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Gelatinization Behavior, Morphological, and Chemical Properties of Flour of Cassava, Sago, and Wheat

Setya Budi Muhammad Abduh* *,1
***Nurwantoro* 1**
***Sri Mulyani* 1**
***Arif Rizqi Nurwidiyanto* 1**
***Sri Hestiningsih Widiyanti* 2**
[1] *Department of Food Technology, Faculty of Animal and Agricultural Sciences, Universitas Diponegoro, Semarang, Indonesia*
[2] *Regional Research and Innovation Agency of the Province of Central Java, Indonesia*
e-mail: setya.abduh@live.undip.ac.id

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Abstract. Gelatinization is an important property tailoring the functionalities of starch present in flour. This study aimed to investigate the gelatinization properties of Indonesian cassava and sago flours, namely tapioca, modified cassava flour, modified cassava starch, sago starch, and from soft and hard wheat. The gelatinization properties were investigated based on pasting and thermal properties, which were analyzed by means of a rapid visco analyzer (RVA) and differential scanning calorimetry (DSC), respectively. In addition, the morphological property was investigated using polarized microscopy, and chemical properties, namely solid, protein, lipid, ash, and crude fiber, were analyzed respectively using thermogravimetry, Kjeldahl, solvent extraction, and acid hydrolysis. It is found that flours of cassava, wheat and sago show pasting temperature (°C) of 69 – 71, 83 – 85, and 74; peak viscosity (cp) of 5400 – 5800, 2400 – 2700, and 2065; breakdown viscosity (cp) of 2600 – 4000, 900 – 1200, and 1493, setback viscosity (cp) of 1000 – 1500, 1000 – 1100, and 1063, final viscosity (cp) of 2800 – 3100, 2500 – 2700, and 1635. For gelatinization temperature (°C), they show onset temperature of 66 – 69, 54 – 60, and 72.04; peak temperature of 70 – 74, 60 – 64, and 75.93; conclusion temperature of 78 – 81, 66 – 69, and 80.99; and enthalpy change (J/g) of 8 – 12, 3 – 6, and 9.78. It can be concluded that flour and starch of cassava show the highest pasting profile (temperature and viscosity), while sago shows the lowest among the samples. Sago shows the highest gelatinization temperatures but the lowest enthalpy among samples. Starches of cassava show a round granular shape, smaller than wheat, while sago shows an oval shape. Considering the chemical composition, higher protein leads to higher pasting temperatures, and higher amylopectin content leads to higher peak and breakdown viscosities that might influence the gelatinization properties of flours.

Keywords: Chemical Composition, Gelatinization, Morphological Properties, Pasting Properties, Thermal Properties

INTRODUCTION

Starch naturally exists as a semicrystalline granular structure, a polymer of glucose in linear α 1,4-glycoside bonds (amylose) and branched at α (1,6)-glycoside bonds

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(amylopectin) (Liu *et al.*, 2023). The flour of starchy foods such as tuber, cereals, and stems are important for preparing processed foods. Depending on the preprocessing, they may present as isolated starch or starch altogether, with components coming from botanical origin. For instance, flour and starch of tubers and stems may contain cellulose, and those of cereals such as wheat contain protein. The presence of those components may alter the starch gelatinization.

Gelatinization refers to starch swelling at high temperatures under a moistened environment. The swelling is associated with thermal properties referring to the temperature at which starch initiates to melt, maximally melt, end to melt, and heat energy required to melt, which is important for starch processing (Zhao *et al.*, 2023). Starch's gelatinization properties play a pivotal role in its use as a thickening, stabilizing, emulsifying, gelling, and encapsulant (Zhao *et al.*, 2024). Starch granules absorb water and swell during gelatinization in a moist environment and high temperature, resulting in a viscous paste (Kumar and Khatkar, 2017; Li *et al.*, 2024). The temperature, viscosity, and behavior at which starch deforms to paste are pasting properties and affect the food product's texture, digestibility, and end-use (Ocheme *et al.*, 2018). Gelatinized starch is more susceptible to digesting enzymes (Leong *et al.*, 2019).

In Indonesia, cassava is widely prepared with tapioca flour utilized for various purposes. Despite its importance, the utilization of tapioca starch is limited because of its lower retrogradation resistance and thermal instability (Zhao *et al.*, 2022). Performance improvement has been attempted, such as fermentation involving lactic acid bacteria, thus resulting in a higher swelling power and solubility than unfermented tapioca (Karow *et al.*, 2024; Oyeyinka *et al.*, 2020). This flour is widely known as modified cassava flour (MOCAF). It is not only the performance improvement of MOCAF considered excellent, but its origin from a source other than wheat considers MOCAF healthier and gluten-free (Díaz *et al.*, 2019). During MOCAF production, a leftover pulp containing high nutrient content is generated (Tulu *et al.*, 2023). Here, we call the leftover starch modified cassava starch (MOCAS). Unlike MOCAF, which is growingly popular, MOCAS is unknown. Apart from cassava flour, sago flour isolated from stem was recently available in the marketplace. It is another potential of Indonesia as the plant is Indigenous in Maluku and Papua Island, and it yields high starch (Ehara *et al.*, 2018)

Along with Indonesia's native cassava and sago, wheat flour is very popular for its excellent processing performance as a material for various food products. Regarding processing purposes, there are two types of wheat flour, namely soft and hard, referring to lower and higher protein content. The protein content is associated with gluten, which is responsible for the expandability of the flour during processing into food products such as bakery products (Abduh *et al.*, 2023).

Tapioca has been reported to increase the textural and sensorial properties of *poundo* yam, white sauce, and gluten-free bread products (Bortnowska *et al.*, 2016; Oyeyinka *et al.*, 2023; Villanueva *et al.*, 2018) . Furthermore, geographical origin (Boonkor *et al.*, 2022) has been reported to affect cassava starch's pasting and thermal properties. For example, the pasting properties of cassava in Zambia vary with varieties, and so do the thermal properties of wheat (Chisenga *et al.*, 2019; Karwasra *et al.*, 2017). Sago starch varies in viscosity with islands of origin in Indonesia (Du *et al.*, 2020). However, to the author's knowledge, no study has been addressed on the pasting and thermal properties of flour starch of Indonesian Indigenous plants.

Therefore, this study aimed to investigate the gelatinization properties of Indonesian Indigenous plants' flour starch using pasting and thermal properties as the main parameters. Flours of cassava, sago, and wheat representing the main botanical origin of starchy foods, namely tuber, stem, and cereals, were investigated. Tapioca, MOCAF, and MOCAS from cassava were investigated to consider the effect of fiber and fermentation. Soft and hard wheat flours were investigated to consider the effect of protein. Starch microscopy and chemical composition were investigated to reveal the structural properties potentially responsible for the gelatinization properties of flour starch.

MATERIALS AND METHODS

Materials

Tapioca flour (*Rose Brand*) was obtained from PT Budi Starch & Sweetener Tbk. MOCAF and MOCAS (*Hend's*) were obtained from Mekarsari, Boyolali, Indonesia. Soft wheat flour (Kunci Biru, *Bogasari*) and hard wheat flour (*Cakra Kembar, Bogasari*) were obtained from PT Indofood Sukses Makmur Tbk. Sago flour (*Sasapua*) was obtained from PT Austindo Nusantara Jaya Boga.

Analysis of Water Absorption Capacity

Starch gelatinization requires water. Therefore, water absorption capacity (WAC) was determined as follows (Begum *et al.*, 2021). Twenty-five grams of flour were dispersed in 10 – 20 mL of water and kneaded to achieve smoothness. Water absorption capacity was then calculated using Eq. (1).

$$WAC\ (\%) \frac{\text{Amount of water absorbed (ml)}}{\text{Weight of sample (g)}} \times 100 \quad (1)$$

Analysis of Pasting Properties

The pasting properties were analyzed using rapid visco analysis (RVA) 4500 (Laksono *et al.*, 2022; Qi *et al.*, 2021), (Perten Instruments, USA). As much of 3.5 g and 25 ml of water were transferred into a canister. The starch-water suspension was then stirred at 960 rpm for 1 min at 50 °C, then stirred again at 160 rpm, and then heated to 95 °C at a speed of 5.2 °C/min. The paste was held at 95 °C for 5 min, then cooled to 50 °C at a speed of 5.2 °C/min, and then kept at 50 °C for 2 min.

Analysis of Thermal Properties

The thermal properties were analyzed by means of Differential Scanning Calorimetry (DSC) (Abduh *et al.*, 2019) (Shimadzu DSC-60, Kyoto Japan). Three milligrams of starch were transferred into the DSC aluminum pan, added with 7 μL of water, and tightly sealed the DSC pan. After being equilibrated at room temperature for about 1.5 h, the pan was heated to 100 °C at a heating rate of 10 °C/min.

Analysis of Starch Morphology

Twenty milligrams of starch were transferred into a 2 mL centrifuge tube, and one milliliter of water was added. Subsequently, the tube was shaken to dissolve the starch. Then, one drop of suspension was poured onto a microscope slide and covered with a glass cover. An immersion oil was then dripped onto the cover glass before the starch was observed under polarized light microscopy (Olympus CX23 Biological Microscope LED Binocular, Tokyo Japan) (Liu *et al.*, 2019) at 100× magnification. The images were captured using micro cam software (China).

Analysis of Chemical Composition

Moisture content was measured using oven-drying method (AOAC, 1990). The obtained value was then used to determine the solid content. Protein content was determined using the Kjeldahl method (AOAC, 1990). Fat content was measured using the Soxhlet method (AOAC, 1990). Ash content was determined using the furnace method (AOAC, 1990). The crude fiber was determined using the acid-alkali digestion method (AOAC, 1990). The starch content was estimated by difference based on the carbohydrate content (AOAC, 1990) by considering solid content apart from ash, protein, fat, and crude fiber as starch.

Data Analysis

The data of water absorption capacity were analyzed using one-way analysis of variance (ANOVA) followed by Tukey's HSD post hoc test at 95% confidence interval using IBM SPSS Statistics version 29 (IBM Corporation, New York, USA). The chemical composition was presented in descriptive statistics in mean ± standard deviation. Pasting properties and thermal properties were presented in graphs and tables. Furthermore, a Pearson's Correlation Coefficient method using Microsoft Excel 2021 with a standard limit of correlation value of 0.7 was conducted on the data of pasting properties to the rest of the data of starch properties to gain an explanation regarding the determining factors for the pasting properties of starches.

RESULT AND DISCUSSION

Water Absorption Capacity

Table 1 shows the Water Absorption Capacity (WAC) of flour and starch from cassava, sago, and wheat. Of cassava origin, tapioca (70.00%) and MOCAS (76.00%) showed similar values in WAC, whereas in fact, MOCAF (96.00%) showed a significantly higher value than both tapioca's and MOCAS's.

Table 1. Water absorption capacity of tapioca starch, modified cassava flour (MOCAF), modified cassava starch (MOCAS), low protein (soft) wheat flour, high protein (hard) wheat flour, and sago starch

Starch	Water Absorption Capacity (%)
Tapioca	70.00 ± 2.00^{b}
MOCAF	96.00 ± 4.00^{c}
MOCAS	76.00 ± 8.00^{b}
Sago	72.67 ± 1.15^{b}
Soft Wheat	56.00 ± 0.00^{a}
Hard Wheat	60.67 ± 1.15^{a}

Values are expressed as means ± standard deviation (n=3). Means not sharing the same superscript are significantly different $p < 0.05$ analyzed using one-way ANOVA and Tukey's post hoc test.

The high WAC of MOCAF is suggested to be associated with the crude fiber (Table 4) originating from the cassava fiber. As reported, higher fiber provides a higher hydroxyl component (-OH) responsible for the water absorption capacity (Begum *et al.*, 2021). The fact that the protein of MOCAS is higher than that of tapioca (Table 4) could explain that the presence of proteins and starch reduced the density and provided more space for water to bind (Scott and Awika, 2023). The role of protein in the high WAC is also indicated in the wheat sample (Table 1 and Table 4). Hard wheat (60.67%) starch showed a higher WAC than soft (56.00%). Nevertheless, both the starches showed lower WAC than cassava origin. According to the previous finding (Shao *et al.*, 2023), protein and starch are important in WAC. The presence of the hydroxyl group and the breakdown of the starch crystalline structure are linked to an increase in WAC (Marta *et al.*, 2022).

Pasting Properties of Starch

Figure 1 shows the change in viscosity of starches and flours when being heated and cooled to represent their behavior during gelatinization and retrogradation. Table 2 presents some important parameters representing the pasting properties of corresponding starches and flours extracted from the RVA curves.

Pasting temperature (PT) is measured when the viscosity of the paste begins to increase due to heating (Balet *et al.*, 2019). PT of tapioca (69.50 °C), MOCAF (70.05 °C), and MOCAS (70.75) are shown to be comparable (Table 2). Wheat (83 – 84 °C) showed the highest PT (Table 2) and is suggested to be associated with more resistance to swelling of starch granules (Kumar and Khatkar, 2017) due to high amylose content (Table 4). As reported, higher amylose molecules tend to re-associate more easily than amylopectin (Biduski *et al.*, 2018).

Peak viscosity is measured from the final heating phase, where the starch granules reach the final swelling phase, eventually forming a starch paste with the highest viscosity (Balet *et al.*, 2019). Tapioca, MOCAF, and MOCAS showed the highest peak viscosity (PV) among starches. The low PV of MOCAF in the current study (5489 cp) agrees with a study elsewhere (Oyeyinka *et al.*, 2020).

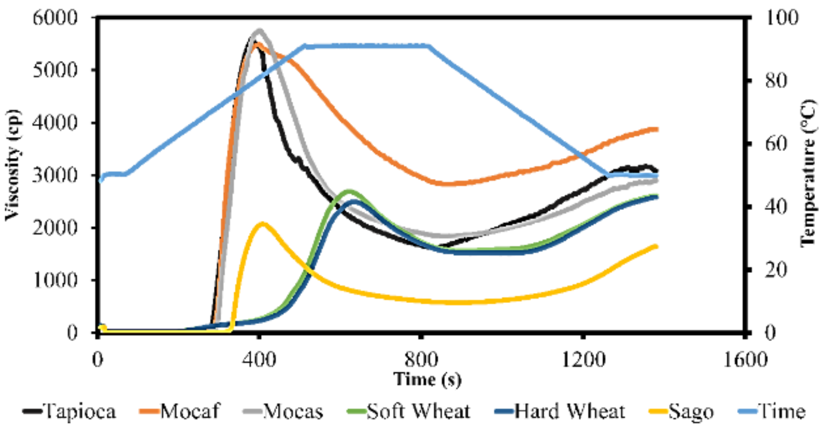

Fig. 1: Pasting properties of tapioca starch, modified cassava flour (MOCAF), modified cassava starch (MOCAS), low protein (soft) wheat flour, high protein (hard) wheat flour, and sago starch

Table 2: Pasting properties of tapioca starch, modified cassava flour (MOCAF), modified cassava starch (MOCAS), low protein (soft) wheat flour, high protein (hard) wheat flour, and sago starch

Types of Starch	Pasting Temperature (°C)	Peak Viscosity (cp)	Breakdown Viscosity (cp)	Setback Viscosity (cp)	Final Viscosity (cp)
Tapioca	69.50	5591	3974	1466	3083
MOCAF	70.05	5489	2665	1052	3876
MOCAS	70.75	5755	3918	1058	2895
Sago	74.00	2065	1493	1063	1635
Soft Wheat	83.15	2684	1121	1044	2607
Hard wheat	84.85	2491	975	1062	2578

The desirable consistency of the paste is achieved through a combination of high viscosity, substantial gel strength, and significant contributions from PV (Alamu *et al.*, 2017). Starch from hard wheat (2491 cp) showed higher PV than soft wheat (2684 cp), which may be due to the higher protein content in hard wheat than soft wheat (Table 4). Protein in starch paste may retain the integrity of starch granules through mechanical shearing during the viscosity test, which prevents the swelling of starch granules and reduces the amount of amylose that leaches out in suspension (Shang *et al.*, 2020). Hard wheat's fat content (Table 4) was lower than soft wheat's. Fat could form a complex with amylose (Table 4), prevent swelling of starch granules, and reduce PV (Katyal *et al.*, 2019).

Breakdown viscosity (BV) refers to the viscosity measured based on the difference between peak viscosity and holding strength, which is the lowest viscosity achieved during the holding phase (Balet *et al.*, 2019). Cassava starch showed the highest breakdown viscosity (BV) compared to the other starch. MOCAF (2665 cp) showed the lowest BV among cassava, agreeing with previous studies of starch (Oyeyinka *et al.*, 2020). In this study, sago (1493 cp) showed a low BV. However, hard wheat (975 cp) showed the lowest BV among its starches.

Setback viscosity (SV) indicates the tendency of starch granules to retrograde when being cooled due to recrystallization and reassembly of amylose molecules (Kumar and Khatkar, 2017). In the current study, starches of different botanical origins showed a close value of setback viscosity (SV) at 1000 cp, but only tapioca showed a distinctly high SV at 1466 cp. This result is similar to previous research (Chisenga *et al.*, 2019; Hustiany, 2014; Karwasra *et al.*, 2017) that tapioca (1454 cp) had higher setback viscosity than cassava (464 cp) and wheat (618 cp) starch. The SV of MOCAF and MOCAS appears to be relatively low. The relatively low SV of soft and hard wheat is suggested to be associated with gluten, hence slowing down the retrogradation (Scott and Awika, 2023).

Final viscosity (FV) is the final viscosity of the pasting cycle (Balet *et al.*, 2019). Final viscosity is measured when the holding temperature has been constant (50 °C) until there is an increase in viscosity within a certain period. Among flours and starches under the study, MOCAF showed the highest final viscosity (3876 cp), while sago showed the lowest (1635 cp).

Thermal Properties

Table 3 and Figure 2 presents parameters of the importance of thermal properties derived from the DSC thermograms. The transition temperatures of gelatinization (T_o, T_p, and T_c) indicate the internal structure of starch crystallinity (Tarahi *et al.*, 2022).

The onset temperature of gelatinization (T_o) indicates the initial temperature of gelatinization. The onset temperature of gelatinization (T_o) of cassava (66 – 69 °C), wheat (54 – 59 °C), and sago (72.04 °C) were found to agree with previous studies (Chatakanonda *et al.*, 2015; Wang *et al.*, 2021). The peak temperature of gelatinization (T_p) shows the peak temperature of gelatinization. The peak temperature of gelatinization (T_p) of cassava (71 – 74 °C), sago (75 °C), and wheat (60 – 64 °C) starches agree with previous studies (Chisenga *et al.*, 2019; Ng *et al.*, 2019; Wang *et al.*, 2021). The high T_p of sago starch indicates its high crystalline structure (Ghalambor *et al.*, 2022). The conclusion temperature of gelatinization (T_c) shows the final temperature of gelatinization. The conclusion temperature of gelatinization (T_c)

of cassava (78 – 81 °C), and sago (80.99 °C) agrees with previous studies (Chatakanonda *et al.*, 2015). Among the starches under the study, T_c of sago was found to be the highest, and of wheat was found to be the lowest (67 – 69 °C).

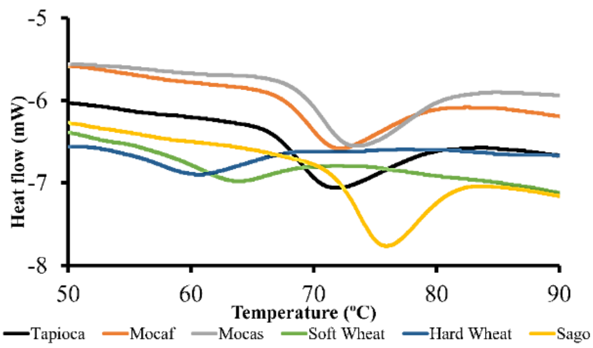

Fig. 2: Thermal properties of tapioca starch, modified cassava flour (MOCAF), modified cassava starch (MOCAS), low protein (soft) wheat flour, high protein (hard) wheat flour, and sago starch

The temperature range of gelatinization (*R*) of starches from tapioca, MOCAF, MOCAS, and hard wheat showed wide ranges (12.02, 11.27, 12.03, and 12.6, respectively), while soft wheat and sago showed a narrow range (9.16 and 8.95, respectively). The narrow *R* of wheat starches indicates stronger crystallinity (Abduh *et al.*, 2019).

The enthalpy change (*ΔH*) shows the crystallinity of the starch and the energy required to unravel the double helix (Tarahi *et al.*, 2022). The enthalpy changes (*ΔH*) of tapioca (10.21 J/g) and MOCAS (11.54 J/g) were similar, but MOCAF (8.75 J/g) was lower, indicating that MOCAF requires less energy than tapioca and MOCAS to gelatinize. Fermentation might play a role in the low *ΔH* of MOCAF due to the presence of fiber (Abduh *et al.*, 2019) Hard wheat showed a *ΔH* (5.28 J/g), indicating a stronger structure than soft wheat (3.57 J/g) suggested due to protein of the hard wheat (Table 4).

Table 3. Thermal properties of tapioca starch, modified cassava flour (MOCAF), modified cassava starch (MOCAS), low protein (soft) wheat flour, high protein (hard) wheat flour, and sago starch

Starch	T_o (°C)	T_p (°C)	T_c (°C)	R (°C)	ΔH (J/g)
Tapioca	66.96	71.87	78.98	12.02	10.21
MOCAF	67.76	72.15	79.03	11.27	8.75
MOCAS	68.44	73.53	80.47	12.03	11.54
Sago	72.04	75.93	80.99	8.95	9.78
Soft wheat	59.25	63.86	68.41	9.16	3.57
Hard wheat	54.86	60.71	67.46	12.6	5.28

T_o: onset temperature of gelatinization;
T_p: Peak temperature of gelatinization;
T_c: Conclusion temperature of gelatinization;
R: Temperature range of gelatinization;
ΔH: enthalpy change of gelatinization

Morphology

Microscopy images of starch granules from different botanical origins are presented in Figure 3. In this study, tapioca, MOCAF, and MOCAS showed the smallest granule size compared to the other starches. The granule size of tapioca is about 13.33 µm (Zhao *et al.*, 2022). Tapioca showed a smooth surface with a round shape (Figure 3). The smooth surface indicates tapioca is pure starch (Oyeyinka *et al.*, 2020). MOCAF exhibits slightly broken granules with pinholes and a rough surface (Figure 3). The shape of the fraction is not very noticeable, owing to MOCAF's short fermentation time (Oyeyinka *et al.*, 2020).

Wheat starch has two different sizes of granules in the same variety, namely A-type granules (flattened and about 20 µm) and B-type granules (spherical and about 7) (Thakur *et al.*, 2019). Soft wheat showed greater A-type granules but fewer B-type granules than hard wheat (Figure 3). This result might be due to the difference in volume distribution of A-type and B-type granules in soft and hard wheat.

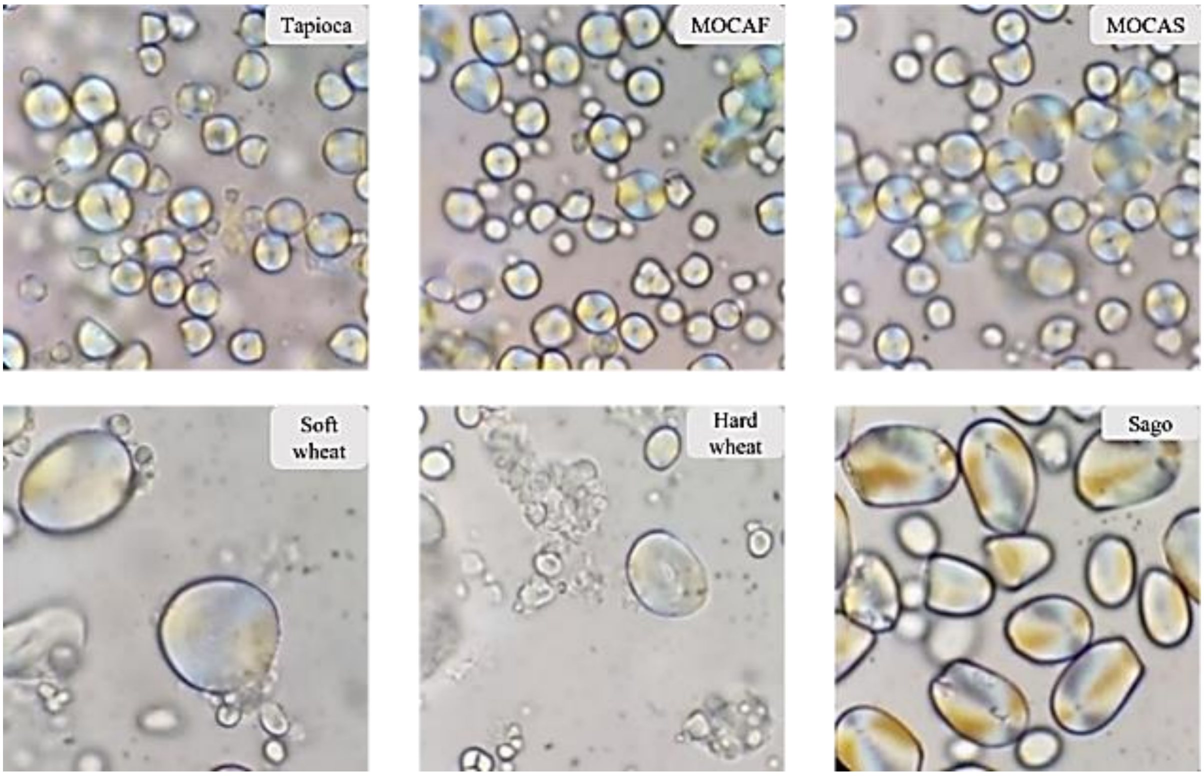

Fig. 3: Microscopy images (100 times magnification) of starch granules of tapioca, modified cassava flour (MOCAF), modified cassava starch (MOCAS), low protein (soft) wheat flour, high protein (hard) wheat flour, and sago starch

Chemical Composition

The chemical composition of starches and flour of different botanical origins is presented in Table 4. Tapioca showed the lowest total solids (87.76%) among starches, whereas MOCAF (89.89%) and MOCAS (89.00%) showed higher total solids than tapioca. The main component of flour is starch. Soft wheat showed the lowest starch content (68.93%). Tapioca showed the highest starch content (82.23%). The low starch content of MOCAF (80.47%) and MOCAS (78.77%) compared to tapioca might be due to the hydrolysis of starch into simple sugars during the manufacturing of MOCAF and MOCAS (Oyeyinka *et al.*, 2020).

Tapioca showed the lowest protein content (0.80%). MOCAF (2.40%) and MOCAS (4.14%) showed higher protein content than tapioca. Higher protein in fermented cassava has been found elsewhere (Hawashi *et al.*, 2019). Hard wheat shows the highest protein content (14.36%). The difference between hard wheat protein (14.36%) and soft wheat (9.25%) protein lies in the hardness of the wheat grain (Shang *et al.*, 2020). Tapioca showed the lowest fat content (1.70%) compared to MOCAF (2.40%) and MOCAS (2.58%).

Tapioca showed the lowest ash content (0.12%). MOCAF showed the highest ash content (1.35%). Sago showed the highest crude fiber content (3.79%), similar to a previous report (Ehara *et al.*, 2018). Hard wheat (2.16%) showed the lowest crude fiber content due to the loss of bran and germ during flour-making.

Table 4. Chemical composition of starches and flours from different botanical origins

Composition	Tapioca	Modified Cassava Flour	Modified Cassava Starch	Soft wheat	Hard wheat	Sago
Total Solid (%)	87.76 ± 0.15	89.89 ± 0.06	89.00 ± 0.05	89.16±0.03	88.01±0.11	88.54±0.39
Protein (%)	0.80 ± 0.16	2.26 ±0.14	4.14 ± 0.02	9.25 ± 0.31	14.36 ± 0.07	1.65 ± 0.38
Lipid (%)	1.70 ± 0.25	2.40 ± 0.26	2.58 ± 0.47	2.03 ± 0.01	1.94 ± 0.01	2.51 ± 0.12
Ash (%)	0.12 ± 0.09	1.35 ± 0.26	0.38 ± 0.35	0.81 ± 0.10	0.62 ± 0.00	0.18 ± 0.03
Crude Fiber (%)	2.91 ± 0.42	3.42 ± 0.51	3.13 ± 0.09	2.37 ± 0.03	2.16 ± 0.08	3.79 ± 0.03
Starch (Estimated) *	82.23 ± 0.08	80.47 ± 0.01	78.77 ± 0.33	74.70 ± 0.35	68.93 ± 0.11	80.41 ± 0.13
Amylose (Estimated)**	13.98^a	8.91^b	8.72^b	18.68^c	17.23^c	22.11^d
Amylopectin Estimation**	68.25^a	71.56^b	70.05^b	56.03^c	51.70^c	58.30^d

*Estimated from predetermined carbohydrate level by difference. **Values were estimated based on some previous studies: tapioca contains 17% amylose and 83% amylopectin of total starch;(Thakur *et al.*, 2019) MOCAF contains 11.03% amylose and 88.97% amylopectin;(Nurhayati *et al.*, 2018) wheat flour contains 25 % amylose and amylopectin 75 % of total starch;(Thakur *et al.*, 2019) sago flour contains 24 – 31% amylose and 69 – 76% amylopectin of total starch (Azfaralariff *et al.*, 2020)

Table 5. Correlation between viscosity and thermal properties and chemical composition of starch

Correlated Parameters	Correlation Coefficient
Pasting temperature (°C) – Onset temperature of gelatinization (T_o, °C)	-0.87
Pasting temperature (°C) – Peak temperature of gelatinization (T_p, °C)	-0.89
Pasting temperature (°C) – Conclusion temperature of gelatinization (T_c, °C)	-0.94
Pasting temperature (°C) – Enthalpy change (ΔH, J/g)	-0.90
Pasting temperature (°C) – Starch content (%)	-0.92
Pasting temperature (°C) – Amylopectin content (%)	-0.94
Pasting temperature (°C) – Protein content (%)	0.93
Pasting temperature (°C) – Crude fiber content (%)	-0.76
Pasting temperature (°C) – Water absorption capacity (%)	-0.76
Peak viscosity (*cp*) – Amylose content (%)	-0.91
Peak viscosity (*cp*) – Amylopectin content (%)	0.91
Breakdown viscosity (*cp*) – Conclusion temperature of gelatinization (T_c, °C)	0.70
Breakdown viscosity (*cp*) – Enthalpy change (ΔH, J/g)	0.80
Breakdown viscosity (*cp*) – Amylose content (%)	-0.73
Breakdown viscosity (*cp*) – Amylopectin content (%)	0.91
Final viscosity (*cp*) – Amylose content (%)	-0.85

Effect of Thermal Properties and Chemical Composition on The Pasting Properties

This section attempted to explain of the factors influencing the pasting viscosity properties of starches, considering thermal properties and chemical composition. Therefore, the parameters of pasting properties were correlated with thermal properties and chemical composition. For this purpose, an absolute correlation value of 0.7 was set. As a result, their correlation coefficients are presented in Table 5, providing some findings as follows.

Some parameters of pasting properties, namely pasting temperature, peak, and breakdown viscosities, were found to correlate with either thermal properties or chemical composition of starch, composing 16 correlations, 12 of which are negative.

Pasting temperature is negatively

correlated with onset (T_o), peak (T_p), conclusion (T_c) temperatures of gelatinization, and enthalpy change (ΔH, J/g) (Table 5) might indicate that starches used in the current study are high in elastic properties rather than viscous relating to the gel formation. Furthermore, the tendency of the starches to form gel is suggested to be associated with the starch content, amylopectin content, protein content (%), crude fiber content, and water absorption capacity (Table 5). As reported, enthalpy of gelatinization (ΔH) represents the degree of crystallization; hence, starch high in ΔH is low in swelling strength (Kumar and Khatkar, 2017).

Pasting temperature is negatively correlated with starch content (r=-0.92), amylopectin (r = -0.94), crude fiber (r=-0.76), and water absorption capacity (r=-0.76), indicating that pasting temperature tends to be high in flour low in starch, amylopectin, crude fiber and low in water absorption capacity.

The effect of amylopectin in lowering the pasting temperature (r=-0.94), increasing peak (r=0.91) and breakdown (r=0.91) viscosities is due to its greater ability to absorb water, which facilitates swelling and gelatinization at lower temperatures compared to amylose-rich starches (Karakelle *et al.*, 2020). Amylopectin is composed of a crystalline region of starch granules. When starch gelatinizes, it begins to bind water and leads the crystalline region of the starch to deform (Kumar and Khatkar, 2017).

The effect of crude fiber in lowering the pasting temperature (r=-0.76) is suggested due to fiber absorbing more water, leading to a relative increase in the concentration of the starches (Sun *et al.*, 2015; Adamczyk *et al.*, 2021) leading to a stronger swelling structure of amylopectin (Bai *et al.*, 2023) thus suppress the gel deformation.

Pasting temperature is positively correlated (r = 0.93) with starch protein, indicating that protein-starch interaction suppresses the pasting behavior (Tarahi *et al.*, 2022). It is suggested that the protein's water-binding capacity competes with starch for available water, thereby inhibiting starch granule swelling (Wu *et al.*, 2022). Thus, a higher temperature is required for starch to deform and paste (Biduski *et al.*, 2018).

The peak, breakdown, and final viscosities are negatively correlated with amylose (r = -0.91; -0.73; -0.85, respectively), which might indicate that starch with high amylose is low in peak viscosity (Biduski *et al.*, 2018). Peak viscosity is the maximum viscosity achieved during the heating and gelatinization of starch granules. The less entanglement of amylose structure during gelatinization leads to a low peak viscosity (Ribeiro *et al.*, 2024).

Breakdown viscosity reflects the stability of the starch paste during cooking. It is the difference between peak viscosity and trough viscosity (the lowest viscosity after holding at maximum temperature). Its low in higher amylose starches indicates that amylose is less stable under heat and shear conditions (Karakelle *et al.*, 2020).

Final viscosity is negatively correlated (r = -0.85) with amylose content, supported by (Cornejo-Ramírez *et al.*, 2018; Karakelle *et al.*, 2020; Kou *et al.*, 2022). Final viscosity is measured after cooling and reflects the retrogradation tendency of starch that is influenced by the reassociation of gelatinized starch.

Breakdown viscosity to be positively correlated (r = 0.80) with the enthalpy change (ΔH). Breakdown viscosity refers to the decrease in viscosity when gelatinized starch pastes are subjected to shear stress during processing. This property is critical in food technology as it affects texture and mouthfeel. The extent of gelatinization influences the breakdown viscosity; higher enthalpy changes typically correlate with increased viscosity due to more extensive swelling and leaching of amylose during gelatinization (Chipón *et al.*, 2022).

Possible Best Use of The Flours

Tapioca flour is best suited for applications like thickening agents, gelling, and encapsulating systems. Its high peak and setback viscosities make it ideal for creating thick pastes and firm gels. Due to its significant susceptibility to retrogradation, tapioca flour is particularly effective in products such as puddings, sauces, and some gluten-free baked goods, where a firm and stable gel structure is required.

Modified cassava flour (MOCAF) is highly recommended for gluten-free baked goods and processed foods that benefit from enhanced water absorption. Its high water absorption capacity (WAC), attributed to its fiber content, low breakdown viscosity, and high final viscosity, ensures stable textures in products like bread and pastries. Additionally, the fermentation process of producing MOCAF offers a healthier alternative, making it ideal for moisture-retentive baked goods.

Modified cassava starch (MOCAS) is ideal for products requiring moderate thickening and a balance between stability and gel strength, such as soups or gravies. Its moderate peak and final viscosity provide a consistent texture without excessive gel formation, while its higher protein content compared to tapioca contributes to enhanced structural integrity, making it versatile for a range of culinary applications.

Sago flour excels in high-temperature processing applications and products requiring low viscosity, such as noodles or clear soups. Its high gelatinization temperature and low viscosity parameters indicate strong resistance to swelling and retrogradation, making it suitable for processes requiring stability under heat. Additionally, its crystalline structure ensures it performs well in environments demanding thermal resilience.

Hard wheat flour is most suitable for bread-making and products that require high elasticity and expansion. With the highest protein content among the flours, hard wheat supports excellent gluten development, which is crucial for the structure and leavening of bread and other similar baked goods. Its high peak viscosity further reinforces its role in creating robust doughs.

Soft wheat flour, on the other hand, is ideal for cakes, pastries, and products that require a soft, tender texture. Its lower protein content and viscosity make it perfect for producing crumbly, delicate baked goods. The low elasticity provided by soft wheat flour ensures a light and tender final product.

Key insights emerge when analyzing these flours. MOCAF shows high fiber content enhances water absorption capacity and texture, making it particularly suitable for moisture-retentive products. The high protein content in hard wheat flour strengthens the dough structure, which is essential for leavened baked goods. High setback viscosity in flours like tapioca is advantageous for products requiring long shelf life or firmness. At the same time, low retrogradation resistance, as in MOCAF, is better suited for soft-textured foods. Finally, sago flour's thermal stability makes it an optimal choice for high-temperature processes or applications needing resistance to retrogradation.

CONCLUSIONS

This study investigated the gelatinization, pasting, and thermal properties of starch and flour derived from Indonesia's indigenous plants, including cassava (tapioca, MOCAF, and MOCAS), sago, and wheat (soft and hard varieties). The results demonstrated significant variations in water absorption capacity, pasting behaviors, and thermal characteristics among the starches, influenced by their botanical origins and compositional differences.

Cassava-derived products exhibited high water absorption capacities, with MOCAF showing the highest values due to its crude fiber content. Pasting properties revealed cassava starches, particularly tapioca, achieved high peak and setback viscosity, making them suitable for thickening applications. Sago starch exhibited high thermal stability, attributed to its crystallinity. Wheat starches, particularly hard wheat, displayed distinctive thermal and pasting properties due to their protein and fat content.

Morphological analysis highlighted distinct starch granule structures across samples, while chemical composition analysis provided insights into the influence of starch, fiber, and protein on functional properties. These findings emphasize the potential of starches from Indonesia's indigenous plants for diverse food applications and underscore the importance of further refining their processing techniques to enhance performance and stability.

Considering the use of the flours, tapioca flour excels in forming firm gels due to its high peak and setback viscosity. At the same time, MOCAF offers superior water absorption and texture stability, which is ideal for gluten-free baked goods. MOCAS provides balanced thickening and gel strength, suitable for soups and gravies. In contrast, sago flour’s thermal stability and low viscosity are ideal for high-temperature processes like noodle production. Hard wheat flour supports elasticity and gluten development for bread-making, while soft wheat flour creates tender textures for cakes and pastries.

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