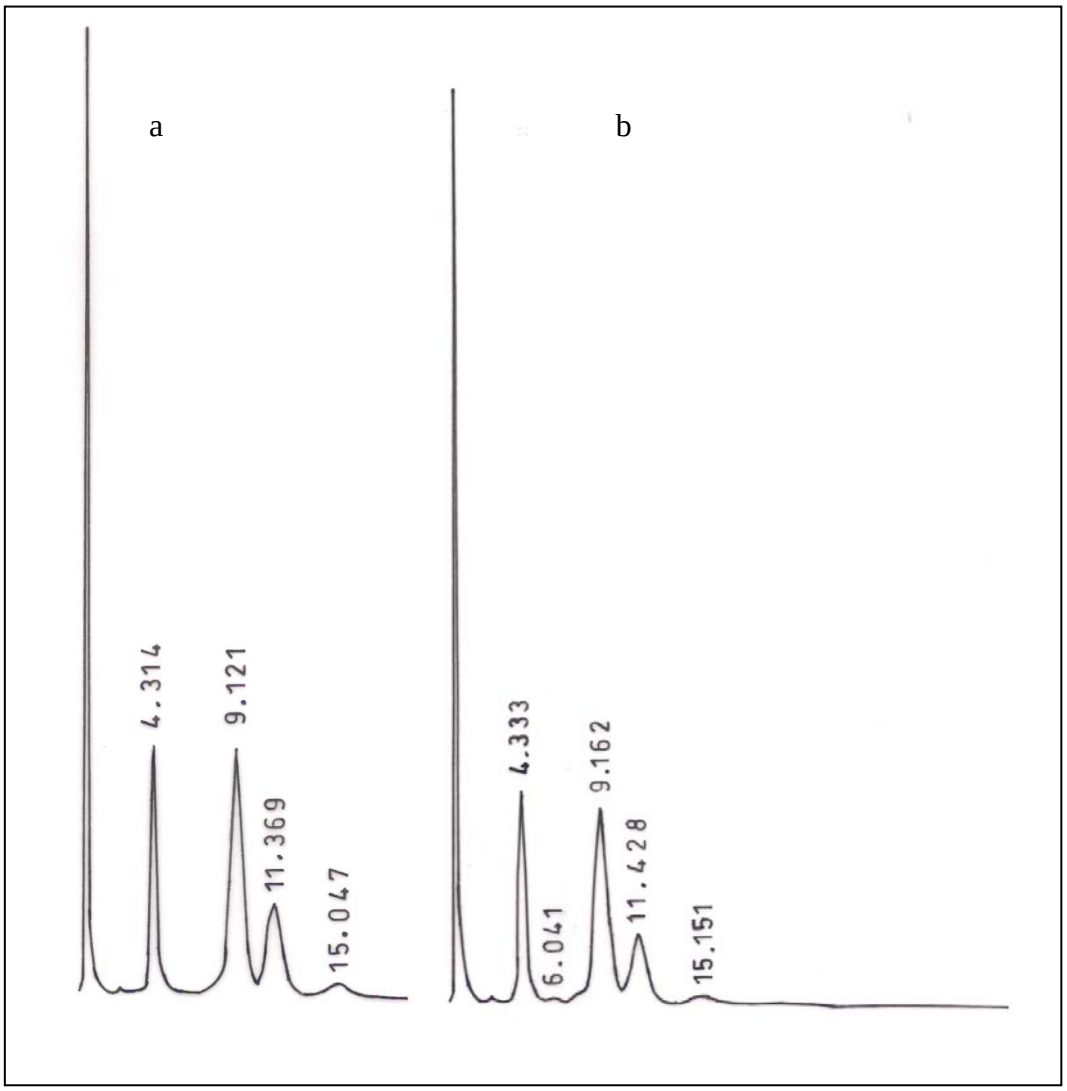


Figure 50. Elution profiles for fatty acids of hydrothermally treated (a) and decorticated (b) finger millet

Figure 51. Translucent endosperm indicating the complete cooking of the decorticated finger millet kernel

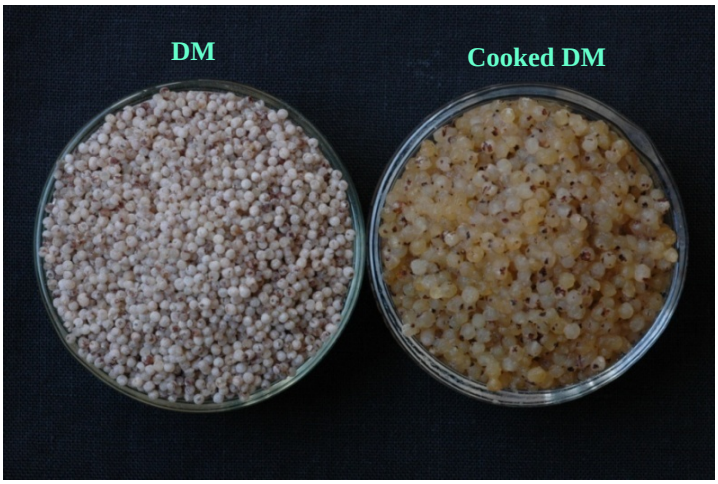


Figure 52. Decorticated and cooked finger millet

after absorption of water without losing much of the solids in the form of solubles. The color of the water during cooking was slightly creamish, indicating solubilization of some of the constituents from the endosperm. The solubles in the residual cooking water was only about 3.5% and it contained 48% amylose and only 0.3% free sugars (Table 35). The solubles in the case of parboiled rice is also about 3% (Pillaiyar and Mohandoss, 1981b).

Table 35. Cooking characteristics of decorticated finger millet

Cooking time (min)	6±1
Moisture uptake (%)	71±2.1
Swelling power (%)	350±2.3
Solid loss (%)	3.7±0.07
Amylose leached (per 100g of leached solids)	48±0.5
Sugars (per 100g of leached solids)	0.3±0.01

Cooking the millet with appropriate amount of water to avoid draining of the solubles was also explored and cooking by the contemporary methods such as, use of pressure cooker, rice cooker and microwave were also found feasible. The millet cooked by any of these methods did not form lumps and retained its discreteness.

The color of cooked millet changed from cream to light brick red on exposure to atmosphere. However, this did not affect its consumer acceptability. This is totally in contrast to the change of native millet meal with dark and unappealing color on cooking. The cooked millet did not exhibit intense characteristic aroma normally associated with the whole meal based products. These features clearly brought out the culinary advantages of the DM for its substitution to rice and wheat, by the non-traditional millet consumers.

During cooking, the characteristic aroma of the millet was perceived but it was of mild nature when compared to that of the whole meal. The DM was also cooked along with *dal* and vegetables similar to the common rice based preparations such as "*bisibelebath*" and it was observed that, addition of these adjuncts did not affect its cooking or eating qualities. Besides, preparation of lemon rice (*chitranna*), tamarind rice (*puliyogare*) or sweet products like *kheer* were also explored and the products were found to have extremely good texture and consumer acceptability.

Recipe	**Mode of preparation**
Bisibelebath	The decorticated millet is cooked with split legumes and vegetables. Spice and condiments are added as per the requirement and seasoned with oil or ghee
Chitranna (lemon rice)	The cooked millet is seasoned with chopped onion, green chilies and mustard seeds. Lemon juice and salt are added as required
Puliyogere	The cooked millet is mixed with spiced tamarind extract and seasoned with oil
Kheer	The millet slightly roasted with ghee and cooked in milk. Jaggery or sugar is added.

Considerably lower cooking time (5 - 6 min) for the DM compared to rice (25 - 30 min) shows that, the DM is comparable to the quick cooking cereals marketed in some of the developing countries. Probably, the smaller size, enhanced porosity, freedom from the seed coat and larger surface area and also the presence of pregelatinized starch might have contributed for the quick cooking properties of the DM. In the case of rice, it has been repeatedly observed that parboiling increases its cooking time compared to raw rice (Bhattacharya and Ali, 1985). The reason attributed for this is the compactness of the gelatinized starchy matter and its complexity with other biochemical constituents. The highly homogeneous mass without any visible cellular structure is normally observed in the case of parboiled rice, but in the case of DM the cellular structure is still visible even though the starch

granules are gelatinized (Figure 36b). This showed that, although the starch granules lost their organization, the thicker cell walls were not fully ruptured but probably get fractured partially and facilitates quick absorption of water.

The hydration characteristics of DM at different temperatures shown earlier in Figure 45, also clearly indicates that, the millet when steeped even at 30^{o}C attains its EMC within 30 min and at much faster rate (15 min) at 70^{o}C. These observations are in concurrence with the quick cooking nature of the DM. The moisture content of cooked millet was 71% on “as is basis” and 82% on “dry weight basis” and the volume of cooked millet was 350%. These values are nearly comparable to the moisture content and the volume of cooked rice (Bhattacharya and Sowbhagya, 1971).

Water uptake by a cereal on cooking for a definite time is also expressed as swelling ratio or swelling number. It is the ratio of the weight of cooked cereal to its original weight. The water uptake of cereals is largely influenced by the surface area besides, its protein and starch content. Generally, physical laws of sorption are applicable to the hydration characteristics of the grain as smaller the grain, larger will be the surface area and quicker will be the hydration. Moreover, whenever the cereal contains pregelatinized starch, which absorbs water not only rapidly but also to a higher extent. In the case of cereals, even though the protein content is considerably lower than the carbohydrates, they too play a major role towards the hydration characteristics as the protein can absorb considerable amount of the water even at low temperature (Vidal et al., 2007).

Various attributes of the texture of the cooked DM derived from the texture profile analysis (TPA) recorded in Food Texturometer are presented in Table 36 and Figure 53 respectively. The soft texture of the product is revealed by the very low energy (0.482N) required to compress it to over 80%. The springiness (0.3) and cohesiveness (0.181) recorded in the TPA shows that the product bounces back to about 1/3rd of its volume after releasing the energy and exhibits very little cohesiveness. This indicates that the millet cooks to soft discrete grains and retains its softness without collapsing and also forming lumps on keeping.

Table 36. Texture profile analysis of decorticated and cooked finger millet*

Product height (mm)	1.8
Hardness (N)	0.5
Springiness	0.3
Adhesiveness (N.S)	-0.1
Cohesiveness	0.2
Gumminess	0.09
Chewiness	0.03

** average of 10 independent determinations*

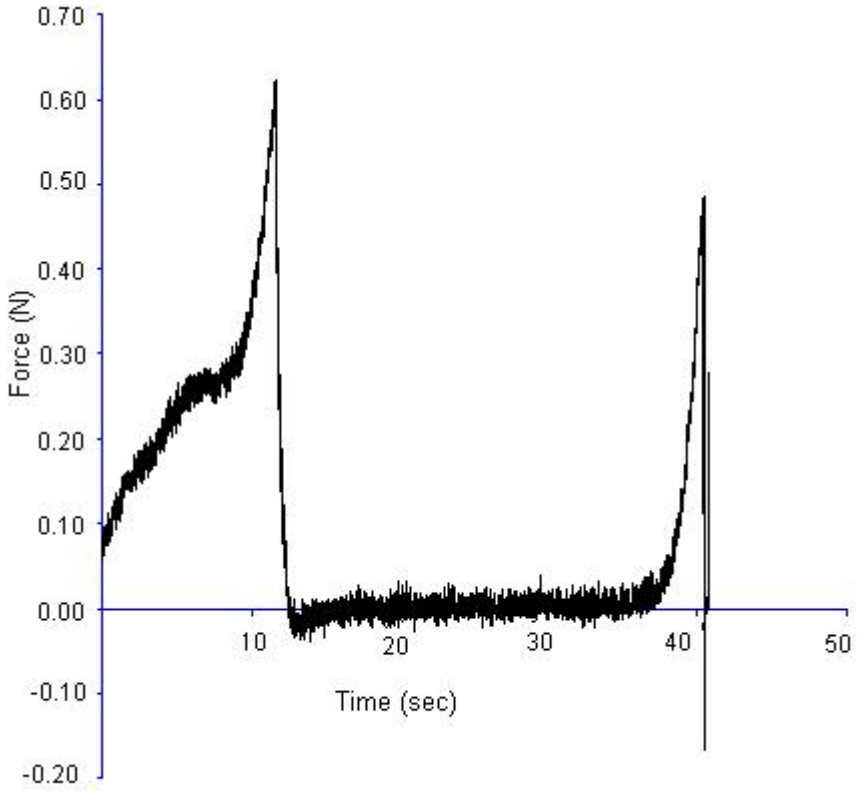


Figure 53. Typical texture profile analysis curve of decorticated and cooked finger millet

The TPA mimics chewing and the mouth feel of the product. The lower values of hardness as well as cohesiveness indicate that the food products based on the DM would be easily swalloable and hence it may be acceptable by all age groups right from pediatrics to geriatrics. The studies on the cooked rice texture, as reported by several workers, indicate that parboiled rice is harder than the raw rice and the stickiness in parboiled rice is lower (Kato et al., 1983). This shows that the TPA for DM is similar to parboiled rice except for its hardness.

The texture of cooked grains is very important for the palatability. Generally, the texture of cooked grains depends on hardness and stickiness of the product. The term hard refers to the textural property manifested by a high resistance to deforming by an applied force where as the term sticky refers to the textural property manifested by a tendency to adhere to a contacting surface (Damardjati et al., 1987).

The mean values for the various attributes of sensory analysis of the cooked DM are presented in Figure 54. The product was of mild reddish color and well accepted by the panelists as it scored an average of 7 points for appearance. The sensory scores for mouth feel was 7.11, which indicated that, the millet cooked to soft edible texture. There were no remarks by any of the panelists about any kind of ‘after taste’ for the product after its consumption. There was positive response from almost all the panelists about its flavor even though, it exhibited mild flavor characteristic to the millet. This is evident from the average score (7.15) for the flavor of the product. No panelists recorded for the lumpiness of the product as the DM cooked to soft discrete grains and the average score for the discreteness was 6.4. The overall acceptability of the cooked DM was 8, which anchors at ‘like very much’ on the 9 point hedonic scale, indicating that, the cooked DM was well accepted by all the panelists.

The cooked millet when served with *sambar*, was well accepted by all the non-traditional millet consumers and majority of them opinioned that the product can be easily substituted for rice and other major cereals. As mentioned earlier, the millet can be conveniently incorporated into traditional

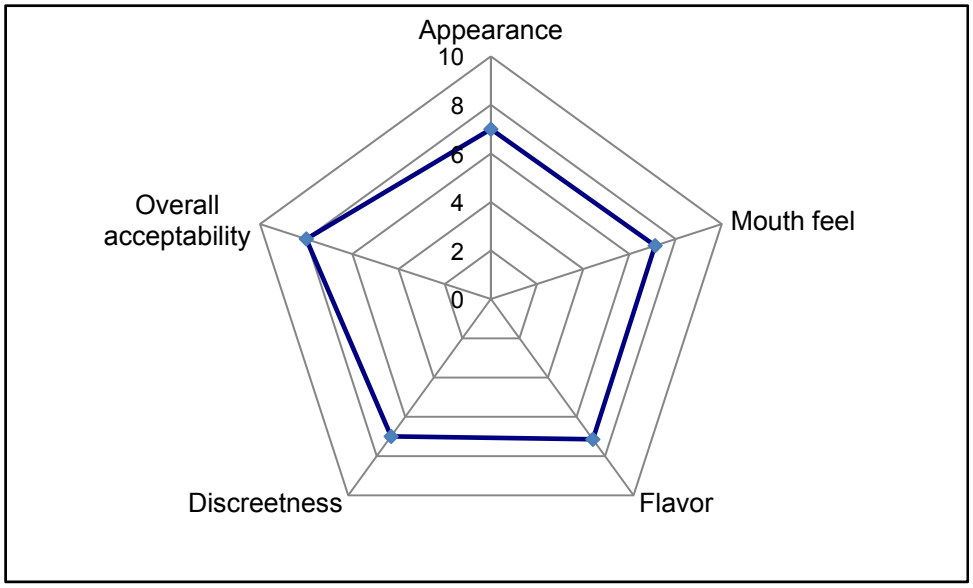


Figure 54. Sensory profile of decorticated and cooked finger millet

products like *chitranna, pongal*, *bisibelebath* which may readily be accepted by both traditional and non-traditional millet consumers.

9. Storage studies

9.1. Sorption behavior

The sorption isotherm of decorticated millet was of sigmoid type which is typical to cereals (Figure 55). The critical moisture content and relative humidity (RH) were 16.5 and 76%, respectively. The moisture content of the millet increased as a function of relative humidity and storage period, and the moisture content of 25.2% was attained at 92% RH, after 7 days of storage, wherein, visible mold growth was noticed. On the other hand, the moisture content of the DM exposed to 86% RH was 18.3% even after 30 days of exposure and it did not show any visible mold growth, however, it turned slightly dark. As expected, the material lost moisture at 56% RH and below and it was only 2.8% at 11% RH on exposing for 30 days and a proportionate increase in moisture content was observed as the RH increased to 76% (16.5%). The sorption isotherm revealed that the DM is less hygroscopic in nature and could be packed in low cost flexible pouches or the conventional packaging sacks normally used for milled rice.

The stability of a food mainly depends on the relationship between the equilibrium moisture content of the food material and its corresponding water activity, at a given temperature. The water sorption isotherms are unique for individual food materials and can be used directly to solve food processing design problems, to predict energy requirement and to determine proper storage conditions (Peng et al., 2007). The information on the sorption behavior is used to calculate moisture change, which may occur during storage and for predicting shelf-life, which in turn determine the quality criteria of a food product.

The effect of exposing the millet to different RH up to 75% (the safest storage RH for the DM) for about 3 months period, on some of its quality characteristics with special reference to color, free fatty acid contents and cooking qualities were also studied. From Table 37, it could be seen that, the material exposed to extremely lower (11%) and also to higher (75%) RH

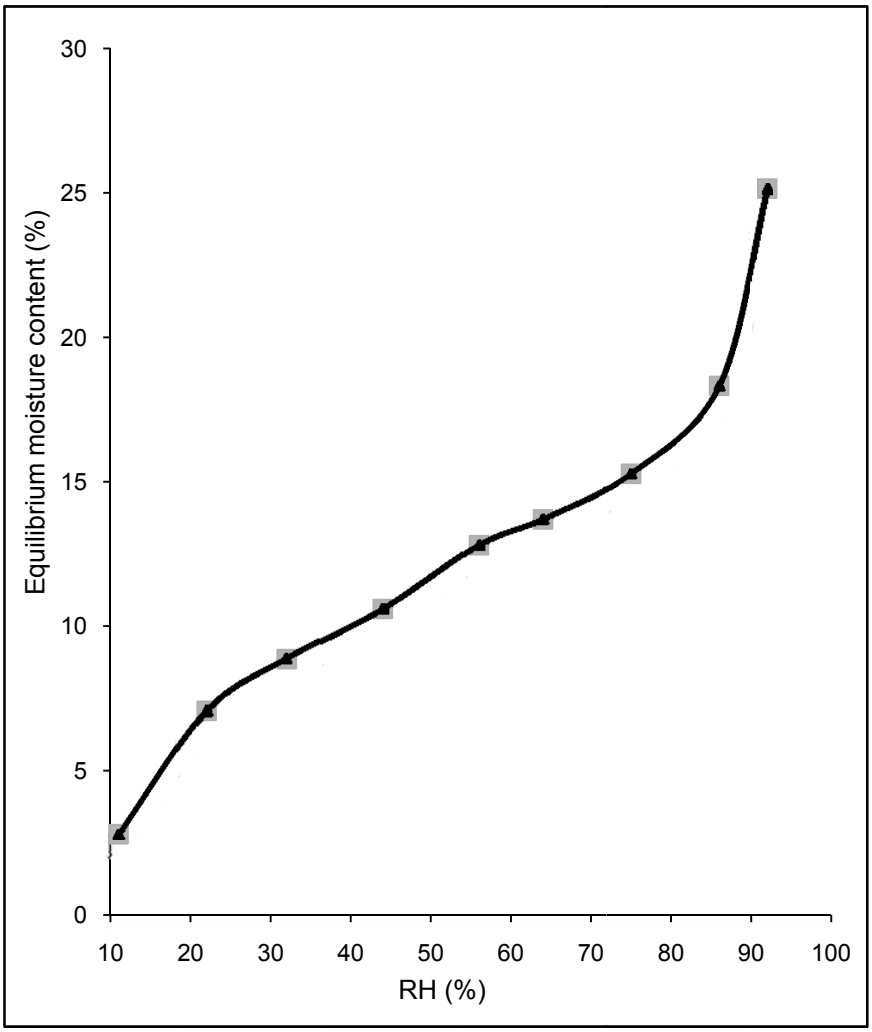


Figure 55. The sorption isotherm of decorticated finger millet

Table 37. Changes in the color indices of decorticated finger millet at different relative humidity during storage*

RH (%)	Storage period (days)																							
	15				30				45				60				75				90			
	L*	a*	b*	ΔE	L*	a*	b*	ΔE	L*	a*	b*	ΔE	L*	a*	b*	ΔE	L*	a*	b*	ΔE	L*	a*	b*	ΔE
11	47.5	4.7	11.8	45.0	47.1	4.6	11.9	45.3	46.1	4.6	11.5	45.3	46.7	4.4	11.9	45.7	46.6	4.3	11.6	45.7	46.1	4.4	11.5	46.2
22	47.3	4.9	12.0	45.2	47.5	4.7	11.7	44.9	47.5	4.7	12.0	44.9	47.2	4.6	11.6	45.3	48.0	4.7	11.7	44.6	48.1	4.5	11.9	44.4
32	48.7	4.7	11.8	43.9	48.2	4.8	11.9	43.3	48.2	4.8	11.6	44.3	48.7	4.6	11.9	43.8	48.4	4.4	11.8	44.0	48.1	4.5	11.6	44.3
44	47.7	4.9	11.7	44.8	47.3	4.7	11.5	45.0	47.3	4.7	11.3	45.0	48.0	4.8	11.5	44.5	47.9	4.4	11.7	44.5	48.3	4.5	11.5	44.1
56	48.1	4.8	11.6	44.4	48.6	4.7	11.8	43.9	48.6	4.7	11.7	43.9	48.1	4.9	11.8	44.4	48.7	4.7	11.6	43.7	48.3	4.7	11.7	44.1
64	47.8	4.8	11.5	44.6	47.7	4.6	11.1	44.6	47.7	4.6	11.1	44.6	45.9	5.0	11.1	46.4	45.1	4.9	11.1	47.1	46.1	4.7	10.9	46.1
75	47.6	5.0	11.9	45.0	47.7	4.9	11.6	44.8	47.7	4.9	11.9	44.8	49.1	4.9	11.6	43.5	49.2	4.7	11.7	43.3	49.2	4.4	11.5	42.3

**Average of two determinations*

exhibited very little variations in its color attributes, as the ΔE values for the former was 46.2 and for the latter was 42.3 after 90 days of exposure. These marginal variations is also reflected by the lightness (L*) values, which was 46.1 and 49.2 at 11 and 75% RH, respectively, after 90 days of exposure. The color indices of the millet exposed to the relative humidity between 11 and 75% did not change appreciably (Table 37).These observations clearly brought out the stability of the DM with respect to its consumer appeal even at different storage conditions. The other important attribute that determines the consumer acceptability of the cereal is the development of off flavor, which is normally measured in terms of free fatty acid (FFA) contents. Interestingly, in the case of DM exposed to different RH, this parameter also did not change appreciably (Table 38). Probably, because of the very low fat content in the millet and also due to inactivation of lipase during hydrothermal treatment. Even, the formation of FFA due to microbial lipase is also ruled out since, the millet at RH lower than 86% did not show any mold growth. This was also confirmed by the very low value for the total plate count (5.9×10^3 cfu/g) at 75% RH (Table 39). The total plate count even for the millet exposed to 86% RH was also well within the permissible level as per the BIS standards for cereals. The development of the oxidative rancidity was minimum probably, because of the natural antioxidant present in the millet. The important observations made during sorption isotherm were; the millet was stable and could be packed in low cost flexible packaging material for storage at places of high humidity and temperature such as a coastal belt of the country.

9.2. Shelf-life

The changes in the moisture and free fatty acid (FFA) contents and also the physical features as well as the cooking quality of the millet during storage are presented in Figures 56- 60. The initial moisture content of the millet was 8.34% which increased to 9.5% at accelerated conditions after 90 days and to 8.7% at ambient conditions after 180 days of storage period. The marginal increase in the moisture content of the millet probably, restricted the increase in the FFA content of the millet, as the FFA content of the DM in both the storage conditions increased from 0.012 to 0.052 and 0.058%, respectively on flour basis (Figure 56). This was also felt by the absence of off flavor in the

Table 38. Changes in the free fatty acid contents of decorticated finger millet exposed to different relative humidity for different days*

RH (%)	Storage period (days)					
	15	30	45	60	75	90
11	0.113	0.141	0.085	0.141	0.141	0.186
22	0.113	0.141	0.085	0.141	0.141	0.186
32	0.113	0.141	0.085	0.141	0.141	0.186
44	0.141	0.141	0.085	0.141	0.160	0.186
56	0.141	0.141	0.085	0.141	0.160	0.186
64	0.141	0.141	0.085	0.141	0.195	0.195
75	0.141	0.113	0.085	0.141	0.198	-

**average of two independent determinations*

Table 39. Total plate count of decorticated finger millet exposed to different relative humidity for 90 days

Relative humidity (%)	Total plate count (cfu/g)*
11	1.5×10^3
22	2.3×10^3
33	3.0×10^3
46	2.9×10^3
56	3.4×10^3
64	5.4×10^3
75	5.9×10^3

**cfu/g: colony forming units per gram of sample*

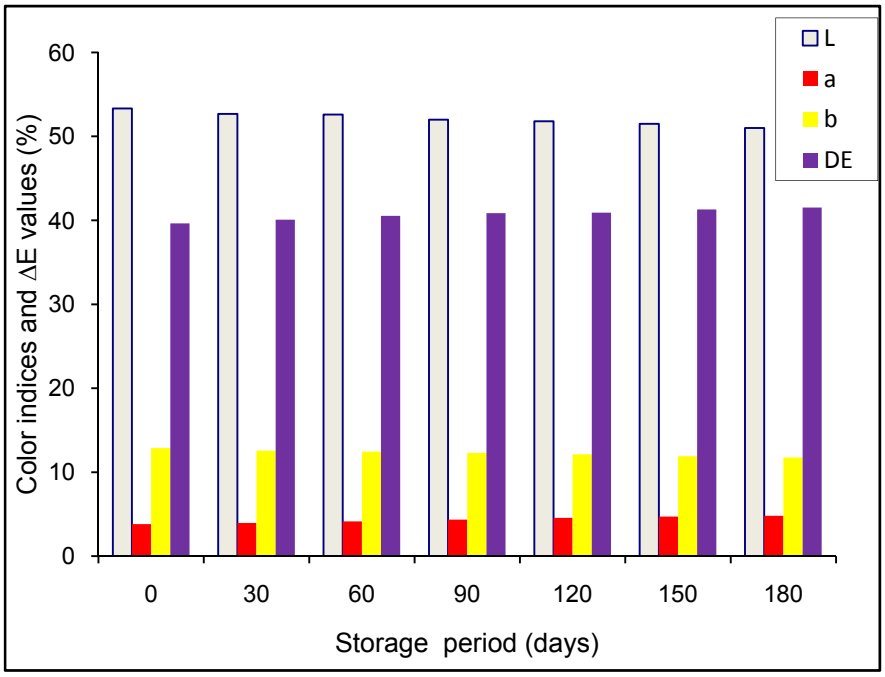


Figure 56. Changes in the color indices of decorticated finger millet at ambient storage condition

millet at both the storage conditions. The changes in the color components of the millet during the storage studies are presented in Figure 57. There were no significant changes in the redness and yellowness values of the millet, but only the lightness and the ΔE values increased slightly. It can be inferred from the color indices of the millet that, the color of the millet remains almost unaffected during the storage period at both ambient and accelerated conditions (Figure 58). Storage of the millet did not affect its cooking time, which remained unchanged at 5±1 min. Even then, both the accelerated and ambient storage conditions did not affect its cooking qualities and texture of the cooked millet, a slight decrease in its swelling power and the moisture uptake was observed (Figures 59 and 60).

In concurrence with the FFA, color and cooking qualities, the sensory analysis of the cooked DM presented in the Table 40, also exhibited marginally lower values for the sensory attributes on storage. The appearance and the discreteness of the cooked millet almost remained constant throughout the storage period. However, the lower score recorded by the panelists for the mouth feel could be due to slight increase in its chewiness. Even though, a slight increase in the FFA was recorded, it was not perceptible on cooking and hence, none of the panelist felt the off flavor. Further, the material remained free flowing without forming lumps or agglomeration on storage for about 90 days at accelerated and for about 6 months at ambient conditions. This showed that the millet has extremely good storage properties.

From the storage studies, it may be inferred that, the DM remains acceptable with respect to its morphological features namely consumer appeal, cooking quality and the overall acceptability. The extremely good storage characteristics indicate its potential for marketability at national and International levels irrespective of the humidity and temperature even when packed at low cost packaging material.

It has been reported repeatedly by several workers that, finger millet has very good storage characteristics, the reasons being, the seed coat rich in polyphenols and spherical shape and tiny size of the kernels. In the case of DM also the shape and size, being common, only the difference is, it is

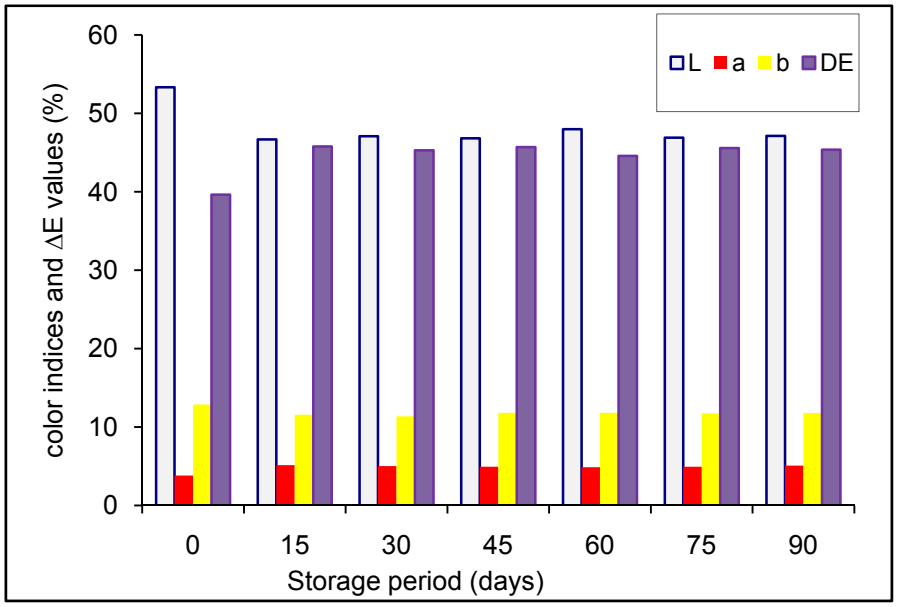


Figure 57. Changes in the color indices of decorticated finger millet at accelerated storage conditon

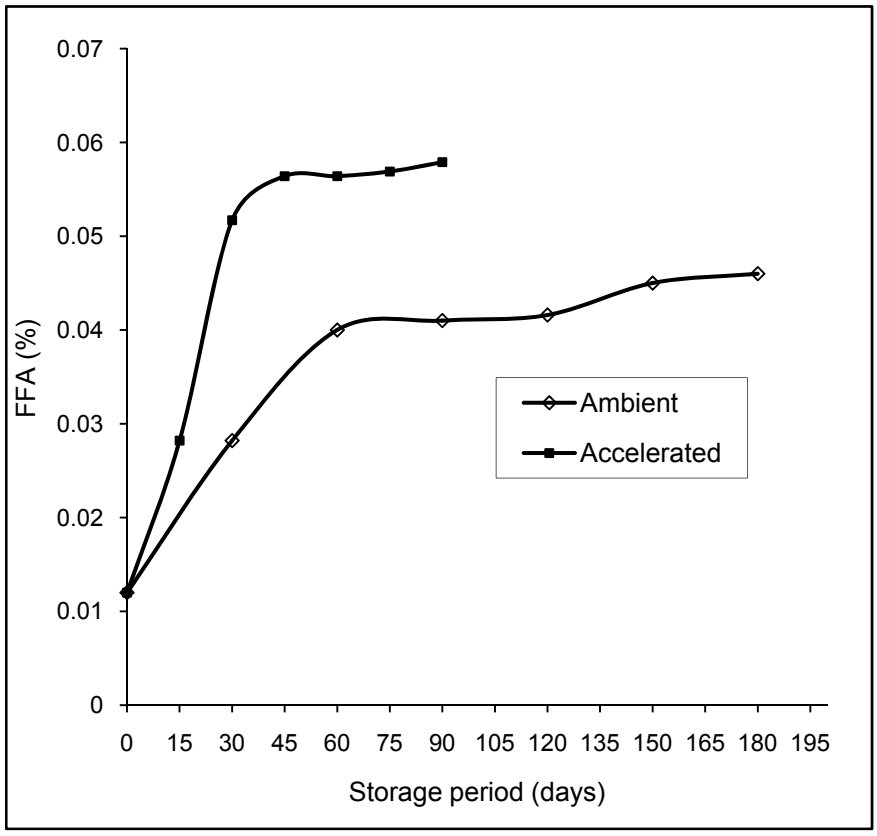


Figure 58. Changes in free fatty acid contents of decorticated millet during storage

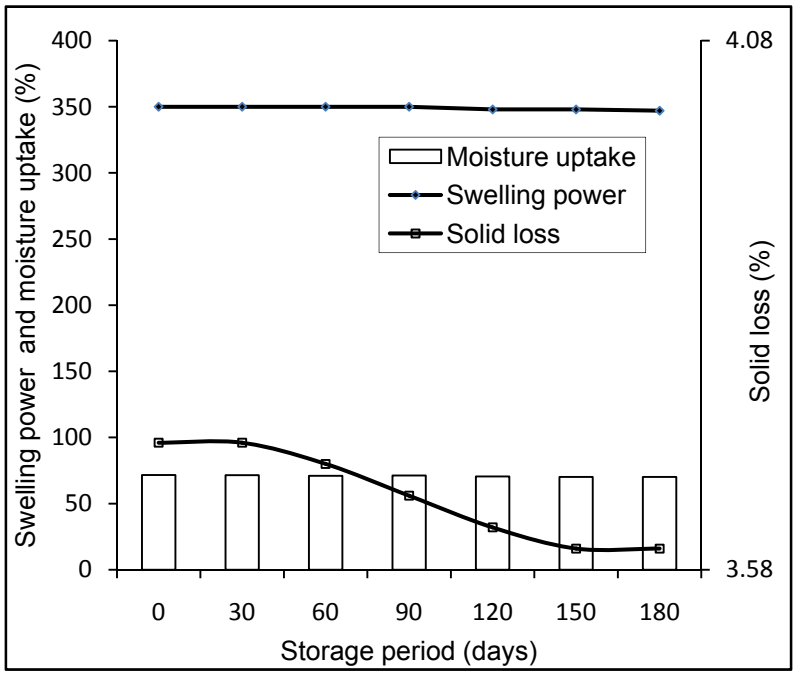


Figure 59. Changes in the swelling power, solubility index and solid loss on cooking of decorticated finger millet stored at ambient conditon

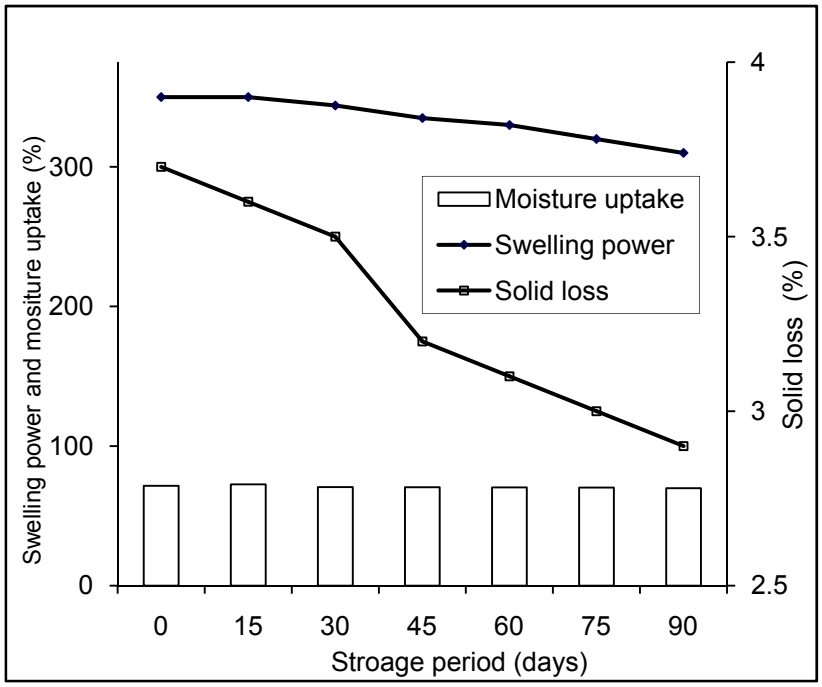


Figure 60. Changes in the swelling power, solubility index and solid loss of decorticated finger millet stored at accelerated conditon

Table 40. Sensory scores of decorticated and cooked finger millet stored for different period

Parameter	Appearance		Flavor		Discreetness		Mouth feel		Overall acceptability	
Storage (days)	Ambient	Accl.	Ambient	Accl.	Ambient	Accl.	Ambient	Accl.	Ambient	Accl.
Control	6.9±1.0	6.9±1.0	7.2±1.2	7.2±1.2	6.4±1.2	6.4±1.2	7.1±1.2	7.1±1.2	8±1.2	8±1.2
15	6.9±1.0	6.4±1.5	7.2±1.5	7.1±1.8	6.4±1.9	8.0±0.9	7.1±1.5	7.0±1.0	8±0.9	8±1.9
30	6.9±1.0	5.8±1.2	7.2±1.3	6.1±1.1	6.5±1.4	7.6±0.5	7.1±1.5	6.6±1.9	8±0.9	8±1.3
45	6.8±1.0	5.5±1.2	7.1±1.3	5.5±1.4	6.6±1.3	7.3±0.6	7.1±1.2	5.6±1.6	8±1.1	8±1.9
60	6.9±1.2	5.4±0.8	7.1±1.6	5.5±0.8	6.6±1.2	7.3±1.0	7.0±1.2	5.4±1.3	8±1.2	7±0.9
75	6.8±1.2	5.2±0.5	7.1±1.2	5.4±0.5	6.6±1.4	7.6±1.0	7.0±1.2	4.6±0.5	8±1.2	7±1.0
90	6.8±1.2	4.5±0.8	7.0±1.0	5.3±0.6	6.8±1.2	7.3±0.6	6.9±1.2	4.3±0.5	8±1.2	7±1.2
120	6.8±1.2	-	7.0±1.2	-	6.8±1.2	-	6.6±1.0	-	8±0.8	-
150	6.8±1.2	-	7.0±1.0	-	6.7±1.3	-	6.5±1.0	-	8±1.1	-
180	6.8±1.2	-	7.0±1.1	-	6.8±1.1	-	6.4±1.0	-	8±1.2	-

Mean scores with a difference of 1 is significant at P<0.05 within the attributes
Accl: accelerated storage condition

decorticated and does not contain the seed coat as in the case of NM. Even then, the DM exhibited very stable shelf-life up to the study period of 6 months (The product remained still acceptable).This may be due to hardening of the millet endosperm during hydrothermal treatment and also due to the beneficial effect of the polyphenols content. It may be noted here that, during the hydrothermal treatment to the millet, the polyphenols present in the seed coat migrates towards the endosperm and probably, this phenomena benefits the millet with their antimicrobial and antioxidant activities. Moreover, very low fat content of the DM (1%) and inactivation of lipase during hydrothermal treatment also help to extend the shelf-life of the DM. Thus, from the shelf-life studies it can be concluded that, the DM does not require the use of synthetic antioxidants for extending its shelf-life and it could be packed in normal packaging material used for wheat or rice products for local consumption and also for transportation.

SUMMARY AND CONCLUSIONS

Decortication characteristics of the hydrothermally treated millet were influenced by the grain hardness, moisture content and also on the milling machinery. Since, the rigidity between the seed coat and the endosperm of the millet increased on hydrothermal treatment, it necessitated pretreatment for decortication. Accordingly, it was observed that, incipient moist conditioning rendered the seed coat leathery and loosened the intactness between the seed coat and the endosperm and facilitated decortication effectively. Among the several cereal milling machineries, horizontal emery disc was found to be advantageous for decortication without causing excessive breakage. It was observed that, the millet at about 15% moisture content was more suitable for decortication. Moistening the HTM with 5% additional water at I-stage and again 4% additional water at II-stage milling was found to be suitable conditions for decortication instead of single stage milling. Under these conditions, the yield of decorticated millet was about 65%. The various parameters influencing the decortication characteristics of the HTM were also optimized through response surface methodology.

The DM resembled the native millet in its overall size but was of creamish and highly appealing color. The DM contained about 4.5% protein, 0.8% fat, 10% dietary fiber, 72% available carbohydrates, 1% minerals and 190 mg/100g of calcium. The carbohydrate and protein digestibility of the decorticated millet were significantly higher than the native millet. The bioavailability of calcium and iron in the DM (62 and 46%, respectively) was significantly higher than the native millet (30 and 10%, respectively). The DM cooked to soft edible texture within 5 min and was readily accepted by all age groups. The sorption isotherm studies revealed that the DM is of very low hygroscopic nature and its critical moisture and humidity for safe storage were 16.5 and 76% respectively. The DM was stable even at 82% RH for more than 30 days without any mold growth. The DM packed in LDPE pouches, remained acceptable for 6 months at ambient and for 3 months at accelerated storage conditions.

From the above observations, the following conclusions can be drawn; incipient moist conditioning of the hydrothermally treated millet was necessary for loosening the intactness of the seed coat with the endosperm. Decortication of the hydrothermally treated millet could be effectively carried out in the carborundum disc mill. Decortication of the millet lowers some of the nutrient contents but enhances the bioavailability of proteins, carbohydrates and minerals. The decorticated millet cooks to soft texture within 5 min and it can be considered as a quick cooking cereal.

INTRODUCTION

Popping of cereals and grain legumes, one of the simplest and least expensive traditional food-processing methodologies, is followed worldwide to prepare RTE food products. Popping ideally creates an aerated, porous and crisp textured product with added benefits of dehydration which is generally microbially safe (Arya, 1992).

Cereal popping is a high temperature short time (HTST) treatment. In India normally, the heat transfer media used for the purpose is either air or salt or sand or oil maintained in a temperature range of 160 - 250^{o}C (Chandrasekhar and Chattopadhyay, 1990). On the other hand, gun popping which is commonly followed in Europe, United States and in most of the East Asian countries, involves heating the cereal in a closed container and exposing the superheated material to atmospheric conditions instantaneously. This causes pressure difference, leading expansion or popping of the grains (Lai and Cheng, 2004).

Puffing of cereal is also followed to prepare ready-to-eat products. Although, both puffing and popping are HTST process, in the case of puffing, the native grains are subjected to HTST treatment whereas, for popping or expansion, parboiled and decorticated grains are used. For puffing as well as popping, the grains are normally equilibrated to 10 - 18% moisture content. In the case of native grains, the seed coat of the kernel acts as pressure vessel or barrier for the escape of the steam resulting in explosion of the entire endosperm. On the other hand, in the case of parboiled and decorticated grains, the steam formed in the voids of the endosperm causes expansion of the gelatinized starch uniformly in all directions. The puffed grains are uneven shaped where as the expanded grains largely retain the shape of the milled grains (Chinnaswamy and Bhattacharya, 1983). In both the cases, the process involves release or expansion of super heated vapor within a grain either to create an internal structure or to expand or rupture an existing structure due to the sudden change in temperature and pressure (Byrd and Perona, 2005). The classic examples of puffed and expanded cereals are popcorn and expanded rice respectively. Expansion of the reconstituted

grains is also done following extrusion cooking for preparation of cereal cryspies.

Generally, puffing of corn, rice, grain amaranthus, chickpea, wheat, sorghum and millets is followed in the region of their production, mainly for using as snack foods and also in the preparation of ready-to-eat nutritious supplementary foods. But preparation of expanded cereal is largely confined to rice. Reports on preparation of expanded product from other cereals are scanty. In the case of finger millet, such a product is not heard. Puffing of finger millet is followed traditionally and the puffed millet is largely pulverized into meal (Malleshi and Desikachar, 1981b), which is locally called as "*Hurihittu*". The product with soft crunchy texture will be ready-to-eat and posses highly desirable aroma. It is normally used after adding salt and seasoning as snack or after mixing with sweetner such as jaggery and milk as supplementary food, mainly by the children. Since, puffed product from the millet is from the whole grain, it contains the seed coat, which imparts fibrous texture and dark color and due to this it has poor sensory attributes.

Processing the millet to prepare expanded millet was not practiced since, decorticated millet was not available so far. Now, the process for decortication of the millet has been developed and the availability of decorticated millet has been made possible, the feasibility of preparing expanded millet, similar to expanded rice was explored.

The endosperm characteristics of the millet are different from that of rice and many other cereals, and very little information is available on the parameters influencing the expansion characteristics of the decorticated millet as well as on the quality characteristics of the expanded millet. Hence, the factors influencing the expansion characteristics such as moisture content of the grains, the temperature of heat transfer media and the pretreatment needed to enhance the expansion of the millet were investigated and also the quality characteristics of the expanded millet were studied.

MATERIALS AND METHODS

1. MATERIALS

1.1. Raw material

The millet was decorticated on pilot scale as described earlier and the decorticated millet (DM) was size graded using the cereal grader fitted with screens of 1405 and 1680 μm openings. The tailings of 1405μ (too bold) and the throughs of 1680 μm (small sized, brokens etc.) were discarded and the grains falling in the range of 1405 - 1680 μm (about 95% of the DM) were used for the expansion studies.

1.2. Heat transfer media

Common salt (Sodium chloride), purchased from the local market (particle size ranging between 355 - 550 μm) was used as heat transfer media for the HTST treatment.

1.3. Popping device

A cylindrical device, (13 cm length and 4 cm diameter with 550 μm perforations) to hold the millet and to facilitate immersion of the grains in hot salt for preparation of expanded millet, was used for the experiments. The schematic diagram of the device is shown in Figure 61.

2. Factors influencing the expansion ratio

The primary parameters, which influence the expansion ratio of the millet, are (a) the material to salt ratio, (b) the moisture content of the grain, and (c) the temperature of the heat transfer media. Hence, the influence of these parameters on the expansion ratio of the millet was determined.

2.1. Material to salt ratio

Experiments were conducted with material to salt ratio in proportions of 1:1, 1:2, 1:3, 1:4, 1:5 and 1:6. The salt was heated to about 230^{o}C (Malleshi and Desikachar, 1981b) and soon after mixing the material with salt, the contents were agitated and the expanded millet was separated from the salt. Based on the quality of the expanded millet obtained, millet to salt ratio of 1:4 was identified as the most suitable proportion and the same was used for all the

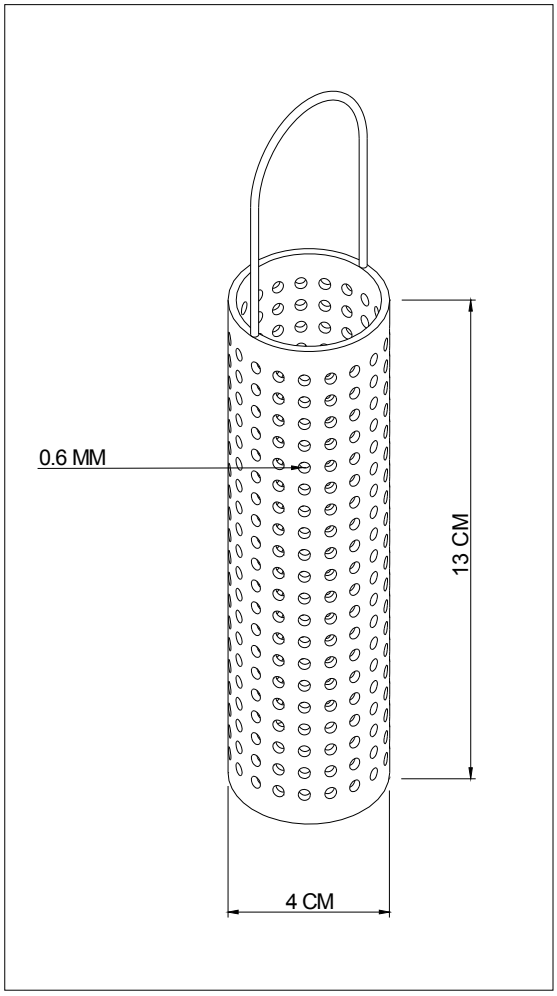


Figure 61. Schematic diagram of the popping device

experiments pertaining to preparation of the expanded millet.

2.2. Moisture content

To determine the influence of grain moisture content on the expansion ratio, the DM (100 g batches) was sprayed with predetermined quantity of potable water to raise its moisture content from 6 - 24% with 2% increment and allowed to temper for 4 h in closed containers with occasional mixing. About 25 g of the millet equilibrated to different moisture levels was taken in the popping device and to that about 100 g of the hot salt ($\sim$ 230^{o}C) was added, the contents were mixed by vigorous agitation till the bursting or hissing sound was ceased. Immediately after that, the salt was sieved off and the expanded millet was put on a vibrating screen to separate the adhering salt, if any. The expanded millet (EM) was equilibrated to room temperature, weighed, transferred to a 100 ml measuring cylinder and compacted by tapping the cylinder on a wooden plank 10 times or till there was no visible decrease in the volume, and the apparent volume was recorded. Based on the weight and volume, the expansion ratio was calculated as follows;

$$\text{Expansion ratio} = \frac{\text{Volume of the expanded millet of known weight}}{\text{Volume of the decorticated millet of same weight}}$$

The process was repeated and the average of the expansion ratio of a minimum of 3 independent determinations was recorded.

2.3. Temperature of heat transfer media

Guided by the experiments on the influence of moisture content of the millet on the expansion ratio, the millet equilibrated to 9$\pm$1% was used for the experiments on determination of the optimum temperature of the heat transfer media. For the purpose, the millet equilibrated to 9$\pm$1% moisture content mixed with the salt heated from 190^{o}C to 250^{o}C with about 10^{o}C increments, separately, and the expanded millet was collected as described earlier. In each case, a minimum of three independent determinations were carried out and the average values of the expansion ratio was recorded.

The maximum expansion ratio of the millet obtained under these experimental conditions was hardly 3.1. Hence, to explore the possibility of

achieving higher expansion ratio of the millet, further experiments on pretreatment to the DM on the following lines were carried out;

(a) Raising the moisture content up to 35 - 40% and allowing to stand for 10 - 12 h to cause mild fermentation, and dehydrating to about 9±1% moisture level and subjected to HTST treatment for preparation of the expanded millet,

(b) Equilibrating the DM to moisture content of about 25±5%, steaming at atmospheric pressure for 10±1 min and imparting mild physical deformation by passing between rolls of a flaker (Aktiebolsget, Malmo, Germany), and

(c) Incipient germination (soaking for 10 h and germination for about 8 h), steaming the sprouts at atmospheric pressure for about 25 min, drying and decorticating.

The expansion characteristics of the millet prepared as per ‘b’ were superior to that prepared following the methods ‘a’ and ‘c’ in terms of expansion ratio (>3.5). Hence, further experiments towards the influence of moisture content of the DM on the degree of deformation and its influence on the expansion characteristics of the millet were conducted.

Since, it was desirable to deform the kernel slightly without causing visible cracks, the DM was equilibrated to 15 - 40% moisture contents with about 5% increment, steamed separately for about 10 min at atmospheric pressure and subjected to mechanical impact just to cause the disruption of the endosperm texture without developing visible cracks. The impacted millet was dried to about 9±1% moisture content and the degree of impact in each case was determined by measuring the diameter ‘a’ and thickness ‘b’ of the individual grains, using a dial calipers (Model 537, Mitutoyo, Japan) with an accuracy of 0.02 mm. The average of 20 independent determinations was reported.

Based on the experiments, the DM was equilibrated to about 40% moisture content, impacted and dried to about 9±1% moisture level. The ratio

of the thickness to the diameter ('b/a') of the impacted grains was determined and the same was referred as the 'shape factor'. To determine the influence of the impact in terms of shape factor, on its expansion characteristics, the DM equilibrated to 40% moisture content was steamed for 10 min at atmospheric pressure and pressed between the rolls adjusted suitably to obtain the shape factor ranging from 0.5 to 0.9 (not fully flaky and not fully spherical).

Mere equilibrating the grains to about 40% moisture content no doubt imparted desirable physical modification without developing visible cracks, but to enhance its effectiveness, steaming the grains equilibrated to 40% moisture content, for about 10 min, was also carried out.

2.4. Drying conditions of impacted millet

Since, the optimum moisture content of the millet plays a crucial role during expansion and the optimum moisture level was 9±1%, the impacted grains were dried to 9±1% moisture level. However, it was noticed that the rate of drying changed the material characteristics which eventually had the influence on the expansion ratio. In view of this, the optimum temperature for drying the material was determined. For the purpose, the impacted material was dried in a mechanical dryer by exposing to air at 40 to 70^{o}C temperature with an increment of 10^{o}C, to 9% moisture level. In each case, the physical features of the dried grains were noted. Subsequently, the dried millet was subjected to HTST treatment and the expansion ratio in each case was determined. It was observed that, drying the impacted material at 42±2^{o}C to 9±1% moisture was most suitable to prepare the EM with over 3 fold expansion ratio. Accordingly, the rate of dehydration (drying time) of the impacted material was determined by exposing the deshaped millet (1 kg batches) in a mechanical drier maintained at 40±2^{o}C.

On the basis of the above experiments, it was inferred that the expansion ratio of the DM mainly depended on;

1. The moisture content of the DM prior to deshaping,
2. The shape factor, and

3. The rate of drying of the deshaped material to about 9±1% moisture level.

Hence, to determine the optimum conditions for preparation of expanded millet following response surface methodology (RSM), the above parameters were considered.

3. Response surface methodology

3.1. Experimental design

A central composite rotatable design (CCRD) with three variables was used to examine the response pattern and to determine the optimum synergy of variables (Cochran and Cox, 1957). The variables and their optimized ranges, as determined by the preliminary experiments were, moisture content of 40%, shape factor ranging from 0.3 -1.0 and drying time of 0 to 150 min, each at 5 levels, namely, -1.682; -1; 0; 1 and 1.682 (Table 41). The treatment schedule for CCRD shown in Table 42 was arranged to allow for fitting an appropriate regression model using multiple regression program. The CCRD combines the vertices of the hypercubes whose co-ordinates are given by a 2*n* factorial design to provide for the estimation of curvature of the model (Joglekar and May, 1987). Six replicates (treatment 15 - 20) at the center of the design were used for estimation of a pure error sum of squares. Experiments were randomized in order to maximize the effects of unexplained variability in the observed responses due to extraneous factors.

3.2. Responses

The responses namely, expansion ratio, sphericity, hardness, bulk density and overall acceptability of the product were selected based on the parameters, which describe the quality criteria of the expanded millet. The expansion ratio and sphericity of the product were determined as described earlier.

The hardness of the expanded millet was measured using texture analyzer (Stable Microsystems, Model TA-HDi, Surrey, UK) with 50 kg load cell, by recording maximum force required to cause 80% compression of the product, at a crosshead speed of 100 mm/min.

Table 41. Variables and their levels for CCRD

	Symbols	-1.682	-1	0	1	1.682	Mean	Standard Deviation
Moisture content (%)	X_1	15	20.07	27.5	34.93	40	27.5	7.43
Shape factor	X_2	0.3	0.44	0.65	0.86	1	0.65	0.21
Drying time (Min)	X_3	0	30.41	75	119.59	150	75	44.59

Table 42. Treatment schedule for five-factor CCRD and response

X_1	X_2	X_3	Expansion Ratio (Y_1)	Bulk density (Y_2)	Sphericity (Y_3)	Texture (N) (Y_4)	Overall acceptability (Y_5)
-1	-1	-1	3.330	0.231	0.863	19.08	5.430
1	-1	-1	3.560	0.230	0.900	18.21	4.860
-1	1	-1	3.042	0.290	0.952	26.29	5.380
1	1	-1	2.100	0.327	0.920	30.16	1.800
-1	-1	1	3.268	0.235	0.898	27.87	3.630
1	-1	1	4.486	0.171	0.904	7.13	6.630
-1	1	1	3.349	0.230	0.930	20.28	5.890
1	1	1	4.252	0.199	0.960	11.69	6.000
-1.682	0	0	3.227	0.238	0.916	22.87	6.330
1.682	0	0	3.463	0.222	0.915	17.45	4.500
0	-1.682	0	4.496	0.171	0.840	19.97	6.750
0	1.682	0	2.800	0.298	0.960	28.04	4.000
0	0	-1.682	2.200	0.350	0.949	32.91	2.970
0	0	1.682	3.628	0.212	0.935	13.2	6.000
0	0	0	3.737	0.206	0.955	13.42	6.000
0	0	0	3.713	0.207	0.955	13.52	5.400
0	0	0	3.639	0.211	0.953	13.96	5.500
0	0	0	3.596	0.214	0.967	14.15	5.300
0	0	0	3.710	0.207	0.956	13.8	5.400
0	0	0	3.741	0.206	0.967	13.5	5.400

The peak force required to compress the sample was referred as a measure of hardness and an average of ten replicate values were reported. The bulk density of the sample was determined by calculating the ratio of weight to volume of the sample, wherein, the volume of the sample was measured by taking a known weight of the sample in a measuring cylinder and tapping the same gently on a wooden plank until no visible decrease in volume was noticed.

The appearance, colour, texture, taste and overall quality of the expanded millet were evaluated by a panel consisting of ten trained members on a nine point hedonic scale ranking 1 for 'dislike extremely' and 9 for 'like extremely' (Watts et al., 1989). The average and the mean values of the scores from all the panelists for each of the attributes were computed and analyzed statistically (Snedecor and Cochran, 1962). The overall acceptability of the product was considered for the response.

3.3. Statistical analysis

A second order polynomial equation was used to fit the experimental data given in Table 42. The model proposed for the response (Y_i) was,

$$Y_i = a_o + a_1X_1 + a_2X_2 + a_3X_3 + a_{11}X_1^2 + a_{22}X_2^2 + a_{33}X_3^2 + a_{12}X_1X_2 + a_{13}X_1X_3 + a_{23}X_2X_3 + \varepsilon$$

where Y_i (i=1 to 5) is the predicted response for expansion ratio (Y_1), bulk density (Y_2), sphericity (Y_3), texture (Y_4) and overall acceptability (Y_5), a_o is the value of the fitted response at the center point of the design, a_i, a_{ii}, a_{ij} being the linear, quadratic, and cross product terms, respectively and ε is the random error. In order to deduce workable optimum conditions, a graphical technique was used (Floros and Chinnan, 1988; Giovanni, 1983) by fixing one variable at predetermined optimum condition. The optimum condition was verified by conducting experiments under these conditions.

Responses were monitored and the results were compared with model predictions. The fitted polynomial equation was expressed as surface and contour plots in order to visualize the relationship between the response and

experimental levels of each factor and to deduce the optimum conditions.

4. Physicochemical characteristics of expanded millet

Following the identified optimum conditions, the expanded millet was produced on semi- pilot scale and its physical properties like color, texture, bulk density and expansion volume were determined as described earlier. The whole meal of particle size less than 250 μm from the EM was used for determining the functional properties as well as the nutrient composition.

The solubility and swelling power at ambient and at 95^{o}C were also determined following the procedures described earlier in Chapter II. For determination of the water and oil absorption of the pulverized material, 1 g each of the meal was mixed with 10 ml of water and the contents were left undisturbed for 30 min, followed by centrifugation. The weight of the residue was noted to determine the cold-water absorption capacity of the millet. The experiment was repeated for the expanded millet in grain form also. Similarly, both the meal and the expanded millet were treated with double-refined peanut oil to determine the oil absorption capacity (Lin and Humbert, 1974). The viscosity at 10% (w/v) of the slurry concentration and also the pasting profile were measured using Brookfield Viscometer and Brabender Visco Amylograph, respectively.

The nutrient composition of the EM was determined as per standard AACC procedures (2000). The carbohydrate digestibility was determined by enzymatic method (Ngo Som et al., 1992) where as the carbohydrate profile was studied by gel permeation chromatography using Sepharose CL 2B column (Chinnaswamy and Bhattacharya, 1986b). The expanded millet was cut into two halves and examined under scanning electron microscope and also the X-ray diffraction studies of its meal were carried out as explained in the Chapter II.

RESULTS AND DISCUSSION

The expanded millet (EM) was free from the adherence of the salt, even though, common salt was used as the heat transfer media for expansion. Common salt was identified as a heat transfer media instead of sand,

generally used for popping of cereals in India, because of its good thermal conductivity and also to avoid the sand contamination of the product. It was noticed that during the experiments on optimizing the millet to salt ratio, the ratio up to 1:3, yielded poor quality expanded material and the product contained a few partially popped grains. The salt heated to 230^{o}C temperature, when fully cover the grains under experimentation, was effective in heat transfer causing expansion within a few seconds of agitation. Accordingly, the ratio of material to salt was fixed at 1:4. Higher ratio was not desirable because it required more time to separate out the salt by sieving, which often caused surface charring. Hence, by keeping this parameter constant, other process variables like moisture content of the grain and temperature of the heat transfer media were optimized.

1. Factors influencing the expansion ratio

1.1 Moisture content

The moisture content of the DM exhibited significant influence on its expansion characteristics, as the DM at 9$\pm$1% moisture content on HTST treatment yielded the product having expansion ratio of 3.1. Under the experimental conditions it was the highest value for the expansion ratio (Figure 62). The expanded millet prepared at moisture content less than 8% exhibited lower degree of expansion and was of intense brown color, whereas, that containing more than 10% moisture exhibited surface hardening as well as partial charring of the expanded grains. From these observations, it was inferred that, the DM equilibrated to 9$\pm$1% moisture content was most suitable for preparation of optimally expanded millet. Accordingly, the DM was equilibrated to about 9% moisture content and used for subsequent experiments.

It is evident that, certain amount of moisture in the grain is essential for its expansion, because the steam formed during the HTST treatment facilitates expansion. In cereals, the expansion is mainly due to the expansion of its starchy endosperm. As soon as the grain comes in contact with the heat transfer media such as air, sand, salt or oil, heated to about 230^{o}C, the heat will be transmitted in to the core of the grain almost instantaneously, and

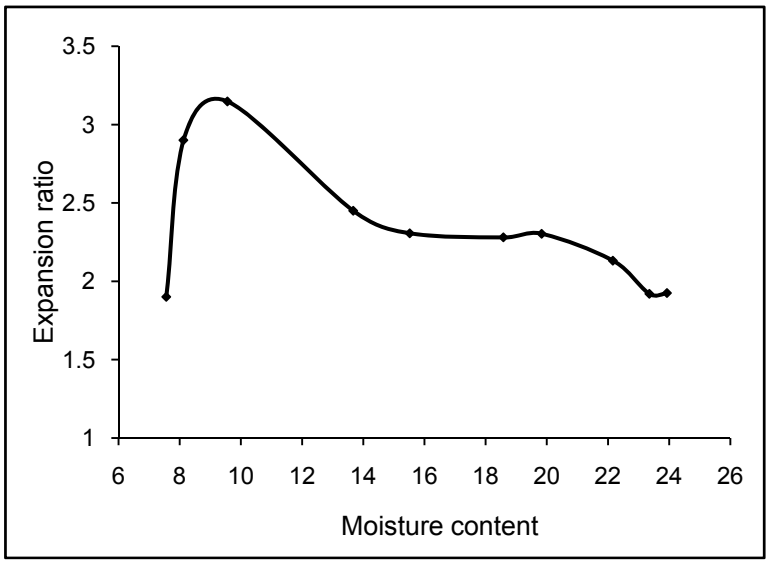


Figure 62. Effect of moisture content on expansion ratio of decorticated finger millet

converts the available water in to steam. The steam builds up pressure inside the grain and explodes leading to expansion of the grain. The superheated water as well as the steam formed exerts vapor pressure in the case of native grains (Hoseney et al., 1983) and when this pressure exceeds the total burst pressure of the pericarp, it explodes (puffing) (Byrd and Perona, 2005). On the other hand, in case of parboiled and decorticated grains, which contain gelatinized starch and seed coat is separated out, the steam formed during HTST treatment creates vacuoles in the endosperm and causes uniform expansion in all directions (Chandrasekhar and Chattopadhyay, 1990).

The effect of moisture content of the cereals on the popping yield as well as the expansion ratio has been studied extensively (Sabri Gokmen, 2004; Konishi et al., 2004) and in the case of paddy and rice, it has been reported that, the moisture content in the range of 14 - 16% is optimum for puffing (Murugesan and Bhattacharya, 1989) and 10 - 11% for preparation of expanded rice (Chinnaswamy and Bhattacharya, 1983). The optimum moisture content identified for finger millet is 9% is nearly comparable with rice. This shows that, for puffing the moisture content required is higher than the popping. This could be due to the presence of native starch in the former and gelatinized starch in the latter. Thus, compared to raw starch, the gelatinized starch requires less moisture to expand or in other words, very less steam pressure may be sufficient to explode the grain. DM being a small sized cereal expands to the optimum level at about 9% moisture content.

1.2. Temperature of heat transfer media

The application of high temperature short time (HTST) treatment invariably requires a heat transfer media and the temperature of the heat transfer media is one of the key factors that influences expansion ratio. As the DM equilibrated to about 9% moisture content on mixing with salt heated to 190 - 260^{o}C, considerable variations in the yield as well as expansion ratio were noticed. While, the yield of the expanded grains and the expansion ratio were considerably lower when treated at temperatures up to 200^{o}C, but both the parameters improved as the temperature increased up to about 230^{o}C. However, at temperatures higher than 230^{o}C, expansion ratio was slightly

lower besides, the quality of expanded grains was poor due to surface charring. Hence, the most suitable temperature of heat transfer media was found to be 225±5°C. In the case of rice also it has been reported that, the optimum temperature for expansion is around 250°C (Chinnaswamy and Bhattacharya, 1983). In consideration of the yield and the expansion ratio of the millet, the optimum temperature for preparation of expanded millet was identified as 225±5°C, and the same was used throughout the studies.

1.3. Degree of impact

During expansion of cereals, no doubt, the grains are given different kinds of pretreatments but in the case of millet, the pretreatment is unique, as a slight disruption in its endosperm organization was essential to obtain the good expansion. This could be achieved by mechanical impact or by incipient germination (Malleshi and Ushakumari, 2007; Meera et al., 2008). However, mechanical impact by passing between the rolls of a flaker was followed as it is technically feasible. As indicated earlier, mild mechanical impact significantly influence the expansion ratio of the millet. But as expected, the moisture content of the decorticated millet influenced the texture of the impacted grains (Figure 63). Accordingly, it was observed that impacting the millet containing less than 16% moisture produced excessive visible fissuring as well as cracks, and also breakage of few grains. But, as the moisture content of the DM increased, the grains exhibited resilience and the millet impacted at 35 - 40% moisture content, was of smooth texture without visible fissures. Further, it was observed that, steaming the material containing about 40% moisture for about 10 min at atmospheric pressure imparted plasticity to the millet probably, due to softening the cell walls and as a result, the impacted millet exhibited resilience to some extent without forming visible cracks. In other words, the grains having moisture content of about 35 - 40% underwent effective transformation to plasticity during steaming. Creation of minute internal fissures by mechanical impact caused conducive environment within the grain for development of steam pressure and better expansion during HTST treatment (Mertens et al., 2003; Malleshi and Ushakumari, 2007).

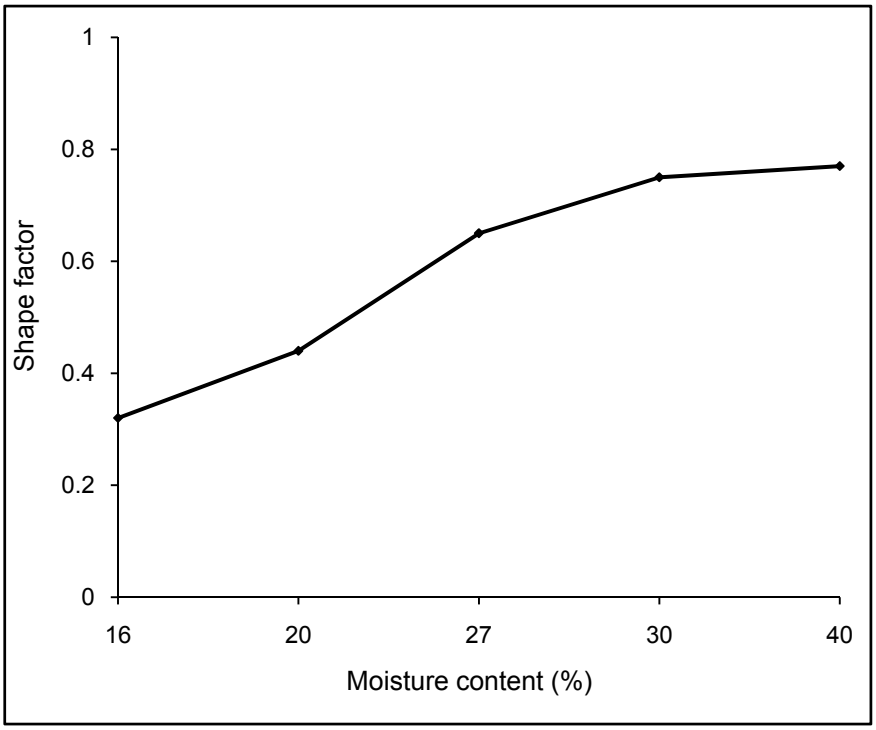


Figure 63. Effect of moisture content on the shape factor of decorticated finger millet

The impact on the kernels was quantified by the physical deformation on the grains in terms of shape factor. The shape factor essentially indicates the degree of flattening of the grain and mainly depends on the moisture content of the material and the clearance (gap) between the rolls of the flaker. Narrower the gap between the rolls, thinner was the product with proportionate increase in diameter of the grains (Figure 64) leading to decrease in the shape factor of the impacted material and *vice versa*.

The degree of impact, measured in terms of shape factor, influenced the shape as well as expansion ratio of the expanded millet. Expanded millet prepared from the sample having the shape factor less than 0.5 was similar to flakes. But as the shape factor increased up to 0.9, the shape of the expanded millet was near spherical but the expansion ratio was slightly lower (Figure 65).

During hydrothermal treatment, the important physicochemical changes that take place are gelatinization of starch, denaturation of the protein and partial fragmentation as well as solubilization of cell wall materials. Due to these changes cementing of biochemical constituents of the endosperm take place thereby enhancing the rigidity or hardness of the kernel (Correa et al., 2007). It was evident from the earlier chapters that, on hydrothermal treatment the hardness of the millet increased by about 5 times of its original value. The texture of the millet kernels differed from rice in terms of cell wall contents as well as their thickness. Probably, this may hinder penetration of heat and formation of steam effectively during HTST treatment minimizing the expansion compared to rice wherein, the cell wall rigidity is very poor. Hence, disruption of the cellular matrix by mechanical impact may create minute fissures in the cell walls and also the disorientation of the cells and facilitate increased degree of expansion during HTST treatment (Ushakumari et al., 2007).

1.4. Dehydration characteristics of the impacted millet

Since, the moisture content of the material would be about 40% prior to impacting, drying the same to about 9% moisture content prior to subjecting to HTST treatment was necessary.

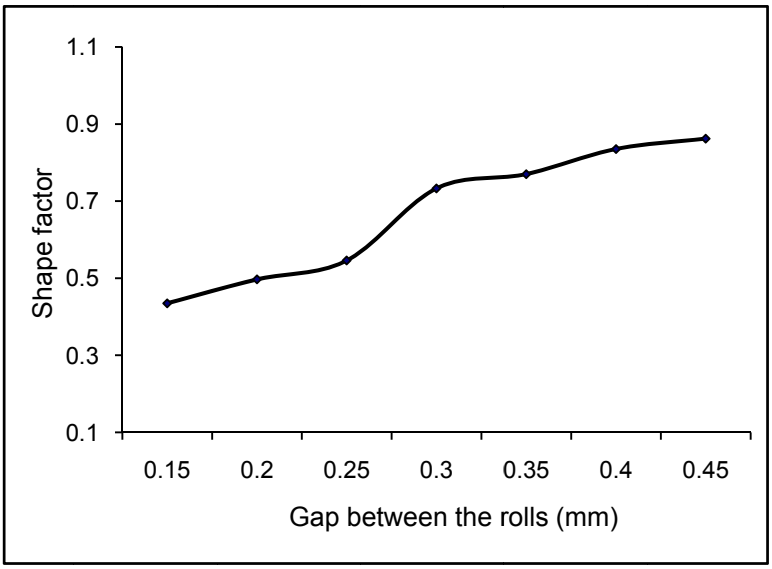


Figure 64. Effect of roll gap of the flaker on the shape factor of decorticated finger millet

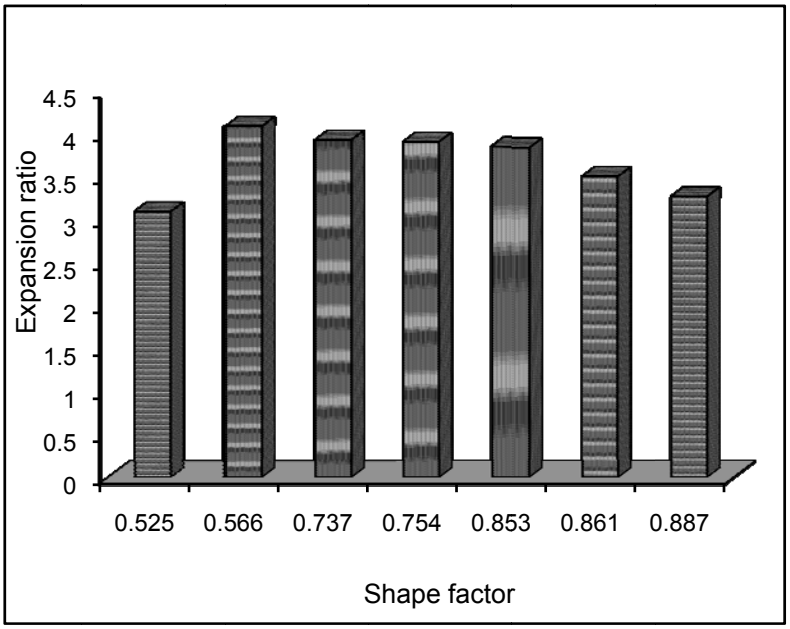


Figure 65. Effect of shape factor on the expansion ratio of decorticated finger millet

The temperature of drying also exhibited definite influence on the expansion characteristics. Accordingly, the material was dried by exposing to different air temperature ranging from 40 - 90^{o}C with about 10^{o}C increment. Drying material by exposing to warmer temperature (>50^{o}C) caused surface hardening and brittleness and affected its expansion ratio. On the other hand, the material dried at about 30^{o}C, required quite longer time and caused mild fermented flavor whereas, that exposed at 42$\pm$2^{o}C produced the millet which expanded with desirable expansion ratio (Figure 66).

Similar to any other cereal, the rate of dehydration of the millet was also asymptotic, showing loss of moisture rapidly during the initial phase, and a very slow rate of dehydration in the later phase (Figure 67), under experimental conditions. Drying the impacted millet at about 40^{o}C lowered its moisture content from about 40 to 12.3% in about 60 min but further lowering it to 9% moisture content, it required around an additional of 40 min and subsequently to about 8.5%, another 50 min was required.

From the forgoing discussions it is evident that, the yield and most of the quality parameters of the expanded millet are influenced by multiple variables such as the moisture content of the material prior to mechanical impact, the shape factor and the kinetics of drying, the drying temperature being constant. Hence, the suitable variables for preparation of expanded grains with maximum expansion ratio with low bulk density having near spherical shape were optimized. The quality parameters such as expansion ratio and bulk density exert direct influence on the food as well as economic value of the expanded millet; since the expanded cereals are normally sold on the measure of their volume and appearance. The bulk density, which in turn indicates the porosity of the material reveals the lightness of the product and also determines its packaging characteristics. In view of these, the expansion ratio, hardness, bulk density, spherecity and overall acceptability of the product were specifically included for optimizing process parameters for preparation of expanded millet following response surface methodology.

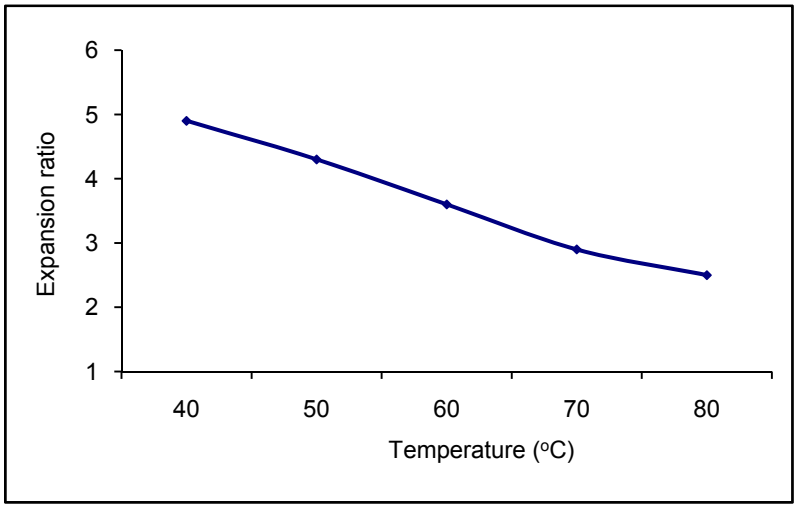


Figure 66. Effect of drying temperature on expansion ratio of decorticated finger millet

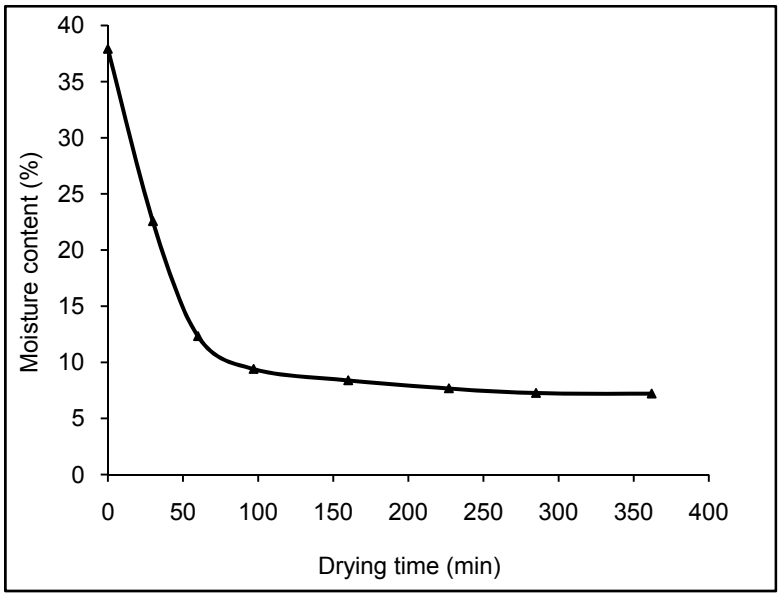


Figure 67. Dehydration curve of decorticated finger millet

2. Response surface methodology (RSM)

In any of the experiments where several factors and interactions of the parameters among them occurs and influence desired responses, RSM is effectively followed not only for optimizing the process variables but also to identify suitable conditions for preparing the product of desired quality characteristics. The RSM is a statistical method that uses quantitative data from an appropriate experimental design to determine and to simultaneously solve multivariate equation. It generally involves an experimental design such as Central Composite Rotatable Design (CCRD) to fit a second order polynomial by a least squares technique (Hunter, 1959). To determine the interrelationship among the test variables and also to describe the combined effect of all the variables in the response, the second ordered polynomial equation as described earlier is used (Rastogi et al., 1998).

2.1. Diagnostic checking of the models

The responses were expansion ratio (Y1), bulk density (Y2), sphericity (Y3), texture (Y4) and the overall acceptability (Y5). The coefficients for the actual functional relations for predicting Yi are presented in Table 43. The insignificant terms were omitted based on Student's t-ratio (Khuri and Cornell, 1987) and the polynomial has been recalculated. The final polynomial, after deletion of all the non-significant terms was reported together with the recalculated coefficient of determination (R2). All the five responses under different combinations as defined in the design were analyzed using the analysis of variance (ANOVA) appropriate to the experimental design. The ANOVA for the data obtained using CCRD is presented in Table 44, and it is evident from that, the sum of squares due to regression (first and second order terms) was found to be significant. The lack of fit was found to be not significant for expansion ratio, sphericity and overall acceptability, but it was significant for bulk density and texture. However, the high values of coefficient of determination (R^2), also suggests that the model is a good fit. R^2 is the proportion of variability in response values explained or accounted for, by the model (Myers, 1971; Montgomery, 1984).

Table 43. Estimated coefficients of the fitted second order polynomial representing the relationship between the responses and the process variables

Coefficients	Expansion Ratio (Y_1)		Bulk density (Y_2)		Sphericity (Y_3)		Hardness (N)(Y_4)		Overall acceptability (Y_5)	
	Original Equation	Recalculated Equation	Original Equation	Recalculated Equation	Original Equation	Recalculated Equation	Original Equation	Recalculated Equation	Original Equation	Recalculated Equation
a_o	3.685	3.628	0.209	0.218	0.959	0.954	13.816	13.816	5.504	5.412
a_1	0.132*	0.132	-0.006		0.003		- 2.595**	-2.595	-0.302	
a_2	-0.348**	-0.348	0.029**	0.029	0.029**	0.029	2.175**	2.175	-0.447**	-0.447
a_3	0.419**	0.419	-0.035**	-0.035	0.002		-4.387**	-4.387	0.716**	0.716
a_{11}	-0.091		0.005		-0.015**	-0.015	1.675*	1.675	-0.054	
a_{22}	0.016		0.007		-0.021**	-0.020	3.034**	3.034	-0.068	
a_{33}	-0.244**	-0.237	0.023**	0.022	-0.006		2.698**	2.698	-0.383*	-0.372
a_{12}	-0.186*	-0.186	0.009		-0.006		2.111*	2.111	-0.738**	-0.738
a_{13}	0.354**	0.354	-0.016**	-0.016	0.004		-4.041**	-4.041	0.908**	0.907
a_{23}	0.199*	0.199	-0.017**	-0.017	-0.003		-2.774*	-2.774	0.593**	0.593
R^2 Values	0.938	0.920	0.960	0911	0.910	0.855	0.933	0.933	0.912	0.866

**Significant at 1% level, *Significant at 5% level

Table 44. Analysis of variance for the fitted second order polynomial model as per CCRD

		Sum of squares				
	df	Expansion Ratio (Y_1)	Bulk density (Y_2)	Sphericity (Y_3)	Hardness (N) (Y_4)	Overall Acceptability (Y_5)
Regression						
First order terms	3	4.292[a]	0.028[a]	0.012[a]	419.485[a]	10.969[a]
Second order terms	6	2.550 [a]	0.013[a]	0.009[a]	463.855[a]	15.878[a]
Total	9	6.842	0.041	0.021	883.340	26.847
Residual						
Lack of fit	5	0.431[b]	0.0019[a]	0.0018[b]	63.389[a]	2.268[b]
Pure error	5	0.017	5.64×10^{-5}	0.0002	0.478	0.320
Total error	10	0.448	0.002	0.002	63.867	2.588
Grand total	19	7.290	0.043	0.024	947.207	29.435

[a] significant at $p \leq 0.001$; [b] Not significant at $p \leq 0.001$

2.2. Responses

The effect of the moisture content, shape factor and drying time on the responses, namely, expansion ratio, bulk density, sphericity, hardness and overall acceptability are presented by the coefficients of second order polynomials (Table 43). A few response surfaces based on these coefficients are shown in Figure 68 (a–e). The response surfaces were selected based on the significant interaction terms between the two variables within the experimental range as indicated in Table 43. Based on the observations of the data and initial optimization of the individual responses, the moisture content of the millet during impacting was kept at the highest level (40%, coded value +1.68) of the design.

A. Effect of shape factor and drying time on the expansion ratio

The shape factor of the grains was found to influence the expansion ratio prominently. The DM having shape factor lower than 0.3 resembled cereal flakes and the expanded millet prepared from that was not spherical. In view of this, the shape factor value of 0.3 was fixed as the lower limit. The expansion ratio was found to be a function of the linear effect of shape factor. As the linear effect ($p \leq 0.01$) was negative, there was a decrease in expansion ratio with an increase in the levels of shape factor for all drying times. The drying time also had a considerable effect on the expansion ratio. Unlike the shape factor, the linear effect of drying time on expansion ratio was positive ($p \leq 0.01$) whereas the quadratic effect ($p \leq 0.01$) was negative, which results in a curvilinear increase in expansion ratio with the drying time for all the levels of shape factor (Figure 68a). It is interesting to note that the interaction between the drying time and the shape factor was also significant (Table 43). At the optimum level of moisture content (40%) and at the maximum drying time (137 min, coded value 1.39) and specific shape factor (0.3, coded value -1.68), the expansion ratio was maximum (5.28). For all the values of shape factor (0.3-1.0, coded values from –1.68 to +1.68), the expansion ratio increased with drying time. At lowest level of drying time (0 min, coded value -1.68), the expansion ratio increased with an increase in shape factor, whereas at the highest level of drying time (150 min, coded value +1.68) the expansion ratio decreased with an increase in shape factor.

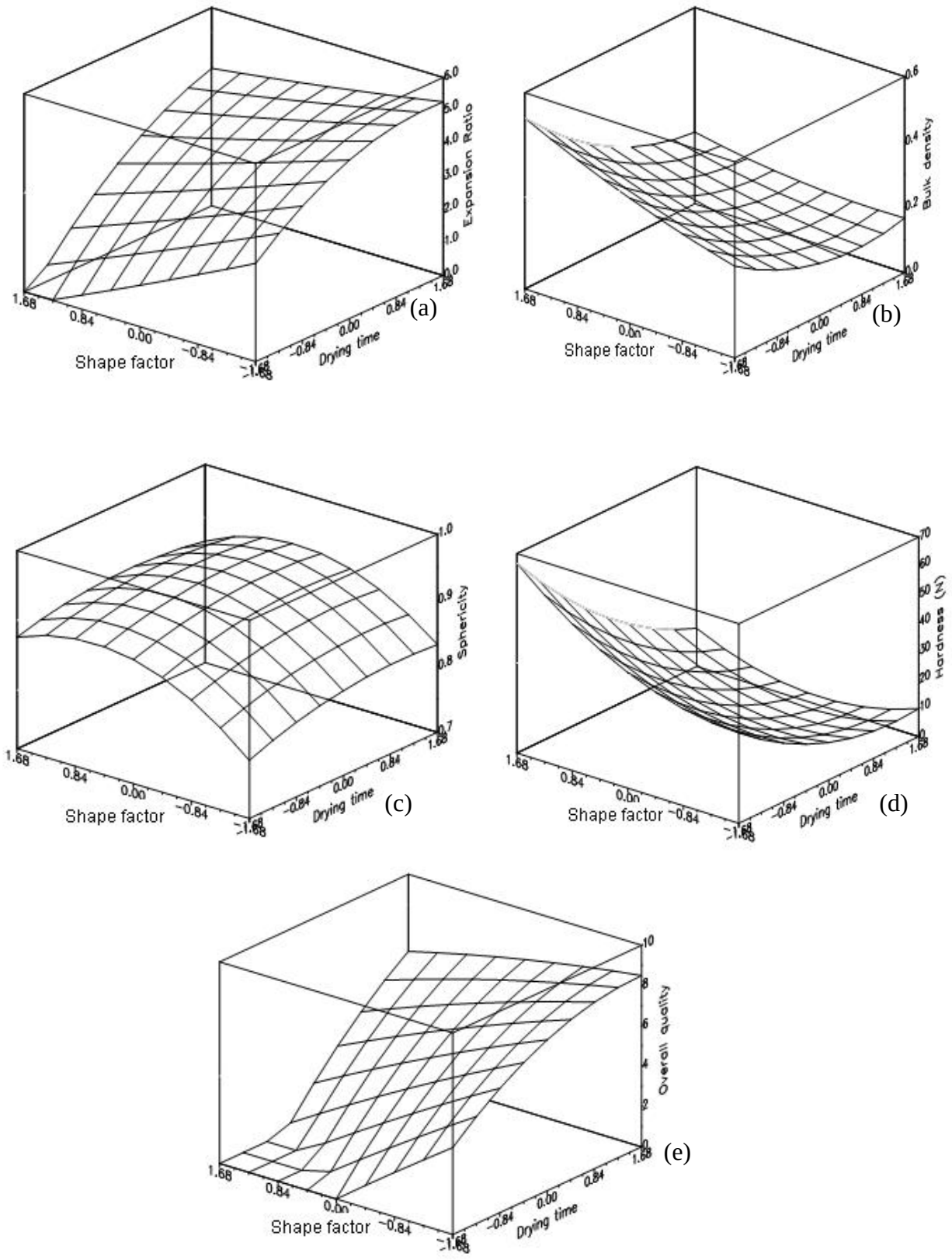


Figure 68. Response surfaces showing the effect of shape factor and drying time on expansion ratio (a), bulk density (b), sphericity (c), hardness (e) and overall quality (e) (For all the experiments moisture content was kept constant at 40%)

B. Effect of shape factor and drying time on bulk density

Bulk density is one of the important physical parameters of cereals and their products, which indicates the compactness or the porosity of the material. It is not only important with respect to the texture of the product but also has relevance to the volume of the packaged material. Similar to puffed products, the expanded products are also generally very light in weight. The linear effect of shape factor was positively related ($p \leq 0.01$) with bulk density whereas the quadratic effect was not significant (Table 43), which resulted in an increase in bulk density with increasing shape factor values for all the levels of drying time (0 to 150, coded value from -1.68 to 1.68, Figure 68b). The drying time showed a marked effect on bulk density with negative linear effect ($p \leq 0.01$) and positive quadratic effect ($p \leq 0.01$). This resulted in a curvilinear decrease in bulk density with an increase in the drying time for all the levels of shape factor (0.3 to 1.0, coded value from -1.68 to 1.68, Figure 68b). The interaction term of shape factor and bulk density was found to be significant (Table 43). The increase in bulk density was higher at lower levels of drying time (0 min, coded level -1.68) as compared to higher levels of drying time (150 min, coded level +1.68). The expanded millet with lowest bulk density (0.15 g/ml) was observed when the drying time was 107 min (coded value 0.74) and shape factor was 0.3 (coded value -1.68) (Figure 68b).

C. Effect of shape factor and drying time on sphericity

For all the levels of drying time (0 to 150, coded value from -1.68 to 1.68), the sphericity increased considerably with increase in shape factor up to a certain level and further, the increase was marginal (Figure 68c). This effect is due to the presence of positive linear term ($p \leq 0.01$) and negative quadratic term ($p \leq 0.01$) of shape factor (Table 43). Similarly, for all the levels of shape factor (0.3 to 1.0, coded value from -1.68 to 1.68), there was no significant increase in sphericity with an increase in drying time, due to the absence of significant linear and quadratic terms of drying time (Table 43). The highest sphericity (0.967) was obtained for the sample with drying time of 75 min (coded value 0.63) and shape factor of 0.74 (coded value 0.43) (Figure 68c). This indicated that, the sphericity was a function of shape factor and the millet impacted to lower degree exhibited higher sphericity values. However, the drying time had

very little influence on sphericity values.

D. Effect of shape factor and drying time on texture

The hardness of the expanded millet was found to be a function of the linear and quadratic effects of drying time. The linear effect ($p \leq 0.01$) is negative, whereas the quadratic effect ($p \leq 0.01$) is positive (Table 43), which results in a parabolic decrease in hardness for all the levels of shape factor (0.3 to 1.0, coded value from -1.68 to 1.68, Figure 68d). The hardness was found to be dependent on the shape factor as its positive linear ($p \leq 0.01$) as well as quadratic ($p \leq 0.01$) effects were significant (Table 43), hence, the overall effect was curvilinear in nature (Figure 68d). At low level of drying time (0 min, coded value -1.68), the hardness increased with increase in the shape factor. Whereas, no marked increase in hardness was observed at maximum level of drying time (150 min, coded level +1.68) with an increase in shape factor. The lowest hardness (2.92 N) was obtained for sample dried for 150 min (coded value +1.68) and impacted to the shape factor 0.84 (coded value -0.18) (Figure 68d). The interaction term for shape factor and drying time was found to be significant ($p \leq 0.05$).

E. Effect of shape factor and drying time on the overall acceptability

The overall acceptability of expanded millet was related to the shape factor of the impacted millet. The linear effect ($p \leq 0.01$) was negative and the quadratic effect was not significant, which resulted in a decrease in the overall acceptability with an increase in the values of shape factor. The drying time had a significant effect on overall acceptability and its linear effect was positive ($p \leq 0.01$) whereas the quadratic effect ($p \leq 0.05$) was negative, which resulted in a curvilinear increase in overall acceptability with the drying time for all the levels of shape factor (Figure 68e). The interaction term of shape factor and drying time was also found to be significant ($p \leq 0.05$, Table 43). The maximum score for the overall quality (9.00) was obtained for the longer drying time of 150 min (coded value +1.68) and lowest level of shape factor of 0.30 (coded value –1.68) (Figure 68e).

2.3. Optimization

In order to deduce the workable optimum conditions, the graphical optimization technique was adopted by fixing one variable, that is, initial moisture content at 40% (coded value +1.68) as predetermined optimum condition. This drastically reduced the amount of time required for investigation of multifactor and the multi-response systems. It also provided comprehensive and informative insight of the system, which leads to process optimization rapidly. The specifications necessary for each response were first set and these were also served as constraints for optimization (Floros and Chinnan, 1988). An acceptable compromise was made following the criteria for the expansion ratio (Y_1) ≥ 4.6, bulk density (Y_2) ≤ 0.17 g/cm^3, sphericity (Y_3) ≥ 0.90, hardness (Y_4) ≤ 5.0 N and overall acceptability (Y_5) ≥ 7.2. The contour plots for the response were generated as shown in Figure 69(a-e). The contour plots were superimposed and the regions that best satisfied all the constraints were identified as the optimum conditions. Superimposed contour plots for each response are shown in Figure 70.

A combination of optimum working conditions (A, B, C and D) selected from the shaded area of the superimposed contour plots, is presented in Table 45. The overlapped area between the horizontal and vertical bars can be recommended as practical optimum zone [shape factor from 0.52 to 0.58 (coded level –0.32 to –0.64), drying time from 135.7 to 150 min (coded level 1.21 to 1.68)] (Figure 70).

2.4. Verification of results

The suitability of the model equations for predicting the optimum response values was tested using the recommended optimum conditions, determined by a RSM optimization approach, which was also used to validate experimental and predicted values of the responses using model equations. It was found that there exists a complex interaction between the variables such as moisture content, drying time and shape factor. The DM at moisture content 40% impacted to shape factor ranging from 0.52 to 0.58 followed by drying for 136 to 150 min at 40$\pm$1^{o}C could be recommended as optimum as well as practical conditions for the range of the variables studied.

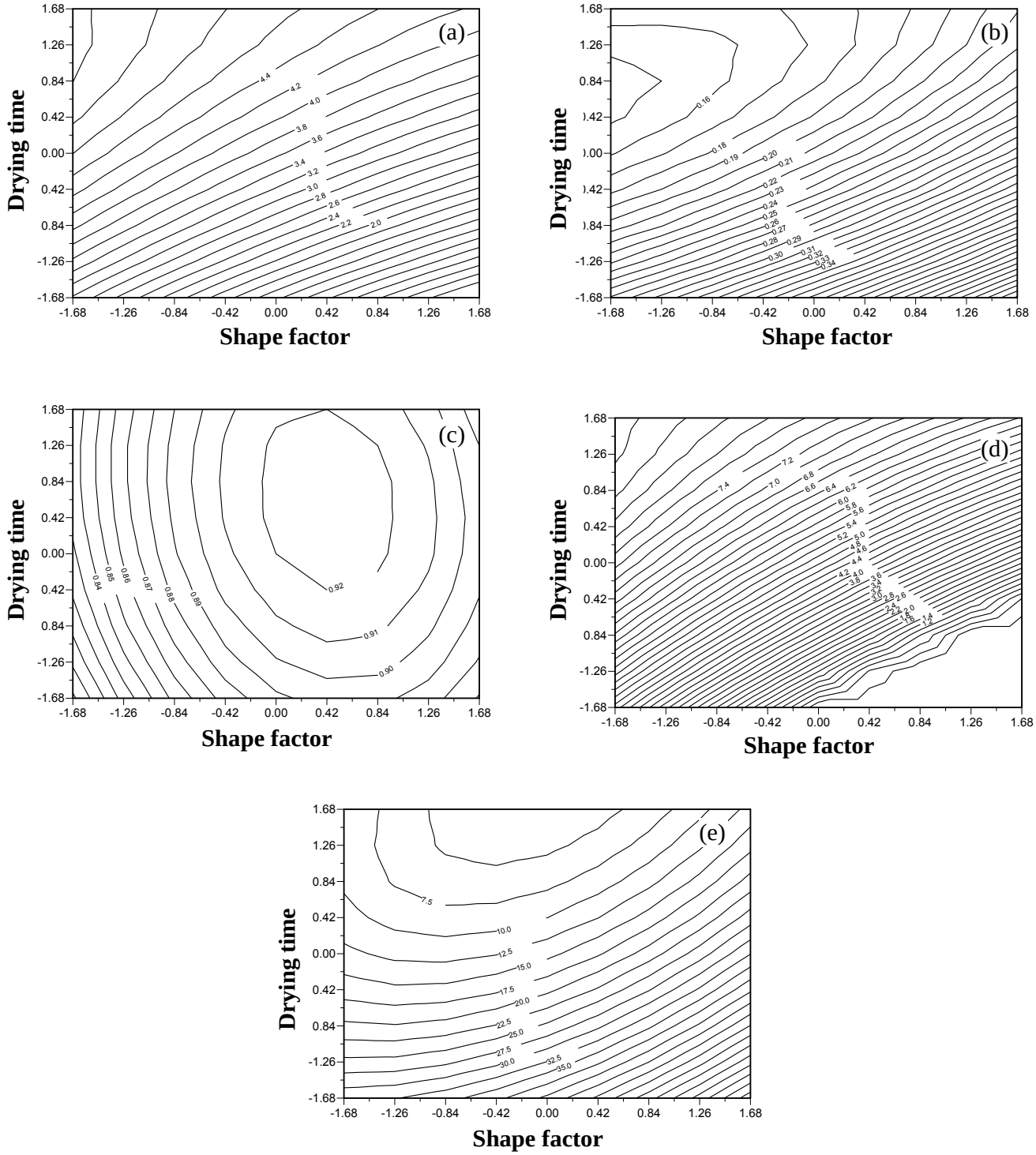


Figure 69. Contour plots showing the effect of shape factor and drying time on expansion ratio (a), bulk density (b), sphericity (c), hardness (d) and overall quality (e) (For all the experiments moisture content was kept constant at 40%).

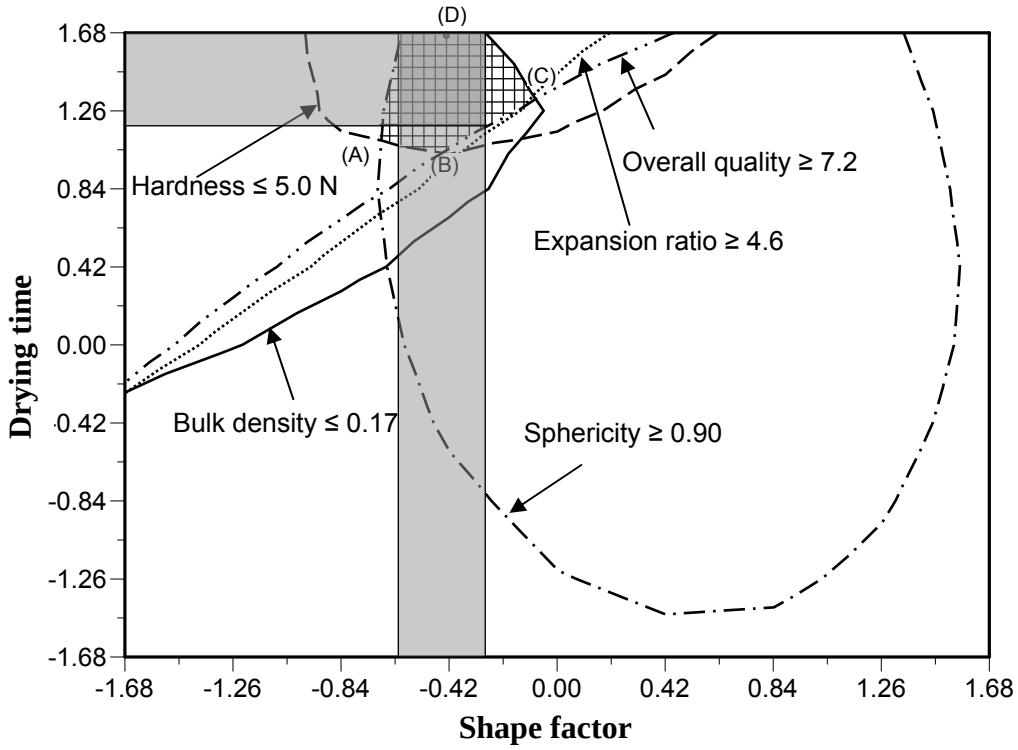


Figure 70. Superimposed contour plots showing the overlapping shaded area (expansion ratio ≥ 4.6, bulk density ≤ 0.17 g/ml, sphericity ≥ 0.90, hardness ≤ 5.0 N and overall quality ≥ 7.2)

Table 45. Feasible and optimum conditions and predicted and experimental values of responses at optimum conditions

Optimum condition	Conditions A		Conditions B		Conditions C		Conditions D	
	Coded	Actual	Coded	Actual	Coded	Actual	Coded	Actual
Moisture (X_1)	1.68	40	1.68	40	1.68	40	1.68	40
Shape factor (X_2)	-0.70	0.50	-0.47	0.55	-0.10	0.63	-0.45	0.55
Drying time (X_3)	1.09	126.57	1.01	120.49	1.34	144.78	1.68	170.59
Responses	Pred. value	Exp. value[a]	Pred. value	Exp. value[a]	Pred. value	Exp. value[a]	Pred. value	Exp. value[a]
Expansion Ratio (Y_1)	4.78	4.70	4.64	4.55	4.61	4.58	4.82	4.77
Bulk density (Y_2)	0.16	0.15	0.16	0.15	0.17	0.16	0.17	0.16
Sphericity (Y_3)	0.90	0.91	0.91	0.90	0.92	0.91	0.91	0.90
Hardness (N) (Y_4)	4.79	4.50	4.93	4.85	3.89	3.79	3.15	3.25
Overall acceptability (Y_5)	7.53	7.40	7.21	7.12	7.25	7.15	7.83	7.60

[a] *Mean value of five determinations, Conditions A, B, C, D and E have been indicated in Figure 73.*

Pred.; predicted
Exp.; experimental

The expanded millet obtained following these conditions will have expansion ratio ≥ 4.6 with bulk density ≤ 0.17 g/ml, sphericity ≥ 0.90, hardness/texture ≤ 5.0 N and overall acceptability ≥ 7.2.

The millet prepared on semi-pilot scale following these conditions was used for determination of the functional properties and also for its suitability for snacks as well as ingredient for multigrain health foods. The process features indicating various unit operations for the preparation of expanded millet is shown in Figure 71.

3. Physicochemical characteristics

3.1. Physical properties

A. Shape, size and appearance

The EM kernels were of near spherical shape with pearly look and mostly translucent (Figure 72). However, a small portion of the expanded kernel adjacent to the embryo was opaque.

B. Color

The EM was light cream color and it differed distinctly from the mild red color of the decorticated millet. The diameter of the individual kernels was 3.56 mm and appeared to be made up of two concentric spheres but differed significantly from the native millet. It was highly attractive and appealing as compared to native as well as the decorticated millet. The bright color of the EM is evident from the slightly lower ΔE value (36.24) as compared to the DM (39.63). The lightness, redness and yellowness values for EM were 55.96, 1.64 and 10.59, respectively as against 53.32, 3.82 and 12.87 of the DM. This indicates that, the redness of the DM decreased almost by 50% and the yellowness decreased slightly on expansion. However, the meal from expanded millet was whiter than the expanded grains with ΔE values of 23.76 (Table 46). Interestingly, the meal from the EM exhibited slightly higher values for redness (1.79), yellowness (12.51) and ΔE (23.76) compared to that of the meal from DM indicating that, the meal from EM is slightly yellowish in color. During expansion, the gelatinized starch undergoes changes from its normal granular state to thin layers creating vacuoles in between the layers.

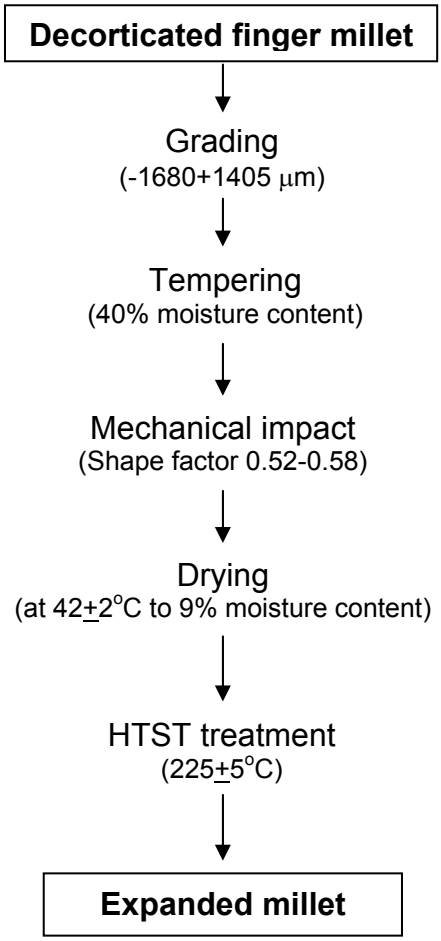


Figure 71. Flow chart for the preparation of expanded finger millet

Figure 72. Photograph of expanded finger millet (about 2 fold magnification)

Table 46. Color indices of decorticated and expanded finger millet grain and the whole meal

Colour	Decorticated		Expanded	
	Grains	Whole meal	Grains	Whole meal
L*	53.32±0.2	76.31±0.2	55.96±0.2	70.29±0.2
a*	3.82±0.06	1.23±0.04	1.64±0.02	1.79±0.02
b*	12.87±0.06	10.82±0.02	10.59±0.04	12.51±0.04
ΔE	39.63±0.2	17.76±0.2	36.24±0.2	23.76±0.2

Probably, this imparts the translucent appearance. However, on pulverization, the inter-space between the layers largely disappears and the meal appears opaque. Moreover, during HTST treatment, the surface of the expanded grains that comes in contact with the hot salt turns slightly yellowish. The light yellowish color of the product also permits coating the same with different spices and condiments including different food colors if desired to improve its consumer appeal.

C. Texture

The texture of the EM measured in terms of hardness presented in Figure 73, shows irregular force-deformation curve with large number of smaller peaks. This reveals that, the product is of crisp, fragile as well as friable texture. The first peak force, the maximum force, number of major peaks and the initial slope of the linear portion of the curve were determined as per Murthy and Bhattacharya (1998). The EM was less hygroscopic as it did not turn soggy even though it was exposed to atmospheric conditions during the measurements. On application of an external force, a typical cracking sound emanated indicating the crispness of the product. The force deformation curve showed two different zones, a sharp initial peak followed by a number of multiple peaks. The initial peak probably represents the resistance offered by peripheral layer and the multiple peaks represent the resistance offered by the inner layer of the endosperm. During expansion, the embryo and the scutellum do not expand efficiently. These factors contribute for the total hardness of the product. The initial slope of the force deformation curve (FDC), conventionally called as firmness, is the resistance offered by the whole grain (Mazumder et al., 2007). The product exhibited very low initial peak and slope values (2.14 N and 8.53 N/s). The hardness of the expanded product (4N) was several folds lower than the decorticated millet (160N) as well as native millet (36N). The low bulk density (0.14 g/ml) values of the product falls in line with the crispness as well as the hardness of the EM.

The textural features of the expanded millet differed considerably from the native as well as the HTM. As explained earlier, the FDC of NM shows the fragile nature of its endosperm, whereas, that of HTM exhibited hard and

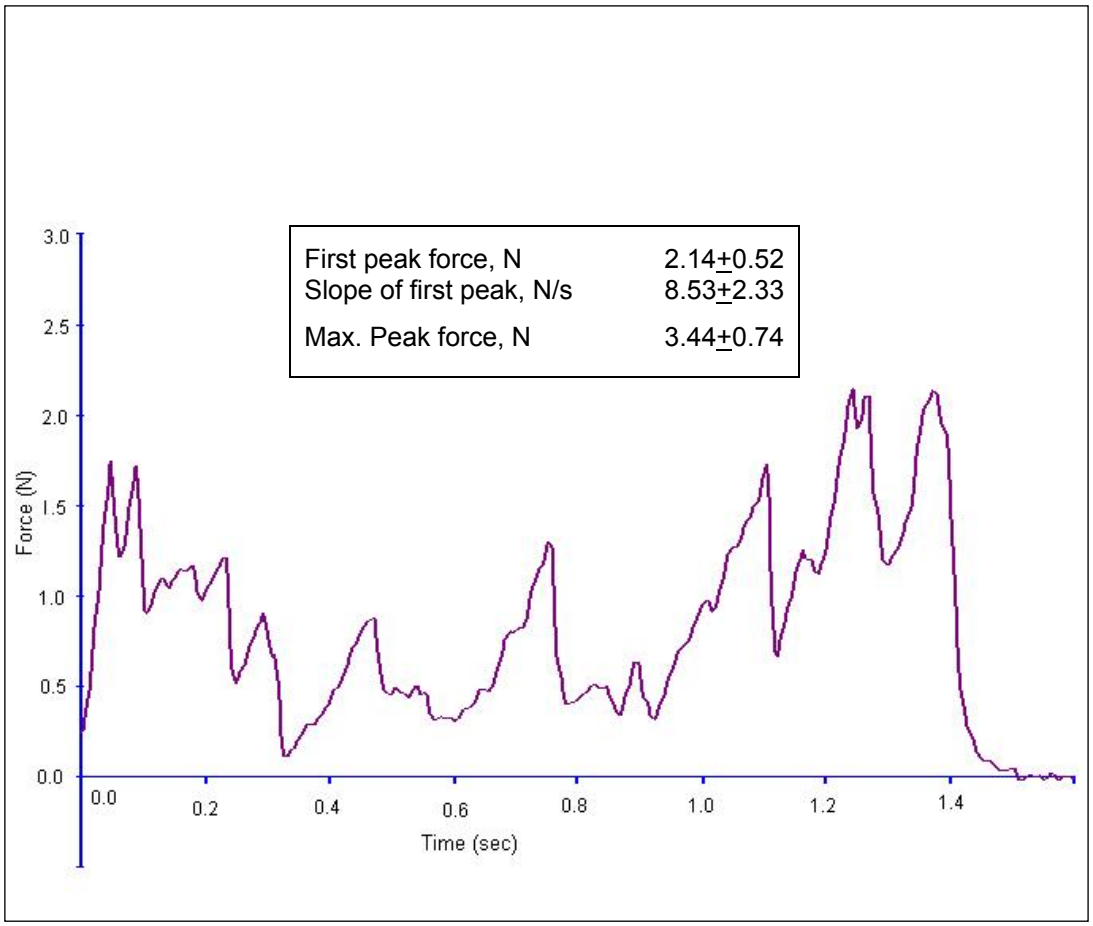


Figure 73. A typical force deformation curve for texture of expanded finger millet

homogeneous structure. However, the FDC of EM depicts the crisp and highly porous texture of the product which crumbles easily offering very little resistance to external force. These specific features reveal the highly desirable texture for use of the expanded millet for snack and such other products.

The texture with special reference to crispness is one of the important quality characteristics of the cereal snacks. In the case of popped, expanded and extrusion cooked products, the texture is normally recorded by the hardness measured in terms of force required to compress or crumble the product. Expanded rice exhibits a matrix of void spaces with variable size (Chandrasekhar and Chattopadhyay, 1990), but in the case of expanded finger millet, the major portion appears like a soap bubble made up of thin concentric layers. This may be due to the pre-treatment given to the decorticated millet in terms of impacting and loosening the internal texture or could be the inherent property of the millet.

3.2. Nutrient composition

The EM contained 4.7, 0.74, 11 g% and 190 mg% of protein, ether extractives, dietary fiber and calcium. These values were almost comparable to protein, ether extractives, dietary fiber and calcium contents of DM namely, 4.7, 0.77, 10 g% and 190 mg% respectively (Table 47). This shows that HTST treatment to DM did not cause major changes in its composition. A slightly higher percentage of dietary fiber in EM compared to DM may be due to the formation of resistant starch during the HTST treatment. The EM still remains as a calcium rich cereal and hence, there exists potential for its utilization as a calcium rich snack or as a breakfast cereal and also as a cereal base in supplementary food formulations.

The carbohydrate digestibility of the expanded millet was over 99% on the starch basis and the digestion was also very rapid. The high percentage of digestibility and the quick digestion indicates that the expansion process has reduced the complex nature of the millet carbohydrates. It also shows the starch has not undergone extensive retrogradation.

Table 47. Physicochemical properties of decorticated and expanded finger millet

Parameter	Decorticated	Expanded
Bulk density (g/ml)		
Grains	0.796±0.01	0.141±0.01
Flour	0.767±0.01	0.5±0.01
Expansion ratio	-	5.64±0.1
Expansion volume (ml)	-	7.1±0.1
Viscosity 10% slurry (cP)		
Cold paste	22±0.7	110±0.7
Cooked paste	463±2	726±1
Solubility (g%)		
30 ^{o}C	2.9±0.1	3.4±0.1
95 ^{o}C	3.5±0.1	3.8±0.1
Swelling (g%)		
30 ^{o}C	306±1	452±1
95 ^{o}C	496±2	486±1
Water absorption capacity (%)		
Grains as such	-	152±1
Flour	242±1	240±1
Oil absorption capacity (%)		
Grains as such	-	461±1
Flour	167±1	507±1
Moisture (g%)	10.46±0.07	10±0.07
Ether extractives (g%)	0.77±0.01	0.74±0.02
Protein (g%)	4.43±0.02	4.69±0.02
Dietary Fiber (g%)		
Insoluble	7.8±0.06	9.5±0.05
Soluble	2.3±0.01	1.8±0.01
Total	10.1±0.1	11.3±0.1
Minerals (mg%)	1.00±0.03	1.12±0.02
Calcium (mg%)	190±2	190±1
Carbohydrate digestibility (%)	78±1	99±1
Protein digestibility (%)	91±1	97±1

Normally, the starch undergoes retrogradation during hydrothermal treatment of cereals but the extent of its formation in finger millet is very low (Mangala et al., 1999).

The carbohydrates elution profile through Sepharose CL-2B of the expanded millet indicated the presence of two main fractions, namely Fraction I and Fraction II (Figure 74). Fraction I was the initial major peak, which constituted about 49% of the carbohydrates while, the Fraction II represented the second peak with 51% of the total carbohydrates. The broad nature of the II peak could be due to thermal degradation of the starch into lower molecular weight dextrins.

The fatty acid composition of the expanded millet is presented in Table 48 and a typical elution profile in Figure 75. Oleic acid (62%) was the major fatty acid detected followed by palmitic acid (19%), and Linoleic acid formed a minor component (2%). There was substantial difference between the fatty acid profiles of the EM and DM. The oleic acid content increased from 50 to 62% but the palmitic and linoleic acid contents decreased from 26 to 19% and 20 to 2%, respectively on expansion of the DM. This shows that the heat treatment substantially reduces the unsaturated fatty acids mainly linoleic acid. This may probably due to breakdown of the double bonds, besides, complexing of the amylose preferentially with the unsaturated fatty acids during HTST treatment (Mikus et al., 1946). Karkalas et al. (1995) also reported formation of the amylose-lipid complex in the native granules with linoleic acid whereas, Borras et al. (2006) reported that, the complexing of amylose with lipid indicate the higher expansion ratio in case of pop corn.

3.3. Functional properties

The solubility index and swelling power of the EM were typical to the expanded cereals. At 30^{o}C, about 3.4% of the EM was soluble and it almost remained constant even at 97^{o}C. The swelling power at 30^{o}C (452%) and 97^{o}C (486%) were also comparable. The solubility index of EM was slightly higher than that of DM at both the temperature but the swelling power of EM at 30^{o}C was significantly higher (452%) than the DM (306%).

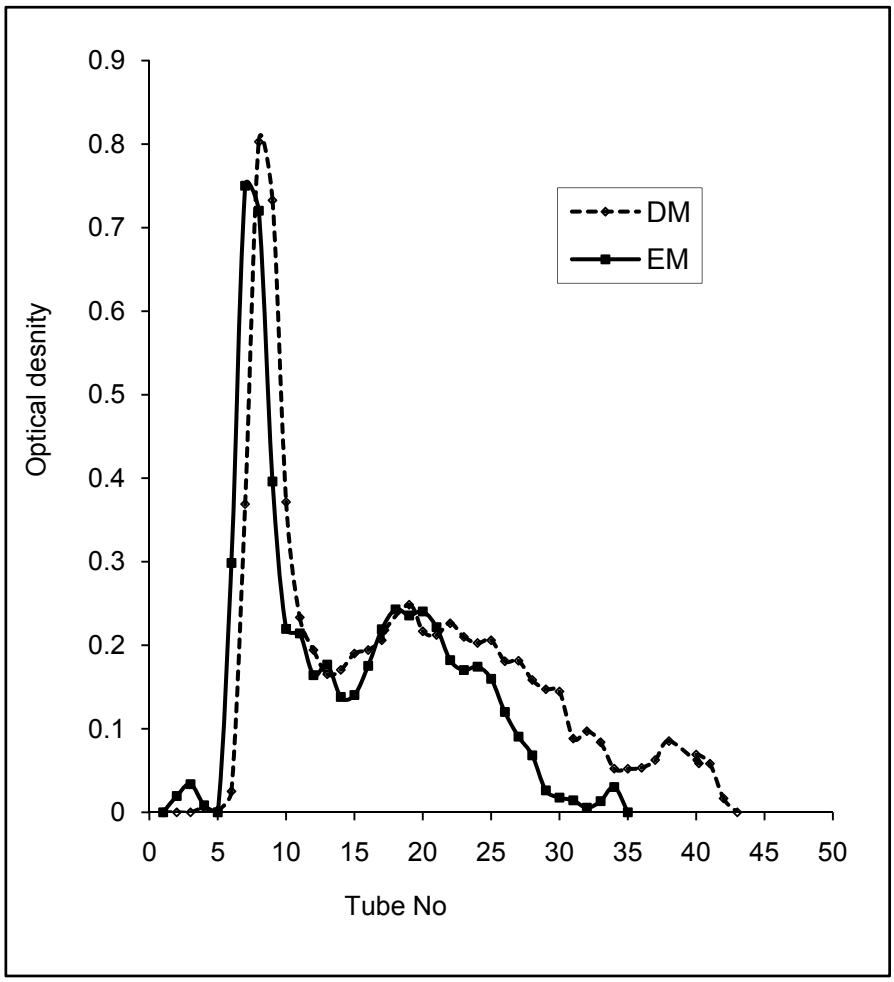


Figure 74. Gel permeation chromatograms for carbohydrates of decorticated and expanded finger millet

Table 48. Fatty acids composition of expanded finger millet

Fatty acid	Decorticated	Expanded
Palmitic (16:0)	26.18±0.03	19.37±0.02
Stearic (18:0)	0.12±0.02	0.40±0.02
Oleic (18:1)	50.43±0.40	61.68±0.40
Linoleic (18:2)	20.26±0.20	2.14±0.10
Linolenic (18:3)	2.60±0.10	-
Aracheodoneic (20:0)		1.009±0.10

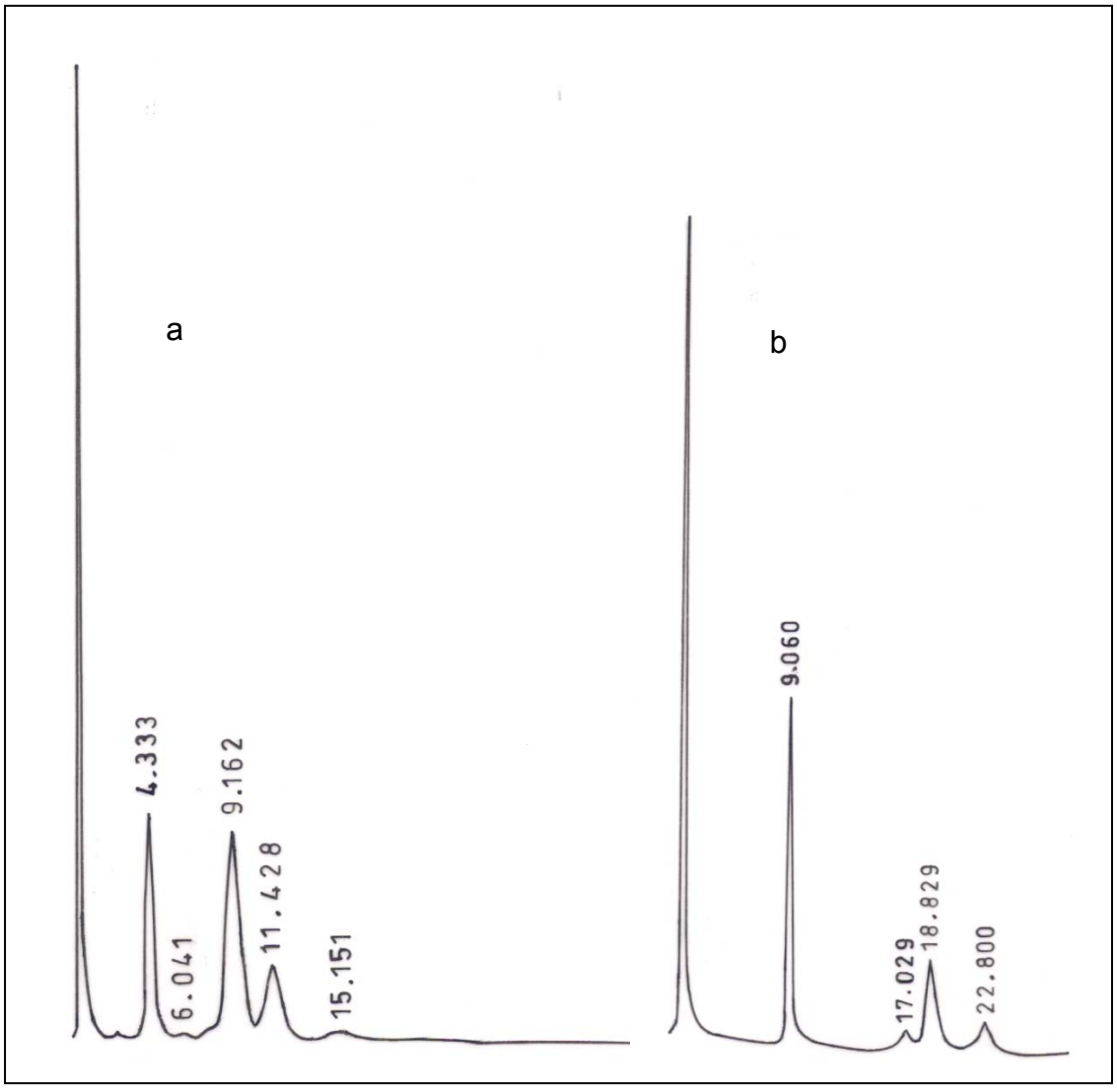


Figure 75. Fatty acids profiles of decorticated (a) and expanded (b) finger millet

However, the swelling powers at 95^{o}C for both the samples were comparable. Higher swelling power indicates its high water absorption capacity and its suitability for use as low calorie food. The increase in solubility on expansion may be due to formation of low molecular weight carbohydrates as a result of the thermal degradation during the HTST treatment whereas, the higher values for the swelling power could be due to high porosity of the matrix formed by gelatinisation of starch during expansion which facilitates absorption of water and swelling of the endosperm constituents.

The water absorption index value for the EM grains was 152% whereas of its flour was 240%. These properties of the millet flour may be gainfully utilized in improving the texture as well as shelf-life of bread and such other products. The product may preferentially absorb the free water in the bread released during the staling and may keep it soft and enhances its storage life (Mariotti, et al., 2006).

Similar to water absorption capacity, the oil absorption capacity of the EM grains (461%) and its meal (507%) was considerably higher than that of the decorticated millet. This may be due to the porous nature of the product and also due to the presence of void spaces and air cavities formed during expansion of the kernel (Table 47).

The viscograms of the EM (cold and the cooked paste viscosity) at 10% slurry concentration determined in both Synchro-Lectric viscometer and the Brabender visoamylograph are presented in Table 49 and also in Figure 76. Significant cold paste viscosity (110 cP) was observed revealing the presence of high proportion of pregelatinized starch in the EM. Slight increase in viscosity observed at about 46^{o}C could be due to the absorbance of water by the NSP constituents of the EM and also could be due to the dextrinization of the starch (Table 49), but the negligible difference between the total set back and peak viscosity clearly indicated that the degree of retrogradation of starch is very low. This also confirms the breakdown of high molecular weight starch to lower molecular weight dextrins. The pregelatinized nature of the EM indicates that the product is of ready-to-eat nature, especially suitable as snacks, supplementary foods and also as thickner in beverage formulations.

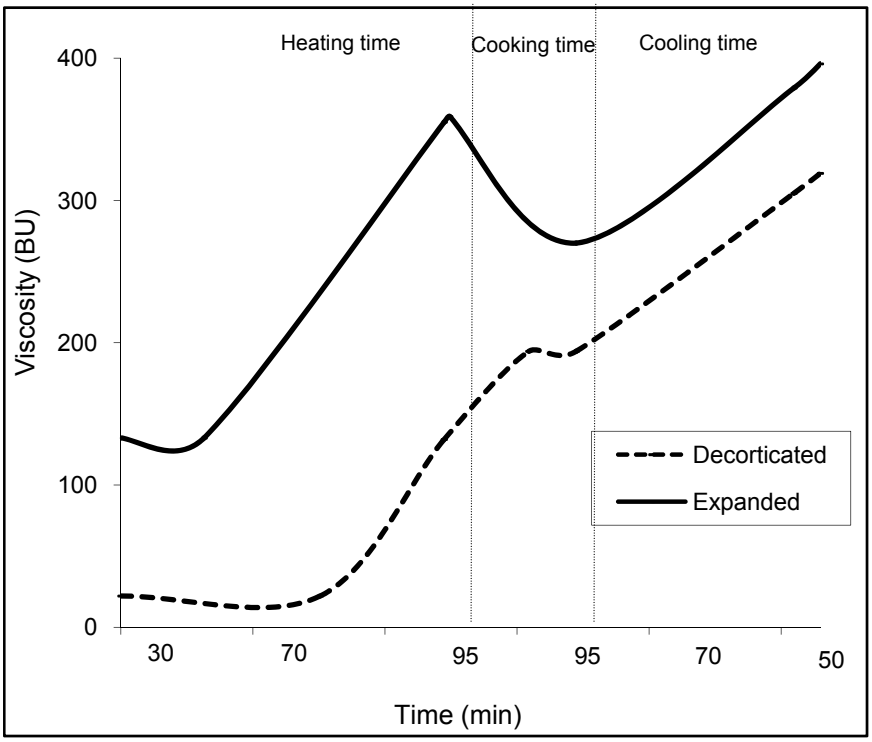


Figure 76. Pasting profiles of decorticated and expanded finger millet

Table 49. Pasting characteristics of decorticated and expanded finger millet*

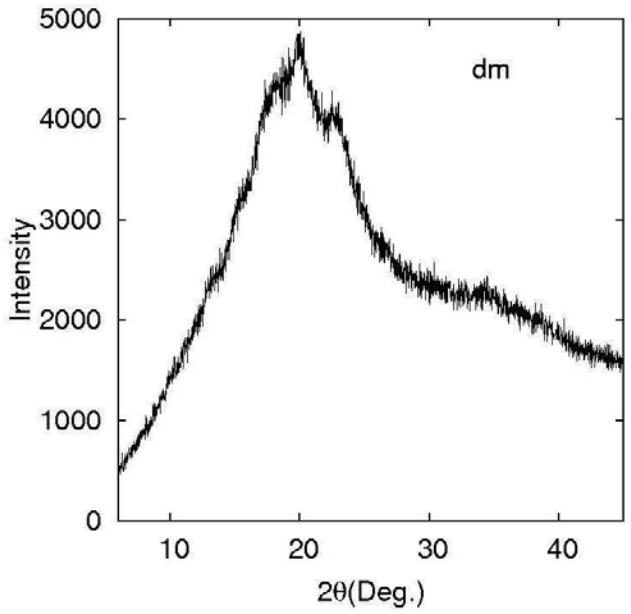
Parameter	Decorticated	Expanded
Peak viscosity (BU)	194	359
Trough viscosity (BU)	194	270
Breakdown (BU)	319	88
Setback (BU)	0	106
Final viscosity (BU)	109	396
Pasting temperature (^{o}C)	69.3	46.1

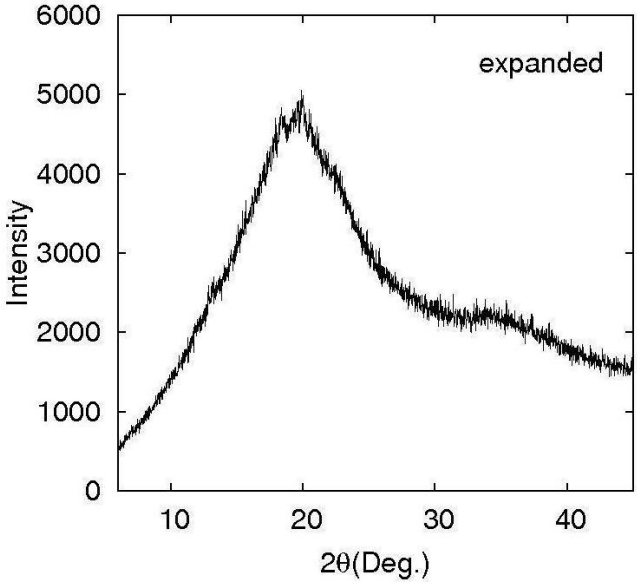
**average of two independent determinations*

The X-ray diffractogram presented in Figure 77, clearly shows that the crystalline features of the DM did not change drastically due to the HTST treatment. However, a slight increase in the microstructural parameters such as the number of unit cells and crystallite size was observed in the EM compared to the DM. This may be due to transformation of the endosperm from a homogeneous mass into an orderly network of honeycomb structure due to the HTST treatment.

3.4. Scanning electron microscopy

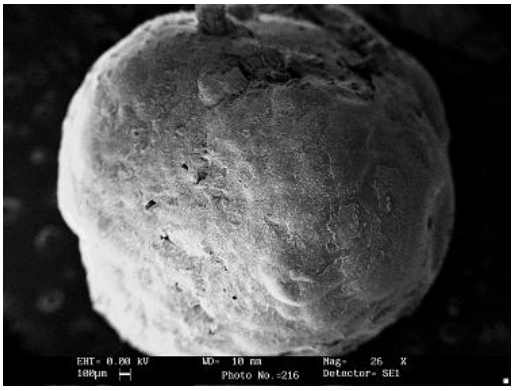
The scanning electron photomicrographs of the EM (Figure 78) depict the surface topography of the expanded grain and also the transverse sections representing two halves. The topography of the expanded grain appeared like a bulged sphere (Figure 78a). Its magnified (3 KX) image (Figure 78b) reveals that the surface of the expanded grain contains uneven ridges and furrows even though, it appeared smooth to naked eyes. But interestingly, the transverse section of the grain (Figure 78c) exhibits a large air vacuole or cavity inside, covering almost 80% of the total kernel size. This is probably because, the EM is made up of a thin starchy film similar to soap bubble, surround by outer layers in the form of concentric sphere, cross linked by a matrix of several air cavities of irregular size. The matrix of air cavities is prominent towards the embryo (Figure 78d). The size of this air cavity is proportional to the expansion ratio of the millet. This may be due to the pretreatment given to the gelatinized starch, which explodes into a thin film creating a big vacuole inside the grain during HTST treatment. This typical phenomenon is not reported in case of expanded rice wherein, the structure is made up of regular or irregular matrix of void spaces (Chandrasekhar and Chattopadhyay, 1990). It may be noted that the nature of millet starch differs from that of rice starch with respect to some of its physicochemical properties and molecular organization (Mohan et al., 2005).



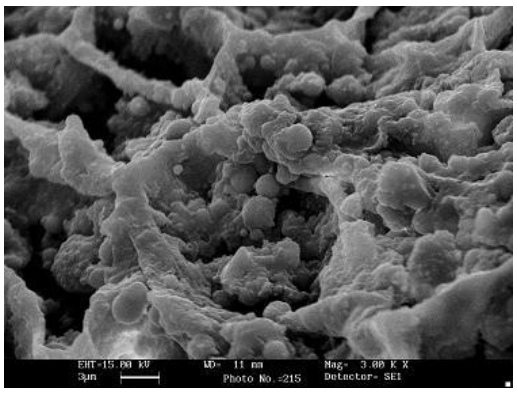


Parameter	Decorticated	Expanded
2θ in Deg	19.81	19.46
'd' in Å	4.48	4.56
<N>	1.78	1.87
P	1.39	1.46
g' (%)	0.10	0.10
Δ (%)	2.51	2.36
D = N.d in Å	7.97	8.52

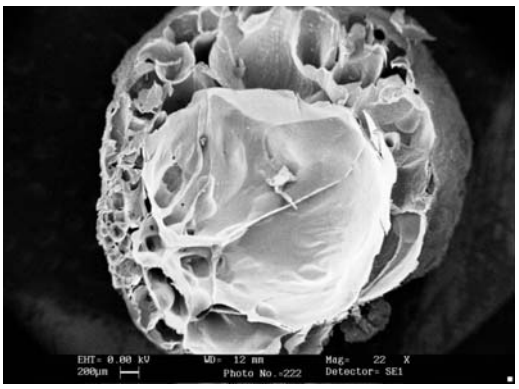
Figure 77. X- ray diffractograms of decorticated and expanded finger millet



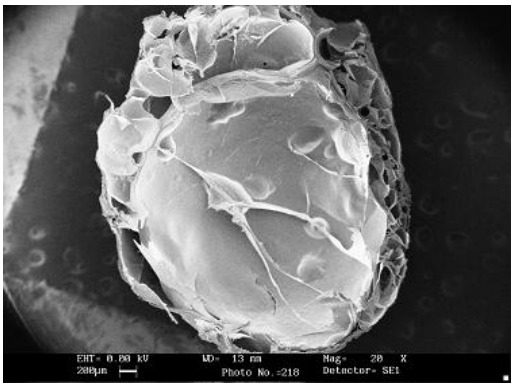
a. Expanded kernel (26 X)



b. Surface (3.00 KX)



c. Transverse section - opaque portion (22 X)



d. Transverse section - transparent portion (20 X)

Figure 78. Scanning electron photomicrographs of expanded finger millet

SUMMARY AND CONCLUSIONS

The decorticated millet was further processed to prepare expanded millet. The expansion characteristics of the decorticated millet were mainly influenced by its moisture content and the temperature of heat transfer medium. However, loosening the endosperm rigidity slightly by mechanical impact to the kernel enhanced its expansion ratio substantially. The optimum conditions for preparation of well expanded millet (nearly 4.5 expansion ratio) were found to be; equilibrating the DM to 40% moisture content, flattening to shape factor ranging from 0.52 to 0.58, drying to moisture content of 9$\pm$1% and subjecting it to high temperature short time treatment at 225$\pm$5^{o}C. The factors influencing the expansion characteristics were also verified by response surface methodology.

The expanded millet is a ready-to-eat product with the bulk density, sphericity, hardness and overall acceptability values of 0.17 g/ml, 0.90, 5.0 N and 7.2, respectively. The nutrient profile of the expanded millet was comparable to that of the decorticated millet, indicating very little changes in the major nutrient contents during the processing. The carbohydrate digestibility of the expanded millet was significantly higher than that of the native and the decorticated millet. The microscopic examination of the expanded millet indicated the presence of two concentric spheres with an air vacuole inside similar to a thin soap bubble.

In conclusion it may be stated that, slightly loosening the endosperm rigidity of the decorticated millet by mechanical impact significantly improves its expansion characteristics. The expanded millet is a novel ready-to-eat cereal and can be coated to prepare either sweet or savory snacks and can be used as a breakfast cereal and also for the preparation of supplementary foods and health bars.

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