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HEAT-MOISTURE TREATMENT OF FOXTAIL MILLET STARCH: EFFECT ON PASTING, TEXTURAL AND RHEOLOGICAL PROPERTIES

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ABSTRACT

The impact of heat-moisture treatment carried out at moisture content basis of 20%, 25%, and 30% on the physicochemical, textural, pasting and rheological characteristics of foxtail millet starch was evaluated. The swelling capacity and solubility index of modified starches accelerated with temperature but decreased significantly ($p \leq 0.05$) with increased moisture percent. The decreased swelling capacity and solubility could be caused by the reduced stability of granules arising due to the disentanglement of double helices in the crystalline region of the starch granules. The heat-moisture treated foxtail millet starch depicted a decrease in the birefringence intensity at the granular centre and remained unaltered at the periphery. The reorientation of molecules of heat-moisture treated starches resulted in a significant ($p \leq 0.05$) decrease in peak viscosity, breakdown, and final viscosity. The significant ($p \leq 0.05$) increase in the gel hardness was observed for HMT20 as comparison to native starch. Dynamic rheological properties of the native and modified foxtail millet starches revealed the fragile gel structure. The increase in loss tangent of paste resulted in the gummy nature of starches.

1. Introduction

Foxtail millet is receiving recognition due to its excellent nutritious content, more adaptability to the environment, and good health benefits. It belongs to family Poaceae and genus Setaria. Foxtail millet is underutilized and drought tolerant crop. The foxtail millet grain contains starch, protein, lipids, dietary fiber, and minerals. Starch is the major carbohydrate present in the millet grain and the amount of amylose and amylopectin is responsible for the production and quality of the millet-based products (Sharma and Niranjan, 2018). Some studies found that changes in the food quality i.e. texture depend on the kind of starch in preference to the quantity of starch (Da Mota *et al*., 2000).

The physicochemical and functional properties as well as liable modifications of starch depend upon the amount of amylose and amylopectin and their association within starch molecules. Despite the wide usage of starch in food and other non-food applications, native starch had some flaws which limited its commercial use (Hoover, 2010). Native starches have some poor functionality like thermal properties, unstable texture, poor stability, poor heating, and cooling stability, shear during processing. Therefore, it is necessary to modify native starch to overcome all these flaws and to intensify its properties to meet current technological advancements (Zavareze and Dias, 2011). The natural form of starch is often modified with the aid of physical, enzymatic, and chemical methods.

Heat-moisture treatment (HMT) is the physical method commonly used to enhance the physicochemical characteristics of native starch. HMT brings out the physicochemical changes in starch by disintegrating the crystalline structure

of starch and promoting the interaction between the starch chain in the amorphous and crystalline zone (Zheng *et al*., 2018). The moisture content, heating time, the temperature throughout the treatment, and arrangement of amylopectin and amylose chains in native starch molecules determine the magnitude of changes that occurs during HMT. Several studies have been found on heat moisture treated starches of various crops like potato (Colussi *et al*., 2020), wheat (Li *et al*., 2019), pearl millet (Sharma *et al*., 2015), and proso millet (Zheng *et al*., 2019). However, there is no study on the effect of HMT at different moisture levels on the physicochemical and rheological characteristics of foxtail millet starch. Hence, the goal of this study was to analyze the impact of heat-moisture treatment at different moisture levels (20-30%) on the physicochemical, textural, pasting, and rheological characteristics of foxtail millet starch. The knowledge of the influence of heat moisture treatment on the functional and rheological characteristics of foxtail millet starch can prove useful for the application of foxtail millet starch for the formulation of novel processed foods.

2. Materials and methods

2.1. Starch extraction from foxtail millet

Commercial foxtail millet grains were obtained from a local market, Haryana (India). The grains were ground to obtain flour using laboratory mill (Milcent mill). The starch from foxtail millet was extracted according to the procedure of Balasubramanian *et al*. (2014) with slight changes. The millet flour was soaked in NaOH (0.5%, 1:6 w/v) for 60 min with regular shaking and centrifuged (Sigma 3-18KS, Germany) at 3000 rpm. The supernatant was decanted; the sediment was re-dissolved in distilled water and washed again and again to obtain the white residue. Then pH of the slurry was set using HCl (0.1 N) to 7.0 and dried in an air oven (at 50 °C). The dried starch was ground, sieved from 100 µm sieve, and packed in an airtight bag till further used.

2.2. Heat-moisture treatment of foxtail millet starch

The foxtail millet starch was modified using the procedure reported by Sun *et al.* (2014). The moisture level of foxtail millet starch was equilibrated to 20, 25, and 30 %. The starch was heated for 8 hours at 110°C in an oven and dried at 40°C. The samples were then grounded and screened through a sieve of pore size 100 µm, then stored in airtight pouches till further analysis.

2.3. Chemical analysis

Native foxtail millet starch was analyzed for chemical analysis i.e., moisture, fat, protein, ash, and crude fiber using the standard AACC method (2000).

2.4. Physicochemical properties

2.4.1. Water binding, oil binding capacity, least gelation concentration and bulk density

The water binding and oil binding capacity of starch samples were measured by applying the procedure described by Sosulski *et al*. (1976). The LGC of starch samples was evaluated by using the procedure of Coffman and Garcia (1977). The bulk density of native and HMT starch samples was determined using the procedure of Owalabi *et al*. (2010).

2.4.2. Swelling capacity and solubility index

The swelling capacity and solubility of starch extracted from foxtail millet were measured by the procedure of Sosulski *et al*. (1976) with slight changes. The starch sample (0.5 g) was slightly mixed with distilled water (25 ml) and the suspension was heated at varying temperature at 55°C, 65°C, 75°C, 85˚C, and 95°C for 15 min in a shaking water bath. Then removed the tubes from the water bath, centrifuged (Sigma 3-18KS, Germany) the paste for 10 min at 3000× g, and then poured the supernatant in a petri plate. The weight of sediment was then recorded and the supernatant was dried for 3 h at 105° C. Swelling capacity and solubility were measured as follows:

$$\text{Swelling capacity (g/g)} = \frac{\text{Weight of swollen granules}}{\text{Dry weight of a sample}} \quad (1)$$

$$\text{Solubility index (g/g)} = \frac{\text{Weight of solubles}}{\text{Dry weight of a sample}} \quad (2)$$

2.4.3. Polarized microscopy

The microstructures of native and HMT starch were studied using a polarized microscope (Olympus CX 21 iLed) at a magnification of 400 x.

2.4.4. Pasting properties

The native and HMT foxtail millet starch were analysed for their pasting characteristics using the rapid visco-analyzer (RVA Starch Master TM, Newport Scientific, Australia). The aqueous starch suspension was made by dispersing 3g of starch in 25 ml of distilled water in an RVA canister. The heating cycle involved holding the starch slurry at 50°C for 1 min before being heated to 95°C for 3 min 42 s followed by retaining at 95°C for 2 min. Following the heating cycle, the cooling cycle began with a drop in temperature to 50°C in 3 min 48 s, which was maintained for 2 min at 160 rpm. The peak time, pasting temperature, peak viscosity, hot paste viscosity, final viscosity, breakdown, and setback were evaluated through the pasting graph.

2.4.5. Particle size distribution

The particle size analyzer (Mastersizer 3000, Malvern, UK) with an attached wet dispersion unit was used to analyze the size of native and HMT foxtail millet starch. The suspension of samples was added to the port within an obscursion range of 12-20% and the distribution of particles was expressed by function of diameter i.e. Dv 10, Dv 50 and Dv 90. The analysis of starch particles distribution was based on the phenomena of diffraction of light.

2.4.6. Texture analysis

The texture analyzer (TA.XT plus, Stable Micro Systems, Godalming, UK) was used to assess the textural profile of native and HMT foxtail millet starch gels (10% w/v). The 5 mm diameter cylindrical probe (P/0.5R Derlin) was punctured into the gel to the depth of 10 mm at a pre and post speed of 1 mm/s to analyze the texture of gel. The different textural attributes including hardness, springiness, cohesiveness, gumminess, chewiness and resilience were measured using the software.

2.4.7. Rheological properties

Dynamic visco-elastic and steady flow behavior of starch pastes of native and HMT foxtail millet starches were measured by dynamic rheometer (Dynamic Rheometer, Anton Paar) using the cone (1º cone angle) and plate geometry sensor (diameter 40 mm, 0.08 mm gap) (Shrivastava *et al.*, 2018). The rheological determination for dynamic-viscoelastic behavior was performed in two steps: (1) deformation sweep to measure the maximum distortion achievable by the paste within the linear viscoelastic region at a constant frequency of 10 rad/s and (2) frequency sweeps, 0.1–100 rad/s range at 0.5% strain within the linear viscoelastic zone.

The viscosity of native and modified starches was determined by measuring the steady flow characteristics of starch pastes at 25°C. The shear rate was increased in 3 min sfrom 0 to $300s^{-1}$ and the viscosity was determined as a function of shear rate.

2.5. Statistical analysis

The analysis of all the observations was carried out by applying one way ANOVA (SPSS 19). The significant difference among the mean values was measured at $p<0.05$.

3. Results and discussion

3.1 Physicochemical properties

The average yield of isolated foxtail millet starch was found to be 61 % (dry basis). Chemical analysis was done to assess the purity of the obtained starch. The recovered starch had 11.58% moisture, 0.68% fat, 1.36% protein, 0.75% crude fibre, and 0.3% ash content. The minimal residual crude fibre, ash and protein concentration suggested that the starch was effectively isolated with high purity. The observed values were in agreement with the previously reported results (Babu *et al.*, 2019; Bangoura *et al.*, 2012).

Table 1 shows the effects of HMT on the physicochemical parameters of foxtail millet starch. The WAC of foxtail millet starch increased significantly ($p<0.05$) from 131 to 157% after heat moisture treatment and was observed to be highest for HMT30. The hydrothermal treatment of starch enhanced the water-binding tendency which resulted in the increased value of WAC. The hydrophilic affinity of starches inclined with the increasing moisture levels from 20 to 30%. Adebowale *et al.* (2005) also noted that the WAC of finger millet starch increased after hydrothermal treatment which suggested the high-water holding efficiency of starch. The oil absorption capacity of foxtail millet starches ranged from 123 to 158%. The OAC of foxtail millet starch significantly expanded ($p<0.05$) to a great extent after HMT and was observed to be highest for HMT30. The hydrophobic affinity of starches increased with the increasing moisture levels during hydrothermal treatment. Olayinka *et al.* (2008) also reported similar results for white sorghum starches. It has been reported that the formation of the lipophilic layer after the treatment on the surface of the starch molecule could be responsible for the increase in oil absorption capacity (Abraham, 1993). The similar results regarding the increased WAC and OAC have been noted for wheat and potato starches (Kulp and Lorenz, 1981) and finger millet starch (Adebowale *et al.*, 2005).

The LGC may be defined as the least amount of starch that is required to form a gel. The higher the amount of starch needed for gel formation the higher will be the LGC. The LGC of foxtail millet starch revealed that there was no change in the LGC after the hydrothermal treatment. The bulk density of foxtail millet starch increased significantly ($p<0.05$) after HMT and was observed to be highest for HMT30 (0.71g/cm^3). Owolabi *et al.* (2010) also observed that the bulk density of corn starch increased after hydrothermal treatment which is an indication of the improved flowability of starch.

Table 1. Physico-chemical properties of native and heat-moisture treated foxtail millet starch.

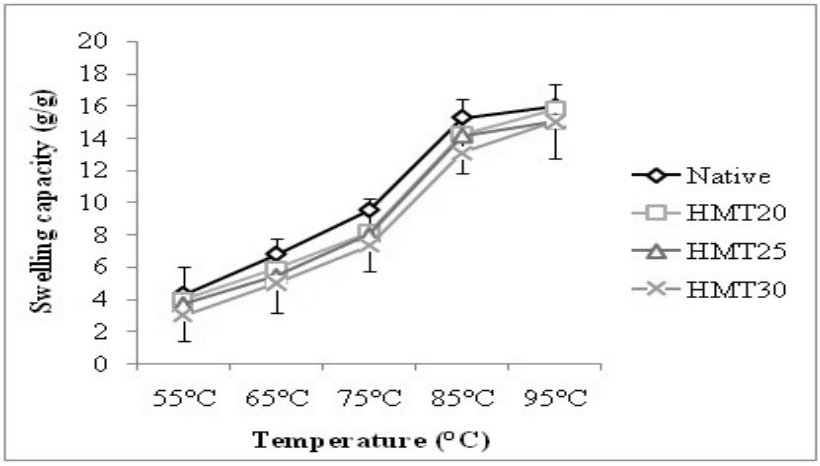
Sample	WAC (g/100g)	OAC (g/100g)	LGC (%)	Bulk density (g/cm^3)
Native	131.00±1.00^a	123.25±0.75^a	8	0.62^a±0.00
HMT20	142.25±0.75^b	143.00±1.00^b	8	0.66^b±0.00
HMT25	148.75±0.25^c	151.00±1.00^c	8	0.68^c±0.01
HMT30	157.25±0.75^d	158.00±1.00^d	8	0.71^d±0.00

The values are expressed as the mean +SD of three independent determinations.
Where, HMT20 = Heat-moisture treatment at 20% moisture content; HMT25 = Heat-moisture treatment at 25% moisture content; HMT30 = Heat-moisture treatment at 30% moisture content; WAC = Water absorption capacity; OAC = Oil absorption capacity; LGC = Least gelation concentration

3.2. Swelling capacity (SC) and solubility index (SI)

The swelling capacity and solubility index of the foxtail millet starches were assessed within a temperature range of 55 to 95ºC and are shown in figure 1 (a) and (b), respectively. It was seen that both swelling and solubility increased with increasing temperatures. The swelling capacity and solubility index reflects the presence of strong binding forces among the starch molecule due to the interaction of the crystalline and amorphous zone. The SC of native and modified foxtail millet starch ranged from 15.0 to 16.0 g/g at 95°C. After HMT, the swelling capacity was found to be significantly reduced ($p\leq0.05$)**.** The higher the degree of hydrothermal treatment lower was the swelling capacity. The reduction in SC might be due to alteration in structure within the starch molecules and formation of more starch molecules interactions after HMT.

The stability of starch granules increases due to the formation of more crystallites during HMT and thus leading to the decrease in SC. The decrease in SC after HMT as reported in present study is similar as noted in previous studies on rice starch (Hormdok and Noomhorm, 2007), finger millet starch (Adebowale *et al*., 2005), Sorghum (Olayinka *et al*., 2008), and pearl millet starch (Sharma *et al*., 2015). Just like swelling capacity, SI also followed the same trend and significantly reduced ($p \leq 0.05$) after the HMT modification. HMT30 showed the lowest value of solubility (14.93 g/g) while native starch showed the highest value (15.75 g/g) for solubility at 95ºC. Similar results of decreasing solubility after heat moisture treatment have been earlier noted for water chestnut (Yadav *et al*., 2013), and pearl millet starch (Sharma *et al*., 2015). The reduced solubility after HMT reflects the formation of stronger bonds due to more interactions between starch molecules and thus preventing the leaching of amylose (Zavareze *et al*., 2010).



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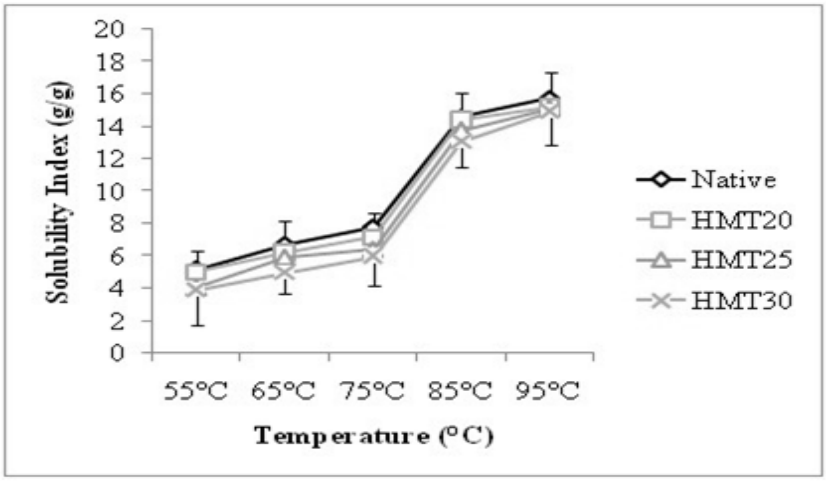

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Figure 1. (a) Swelling capacity of native and HMT foxtail millet starch (b) Solubility index of native and HMT foxtail millet starch

The swelling and solubility index of hydrothermally treated starch samples decreased with the increase in moisture content. The leaching of typically associated amylose molecules and lipids into the continuous phase is proportional to the swelling of starch granules,

which is proportional to the pasting temperature (Yu *et al*., 2018). The inclusion of amylose and lipids in the granule reduces starch swelling, in contrast to amylopectin, which contributes mostly to water intake (Abedi *et al*,. 2019; Agi *et al.* 2019). Amylose and lipid content, as well as the structure of amylopectin, all have a role in starch granule swelling (Li *et al*., 2019). Leach *et al.* (1959) noted that the structural reorganization inside the starch granules following the hydrothermal treatment resulted in the decreased swelling and solubility index. Hoover and Vasantham (1994) reported that the alteration in the organization of crystallites and the interactions between the starch molecules in the amorphous region could be responsible for decreased swelling and solubility index after hydrothermal treatment**.**

3.3. Polarized microscopy

The microscopic examination of native and HMT foxtail millet starch molecules was done under polarized microscope and the images are depicted in figure 2(a-h).

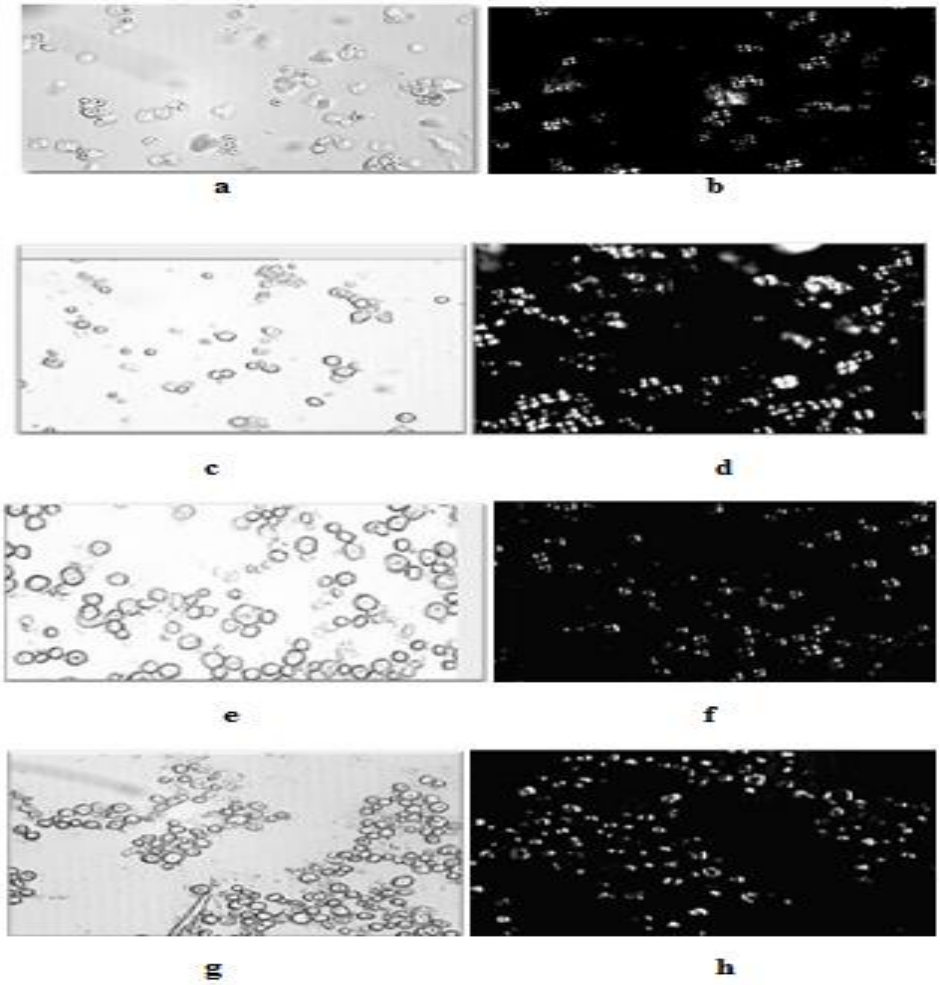


Figure 2. Photomicrographs of (a) native foxtail millet starch under ordinary light; (b) native foxtail millet starch under polarized light; (c) HMT20 foxtail millet starch under ordinary light; (d) HMT20 foxtail millet starch under polarized light; (e) HMT25 foxtail millet starch under ordinary light; (f) HMT25 foxtail millet starch under polarized light; (g) HMT30 foxtail millet starch under ordinary light; (h) HMT30 foxtail millet starch under polarized light

The foxtail millet starch molecules were small, oval to a large polygonal in shape. Wankhede *et al.* (1979) also reported the absence of fissures, barely perceptible hilum,

and strong centric polarization crosses in native foxtail millet starch. The molecular shape and orientation regarding light beam are responsible for the intensity of birefringence. A decrease in the birefringence intensity at the granular centre was observed for HMT foxtail millet starches. The increase in mobility of starch granules due to heat treatment might have resulted in a decrease of birefringence intensity. However, the birefringence intensity of hydrothermally treated starch molecules remained unaltered at the periphery. Chung *et al*. (2010) also reported the least organization of molecules of lentil, navy bean, and pea starches at the centre as compared to the periphery and therefore suggested that these molecules were more likely to be reorganized during hydrothermal treatment. Liu *et al*. (2016) also discovered some grooves and broken granules of coix seeds starch during HMT which might have improved the water absorption, enzyme susceptibility, and adhesion qualities.

3.4. Pasting properties

The pasting behavior of isolated and treated foxtail millet starches are shown in Table 2. The pasting temperature of native starch was discovered to be 79°C and it increased significantly ($p \leq 0.05$) after HMT. The increment in pasting temperatures can be attributed to the transition from an amorphous to a hard crystalline state, as well as the formation of cross-linkages, which demands the requirement of high heat to make paste (Sharma *et al*., 2015). The hydrothermal treatment led to a significant reduction in the hot paste viscosity (HPV), peak viscosity (PV), breakdown viscosity (BD), setback viscosity (SB), and cold paste viscosity (CPV). The PV of isolated foxtail starch was reported to be 1754 cP and the significant decrease ($p \leq 0.05$) in PV was observed for HMT starches. The capability of starch to make a viscous paste determined the cold paste viscosity. The CPV of native starch was 2140 cP which was reduced significantly ($p \leq 0.05$) to 1012 cP for HMT30 starch. The reduction in HPV, PV and CPV after HMT could be due to rearrangement within the granule of the HMT starches. The reinforcement of cross-linkages within starch chains and increase in crystallinity after HMT restricts starch swelling and amylose leaching which resulted in decreased viscosity (Adebowale *et al*., 2005).

Table 2. Pasting properties of native and heat-moisture treated foxtail millet starch.

Sample	PV (cP)	HPV (cP)	BD (cP)	CPV (cP)	SB (cP)	Peak time (min)	PT (°C)	Stability Ratio	Setback Ratio
Native	1754±2.34^{d}	1062±1.78^{c}	693±5.24^{d}	2140±4.43^{d}	1079±4.91^{c}	5.00±0.30	79.10±0.17^{a}	0.82	2.02
HMT20	1139±1.15^{c}	766±2.31^{b}	373±3.28^{c}	1208±3.75^{c}	442±4.01^{b}	5.03±0.15	82.18±0.20^{b}	0.94	1.57
HMT25	901±2.02^{b}	694±1.11^{a}	208±4.01^{b}	1028±2.08^{b}	334±5.21^{a}	5.18±0.35	86.48±0.23^{c}	0.88	1.48
HMT30	855±2.33^{a}	688±2.03^{a}	167±3.21^{a}	1012±1.76^{a}	323±1.77^{a}	5.48±0.30	86.48±0.23^{c}	0.84	1.47

The values are expressed as the mean +SD of three independent determinations.
Where, PV= Peak viscosity, HPV= Hot paste viscosity, BD= Breakdown viscosity, CPV= Cold paste viscosity, SB= Set back viscosity, PT= pasting temperature.

The reduction in viscosity after HMT as reported in present study is similar as noted in previous studies on oat, lentil and yam starches (Hoover and Vasantham, 1994), rice starch (Hormdok and Noomhorm, 2007) and finger millet starch (Adebowale *et al*., 2005).

Watcharatewinkul *et al*. (2009) reported that the alteration in pasting viscosity possibly because of the interconnection of the starch chains in the amorphous regime of the molecules and the altered crystallinity of starch molecules during HMT. The BD value of foxtail millet starch was reduced significantly ($p \leq 0.05$) after heat moisture treatment. The lowest value of BD was observed for HMT30 (167 cP) while the highest value was observed for native (693 cP). The lower BD value indicates the heat stable behaviour of HMT starches. Various heat-processed food products could be formed with starches having lower BD due to their thermo-stable behaviour. The ability to retrograde is measured by the setback (SB) value of the starch paste, which dropped significantly ($p \leq 0.05$) after hydrothermal treatment. Retrogradation occurs due to the rearrangement of the linear structure of amylose molecules. The decrease in SB value after HMT might be due to more interactions between amylopectin and amylose chains and low amylose leaching. Starches with a lower setback value can be employed in the production of canned and frozen foods.

3.5. Particle size distribution

The size distribution of the particles is crucial aspect which also influences the functional properties like swelling power, pasting and rheological characteristics of starch. The size distribution of the particles of isolated and treated foxtail millet starch is given in Table 3. The size of the particles in isolated foxtail millet starch ranged from 0.35-14.5 µm whereas in heat- moisture treated sample, the size of particles increased with increased moisture content. All the samples i.e. native and HMT foxtail millet starches showed bimodal distribution. The increase in the size of starch particles during HMT could be due to the agglomeration that occurred under the influence of with high moisture content during heating process (Chandla *et al*., 2007). Zavareze *et al*. (2010) also observed the increase in size of rice starch particles treated hydrothermally for 25 min which was ascribed to their partially gelatinization at higher moisture content during heat moisture treatment.

Table 3. Particle size distribution and textural parameters of native and heat-moisture treated foxtail millet starch.

Samples	Particle size distribution			Textural parameters				
	Dv 10 (µm)	Dv 50 (µm)	Dv 90 (µm)	Hardness (g)	Adhesiveness (g/s)	Spiringiness (mm)	Cohesiveness	Gumminess (g)
Native	0.57±0.03^{a}	6.25±0.03^{a}	9.34±0.03^{a}	84.80±1.63^{a}	43.34±1.20a	0.98±0.02^{c}	0.57±0.01^{b}	48.07±1.00^{b}
HMT20	10.37±0.15^{b}	27.53±0.23^{b}	113.67±1.77^{b}	102.76±2.03^{b}	40.72±1.31^{a}	0.96±0.01^{b}	0.56±0.01^{a}	57.82±1.08^{c}
HMT25	10.23±0.26^{b}	30.30±0.15^{c}	134.0±2.08^{c}	82.21±1.91^{a}	41.70±0.68^{a}	0.95±0.02^{a}	0.59±0.01^{c}	49.34±1.03^{b}
HMT30	10.47±0.20^{b}	33.37±0.29^{d}	133.0±2.30^{c}	81.43±1.85^{a}	41.03±0.87^{a}	0.95±0.01^{a}	0.61±0.01^{d}	43.92±1.15^{a}

The values are expressed as the mean +SD of three independent determinations.
Dv 10, Dv 50, Dv 90= 10 %, 50%, 90% particles are finer than given value.

3.6. Texture analysis

The textural data of isolated and HMT foxtail millet starch is shown in Table 3. The bond forming ability of starch granules with water determines the gel strength. The gel hardness of foxtail millet starch increased

significantly ($p \leq 0.05$) for HMT20 (102.76 g) as comparison to that of native starch (84.80 g). The formation of more cross-linkages in amylose portion among starch molecules and development of more junction zones during HMT resulted in the increased hardness of gel (Chandla *et al*., 2007). However, HMT25 (82.21 g) and HMT30 (81.43 g) showed the decrease in gel hardness, although it was non-significant. The decrease in gel hardness of the starch subjected to HMT for comparatively longer duration might be due to partial gelatinization of starch molecules during HMT which ultimately resulted in the rupturing of starch granules and formation of weak gel (Liu *et al*., 2000). Hormdok and Noomhorm (2007) also reported the similar results for rice starch after HMT. No significant difference ($p \leq 0.05$) was observed between the values of adhesiveness in native and HMT foxtail millet starch. The value of cohesiveness varied from 0.56 (HMT20) to 0.61 (HMT 30). However, the impact of hydrothermal treatment was inconsistent on cohesiveness and gumminess.

3.7. Rheological properties

3.7.1. Oscillatory properties

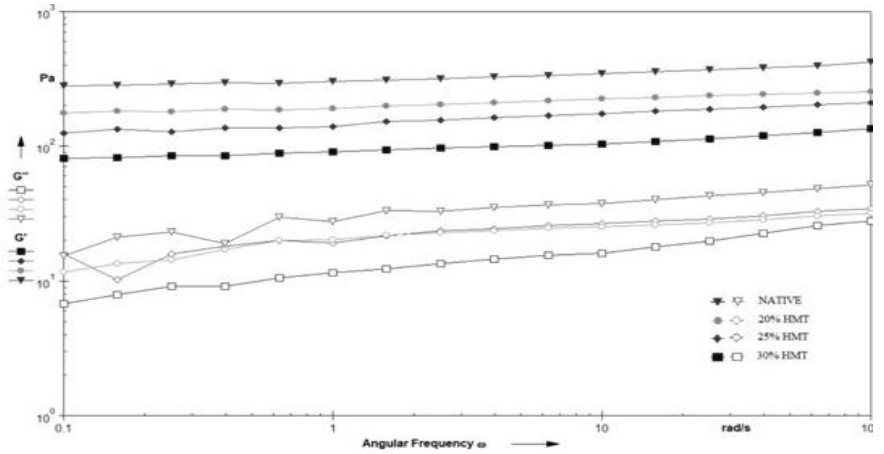
The dynamic viscoelastic behavior of the native foxtail millet starch and HMT starch with different moisture content is shown in figure 3 (a) and (b). With an increase in frequency, both the storage modulus (G′) and the loss modulus (G″) expanded. The value of storage modulus (G′) was exceeding the value of loss modulus (G″) in all the starch samples and for the similar gels, the values of G′ and G″ did not cross over across the uniform frequency specifying a weak gel characteristic. The increase in G′ and G″ was reported with the frequency rise. The value of G′ and G″ was lower for HMT starches and it decreased more with increasing moisture content. The decrease in G′ values of HMT starches might be because of deformation of starch granules or lower continuous phase elasticity. A decrease in G′ values was observed in HMT25 and HMT30 samples which specified the softer gel formation in these two modified starch samples, in contrast, to native and HMT20 samples. Similar observations have been noted for heat moisture treated pearl millet starch (Sharma *et al*., 2015).

Tan δ (G″/G′) describes the visco-elastic character of starches and was found to be below than 1 for all samples, showing an elastic nature. However, the values of tan δ increased after HMT showing an increase in the viscous nature of HMT starches, and maximum values for tan δ were observed for HMT30. The alteration of the gel structure of HMT25 and HMT30 to a fluid state without a sharp broken end indicates the balanced arrangement of elastic and viscous sections. The starch gels indicated shear-thinning behavior and the decrease in rigidity of starch gel was noted with increasing moisture content during HMT. Liu *et al*. (2016) also discovered that following HMT, the G' and G" modulus of coix seeds starch suspensions reduced. HMT causes the suspensions to have a weaker structure and less gel-like behaviour as indicated by lower tan δ values for native coix starches. This effect could be owing to the breakdown of starch granules crystalline structure during HMT, which imparts them more viscous character (Sui *et al*. 2015).

3.7.2. Steady shear properties

The change in starch structure caused by shearing force is referred to as steady flow behaviour. The steady flow behavior of isolated and HMT foxtail millet starch is shown in figure 3 (c). All the pastes showed the shear thinning behavior as there was a decrease in viscosity with increasing shear rates. The viscosities of HMT starches were less in comparison to the native starch. This behavior suggested that modified starches were less stable against high shear rates and hence, HMT starches cannot be suitably used as a thickener in high shear processing conditions. Similar behavior has also been reported for heat moisture treated sago and arenga starches (Adawiyah *et al*., 2017) and it was suggested that HMT starches could find applications in products having lower moisture content and low shear processing such as cookies. The hydrothermal treatment of arrowroot starch resulted in a lower consistency index, reflecting a decreased perceived

viscosity. The apparent flexibility of arrowroot starches was also lowered by the HMT (Pepe *et al*., 2015).



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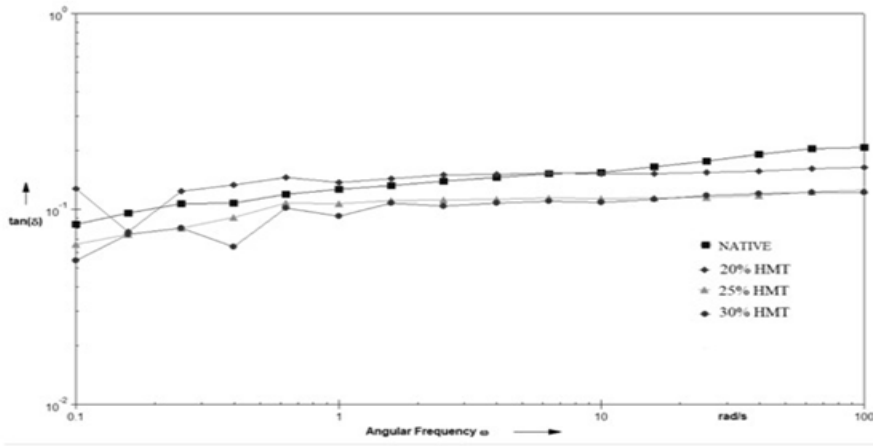
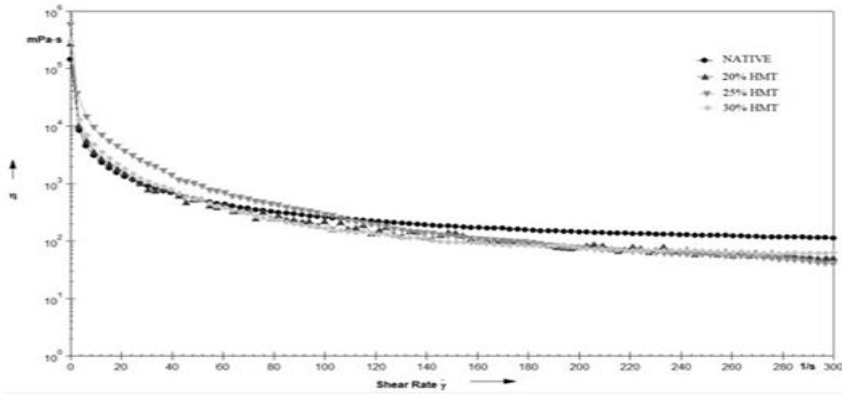


b



c

Figure 3. Dynamic mechanical spectra of (a) native and HMT foxtail millet starch (b) Dynamic mechanical loss tangent (tan ϱ) of native and HMT foxtail millet starch (8% suspension, w/w) (c) Flow curve of native and HMT foxtail millet starch (8% suspension, w/w)

4. Conclusions

In this study, the foxtail millet starch was modified by the HMT at different moisture level i.e. 20%, 25%, and 30%. The creation of cross-linkages and the conversion of the amorphous zone into a more compact crystalline zone during HMT, the SP, SI, and pasting parameters were considerably altered. The reorientation of molecules of hydrothermally treated starches resulted in a significant decrease in viscosities and increase in pasting temperature. The decrease in peak viscosity eventually resulted in lower swelling capacity and lower amylose leaching. HMT20 showed a significant increase in gel hardness however, no significant difference ($p \leq 0.05$) in gel hardness of HMT25 and HMT30 with native foxtail millet starch was observed. The rheological characteristics of native and HMT foxtail millet starches in dynamic state revealed the weak gel structure. The increase in loss tangent of paste resulted in the viscous behavior of starches. Therefore, the study concluded that the foxtail millet starch with some specific characteristics can be obtained by giving heat moisture treatment at different moisture level. This research will be helpful in the development of some new food products using hydrothermally treated foxtail millet starch.

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