

Structural, physicochemical and rheological properties of starches isolated from banana varieties (*Musa* spp.)

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ABSTRACT

Banana starches were isolated from five banana varieties in Tanzania to analyze the proximate composition, structure, physicochemical and rheological properties. The amylose content of banana starches was $29.92 \pm 0.17\%$ – $39.50 \pm 0.08\%$ and the resistant starch content of cooked banana starches ranged from $44.74 \pm 1.72\%$ to $55.43 \pm 1.52\%$. Banana starch granules presented irregular shapes with particle size of 21.73 to $24.67 \mu\text{m}$ and showed B-type or C-type crystalline patterns with crystallinity of 36.69% to 41.83% . The solubility and the swelling power were $2.5 \pm 0.42\%$ – $4.4 \pm 0.57\%$ and $11.27 \pm 0.04\%$ – $12.48 \pm 0.71\%$, respectively. Mzuzu and Malindi starches possessed lower gelatinization temperature. The high gelatinization peak viscosity (2248 ± 67 – 2897 ± 71 cP), low breakdown (556 ± 7 – 960 ± 41 cP) and low setback (583 ± 29 – 864 ± 118 cP) indicated banana starch could replace chemically cross-linked starch for applications that require stable viscosity. The rheological analysis showed that banana starches exhibited shear thinning behavior and had great processing adaptability. The results all above will provide basic data for the development and utilization of banana starch.

Introduction

Banana (*Musa paradisiac*), belonging to Musaceae, *Musa*, is a perennial herb. It is native to Southeast Asia and is widely grown in tropical and subtropical regions. As an important cash crop, banana is widely consumed by the world's population and plays a crucial role in the economy of developing countries by providing the main income and food source for the residents of the growing areas (Zhang, Whistler, BeMiller, & Hamaker, 2005). Banana is rich in carbohydrates, vitamins, minerals, resistant starch (RS), and bioactive compounds. Moreover, banana has low salt and high potassium content, which is beneficial to control blood pressure (Singh, Singh, Kaur, & Singh, 2016).

Starch is an important natural carbohydrate source for human beings. As the main component of bananas, banana starch has attracted the interest of researchers because of its special structural and physicochemical properties. Banana starch is primarily isolated from unripe bananas by virtue of the high contents of total starch (70 %–80 %

(Zhang et al., 2005) and RS contents, with the plant ripening, the total starch and RS contents in banana decrease and the soluble sugar content increase (Bi et al., 2019; Dhull, Malik, Kaur, Kumar, Kaushal, & Singh, 2020). The level of RS in functional products could potentially improve human health and broaden the application of banana starch. The amylose content of banana starch has attracted attention because it has an impact on the physicochemical properties of starch to some extent and amylose is conducive to form film because of its high anhydrous nature (Kaur, Dhull, Kumar, & Singh, 2020). The properties of banana starch are different among different varieties and sources (de Barros Mesquita, Leonel, Franco, Leonel, Garcia, & dos Santos, 2016). Microscopically, the starch granules of different banana varieties (*Dominica Hartón*, *FHIA 20* and *Gros Michel*) from Colombia showed irregular, elongated and spherical shapes (Chávez-Salazar, Bello-Pérez, Agama-Acevedo, Castellanos-Galeano, Álvarez-Barreto, & Pacheco-Vargas, 2017). The banana starches isolated from varieties obtained from China showed C-type diffraction pattern with low digestibility (Bi et al.,

Abbreviations: RS, Resistant starch; DO, Degree of order; DD, Degree of double helix; S, Solubility; SP, Swelling power; APS, Average particle size.

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2017). The starch from Brazilian varieties *Grand Naine* showed higher swelling power (15.19 g/g), *Prata-Anã* presented higher solubility (11.61 %) and lower final viscosity and setback (de Barros Mesquita et al., 2016). For *Cavendish* banana starch, the gelatinization temperature was reported in the range of 70.1–74.6 °C (Zhang et al., 2005). Banana from different regions also have a certain effect on its starch quality. Moreover, there is a relative lack of research on the rheological properties of banana starch, such as temperature sweep. At present, consumers are increasingly pursuing healthy and functional products. Hence, products related to banana starch, such as bread, pasta, and cookies, have been widely studied and developed. In addition, the novel applications of banana starch, such as nanomaterials, edible films, water-soluble casings for detergents and insecticides, biodegradable flexible bags, and coatings, have advanced on account of the natural abundance, biocompatibility, easy structural modification, and polymerized matrix of starch particles (Dhull et al., 2020; Kaur et al., 2020).

Tanzania has a long banana planting history and rich banana resources. Nowadays, bananas still represent a crucial economic income for fruit farmers in Tanzania, but resources are seriously wasted in the banana fresh fruit trading and industry because banana is a typical respiratory climacteric fruit, which results in great economic losses and is ascribed to the lack of processing capacity and relevant research in Tanzania. Therefore, the research demand for banana starch is becoming increasingly prominent based on the purpose of improving the value of the banana industry, as it can help to boost their application in processed foods and become a commercially viable commodity with low production cost (Zhang et al., 2005). The characteristics of banana starch varies remarkably by cultivars, geographical locations, regional climatic factors, especially regarding starch content and the properties of bananas from different origins (Salazar et al., 2022). In this regard, there are few studies on the banana varieties from Tanzania. Therefore, it is of significance to study representative varieties of different genotypes of banana from Tanzania and evaluate the structural, physicochemical, rheological and functional properties, as well as their relationship. The comprehensive analysis of banana starch properties will serve as the basis for solving the problems of banana waste in Tanzania, promoting the banana industry and improve starch utilization.

Materials and methods

Materials

Five varieties of unripe green bananas from Tanzania, namely, Mzuzu (*Plantains*), Malindi (*Cavendish* sp.), Mshale (*Musa* AA Pisanello), Bukoba (East African highland banana, *Musa* AAA), and Moshi (*Musa acuminata*). Thermostable α -amylase was obtained from Solarbio Science & Technology Co., Ltd. (Beijing, China). Glucoamylase solution was obtained from Yuanye Biotechnology Co., Ltd. (Shanghai, China).

Preparation of banana starch

Banana starch was prepared using the water-alkaline extraction method according to Jiang et al. (2015) with some modifications. Five varieties of unripe green bananas were peeled, sliced into thin slices, and immediately dipped in a 0.3 % (w/v) citric acid solution for 10 min to reduce browning phenomena. Then, the banana slices were sun-dried naturally for 2 sunny days, ground 2–3 times using a high-speed crusher, and sieved through a 60-mesh sieve. Banana flour was soaked in distilled water for 20 min and then homogenized with a blender. The homogenate was filtrated through a 100-mesh sieve. The collected filtrate was diluted with water and centrifuged (3800 rpm, 15 min) repeatedly. The soluble fibers in the precipitate were removed by adding 1.0 L of NaOH solution (0.3 %, w/v). The pure precipitate was washed with water repeatedly until it became neutral and then centrifuged at 3800 rpm for 15 min. The final precipitate was dried at 45 °C for 24 h and milled. After 100-mesh screening, banana starch was transferred

into self-sealing bag and stored hermetically in refrigerator at 4 °C for analysis.

Determination of proximate composition

The moisture and ash contents of banana starches were determined according to the guidelines of The Association of Official Analytical Chemists (2005). Total starch content was examined by a corresponding assay kit (Megazyme, Wicklow, Ireland). Amylose content was measured according to the method of Li and Zhu (2017).

RS content was determined according to the method described by Goñi, Manas, Garcia-Diz, Mañas, and Saura-Calixto (1996) with some modifications. Banana starch (100 mg) was dispersed in 9.0 mL of phosphate buffer solution (pH 6.4) and 1.0 mL thermostable α -amylase (2000 U). The mixture was cooked in a boiling water bath for 30 min and centrifuged (3800 rpm, 20 min) after cooling to room temperature. The precipitate was washed with 10 mL of distilled water at least once and then added with 3.0 mL of distilled water and 3.0 mL of 2 mol/L KOH solution. The precipitation mixture was shaken at room temperature for 30 min and adjusted to neutrality with 2 mol/L HCl. Then, 3.0 mL of sodium acetate buffer (pH 4.5) and 1.0 mL glucoamylase solution (3000 U) were added. The mixture was incubated in a shaking water bath at 60 °C for 1 h and centrifuged at 3800 rpm for 20 min. The supernatant was collected and the precipitate was washed at least twice. Then, the supernatants were combined and the volume was completed to 50 mL.

Glucose content was determined by glucose oxidase–peroxidase (GOPOD) method. The supernatant (0.1 mL) was mixed with 3.0 mL of GOPOD, incubated in a water bath at 50 °C for 20 min, then cooled to room temperature. The absorbance of the mixture was determined at 510 nm with 0.1 mL of acetate buffer as the blank and 0.1 mL of 1 mg/mL glucose standard solution as the control. RS content was calculated by the following formula:

$$RS (\%) = \frac{(A_1 - A_0) \times V_0}{V_1 \times W \times 1000} \times 0.9 \times 100$$

where A_1 is the content of reducing sugar in the sample, A_0 is the content of reducing sugar in the blank sample, V_0 is the constant volume, V_1 is the volume of liquid collected during measurement, and W is the weight of the sample.

Scanning electron microscopy

The morphological properties of banana starches were observed with a scanning electron microscope (Nano SEM-450, FEI, America) at 2500× and 6000× magnifications.

Particle size analysis

The particle size distributions of banana starches were determined using a laser particle size analyzer (LS13320, Beckman Coulter, Inc., America) with the help of a Scirocco dry disperser unit for dispersing the powders.

X-ray diffraction (XRD)

Crystallization characteristics of banana starches were tested with an X-ray diffractometer (D8 ADVANCE A25, Bruker, Germany) employing Cu-anode as the target. The diffraction angle (2θ) ranged from 5° to 40° with a scanning step of 0.02° and a scanning speed of 6°/min. The crystallinity of each starch variety was analyzed by Jade 6.0 software.

Fourier transformed infrared spectrometry (FTIR)

A fourier transform infrared spectrometer (Vetex 70, Bruker, Germany) was used to analyze the degree of order (DO) and degree of

double helix (DD) of banana starches through the method of Zeng et al. (2015) with slight modifications. Samples were mixed evenly with dried KBr (1:100, m/m) and placed into a vacuum compression and pressured into a slice. The spectra were set from 400 to 4000 cm^{-1} and the obtained spectra were processed by OPUS software.

Solubility (S) and swelling power (SP)

S and SP of banana starches were measured following the method of de Barros Mesquita et al. (2016) with slight modifications. The starch suspension (1 %) was heated in a thermostatic oscillating water bath at 85 °C for 30 min, cooled to room temperature, and centrifuged at 3800 rpm for 15 min. The supernatant was poured into an aluminum box with constant weight and dried to a constant weight (m_s) at 105 °C. The remaining sediment paste was weighed (m_p) immediately. All measurements were conducted in duplicate. The S (%) and SP (g/g) were calculated by the following formulas:

$$S (\%) = \left(\frac{m_s}{m_0} \right) \times 100$$

$$SP (\text{g/g}) = \frac{m_p}{m_0 \times (100-S)}$$

where m_s is the weight of dissolved matter in the supernatant, m_0 is the weight of the sample, and m_p is the weight of the remaining sediment paste.

Thermal properties

A differential scanning calorimeter (DSC, Q2000, Waters, American) was used to assess the thermal transitions associated with starch gelatinization. The thermal properties of banana starches were determined through the method described by de Barros Mesquita et al. (2016) with some modifications. Starch (2.0 mg) was dispersed in 6 μL of distilled water in an aluminum pan, hermetically sealed, and equilibrated for 12 h prior to testing at 4 °C for differential scanning calorimetry. Starch dispersion was gelatinized from 30 °C to 110 °C at a heating rate of 10 °C/min against a sealed empty aluminum pan as blank.

Pasting properties

Pasting properties were analyzed by a rapid viscosity analyzer (TechMastet, Perten, Sweden) using a 10 % starch suspension (g/100 g) with Standard 1 program. The method described by de Barros Mesquita et al. (2016) was carried out, and the main pasting parameters were automatically obtained from the pasting curves using the instrument software.

Rheological properties

TA Instruments rheometer (TA Instruments, DHR-1, USA) with a 40 mm parallel plate geometry and a Peltier plate was used to access the rheological properties of banana starches. The 2 % starch pastes were placed between the parallel plate with a gap of 1000 μm . Method from Jiang et al. (2020) was carried out to determine the steady shear and dynamic oscillatory of starches. The apparent viscosity–shear rate behavior of banana starches was determined as a function of shear rate from 0.1 to 1000 s^{-1} at 25 °C. The restoration of shear structure of banana starch pastes were tested with constant strain of 5 % at 25 °C. Frequency sweep experiments were performed with constant strain of 5 % and frequency varying from 1 to 100 Hz. Oscillation temperature ramp was obtained from the heating and cooling process (the temperature range was between 50 and 95 °C).

Statistical analysis

All measurements were performed in duplicate. Data were analyzed with Minitab 18.0 software. The results were expressed as mean \pm standard deviation (SD). Significant differences were obtained by analysis of variance (ANOVA) followed by Duncan's multiple range test ($P < 0.05$).

Results and discussion

Proximate composition

Starch samples significantly differed in proximate composition ($P < 0.05$) (Table 1). The total starch contents of five banana starches were in the range of 81.71 \pm 1.20 %–91.69 \pm 1.91 %. The starch yield during the extraction process was affected by other components, such as hemicellulose, lignin, and pectin, as well as their physical interaction with starch (Agama-Acevedo et al., 2014). Ash represents the total mineral content in the sample, which is one of the important bases to judge the purity of starch. The ash contents of five starch samples possessed the range of 0.16 \pm 0.00 %–0.28 \pm 0.01 %, which were lower than those of *Enano*, *Morado*, *Valery*, and *Macho* banana starch (1.11 %–1.43 %) grown in Mexico (Utrilla-Coello et al., 2014). The results indicated that the banana starches extracted by the water–alkaline extraction method met the experimental requirements. As the main component of the amorphous region of starch granules, amylose affects starch gelatinization and digestion characteristics (de Barros Mesquita et al., 2016). The amylose contents of banana starches differed from 29.92 \pm 0.17 % to 39.50 \pm 0.08 %, which were higher than the 23.75 %–31.88 % and 19.32 %–26.35 % of Mexican varieties reported by Agama-Acevedo et al. (2014) and Utrilla-Coello et al. (2014), respectively. The difference was in connection with plant variety and maturity (Chávez-Salazar et al., 2017). The highest and lowest amylose contents were obtained by Mzuzu and Bukoba, respectively. Banana starch with high amylose content could be considered to make edible films (Sanchez, Pinzon, & Villa, 2022).

The RS contents of the cooked banana starches ranged from 44.74 \pm 1.72 % to 55.43 \pm 1.52 %, which were within the 37.5 %–55.5 % of Mexican varieties reported by Reyes-Atrizco et al. (2019) but were higher than those of cooked banana starches from China (19.04 %–22.31 %) and lower than those of raw starches (85.20 %–92.16 %) reported by Bi et al. (2017). The differences may be due to the disparities in varieties, ripening stages, and determination methods. As reported by Bi et al. (2017), the enzyme binding sites in starch granules increases with the expansion and rupture of starch during heating and cooking, which results in a remarkable increase in digestibility. This occurrence can explain why the RS content of cooked starch was lower than that of raw starch. Mshale displayed the highest RS content, which indicated that it had the most prominent ability to resist enzyme digestion. The lowest RS content was presented by Malindi, but it was still much higher

Table 1

Proximate composition of banana starches (% , dry basis).

Sample	Moisture	Total starch	Amylose	Resistant starch	Ash
Mzuzu	7.58 $\pm 0.06\text{d}$	89.26 $\pm 0.84\text{b}$	39.50 $\pm 0.08\text{a}$	45.50 $\pm 1.11\text{c}$	0.16 $\pm 0.00\text{e}$
Malindi	6.40 $\pm 0.01\text{e}$	91.69 $\pm 1.91\text{a}$	33.37 $\pm 0.34\text{d}$	44.74 $\pm 1.72\text{c}$	0.26 $\pm 0.00\text{b}$
Mshale	10.31 $\pm 0.24\text{b}$	83.17 $\pm 0.37\text{d}$	36.94 $\pm 0.17\text{b}$	55.43 $\pm 1.52\text{a}$	0.17 $\pm 0.00\text{d}$
Bukoba	11.51 $\pm 0.12\text{a}$	85.25 $\pm 0.72\text{c}$	29.92 $\pm 0.17\text{e}$	46.32 $\pm 1.22\text{c}$	0.28 $\pm 0.01\text{a}$
Moshi	8.82 $\pm 0.32\text{c}$	81.71 $\pm 1.20\text{d}$	35.10 $\pm 0.08\text{c}$	50.80 $\pm 2.69\text{b}$	0.25 $\pm 0.01\text{c}$

Results are expressed by mean \pm SD ($n = 2$). Values with the different letters in the same column are significantly different ($P < 0.05$).

than the gelatinized corn starch (2.02 %) and potato starch (3.52 %) (Liu et al., 2021). The banana starch is an excellent source of RS and has good digestion resistance, therefore, banana starch is commercially acceptable as a functional dietary food.

Morphology

The morphology of banana starch granules is shown in Fig. 1. The banana starch granules presented irregular shapes, including flat, irregular oval, slender rod, and cone shapes. The surface of banana starch granules was dense and smooth, and the size of starch granules of the same variety varied greatly. These findings were in line with the previous report on varieties of *Grand Naine* and *Prata-Anã* grown in Brazil (de Barros Mesquita et al., 2016). The differences in the particle shape of the starches from different banana varieties could be attributed to the genetics and growing conditions. Several small protuberances, which were the fiber, pectin, and other impurities left during the process of starch extraction, were observed on the surface of a few granules. Some starch granules had fracture surfaces, which may be caused by mechanical damage during milling and beating. The smooth, dense, and large granules of banana starch are one of the reasons for its digestion resistance (Bi et al., 2017), because they weaken the action of enzymes in invading the pores on the surface of granules (Jiang et al., 2015). Correspondingly, Mshale and Moshi with larger granules had higher RS contents, whereas Mzuzu, Malindi and Bukoba with slenderer and smaller granules had lower RS contents (Table 1).

Particle size

The particle sizes of banana starches are presented in Table 2. The particle size distribution of banana starch samples was 6.158–69.614 μm , which was within the result (1.0–200 μm) of varieties (*Enano*, *Morado*, *Valery* and *Macho*) grown in Mexico reported by Utrilla-Coello et al. (2014). Banana starch granules had a wide range of particle size distribution because of their rod shape, which was consistent with those Mexican varieties reported by Agama-Acevedo et al. (2014). The average particle size (APS) of banana starches from different varieties remarkably differed from $21.73 \pm 0.08 \mu\text{m}$ to $24.67 \pm 0.16 \mu\text{m}$ ($P < 0.05$). Bukoba possessed the lowest APS value and a broad particle size distribution range, which may be linked to the uneven existence of more slight particles. The APS value of Mshale was the highest, which indicated that more large particles existed in Mshale. Large starch granules ($>10 \mu\text{m}$) of banana are approximately necessary for manufacturing biodegradable plastic films (Bezerra, Amante, de Oliveira, Rodrigues & da Silva, 2013). The size distribution of starch granules from different botanical origins varies with various genotype and growth conditions, which are likely to affect physicochemical and digestibility properties

(Toro et al., 2016).

XRD analysis

The XRD patterns of the five banana starch varieties is exhibited in Fig. 2a. Mshale and Bukoba showed B-type crystalline patterns with diffraction peaks near 5.6° , 15° , 17° , 22° , and 24° . In comparison, Mzuzu, Malindi, and Moshi showed C-type crystalline patterns with main diffraction peaks near 17° and two minor peaks near 15° and 23° . Similar to the results of the present study, Marta et al. (2019) found that B-type crystal in cooking banana starch and C-type crystal in dessert banana starch from Indonesian varieties of *Kapas*, *Nangka*, *Kepok* and *Ambon*. Starches with B-type and C-type crystals are more resistant to pancreatic amylase than A-type starch (Freitas & de Q. Tavares, 2005). Therefore, the bananas varieties from Tanzania have better resistance to digestive enzyme. The detected crystalline patterns varied greatly with plant growing conditions, varieties, climates, and maturity (Jiang et al., 2015). Additionally, the starch isolation technique (alkaline or non-alkaline) could lead to different crystalline types because it has an obvious effect on the internal organization of banana starch granules (Utrilla-Coello et al., 2014). The crystallinity of the five banana starches ranged from 36.69 % to 41.83 %, which was similar to the Indonesian varieties (33.20 %–39.36 %) reported by Marta et al. (2019) but was higher than the Chinese varieties (29.84 %–33.02 %) reported by Bi et al. (2017). The difference was attributed to the different genotypes from various botanical origins. The crystallinity in the present study showed a negative correlation with amylose content (Table 1), which was in line with the result of the previous study (Yuan, Ye, Chen, Li, & Zhao, 2021).

FTIR

Fig. 2b shows that the FTIR spectra of banana starches had three strong absorption peaks at 3237 , 1082 , and 1020 cm^{-1} . The medium-width absorption peak at the region around 3200 cm^{-1} corresponded to the symmetric and asymmetric stretching of intramolecular and intermolecular hydroxyl groups (Pelissari, Andrade-Mahecha, do Amaral Sobral, & Menegalli, 2012). The absorption bands at 1000 – 1300 cm^{-1} were caused by the bending vibrations of C–OH bonds, the skeletal vibrations of C–O–C bonds, and the stretching of C–O and C–C bonds, which were the typical characteristic bands found in starch (Fan et al., 2012). The peaks around 1082 cm^{-1} were ascribed to the C–O–C stretching vibrations of anhydroglucose ring, especially the C–OH groups (Govindaraju et al., 2021).

The FTIR spectra had three typical absorption peaks at 995 , 1022 , and 1047 cm^{-1} . The value of $1047 \text{ cm}^{-1}/1022 \text{ cm}^{-1}$ represents the ratio of the ordered crystalline region to the amorphous region in starch,

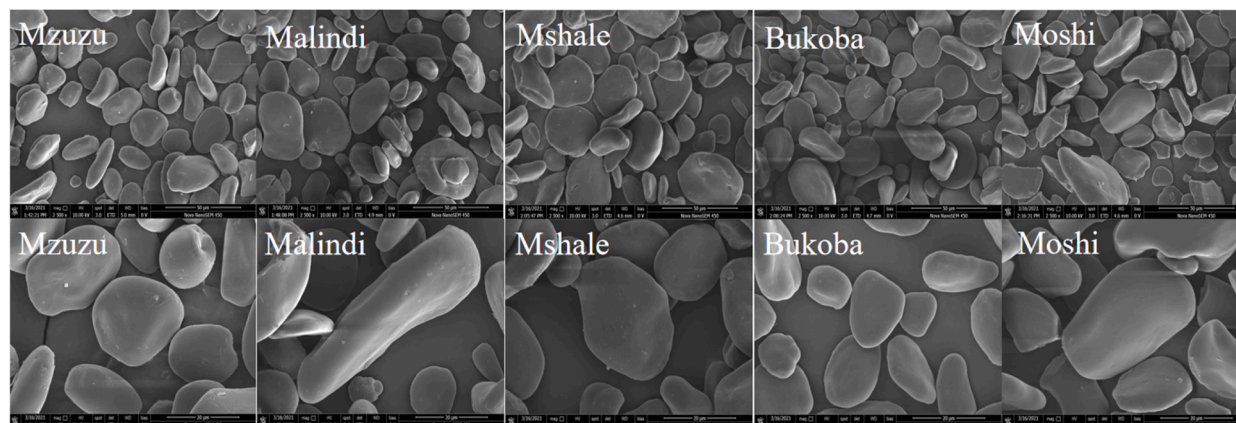


Fig. 1. Scanning electron microscopy (SEM) images of banana starches at $2500 \times$ magnification (first line) and $6000 \times$ magnification (second line).

Table 2
Particle sizes, molecular orders, hydration properties of banana starches.

Sample	Particle sizes		Molecular orders		Hydration properties	
	Distribution (μm)	APS (μm)	DO	DD	S (%)	SP (g/g)
Mzuzu	6.158–57.767	22.09 \pm 0.388c	1.160 \pm 0.006c	0.951 \pm 0.039a	4.40 \pm 0.57a	11.90 \pm 0.21a
Malindi	6.760–69.614	22.94 \pm 0.191b	1.173 \pm 0.015b	0.944 \pm 0.022a	2.70 \pm 0.43c	12.42 \pm 0.07a
Mshale	7.421–52.622	24.67 \pm 0.163a	1.164 \pm 0.001c	0.948 \pm 0.027a	2.50 \pm 0.42c	11.27 \pm 0.04a
Bukoba	5.610–57.766	21.73 \pm 0.085d	1.175 \pm 0.000b	0.933 \pm 0.001a	2.90 \pm 0.15c	12.48 \pm 0.71a
Moshi	8.147–63.414	23.06 \pm 0.014b	1.196 \pm 0.001a	0.894 \pm 0.008b	3.49 \pm 0.40b	11.72 \pm 0.53a

Results are expressed by mean \pm SD ($n = 2$). Values with the different letters in the same column are significantly different ($P < 0.05$). APS: average particle size; DO: degree of order ($1047 \text{ cm}^{-1}/1022 \text{ cm}^{-1}$); DD: degree of the double helix ($995 \text{ cm}^{-1}/1022 \text{ cm}^{-1}$); S: solubility; SP: swelling power.

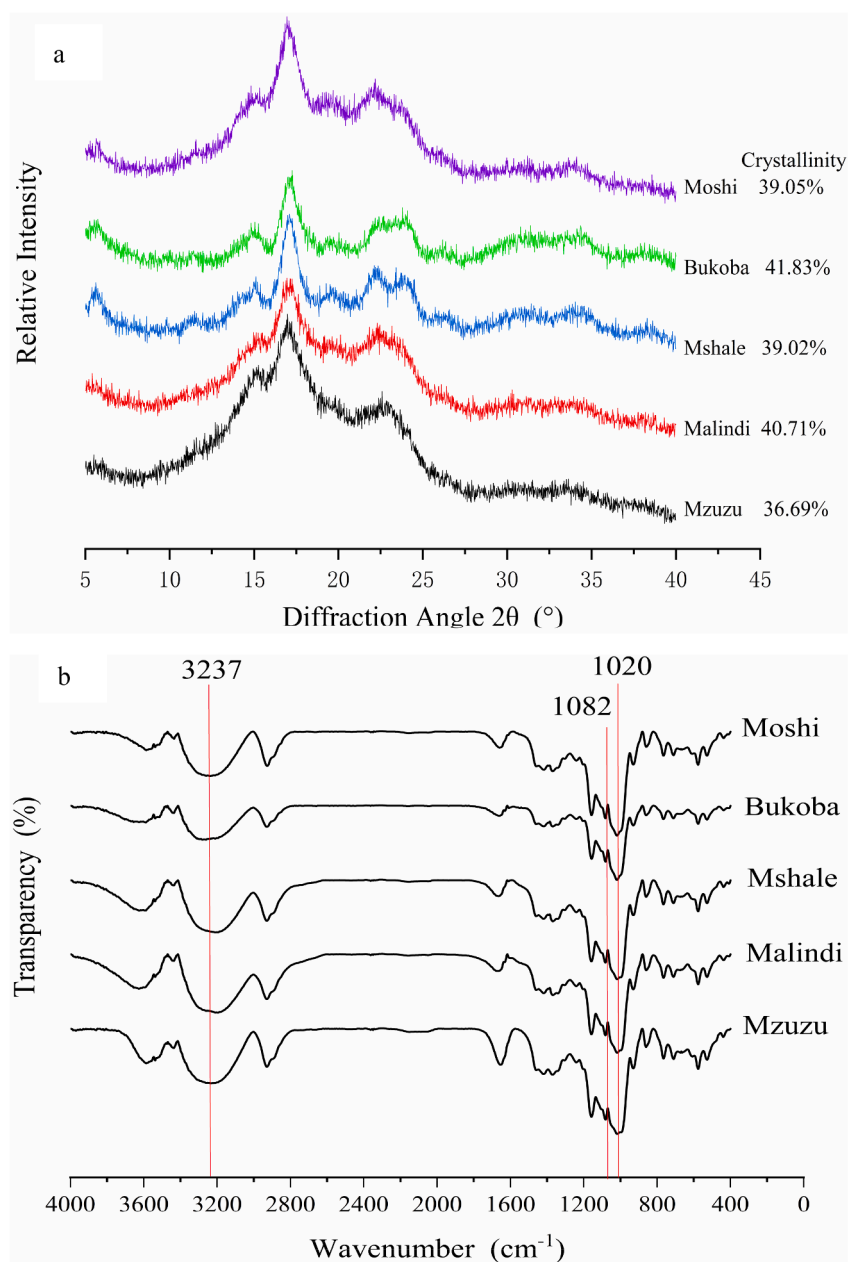


Fig. 2. XRD pattern and crystallinity of banana starches (a). FT-IR spectrum of banana starches (b).

which is called short-range order and recorded as DO (Jiang et al., 2015). DD is expressed by the intensity ratio at $995 \text{ cm}^{-1}/1022 \text{ cm}^{-1}$. All starches displayed similar infrared spectra with DO of 1.160 ± 0.006 – 1.196 ± 0.001 and DD of 0.894 ± 0.008 – 0.951 ± 0.039

(Table 2). Mzuzu with highest amylose content had the lowest DO, indicating that it had the largest amorphous region. Bukoba with lowest amylose content showed higher DO, suggesting that it had the more crystalline region. The results were substantially consistent with the

results obtained by XRD. The values of DO were greater than those (0.565–0.607) of pumpkin starch reported by Yuan et al. (2021), thus, banana starch had a tighter structure that was more difficult to break down than pumpkin starch.

Solubility (S) and swelling power (SP)

The S and SP of banana starches at 85 °C are exhibited in Table 2. The S value of different banana starches ranged from $2.50 \pm 0.42\%$ to $4.40 \pm 0.57\%$, which was lower than that of corn starch ($\sim 10\%$) with an amylose content of 33.19% reported by Li et al. (2015). The variance could be attributed to the more ordered and compact structure of banana starch. No considerable difference in S was observed among Malindi, Mshale and Bukoba ($P > 0.05$), but their S values were significantly lower than those of Mzuzu and Moshi ($P < 0.05$). The SP value of the five banana starch varieties was not substantially different ($P > 0.05$), ranging from 11.27 ± 0.04 to 12.48 ± 0.71 g/g with an average of 11.96 g/g. In comparison to corn, chayote, and cassava starches, banana starch swelled more slowly and displayed lower SP, suggesting that there was a strong micellar arrangement in banana starch that needed to be broken (Ratnayake, Hoover, & Warkentin, 2002). The lower S and SP of banana starches may be ascribed to the higher amylose content (Table 1), because amylose played an important role in limiting the water absorption and expansion of starch (Khoosani, Bekhit, & Birch, 2019). In addition, the banana starch granules with smooth and dense surfaces were detrimental to water infiltration into the granules for starch hydration and leaching (Du et al., 2020). However, the opposite conclusion was found in Mzuzu with the highest amylose content ($39.50 \pm 0.08\%$) and the highest S ($4.40 \pm 0.57\%$). Similar results were reported by Utrilla-Coello et al. (2014) on varieties (*Enano*, *Morado*, *Valery* and *Macho*) grown in Mexico. Amylose is associated with the amorphous part of starch particles, the effective penetration of water promoted by higher temperature is more important in these particle areas (Utrilla-Coello et al., 2014). As analyzed before, Mzuzu had the largest amorphous region and might contain more short branched chains, thus it was difficult to form thermally stable microcrystals, resulting in the maximum solubility of Mzuzu. This was also consistent with the lowest gelatinization temperature of Mzuzu (Table 3).

Table 3
Thermal and pasting properties of banana starches.

	Mzuzu	Malindi	Mshale	Bukoba	Moshi
T_o (°C)	57.33 $\pm 0.15d$	59.55 $\pm 0.97c$	62.00 $\pm 0.92a$	62.51 $\pm 0.15a$	60.37 $\pm 0.35b$
T_p (°C)	60.64 $\pm 0.19e$	62.76 $\pm 0.05d$	64.36 $\pm 0.08b$	65.17 $\pm 0.09a$	63.31 $\pm 0.25c$
T_c (°C)	66.02 $\pm 0.27d$	68.22 $\pm 0.14c$	69.06 $\pm 0.16b$	69.74 $\pm 0.05a$	68.26 $\pm 0.33c$
ΔH (J/g)	11.18 $\pm 0.79c$	12.59 $\pm 0.05b$	13.81 $\pm 0.49a$	13.65 $\pm 0.51a$	13.85 $\pm 0.86a$
Pasting temperature (°C)	74.3 $\pm 1.2a$	68.5 $\pm 0.0a$	71.0 $\pm 1.3a$	72.2 $\pm 0.6a$	70.2 $\pm 0.1a$
Peak viscosity (cP)	2897 $\pm 71a$	2801 $\pm 44b$	2620 $\pm 8c$	2717 $\pm 43b$	2248 $\pm 67d$
Breakdown (cP)	960 $\pm 41a$	615 $\pm 57c$	556 $\pm 7c$	748 $\pm 129b$	731 $\pm 34b$
Final viscosity (cP)	3201 $\pm 148a$	2769 $\pm 131b$	2812 $\pm 6b$	2737 $\pm 116b$	2163 $\pm 10c$
Setback (cP)	864 $\pm 118a$	583 $\pm 29c$	748 $\pm 4b$	768 $\pm 56b$	646 $\pm 22c$

Results are expressed by means \pm SD ($n = 2$). Values with the different letters in the same column are significantly different ($P < 0.05$). T_o : Onset gelatinization temperature; T_p : Peak gelatinization temperature; T_c : Conclusion gelatinization temperature.

Thermal properties

The thermal properties of banana starches are summarized in Table 3. The onset gelatinization temperature (T_o , 57.33 ± 0.15 – 62.51 ± 0.15 °C), peak temperature (T_p , 60.64 ± 0.19 – 65.17 ± 0.09 °C), conclusion temperature (T_c , 66.02 ± 0.27 – 69.74 ± 0.05 °C), and gelatinization enthalpy (ΔH , 11.18 ± 0.79 – 13.85 ± 0.86 J/g) were lower than those of Mexican varieties (*Enano*, *Morado*, *Valery*, and *Macho*) reported by Utrilla-Coello et al. (2014), whereas the ΔH was higher than that of banana starches (8.04–9.47 J/g) from Colombia varieties (*Dominico Hartón*, *FHIA 20*, and *Gros Michel*) reported by Chávez-Salazar et al. (2017). The thermal properties of different starches varied according to the differences in environmental conditions for growth, varieties, and ripening stages. Mzuzu and Malindi showed wider gelatinization ranges than other varieties, which indicated that their starch granules were more heterogeneous and the arrangement of starch components in the granules may be different (Chávez-Salazar et al., 2017). Mzuzu displayed the lowest T_o and T_p , which was attributed to chain length of amylopectin and crystallinity. According to Hoover et al. (2010), the gelatinization temperature of starch is positively correlated with the chain length of amylopectin, and the long branched chains of amylopectin form thermally stable microcrystals. Hence, Mzuzu may contain more short branched chains and represented lower T_o . In addition, starch granule structure, particle size distribution, and starch purity could interfere with starch gelatinization. Few macromolecules, such as lipid and protein, prevented water from entering the crystalline region of starch granules owing to the higher starch purity of Mzuzu and Malindi varieties. Therefore, the gelatinization of Mzuzu and Malindi required lower phase transition temperature and energy. The ΔH values of Mshale, Bukoba, and Moshi were not remarkably different ($P > 0.05$), but they were significantly higher than those of Mzuzu and Malindi ($P < 0.05$). The results suggested that Mshale, Bukoba, and Moshi had more double helix arrangements for amylopectin chains (Agama-Acevedo et al., 2014).

Pasting properties

The pasting properties of banana starches are shown in Table 3. No significant difference in pasting temperature was observed among the banana starch varieties ($P > 0.05$). The highest pasting temperature was presented by Mzuzu owing to the high resistance of the starch granule to swelling, which may be related to its highest amylose content. The peak viscosity of banana starches significantly varied from 2248 ± 67 cP to 2897 ± 71 cP ($P < 0.05$), which was lower than that Mexican varieties (4026–4848 cP) reported by Agama-Acevedo et al. (2014), but was higher than those of corn starch (470 cP) and wheat starch (65 cP) (Zhang et al., 2005). The result suggested that banana starch paste had application potential as a functional starch thickener by right of its high viscosity at 95 °C. Peak viscosity reflects the ability of starch granules to absorb water and expand, which is in connection with the starch granule size, amylose-to-amylopectin ratio, and chain-length distribution of amylopectin (Bashir, Tanya, Kumar, & Prakash, 2017). Moshi exhibited the lowest peak viscosity in the present study, which indicated that the Moshi starch had a minor compact arrangement of amylopectin (Agama-Acevedo et al., 2014). The breakdown and setback which reflect the hot paste stability at 95 °C and cold paste stability at 50 °C of the starch samples were 556 ± 7 – 960 ± 41 cP and 646 ± 22 – 864 ± 118 cP, respectively. The breakdown value of starch paste is correlated with the content of long branched chains in the starch, the setback is in line with the amylose content. Malindi and Mshale presented lower breakdown values, which suggested that they possessed strong resistance to shear force and heat. The setback values of Malindi and Moshi were lower, indicating their favourable cold paste stability and low tendency of retrogradation. Therefore, banana starch is suitable for making elastic foods such as Chinese vermicelli, besides, it showed better properties that are comparable to slightly cross-linked starch and are expected to be

used in various applications requiring stable viscosity to reduce and replace the use of chemically cross-linked starches (Kaur et al., 2020).

Rheological properties

The steady-state flow

The relationship between shear stress and shear rate of banana starches was analyzed and fitted to the Herschel-Bulkley ($\tau = \tau_0 + K\dot{\gamma}^n$) mathematical model (Table 4, supplementary materials). The coefficient of determination (R^2) of banana starch pastes was 0.9991–0.9999, indicating that this model can describe the flow characteristic of different starch pastes well even at low shear rates (Li & Zhu, 2017). The yield stress (τ_0) refers to the force required when the fluid begins to flow and the consistency coefficient (K) reflects the viscosity of the starch paste which is related to the consistency or concentration of the fluid.

The lower τ_0 and higher K value of Malindi indicated it has better liquidity and thickening ability. The flow behavior index (n) reflects the difference between non-Newtonian fluid and Newtonian fluid and the system is pseudoplastic fluid when $0 < n < 1$. The value of n ranged from 0.55 to 0.66 (Table 4, supplementary materials), which indicated that banana starch pastes presented the pseudoplastic non-Newton fluidity behavior. The viscosity–shear rate curve also revealed a pseudoplastic behavior of banana starches (Fig. 3a), since the viscosity decreased with the shear rate increasing which exhibited shear thinning behavior of banana starches. The shear thinned starches could be used for producing lubricants and hydrogels (Punia et al., 2021), besides, the processing and production of shear thinning liquid is conducive to the filling material, transportation and molding of large film forming liquid, and can reduce the wear and energy loss and material loss of processing equipment.

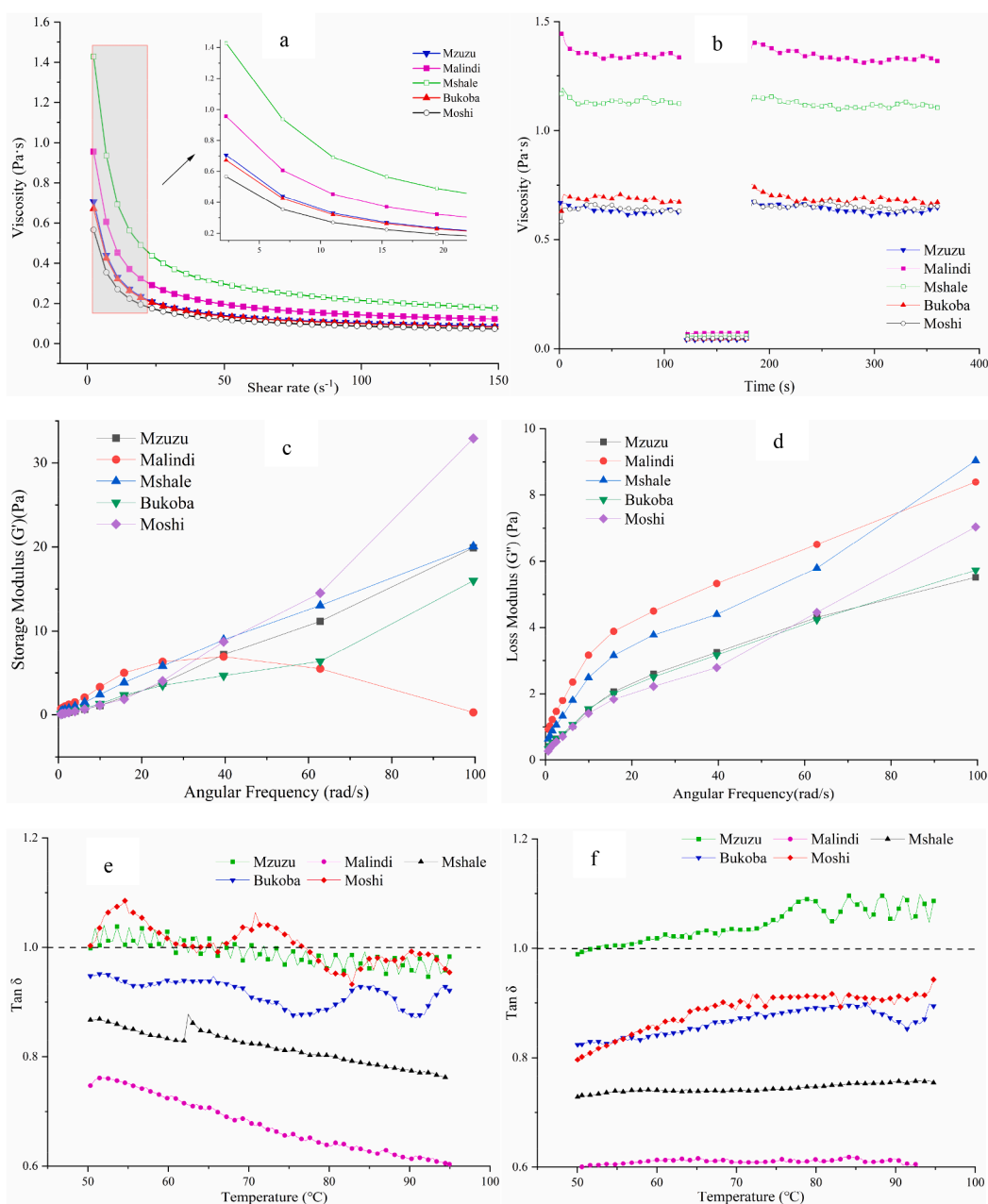


Fig. 3. Rheological properties of 2% (w/v) banana starch pastes. Viscosity–Shear rate profile (a); The restoration of shear structure (b). Dynamic rheological properties, frequency dependence of storage modulus G' (c) and loss modulus G'' (d). Variations of $\tan\delta$ with temperature, the heating process (e) and the cooling process (f).

The flow curves of starch pastes from different banana cultivars exhibited hysteresis loops. The area of hysteresis loop are positively correlated with thixotropy (Kong, Kasapis, Bertoft, & Corke, 2010) and large thixotropy indicates that the structure is difficult to restore after shear failure. The order of hysteresis loop area was Malindi > Mshale > Mzuzu > Moshi > Bukoba (Table 4, supplementary materials), which was probably affected by the content of amylose and internal chain structure of amylopectin (Wang et al., 2010). All starch pastes returned to the original viscosity after high-speed shear (Fig. 3b). The basically consistent results of thixotropy and the restoration of shear structure determination showed that banana starches easily restored to the original structure after shear action, had a better structure stability and recovery ability.

Dynamic rheological behavior

Frequency scanning can be used to explain the dynamic rheological behavior of samples (Kong, Kasapis, Bertoft, & Corke, 2010). The storage modulus (G') and loss modulus (G'') of banana starch varieties increased steadily during frequency scanning range except Malindi (Fig. 3c and d). The intersection of G' and G'' curves were found in all banana starches at 10–15 rad/s, from where the paste began to exhibit elastic behavior, which could be attributed to the rearrangement of leached amylose (Jiang et al., 2020). Two intersections of G' and G'' curves were found in Malindi at around 10 and 45 rad/s respectively, indicating a transform of adhesive-elastic-adhesive behavior. The higher G' of other banana starch pastes at higher angular frequency revealed a elastic gel structure with high degrees of cross-linking (Ai, & Jane, 2015), so it was suitable to prepare films at a appropriate concentration.

Temperature sweep

Due to the low concentration of starch paste, G' and G'' are small (<4.0 Pa), the degree of cross-linking between starch chains in the banana starch gel system is low and form a weak and soft gel, which in turn shows better mobility and processing adaptability. The $\tan\delta$ (G''/G') was slightly reduced in both the heating and cooling processes (Fig. 3e and 3f), which can be attributed to the continuous swelling of starch granules produced by a tightly packed network (Wu, Dai, Gan, Corke, & Zhu, 2016). At the heating stage (Fig. 3e), Mzuzu and Moshi represented sol to gel transitions at around 70 °C and 78 °C respectively and the cross point of $\tan\delta$ and “1” is considered to be the gelling point (Hsu, & Jamieson, 1993). The $\tan\delta$ of other varieties <1 throughout the range of temperature and exhibited elastic behavior consistently. During the cooling period (Fig. 3f), banana starch pastes performed elastic behavior throughout the temperature range except Mzuzu. With temperature decreasing, paste of Mzuzu was predominant in elastic behavior at around 51 °C, which could be considered as the gelling point of it. The elastic behaviors of banana starches made them excellent potential as additives for gel-type foods, providing a soft texture and maintaining food softness even at low temperatures. These properties of starches have potential applications in foods such as baby food, sauces, bread, jellies, sweets and sausages (Chel, Barbosa, Martinez, Gonzalez, & Betancur, 2016).

Conclusion

The starches isolated from five banana varieties showed variations in morphological structure and physicochemical properties, which make banana starch a possible candidate as replacement of traditional starch in different application fields. Banana starch had high amylose content, and the starch granules were smooth, dense, and resistant to hydrolysis. Therefore, banana starch can be considered for use to make edible films. Due to the higher RS content of cooked banana starches, the varieties had excellent resistance to enzyme digestion and had great potential in the field of functional dietary food products. The highest gelatinization peak viscosity was presented by the Mzuzu variety, which provides favorable conditions for its application as a thickener. Compared with

other varieties, Malindi and Mshale showed strong resistance to expansion and shear force and great paste stability. Thus, they can be utilized in various products requiring stable viscosity rather than chemically cross-linked starch. The shear-thinning behavior showed a better processing adaptability of banana starches. These findings provide data for the utilization of banana starch in different applications. Moreover, the production of banana starch will contribute to the banana trade and starch product market in Tanzania.

CRediT authorship contribution statement

Min Yang: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Lei Chang:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Fan Jiang:** Methodology, Validation. **Ning Zhao:** Validation, Software. **Pengtao Zheng:** Resources. **Jonatha Simbo:** Resources. **Xiuzhu Yu:** Writing – review & editing, Supervision. **Shuang-kui Du:** Conceptualization, Writing – review & editing, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.fochx.2022.100473>.

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