

Physicochemical, Morphological, and Pasting Diversity of Native Sago Starch Samples from Seventeen Indonesian Regions

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Abstract

Sago is an important tropical crop that provides important benefits to humans because of its high starch content. Sago starch varies in structure and function depending on its origin. However, data regarding the physical, structural, viscosity, and functional properties of native Indonesian sago starch from diverse geographical sources remain limited. This study aimed to characterize the physical, structural, and pasting properties of local Indonesian sago starch. Physical analysis revealed a bright color (L^* values of 75.54–91.95), positive a^* values (0.60–6.03) indicating redness, and positive b^* values (2.57–18.57) indicating yellowness. SEM analysis showed sago starch granules ranging from oval to elliptical, with average diameters of 22.23–35.30 μm ; larger granules were associated with greater swelling and higher viscosity. Pasting properties (RVA) revealed significant differences in peak viscosity, ranging from 1028 to 5057 cP. Based on pasting behavior, sago starch samples from different origins were categorized into five clusters. Cluster 1 (Lingga, Luwu, Sentani) showed high swelling, low thermal stability, and high retrogradation. Cluster 2 (Tembilahan, Pontianak) exhibited low swelling and high granular stability. Cluster 3 (Timika) was prone to disintegration but formed

a rigid gel. Cluster 4 (Indragiri Hilir, Banjarmasin, Banda Aceh, Halmahera, Mamuju, Kendari, Central Moluccas, East Luwu, Meranti) displayed an intermediate profile with distinct degradation. Cluster 5 (North Luwu and Biak) showed low to moderate viscosity and retrogradation. FTIR spectra indicated that the sago starch retained its native structure. Integrated analysis suggests that native Indonesian sago starch samples from various geographical regions exhibit substantial variation in physicochemical and functional properties. These structural and functional properties provide a preliminary basis for evaluating the potential uses of the starch in region-specific food and industrial applications.

Keywords: granule morphology, *Metroxylon sagu*, Rapid Visco Analyzer, starch diversity, tropical starch

Introduction

The global food system faces mounting challenges driven by rapid population growth, climate change, land degradation, and disruptions to international supply chains for staple commodities. Recent instability in wheat and other cereal markets has further exposed the vulnerability of countries that depend

heavily on a narrow range of carbohydrate sources. This underscores the need to diversify toward sustainable carbohydrate crops, particularly those that can be cultivated under marginal agroecological conditions and strengthen local food security. In this context, sago palms (*Metroxylon* spp.) are a strategic tropical commodity because of their high starch productivity, adaptability to wetlands and marginal lands, and versatility for food, industrial, and bio-based applications.

Sago starch is the sago palm's primary economic product and has attracted growing interest as a multifunctional biopolymer. In its native form, sago starch has been used as a raw material for food products (Karim et al., 2008; Sidiq et al., 2022), renewable energy (Kartika et al., 2024), liquid sugar (Budiyanto et al., 2019), biodegradable packaging (Ruamcharoen et al., 2024), pharmaceutical excipients (Setiawan et al., 2022), biochar-based materials (Bohari et al., 2020), growing media (Jaya et al., 2024), and various traditional household and craft applications (Mahulette et al., 2021; Soegiono & Arifin, 2024). This functional diversity is closely linked to sago starch's physicochemical properties, including granule morphology, molecular organization, pasting behavior, hydration capacity, and response to heat treatment. As one of the world's largest sago-producing countries, Indonesia has considerable potential to develop sago starch as both a regionally important and globally relevant carbohydrate source. Sago production in Indonesia spans several key provinces, including Aceh, Riau, Riau Islands, South Kalimantan, South Sulawesi, Southeast Sulawesi, Maluku, North Maluku, West Papua, and Papua (Statistics of State Crops, 2023). However, optimizing sago utilization requires a deeper understanding of the properties and functional performance of native sago starch across different geographic origins.

The physical, structural, and functional properties of native sago starch can vary substantially depending on genetic background, growing environment, soil and climate conditions, plant maturity, extraction method, and post-

harvest handling (Karim et al., 2008). Such variability influences starch quality and suitability for specific applications. For example, granule size and morphology affect water absorption and swelling behavior; molecular interactions and hydrogen bonding influence gelatinization and paste stability; and color attributes may reflect differences in purity, residual pigments, and non-starch components (Karim et al., 2008; Sarungallo et al., 2021). Consequently, elucidating the structure–function relationships of native sago starch is essential to advance quality standardization, guide the selection of appropriate starch sources, and optimize its use in both food and non-food industries.

Starch color, morphology, and pasting properties can be altered by processing treatments such as ozone exposure (Cahyono et al., 2024), irradiation (Rostamabadi et al., 2023), cross-linking (Muljana et al., 2023), acetylation (Cahyono et al., 2024), drying (Bertulfo et al., 2022), and blanching (Jiao et al., 2019). In product manufacturing, further processing is also constrained by the characteristics of the raw materials employed (Che Hamzah et al., 2022). For instance, washing sago starch as a raw material can improve its functional characteristics (Budiyanto et al., 2023).

Although previous studies have reported the physicochemical and functional properties of sago starch, most have been limited to specific origins or have examined characteristics in isolation. Such fragmented approaches cannot reveal how regional differences in granule morphology, molecular structure, visual quality, and pasting properties collectively shape the overall performance of native sago starch. Comprehensive characterization therefore requires integrating multiple, complementary analytical techniques. Despite Indonesia's status as a major sago-producing country, integrated information on the structure–function relationships of native Indonesian sago starch from diverse origins remains limited. In particular, comparative studies that combine colorimetric, scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and Rapid Visco Analyzer (RVA) data within a

single interpretive framework are scarce. Such an approach is needed to determine whether regional differences in native sago starch are driven primarily by granule morphology, molecular interactions, hydration behavior, or pasting performance.

Accordingly, this study aimed to evaluate the physical, structural, and pasting properties of native sago starch collected from 17 major sago-producing regions in Indonesia using an integrated analytical framework comprising colorimetry, SEM, FTIR, and RVA. A secondary objective is to elucidate the relationships among geographic origin, granule morphology, molecular structure, and functional performance of Indonesian native sago starch. The findings provide a scientific basis for quality mapping, selection of region-specific raw material, and future studies on sago starch utilization in food and industrial applications.

Unlike previous studies that primarily focused on individual cultivars, specific regions, or selected physicochemical properties, this work comprehensively compared native sago starch from seventeen major sago-producing regions in Indonesia through an integrated evaluation of proximate composition, color, granule morphology, FTIR spectroscopy, and pasting properties. This approach yields new insights into the geographical variability of Indonesian native sago starch and offers a scientific basis for raw material selection and its potential utilization in diverse food-processing applications. Starch characteristics are influenced not only by post-harvest processing but also by genetic background and environmental conditions during plant growth. Therefore, evaluating starch properties from geographically diverse sago-growing regions can provide valuable baseline data for sago starch quality mapping and application-oriented research.

Materials and Methods

Materials

Sago starch samples were collected from 17 regions across the 12 sago-producing

provinces in Indonesia. These 17 regions represent the geographic, physicochemical, structural, and functional diversity of sago starch in Indonesia (Budiyanto et al., 2026). The sago starch used contained moisture (10.63%–15.37%), ash (0.03%–0.61%), fat (0%–0.14%), protein (0.15%–0.27%), carbohydrate (84.26%–94.93%) and starch (81.63%–86.25%) (Budiyanto et al., 2026). Sago starch samples were collected in 2024 from local processors in 17 regions from sago palms aged 9–12 years. The starch was produced by wet extraction, drying, sieving (100 mesh), packaging, and storage. Post-collection handling was standardized across 17 samples. Approximately 1.5 kg of dried sago starch was obtained in tightly closed plastic packaging. Next, the dried starch was milled and sieved (100 mesh) and stored until analysis. Analytical-grade chemicals were used analytical-grade chemicals. The equipment included a balance, Chroma Meter (CR-400, Konica Minolta, Japan), Rapid Visco Analyzer (Perten Instruments Co., Ltd., Stockholm, Sweden), blender, FTIR spectrometer (Thermo Fisher Scientific, Madison, WI, USA), scanning electron microscope (Hitachi SU3500), and various laboratory glassware.

We collected native sago starch samples from seventeen major sago-producing regions representing western, central, and eastern Indonesia. These regions encompass diverse agroecological conditions, including differences in rainfall, soil characteristics, and growing environments. Although the botanical varieties or accessions were not individually identified, the samples represent the geographical diversity of Indonesian native sago resources

Color Measurements

Color measurements were performed using a Chroma Meter with a D65 standard light source in the CIE $L^*a^*b^*C^*$ color space. L^* indicates a lightness value ranging from 0 (black) to 100 (white). a^* indicates the red (positive values) to green (negative values) axis. The b^* value represents the blue (negative values) to yellow (positive values) axis. C^* denotes color

intensity, with higher values corresponding to more vivid colors. The h° angles, representing the dominant perceived color, was calculated using the arctangent function of the b^*/a^* ratio and expressed in degrees. The h° angles of 0° , 90° , 180° , and 270° correspond to red, yellow, green, and blue, respectively (Baig et al., 2024). Color measurements were performed in triplicate, and the results are presented as mean $\pm$ standard deviation (SD).

Scanning Electron Microscopy (SEM)

We examined the morphology of sago starch granules using a scanning electron microscope (SEM; Leica Cambridge). Starch samples (1 g) were coated with a gold–palladium layer before observation at an accelerating voltage of 20 kV (Majzoobi et al., 2012). Ten measurements were performed for each starch sample. Granule diameters were randomly selected and expressed as mean $\pm$ SD.

Analysis of Pasting Properties

Pasting properties were determined using a Rapid Visco Analyzer (RVA4500, Perten Instruments, Sweden). Starch samples (3.5 g, 14% moisture basis) were dispersed in 25 ml of distilled water and analyzed using the STD1 profile. The test followed AACC Method 76–21.01 and ICC Standard No. 162, with an initial stirring speed of 960 rpm for 10 s, followed by 160 rpm throughout the heating–cooling cycle (Widowati et al., 2025).

FTIR Analysis

FTIR spectra of samples were recorded using a Thermo Scientific Nicolet iS-10 FTIR equipped with an ATR diamond crystal. Approximately 3 mg of the sample was placed directly on the ATR crystal. FTIR spectra were recorded over a wavenumber range of $4000\text{--}400\text{ cm}^{-1}$ at room temperature, averaging 64 scans at a resolution of 4 cm^{-1} . A background spectrum was measured before analysis and automatically subtracted (Nasir et al., 2020).

Data analysis

Data were analyzed using one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test for multiple comparisons at $p < 0.05$. Statistical analyses were performed using SAS Portable Version 9.1.3, while clustering was performed using RStudio Version 4.4.2 (Budiyanto et al., 2026). Data are expressed as mean $\pm$ standard deviation of three replicates.

Results and Discussion

The characteristics of sago starch were evaluated based on color, granule morphology, viscosity, and molecular structure. These attributes varied among regions and were associated with differences in processing conditions, including extraction and drying processes. To characterize sago starch, we performed color analysis, scanning electron microscopy (SEM), Rapid Visco Analyzer (RVA), and Fourier transform infrared spectroscopy (FTIR). RVA profiles the functional response of starch paste during heating and cooling cycles, whereas FTIR identifies molecular structural features and hydrogen-bonding patterns within the starch.

The observed variation in starch morphology, chemical composition, and functional properties among regions was associated with differences in genetic resources and environmental conditions, including soil type, rainfall, and temperature. Similar genotype $\times$ environment interactions have been reported to influence starch biosynthesis and functional properties in several tropical starch crops.

Color Characteristics of Sago Starch

Color, as an important physical parameter, was used to evaluate the visual characteristics of sago starch from various regions in Indonesia. Color values (L^* , a^* , b^* , C^* , and h°) reflected variations in starch appearance arising from differences in starch content, non-starch components, environmental factors, and

processing methods. The color characteristics of the 17 native sago starches are presented in Table 1.

L* values for sago starch ranged from 75.54 to 91.95, indicating brightness from relatively dark to bright white. Sago starch from Lingga, Indragiri Hilir, Pontianak, and Meranti exhibited L* values >90, suggesting high brightness and possibly low impurity content. In contrast, sago starch from Timika had the lowest L* value (75.54), indicating a darker color. This darker appearance may be attributed to residual pigments, non-starch components, impurities, and differences in extraction conditions (Aziz & Sobri, 2015). Food applications generally prefer starch with high lightness (high L* values). Mature starch tends to have higher L* values (Uthumporn et al., 2014). However, lightness (L*) has been reported to decrease, while a* tends to increase, with protein addition (Maya et al., 2020), hydrolysis (Budiyanto et al., 2019), and thermal treatment (Ying et al., 2020). Conversely,

increases in brightness (L*) have been attributed to enzyme treatment of sago starch, which reduces pigments and impurities (Pinyo et al., 2016), and to ozone oxidation (Sumardiono et al., 2021). In starch-based food applications, higher brightness values are generally preferred because they provide a more neutral appearance and greater formulation flexibility, particularly in products where whiteness is an important quality attribute.

Sago starch had positive a* (reddish) and b* (yellowish) values, ranging from 0.60–6.03 and 2.57–18.57, respectively. Higher a* values (>5) were observed in sago starch from Biak, Sentani, and Timika. Meanwhile, sago starch from Sentani and Timika showed higher positive b* values. High b* values indicated a more pronounced yellowish coloration. The color of sago starch indicated residual non-starch components that can alter visual quality and potentially affect the starch's hydration behavior and thermal response. Thermal treatment could increase the

Table 1

Color Characteristics of Native Sago Starch Samples from Seventeen Indonesian Regions

No	Origin sago starch	L	a*	b*	C*	h°
1	Lingga	91.95 ± 0.01 ^a	4.73 ± 0.08 ^c	4.41 ± 0.09 ^h	6.47 ± 0.12 ^{gh}	43.01 ± 0.07 ^j
2	Indragiri Hilir	90.66 ± 0.09 ^b	3.62 ± 0.03 ^{fg}	5.41 ± 0.07 ^f	6.50 ± 0.04 ^{gh}	56.12 ± 0.40 ^f
3	Banjarmasin	89.20 ± 0.12 ^{de}	2.71 ± 0.01 ⁱ	3.53 ± 0.08 ^{ij}	4.46 ± 0.06 ^j	52.51 ± 0.66 ^g
4	Banda Aceh	81.66 ± 0.02 ^j	3.45 ± 0.06 ^{fg}	8.64 ± 0.04 ^c	9.31 ± 0.05 ^{cd}	68.21 ± 0.28 ^b
5	Halmahera	88.90 ± 0.07 ^e	2.58 ± 0.03 ⁱ	2.57 ± 0.08 ^k	3.64 ± 0.06 ^k	44.84 ± 0.75 ⁱ
6	Mamuju	88.17 ± 0.05 ^f	3.10 ± 0.05 ^h	3.74 ± 0.02 ⁱ	4.86 ± 0.02 ⁱ	50.32 ± 0.14 ^h
7	Kendari	82.86 ± 0.11 ⁱ	0.60 ± 0.11 ⁱ	4.36 ± 0.08 ^h	4.40 ± 0.07 ^j	82.04 ± 0.60 ^a
8	Tembilahan	89.80 ± 0.03 ^c	3.09 ± 0.03 ^h	3.19 ± 0.02 ^j	4.44 ± 0.04 ^j	45.93 ± 0.14 ⁱ
9	Pontianak	90.68 ± 0.06 ^b	3.69 ± 0.06 ^f	4.89 ± 0.01 ^g	6.13 ± 0.02 ^h	52.94 ± 0.12 ^g
10	Central Moluccas	85.79 ± 0.03 ^g	3.96 ± 0.03 ^e	7.76 ± 0.10 ^d	8.71 ± 0.10 ^g	62.97 ± 0.18 ^d
11	Meranti	90.39 ± 0.14 ^b	3.73 ± 0.14 ^f	5.35 ± 0.07 ^f	6.52 ± 0.05 ^g	55.14 ± 0.40 ^f
12	North Luwu	85.38 ± 0.20 ^h	4.15 ± 0.20 ^d	8.74 ± 0.12 ^c	9.67 ± 0.14 ^c	64.58 ± 0.52 ^c
13	East Luwu	85.08 ± 0.08 ^h	3.65 ± 0.08 ^f	6.56 ± 0.04 ^e	7.51 ± 0.03 ^f	60.87 ± 0.28 ^e
14	Biak	89.51 ± 0.10 ^{cd}	6.03 ± 0.02 ^a	8.92 ± 0.06 ^c	10.77 ± 0.06 ^b	55.93 ± 0.11 ^f
15	Luwu	85.41 ± 0.20 ^h	2.96 ± 0.20 ^h	8.58 ± 0.13 ^c	9.08 ± 0.12 ^{de}	43.01 ± 0.07 ^j
16	Sentani	83.17 ± 0.20 ⁱ	5.37 ± 0.20 ^a	9.66 ± 0.19 ^b	11.05 ± 0.18 ^b	52.51 ± 0.30 ^g
17	Timika	75.54 ± 0.16 ^k	5.89 ± 0.18 ^a	18.57 ± 0.34 ^a	19.48 ± 0.39 ^a	44.84 ± 0.75 ⁱ

Notes. The values followed by the same letter in the same column indicate no significant difference by the Tukey test ($P < 0.05$). L*: lightness, a*: red (+) to green (–), b*: yellow (+) to blue (–), C*: chroma, h°: hue angle.

b^* value (yellowness) due to structural changes and mild Maillard reactions (Ying et al., 2020). The C^* value indicated the color intensity of sago starch. Sago starch from Timika, Sentani, and Biak had a high C^* , indicating a darker and less neutral color. Conversely, starch from Riau and Kalimantan had a lower C^* , indicating a paler and more neutral color. The h° values ranged from 43.01 to 82.04, indicating a color variation from reddish yellow to greenish-yellow. Sago starch from Kendari had the highest h° value (>80), indicating a relatively more neutral greenish-yellow color, while lower h° values in some Papuan samples indicated a stronger reddish-yellow tendency. The h° angle was used to determine the dominant color (Krisbianto & Minantyo, 2024).

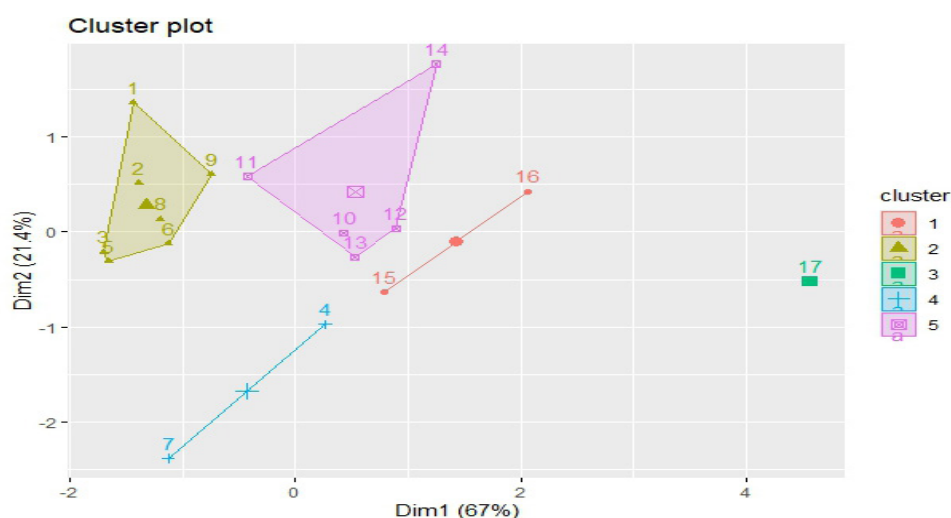
The color parameters (L^* , a^* , and b^*) of sago starch samples from 17 regions were clustered to determine the similarity of their color characteristics. Figure 1 shows that native Indonesian sago starch could be grouped into five clusters with varying levels of color similarity. Dim1 and Dim2 together explained 88.4% of the total variation in the dataset, indicating that the two-dimensional PCA plot captured most of the variability among the starch samples.

Cluster 1 showed that Luwu sago starch and Sentani sago starch had similar features, with a more intense red-yellow color than the other clusters. Cluster 2 comprised a relatively homogeneous group of sago starches from Lingga, Indragiri Hilir, Banjarmasin, Halmahera, Mamuju, Tembilahan, and Pontianak, characterized by a reasonably brilliant color and low yellow intensity. Cluster 3 was characterized exclusively by the sago starch sample from Timika, which exhibited a distinct color profile. The distinction was generally due to low L^* and high b^* values, indicating an intense yellow color. Cluster 4 consisted of Pontianak and Tembilahan sago starches. It represented a distinct group with similar color properties, but different from the main cluster. Cluster 5 included Central Moluccas, Meranti, North Luwu, East Luwu, and Biak, with a transition-area coloration pattern and relatively high variation in brightness and yellowness.

Overall, the clustering results indicated that the CIE $L^* a^* b^*$ color parameters effectively differentiated sago starches from different geographical origins. The color of sago starch were likely influenced by its origin/environment, maturity level, starch chemical composition,

Figure 1

Color clustering of Native Sago Starch Granules from Seventeen Indonesian Regions



Note. 1. Lingga, 2. Indragiri Hilir, 3. Banjarmasin, 4. Banda Aceh, 5. Halmahera, 6. Mamuju, 7. Kendari, 8. Tembilahan, 9. Pontianak, 10. Central Moluccas, 11. Meranti, 12. North Luwu, 13. East Luwu, 14. Biak, 15. Luwu, 16. Sentani, 17. Timika.

non-starch content, and processing. These color differences could be used to guide the selection of sago starch for specific processed food applications.

Morphological Characteristics

Figure 2 shows the morphology of sago starch as observed by SEM. Sago starch exhibited intact granules with smooth surfaces, with no fragmentation. This finding indicated that sago starch showed no obvious evidence of physical or chemical modification. The dominant granule shapes were oval, elliptical, and irregular oval. Most exhibited oval-to-elliptical shapes with smooth, intact surfaces. Starch from Lingga, Indragiri Hilir, Pontianak, and North Luwu exhibited a balanced oval-ellipsoidal morphology, while starch from Halmahera, Kendari, Tembilahan, and Luwu showed more elongated ellipsoidal granules. In contrast, starch from Biak, Sentani, and Timika was irregularly oval or irregularly elliptical.

Sago starch exhibited a smooth surface without fragmentation. Unmodified sago starch had a smooth, relatively intact surface, was oval (Marta et al., 2022), and partially spherical (Lee et al., 2022). Oval-shaped granules, which were generally large, were associated with higher peak viscosity and greater swelling (Mei et al., 2020). Larger granules were associated with greater hydration capacity and vigorous expansion, which had implications for starch pasting properties in food systems (Chi et al., 2021; Ying et al., 2020). Starch modification, by contrast, influenced gelatinization dynamics and final paste viscosity (Chi et al., 2021) and caused structural changes beneficial for industrial applications (Paternina-Contreras et al., 2025).

Starch granule characteristics influence water absorption, swelling, and gelatinization behavior. However, swelling capacity and pasting performance depend not only on granule size but also on intrinsic starch properties and granular structure. RVA analysis showed that Timika, Luwu, and Sentani had the highest peak viscosity values (5057, 4087.5, and 4004 cP, respectively). In contrast, Pontianak and

Tembilahan exhibited the lowest values (1028 and 1456 cP), indicating differences in starch structural properties among regions. The starch granules showed no apparent structural damage under the controlled extraction conditions (Teobaldi et al., 2025).

The average granule diameter varied among sago starch samples, ranging from 22.23 to 35.30 μm , indicating differences in granule size and morphology among samples from different regions. Extraction and drying did not change the fine granules of sago starch (Sarungallo et al., 2021). However, environmental conditions may have caused variability in sago starch morphology. This finding was consistent with the reported influence of region of origin and environment on starch morphology and production (Masluki et al., 2024).

The intact and smooth surface of native starch granules was considered important for normal gelatinization behavior and predictable pasting properties. These microstructural differences could have influenced water absorption, granule swelling, and pasting behavior during heating.

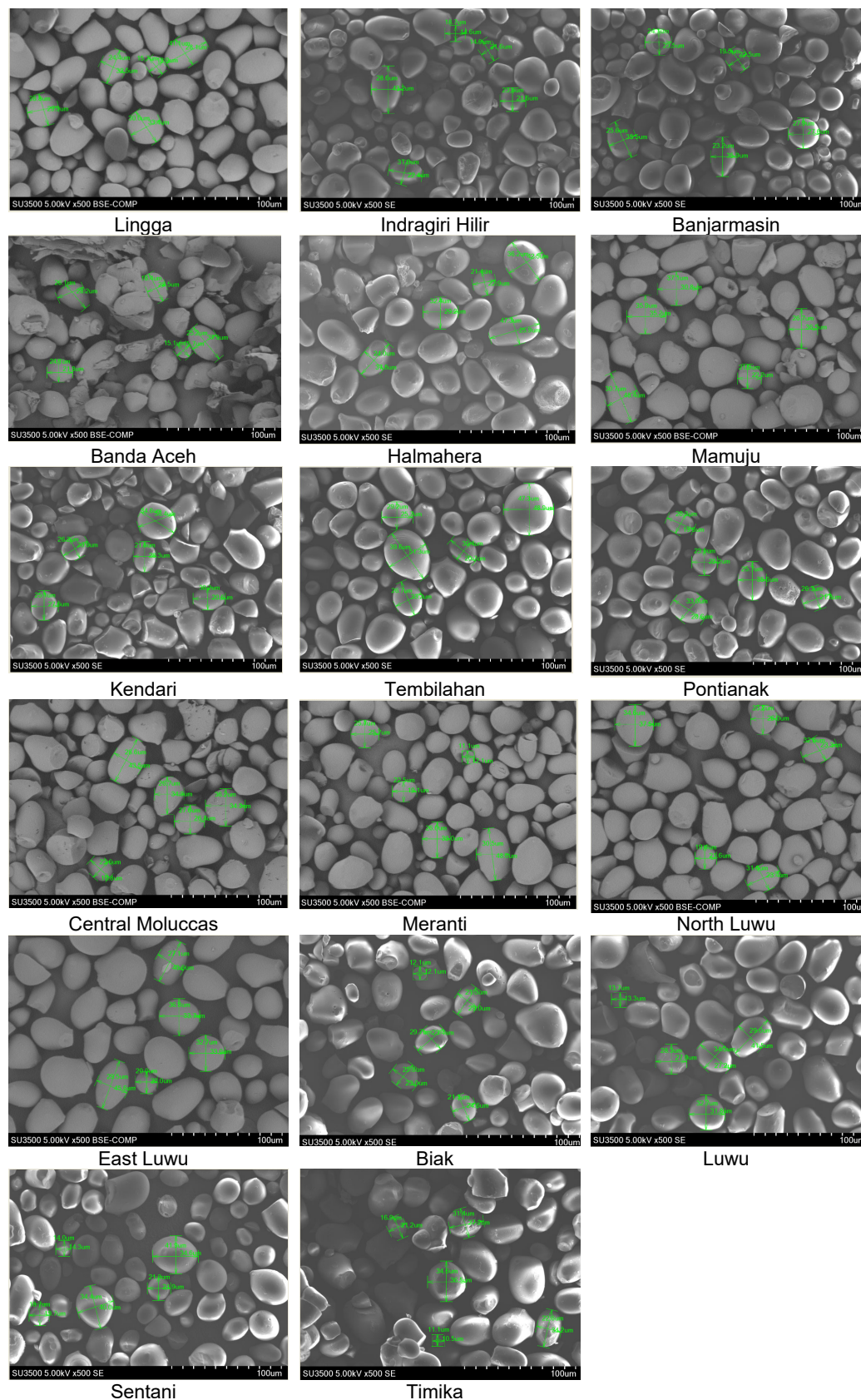
Pasting Properties of Native Indonesian Sago Starch

Pasting properties are important in industrial applications (Ghalambor et al., 2022). During measurement, the starch underwent heating, cooling, and holding phases, and its viscosity changed over time and temperature (Keskin et al., 2022). The pasting properties of 17 sago starch samples are presented in Table 3, whereas the gelatinization profiles are shown in Figure 3. RVA analysis revealed considerable variation in peak, trough, breakdown, final, and setback viscosity, as well as peak time and pasting temperature. These results indicated that geographic origin significantly affected the functional properties of native sago starch during heating and cooling.

Sago starch exhibited a gelatinization pattern unique to native starch. This process included an initial low-viscosity phase, a rapid increase in viscosity during heating, a decrease

Figure 2

Morphology of Native Sago Starch Granules from Seventeen Indonesian Regions



in viscosity during holding at high temperatures, and a recovery in viscosity during cooling. The viscosity increase reflected water absorption and granule swelling. The decrease in viscosity during the holding stage indicated heat- and shear-induced starch granule disruption. The subsequent increase in viscosity during cooling reflected the reassociation of starch molecules, particularly amylose.

Overall, all samples showed a consistent gelatinization pattern: a rapid increase in viscosity upon heating, a decrease during the high-temperature holding phase, and a recovery upon cooling. This behavior was consistent with the general characteristics of unmodified sago starch, in which granules absorbed water, swelled, partially fragmented at high temperatures, and then reorganized upon cooling. Differences in the pasting curves among regions indicated intrinsic variations in starch granule swelling and starch-molecule reassociation during cooling. These differences

may reflect variations in molecular organization (*amorphous* vs. *crystalline*) and internal starch interactions across regions.

Peak viscosity (PV) reflects the degree of starch swelling, susceptibility to granule disintegration, and water-absorption capacity (Bolaji et al., 2021; Ghoshal & Kaushal, 2020; Imoisi et al., 2020; Mei et al., 2020). PV varied significantly among samples, reflecting differences in granule swelling capacity and water-binding capacity. As shown in Table 3, PV ranged widely from 1028 cP (Pontianak) to 5057 cP (Timika). Starches from Timika, Sentani, and Luwu had significantly higher PV values. These values indicated greater granule expansion and a higher proportion of amorphous regions within the starch matrix. Samples with high PV generally had larger granules, more extensive swelling, and a relatively higher proportion of amorphous regions and/or varying degrees of amylose-to-amylopectin branching, facilitating easier water diffusion during heating. Previous

Table 2

Morphological Characteristics of Native Sago Starch Granules from Seventeen Indonesian Regions

No	Origin sago starch	Dominant granule shape	Mean diameter (µm)
1	Lingga, Riau Islands	Oval – ellipsoidal	28.28 ± 7.27ab
2	Indragiri Hilir, Riau	Oval – ellipsoidal	24.01 ± 8.51ab
3	Banjarmasin, South Kalimantan	Oval	26.52 ± 5.42ab
4	Banda Aceh, Aceh	Oval – irregular	24.05 ± 6.86ab
5	Halmahera, North Moluccas	Ellipsoidal	31.93 ± 8.80ab
6	Mamuju, West Sulawesi	Oval	32.54 ± 7.94ab
7	Kendari, Southeast Sulawesi	Ellipsoidal	27.12 ± 5.51ab
8	Tembilahan, Riau	Ellipsoidal	35.30 ± 10.79a
9	Pontianak, West Kalimantan	Oval – ellipsoidal	26.36 ± 4.94ab
10	Central Moluccas, Moluccas	Oval	30.10 ± 6.95ab
11	Meranti, Riau	Oval	25.37 ± 10.67ab
12	North Luwu, South Sulawesi	Oval – ellipsoidal	27.32 ± 6.22ab
13	East Luwu, South Sulawesi	Oval	31.90 ± 8.20ab
14	Biak, Papua	Irregular – oval	22.23 ± 6.05b
15	Luwu, South Sulawesi	Ellipsoidal	27.88 ± 8.70ab
16	Sentani, Papua	Irregular – ellipsoidal	26.08 ± 10.57ab
17	Timika, Papua	Irregular – oval	24.32 ± 9.32ab

Note. The values followed by the same letter in the same column indicate no significant difference by the Tukey test ($P < 0.05$).

research on native sago starch has also reported high PV, reaching 5343.5 cP (Perwatasari et al., 2025). Conversely, starch with low PV values (Pontianak, Tembilahan, and Biak) exhibited limited swelling, indicating a more compact granule structure and stronger internal hydrogen bonding. Other research on native sago starch reported a low PV of around 1774 cP (Xian et al., 2024).

Trough viscosity (TV) represented the viscosity remaining after granule breakdown during the holding phase. TV values for sago starch differed significantly ($p < 0.05$), ranging from 239 cP to 2866 cP. Higher TV values, particularly for Timika and Banda Aceh starches, indicated that both samples exhibited greater resistance to thermal and mechanical stress. Conversely, lower TV values indicate extensive granule disintegration during prolonged heating. This variation explains the differences in viscosity

trough depth observed in the RVA curves and highlighted differences in granule integrity among native sago starches.

Breakdown viscosity (BV) was defined as the difference between peak viscosity (PV) and trough viscosity (TV) (Ukpong et al., 2021). BV indicated the degree of structural damage to the starch during the holding period. BV reflected the susceptibility of swollen granules to disintegration under heat and shear, whereas the trough viscosity reflects the starch's ability to maintain stability at high temperatures (Imoisi et al., 2020). As shown in Table 3, BV varied significantly across regions, ranging from 714 cP (Banda Aceh) to 2693.5 cP (Sentani). A high BV indicated starch that swelled extensively but was more susceptible to structural collapse under heat and shear, whereas a low BV reflected greater thermal stability.

Table 3

Pasting Properties of Native Sago Starch Samples from Seventeen Indonesian Regions

No	PV (cP)	TV (cP)	BV (cP)	FV (cP)	SV (cP)	PTi (min)	PTe (°C)
1	3797 ± 0.00 ^c	1528 ± 20.5 ^c	2268.5 ± 20.5 ^b	2195 ± 2.8 ^d	666.5 ± 17.7 ^e	3.8 ± 0.0 ^c	78.3 ± 0.1 ^{bcd}
2	3038.5 ± 7.8 ^f	1189 ± 3.58 ^f	1849 ± 4.2 ^{cd}	1945 ± 8.5 ^f	755.5 ± 4.9 ^d	3.9 ± 0.05 ^{bc}	77.9 ± 0.5 ^{bcd}
3	2554 ± 5.7 ^g	952 ± 0.0 ^h	1602 ± 5.7 ^{ef}	1619 ± 4.9 ⁱ	667.5 ± 4.9 ^e	4.0 ± 0.05 ^{bc}	78.7 ± 0.6 ^{bc}
4	3051.5 ± 26.2 ^f	2337 ± 28.3 ^b	714.5 ± 2.1 ^h	3977 ± 16.9 ^a	1640 ± 11.3 ^a	4.4 ± 0.0 ^a	75.0 ± 0.07 ^e
5	2547.5 ± 3.5 ^g	803 ± 7.1 ⁱ	1744 ± 10.6 ^{ed}	1303.5 ± 2.1 ^k	500.5 ± 9.2 ^f	3.9 ± 0.0 ^{bc}	78.3 ± 0.07 ^{bcd}
6	3143 ± 11.3 ^f	953 ± 7.1 ^h	2190 ± 18.4 ^b	1471 ± 5.7 ^j	518 ± 12.7 ^f	3.8 ± 0.0 ^c	78.2 ± 0.04 ^{bcd}
7	3503.5 ± 26.2 ^d	1451 ± 10.6 ^d	2052 ± 15.7 ^{bc}	2091 ± 19.8 ^e	639.5 ± 9.2 ^e	3.8 ± 0.0 ^c	77.1 ± 0.57 ^d
8	1456 ± 1.4 ⁱ	638 ± 1.4 ^j	818 ± 0.0 ^h	1054 ± 1.4 ⁱ	416 ± 0.0 ^g	3.7 ± 0.0 ^c	77.9 ± 0.6 ^{bcd}
9	1028 ± 7.1 ^j	239 ± 2.8 ⁱ	789 ± 4.2 ^h	365 ± 2.8 ⁿ	126 ± 0.0 ⁱ	3.8 ± 0.05 ^c	78.3 ± 0.07 ^{bcd}
10	3052.5 ± 16.3 ^f	1259 ± 8.5 ^e	1793 ± 24.8 ^{ed}	1806 ± 10.6 ^g	547.5 ± 2.1 ^f	3.8 ± 0.0 ^c	77.5 ± 0.07 ^{cd}
11	3414 ± 32.5 ^{ed}	1300 ± 19.1 ^e	2113.5 ± 51.6 ^b	2048 ± 16.9 ^e	747.5 ± 2.1 ^d	3.9 ± 0.0 ^{bc}	78.3 ± 0.11 ^{bcd}
12	2010 ± 18.4 ^h	629.5 ± 9.2 ^e	1380.5 ± 9.2 ^{fg}	1046 ± 64.4 ⁱ	417 ± 55.3 ^g	3.7 ± 0.05 ^c	79.1 ± 0.04 ^b
13	3248.5 ± 21.9 ^{ef}	1078 ± 14.8 ^g	2170 ± 7.1 ^b	1700.5 ± 4.9 ^h	622 ± 9.9 ^e	3.9 ± 0.05 ^{bc}	78.7 ± 0.6 ^{bc}
14	1574 ± 24.0 ⁱ	355.5 ± 6.4 ^k	1218.5 ± 17.7 ^g	664 ± 19.1 ^m	309 ± 12.7 ^h	3.7 ± 0.05 ^c	79.1 ± 0.07 ^b
15	4087.5 ± 96.9 ^b	1527 ± 25.5 ^c	2560.5 ± 71.4 ^a	2194 ± 19.1 ^d	667.5 ± 6.4 ^e	4.0 ± 0.09 ^{bc}	77.8 ± 0.6 ^{bcd}
16	4004 ± 83.4 ^{bc}	1310 ± 37.5 ^e	2693.5 ± 45.9 ^a	2417 ± 13.4 ^c	1107 ± 24.0 ^b	4.0 ± 0.05 ^{bc}	80.75 ± 0.0 ^a
17	5057 ± 196.6 ^a	2866 ± 21.2 ^a	2191 ± 217.8 ^b	3839 ± 4.2 ^b	973 ± 16.9 ^c	4.3 ± 0.38 ^{ab}	78.625 ± 0.5 ^{bc}

Notes. The values followed by the same letter in the same column indicate no significant difference by the Tukey test ($P < 0.05$). PV = peak viscosity, TV = trough viscosity, BD = breakdown viscosity, FV = final viscosity, SV = setback viscosity, PTi = pasting time, Pte = peak temperature, 1. Lingga, 2. Indragiri Hilir, 3. Banjarmasin, 4. Banda Aceh, 5. Halmahera, 6. Mamuju, 7. Kendari, 8. Tembilahan, 9. Pontianak, 10. Central Moluccas, 11. Meranti, 12. North Luwu, 13. East Luwu, 14. Biak, 15. Luwu, 16. Sentani, 17. Timika.

Final viscosity (FV) represented the viscosity at the end of cooling and correlated with gelation ability, whereas setback viscosity (SV) reflected the extent of retrogradation and reorganization of starch molecules during the same phase (Bolaji et al., 2021). Setback viscosity, calculated as the difference between FV and TV, reflected the extent of post-cooling starch retrogradation. FV values ranged from 365 cP (Pontianak) to 3977 cP (Banda Aceh) and differed significantly ($p < 0.05$). Higher FV values indicated a stronger gel network forming during cooling, driven by the reassociation of soluble starch chains, particularly amylose. SV values ranged from 126 to 1640 cP and reflected differences in molecular reorganization during cooling. Higher setback viscosity (SV) indicated a greater tendency for starch molecules to reassociate during cooling, whereas lower SV suggested a reduced tendency toward molecular reassociation and retrogradation.

Peak time (PT) was defined as the time required to reach full development and just before weakening (Imoisi et al., 2020). Peak time ranged from 3.7 to 4.47 min, indicating differences in swelling and granule-breakdown rates. Pasting temperatures ranged from 75.0

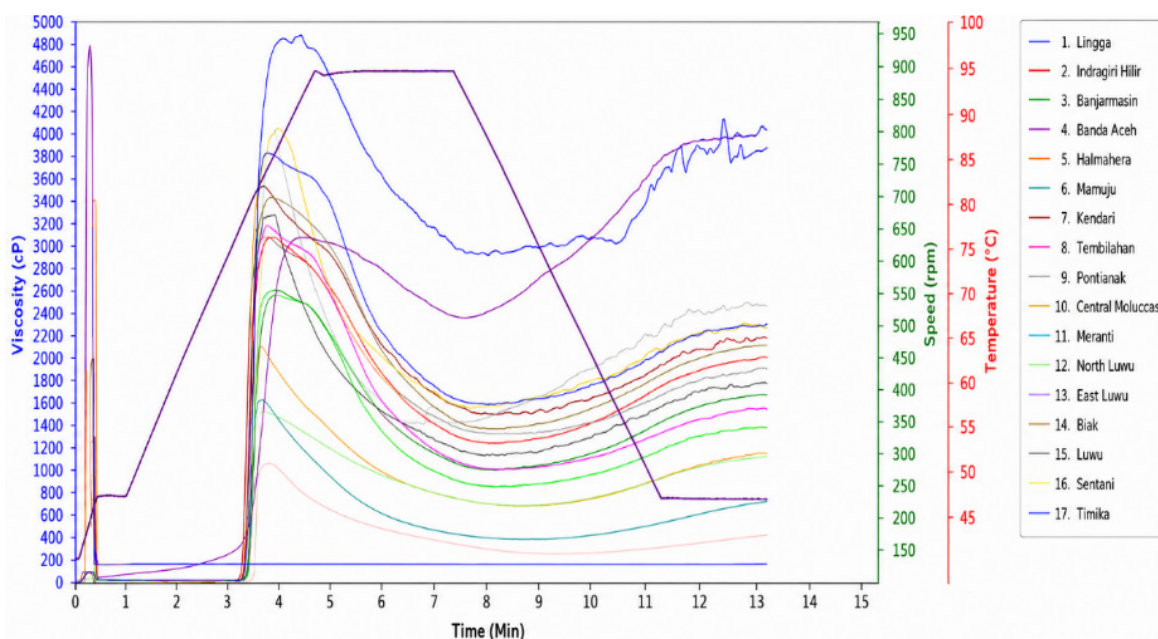
°C to 80.75 °C, reflecting variability in crystalline regularity and granule rigidity. Higher pasting temperatures indicated starches that require greater thermal energy to initiate gelatinization, consistent with a more ordered crystalline structure. Similar studies have shown that the pasting temperature (PT) of sago starch ranges from 78.9 °C to 80.2 °C (Du et al., 2020). A higher PT indicates that sago starch granules are more resistant to swelling.

The RVA profiles and parameters ($p < 0.05$) showed that native Indonesian sago starch samples from different geographic regions differed significantly in gelatinization behavior. This functional variation likely reflected heterogeneity in starch granule architecture and molecular organization driven by genetic and environmental factors. The structural and functional properties of native sago starch varied among regions, providing a preliminary basis for evaluating its potential utilization in future food and industrial applications.

Variations in the RVA profiles of 17 sago starch samples revealed fundamental differences in their molecular structure and composition (Figure 3). In the initial phase (0–3 min), viscosity was relatively stable and low, indicating that the

Figure 3

Pasting Profiles of Native Sago Starch Samples from Seventeen Indonesian Regions



starch granules maintained their integrity and had not yet entered the gelatinization stage. Subsequently, viscosity increased sharply between 3 and 5 min, reaching peak viscosity (PV). This stage represents the maximum hydration and swelling capacity of the starch granules before disintegration. Some samples exhibited very high peak viscosity values (approximately 4800–5000 cP), while others exhibited lower values (2500–3500 cP). Samples with high peak viscosity values generally had more intact granules, thus maximizing water absorption. Conversely, samples with lower values tended to have weaker granule structures, which affected granule expansion. After reaching the peak, all curves showed a marked decrease in viscosity toward the lowest viscosity (TV) during the holding stage at high temperature (~95°C). This decrease reflected granule breakdown, which was related to the granules' resistance to the combination of shear and heat. Samples with a sharp decrease indicated low thermal stability. Samples with a moderate decrease indicated that the granule structure was more resistant to degradation.

During the cooling phase (~8–13 min), viscosity continued to increase, reaching a final viscosity (FV). A high FV was associated with better texture stability in products requiring stability during cooling. This viscosity increase reflected starch-molecule recombination. Variations in final viscosity between samples indicated differences in retrogradation tendencies. Samples that showed a large increase in viscosity during cooling tended to undergo more retrogradation. Differences in viscosity decline (FV–TV) between samples indicated variations in gel stability and the tendency for gel formation during cooling. Higher setback viscosity suggested a greater tendency toward molecular reassociation and retrogradation, whereas lower setback viscosity indicated a reduced tendency for these processes. These differences in RVA profiles suggested substantial variation in the functional properties of native sago starch samples sourced from different geographic regions. Variations in growing conditions, soil conditions, and traditional processing methods are thought

to influence starch molecular structure, thereby affecting gelatinization behavior and pasting properties.

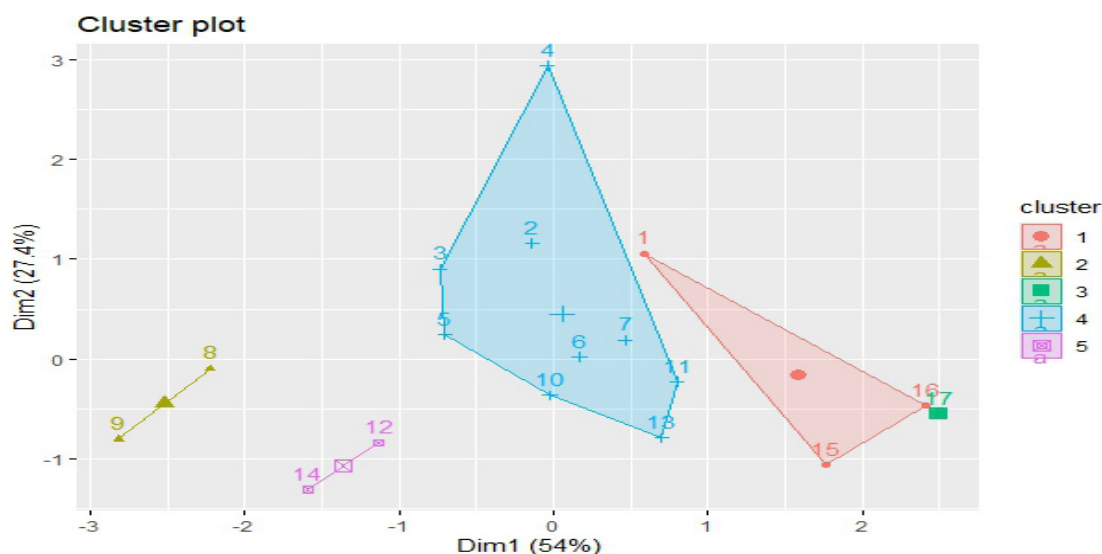
The RVA results indicated that native Indonesian sago starch exhibited highly diverse pasting properties. Differences in peak, breakdown, final, and setback viscosity indicated that each region had a distinct functional profile. Starches with high viscosity, such as those from Timika, Sentani, and Luwu, were considered well suited for pasting and gelling applications. In contrast, starches with lower peak and setback viscosity, such as those from Pontianak and Tembilahan, were presumed more suitable for products requiring lower paste viscosity or reduced retrogradation.

RVA clustering was performed to assess similarity in sago starch properties. The RVA cluster analysis revealed differences in sago starch pasting properties among the regions in Indonesia. The five clusters indicated that pasting behavior varied among samples from different geographical origins. The total diversity was 81.4% (Dim1: 54%; Dim2: 27.4%), as shown in Figure 4.

The pasting properties of sago starch granules differed among sources. Cluster 1 (Lingga, Luwu, Sentani) had high peak viscosity, breakdown, and setback, indicating strong swelling power but poor thermal stability and increased retrogradation. In contrast, Cluster 2 (Tembilahan and Pontianak) showed the lowest RVA metrics, indicating limited granule swelling and good granular stability. Cluster 3 (Timika) demonstrated greater granule disintegration during heating and higher setback viscosity, indicating that the starch granules were more susceptible to breakdown during heating and exhibited a greater tendency for molecular reassociation during cooling. Cluster 4 (Indragiri Hilir, Banjarmasin, Banda Aceh, Halmahera, Mamuju, Kendari, Central Moluccas, Meranti, East Luwu) exhibited intermediate pasting behavior with different setback ranges. Cluster 5 (North Luwu and Biak) generally showed low to moderate viscosity and retrogradation. Overall, the differences indicated that geographical origin significantly affected the functional properties of sago starch.

Figure 4

RVA Pasting Property Clustering of Native Sago Starch from Seventeen Indonesian Regions



Note. 1. Lingga, 2. Indragiri Hilir, 3. Banjarmasin, 4. Banda Aceh, 5. Halmahera, 6. Mamuju, 7. Kendari, 8. Tembilahan, 9. Pontianak, 10. Central Moluccas, 11. Meranti, 12. North Luwu, 13. East Luwu, 14. Biak, 15. Luwu, 16. Sentani, 17. Timika.

The RVA clustering showed that sago starch from different regions in Indonesia have different pasting properties, as reflected in peak viscosity, breakdown, and setback values. The differences indicated an effect of geographical origin on the swelling power, thermal stability, and retrogradation of sago starch.

FTIR Spectrum Characteristics of Sago Starch

The FTIR spectra of 17 sago starch samples are presented in Figure 5. FTIR analysis used a wavenumber range of 500 cm^{-1} to 4000 cm^{-1} , which is considered for functional group analysis in organic samples. (Othman et al., 2024). The FTIR spectra showed a relatively uniform absorption pattern. All samples had the same basic polysaccharide structure as native starch. However, slight differences were observed in the positions and intensities of certain peaks, particularly in the hydroxyl and water-related regions. The broad absorption band observed in the range of 3583–3630 cm^{-1} corresponded to the O–H stretching vibration. This indicated abundant hydroxyl groups and hydrogen-

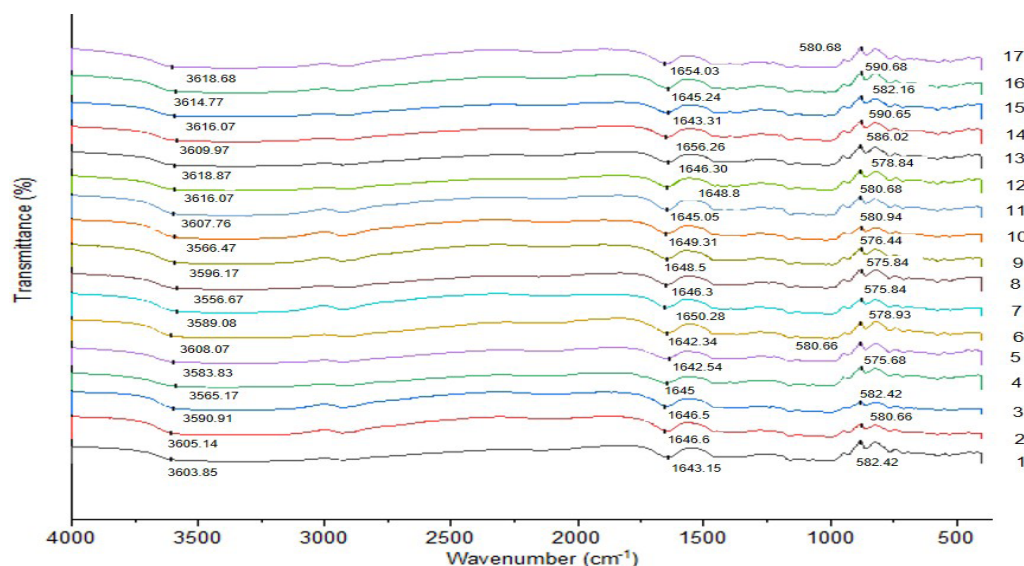
bonding interactions. This range is higher than the typical value reported for sago starch (3305 cm^{-1}), which is attributed to hydrogen-bonded O–H stretching (Taharuddin et al., 2022).

Another consistent absorption peak appeared in the 1643–1654 cm^{-1} range. This corresponds to the H–O–H bending vibration and indicates bound water in the starch granules. Small variations were observed between samples, such as at 1654.63 cm^{-1} (Timika) and 1643.13 cm^{-1} (Lingga). This variation indicated differences in water content or interactions between water and the starch matrix. This finding was comparable to the presence of water adsorbed at a peak around 1639 cm^{-1} (Taharuddin et al., 2022). Water interactions played an important role in swelling and solubility.

In the low wavenumber region, a fairly consistent peak was observed at 878–884 cm^{-1} . This finding was consistent with the broad absorption band in the 1000–990 cm^{-1} range (Salman et al., 2024). This condition reflected the characteristic C–O stretching vibrations of the C–O–C and C–O–H bonds in the glycosidic ring of sago starch.

Figure 5

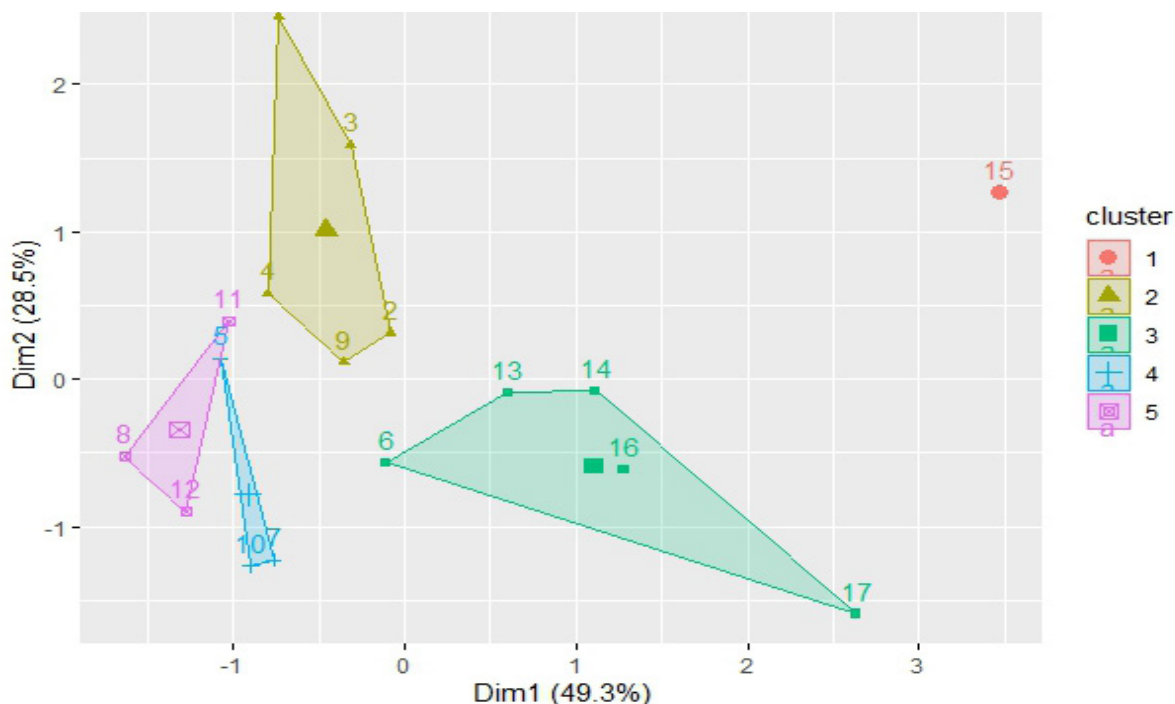
FTIR Spectra of Native Sago Starch Samples from Seventeen Indonesian Regions



Note. 1. Lingga, 2. Indragiri Hilir, 3. Banjarmasin, 4. Banda Aceh, 5. Halmahera, 6. Mamu, 7. Kendari, 8. Tembilahan, 9. Pontianak, 10. Central Moluccas, 11. Meranti, 12. North Luwu, 13. East Luwu, 14. Biak, 15. Luwu, 16. Sentani, 17. Timika.

Figure 6

FTIR Spectral Clustering of Native Sago Starch from Seventeen Indonesian Regions



Note. 1. Lingga, 2. Indragiri Hilir, 3. Banjarmasin, 4. Banda Aceh, 5. Halmahera, 6. Mamuju, 7. Kendari, 8. Tembilahan, 9. Pontianak, 10. Central Moluccas, 11. Meranti, 12. North Luwu, 13. East Luwu, 14. Biak, 15. Luwu, 16. Sentani, 17. Timika.

FTIR absorption patterns of sago starch in the hydroxyl stretching ($3583\text{--}3630\text{ cm}^{-1}$), bound water ($1643\text{--}1656\text{ cm}^{-1}$), and glycosidic ring ($575\text{--}590\text{ cm}^{-1}$) regions revealed differences in molecular characteristics among the samples. The first two principal components accounted for 77.8% of the total variation (Dim1 = 49.3% and Dim2 = 28.5%), representing spectral variation. Cluster 1 (Luwu) was the most distinct due to its unique molecular profile and a relatively high glycosidic ring absorption peak (590.65 cm^{-1}). Cluster 2 (Lingga, Indragiri Hilir, Banda Aceh, Banjarmasin, Pontianak) exhibited similar FTIR patterns and relatively low variation in molecular interactions, with Banda Aceh showing low bound water absorption (1643.15 cm^{-1}). Cluster 3 (Mamuju, East Luwu, Biak, Sentani, and Timika) displayed greater variation in hydrogen bonding and water interactions, with Timika showing the highest bound water absorption (1654.03 cm^{-1}). Cluster 4 (Halmahera, Kendari, Central Moluccas) showed comparable hydroxyl and glycosidic characteristics, with Halmahera exhibiting the highest hydroxyl stretching absorption (3630.87 cm^{-1}). Cluster 5 (Tembilahan, Meranti, North Luwu) showed similar spectral profiles and lower hydroxyl-stretching intensities. Overall, the clustering patterns indicated that geographical origin was associated with variations in hydrogen bonding, water-binding capacity, and the glycosidic structure in sago starch. These variations may influence functional properties such as swelling power, solubility, and gelatinization behavior.

Integrated SEM, FTIR, color, and RVA analyses indicated that the functional properties of native Indonesian sago starch are governed by a complex interplay among granule morphology, molecular organization, hydrogen-bonding patterns, and physicochemical composition. Native starch samples from different geographic regions exhibited substantial variation in starch structure, swelling capacity, gelatinization behavior, paste stability, and retrogradation tendency. This integrated characterization provides a scientific basis for understanding geographical variation in native sago starch and supports quality mapping and raw-material

selection for future application-oriented research. The findings also contribute to developing region-based quality standards for Indonesian sago starch.

Conclusions

Native sago starches from different regions of Indonesia exhibited substantial variability, particularly in color and pasting properties, whereas FTIR spectra were relatively consistent and retained the characteristic features of native starch polysaccharides. These variations suggest that color and RVA pasting behavior could serve as practical criteria for selecting sago starch for specific food or industrial applications. However, the relationship between granule size and pasting behavior was not straightforward, and no statistical correlation analysis was performed to establish a direct structure–function relationship. Consequently, these findings should be regarded as an initial basis for mapping the quality and functional diversity of Indonesian sago starch. Further studies using controlled sampling and comprehensive compositional and statistical analyses are needed to clarify the factors underlying the observed starch variability and structure–function relationships.

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