Science and Technology Indonesia
e-ISSN:2580-4391 *p*-ISSN:2580-4405
Vol. 11, No. 3, July 2026

Research Paper

Check for updates

Clustering in Chemical Characteristics and Contaminant Metal Levels of Indonesian Sago Starch: A Comprehensive Analysis of Purity and Quality

Agus Budiyanto[1,2*], Muhammad Romli[3*], Elisa Anggraeni[3], Edi I. Wiloso[4], Mulyana Hadipernata[5]

[1]*Doctoral Student, Agroindustrial Engineering Study Program, Graduate School, IPB University, Bogor, West Java, 16680, Indonesia*
[2]*Research Center for Equipment Manufacturing Technology, National Research and Innovation Agency, Banten, South Tangerang, 15314, Indonesia*
[3]*Division of Agroindustrial Engineering and Technology, Faculty of Engineering and Technology, IPB University, Bogor, West Java, 16680, Indonesia*
[4]*Research Center for Sustainable Industrial and Manufacturing Systems, National Research and Innovation Agency, Banten, South Tangerang, 15314, Indonesia*
[5]*Research Center for Process Technology, National Research and Innovation Agency, Banten, South Tangerang, 15314, Indonesia*
*__Corresponding author__: agusbudiyanto@apps.ipb.ac.id; mromli@apps.ipb.ac.id

Abstract
Indonesia has the most sago plantations in the world, which means that sago can be used for a wide range of things, including food, animal feed, fuel, fiber, and fertilizer. However, Indonesian sago starch can't be used more widely in either domestic or international markets because there isn't enough information about its chemical composition and contaminant levels. This study examines the chemical composition and heavy metal levels of sago starch from various regions of Indonesia. The results show that the chemical properties of sago starch vary from province to province. For example, the carbohydrate content ranges from 84.26% to 94.93%, while the fat and protein content are relatively low. There are also reports of differences in the amounts of amylose and amylopectin. The levels of heavy metals are very low and meet international safety standards, which means that Indonesian sago starch is safe to eat. Sago starch from Indragiri Hilir, Banjarmasin, and Lingga exhibits chemical properties similar to those from Meranti, Indonesia's primary sago-producing region, suggesting their potential as alternative sources. The appropriate amounts of amylose and amylopectin in these areas make it suitable for food products that require very high flexibility. These results support improving the use of sago starch and help raise the quality and safety standards for Indonesian sago products.

Keywords
Clustering Analysis, Contaminant Metals, Indonesia, Quality, Sago Starch

Received: 2 January 2026, Accepted: 18 March 2026
https://doi.org/10.26554/sti.2026.11.3.758-772

1. INTRODUCTION

Indonesia has the largest sago plantation area in the world, with ten major sago-producing provinces: Aceh, Riau, Riau Islands, South Kalimantan, South Sulawesi, Southeast Sulawesi, Maluku, North Maluku, West Papua, and Papua (Statistik-Perkebunan, 2023). A single sago palm is capable of producing approximately 200–250 kg of wet starch per tree annually. When estimated based on planting density, this yield is equivalent to about 25 tons of dry starch per hectare (Ehara et al., 2018; Abbas et al., 2017). Due to its high carbohydrate content, reaching approximately 84.7 g per 100 g, sago starch is considered a promising alternative food source (Susanto et al., 2024). In addition, sago starch has a relatively low glycemic index and contains a notable amount of dietary fiber, which enhances its potential as a functional food ingredient (Wardono et al., 2021).

The sago starch production process involves several stages, from felling the sago palm, splitting the trunk, crushing the pith, extraction, washing, sedimentation, and drying (Budiyanto et al., 2023; Hammado et al., 2020; Azman et al., 2021). Extraction by grating, in particular, significantly impacts starch yield (Azman et al., 2021) and production capacity (Cipto and Parenden, 2022). Various pretreatment techniques, such as ultrasonic, microwave, and enzymatic, can improve the extraction yield and starch quality (Pinyo et al., 2017). Small farmers mainly produce sago starch in Indonesia, although it is also produced by micro, medium, and large industries.

Sago starch is essential for making local dishes such as papeda, which are closely liked to culture and nutrition (Setiawan et al., 2022). Sago starch, extracted from sago palms in regions such as Indonesia and India, is used as a thickener, stabilizer, and gelling agent in food products. Sago starch can be used in various food and non food industries due to its unique properties. The enhanced functional properties of modified sago starch indicate its potential as a viable alternative to conventional starch sources, including wheat (Lee et al., 2022).

Sago starch's physicochemical and functional properties make it suitable for application in food products such as Chinese steamed buns (Bunyasetthakun et al., 2020). In the non-food industry, sago starch is used for renewable fuels (Jahiding et al., 2024), innovative packaging materials (Fadhallah et al., 2023), with glycerol to increase the flexibility of films for various industrial purposes (Sondari and Iltizam, 2018), and coating materials for packaging (Tabari, 2017).

Understanding the chemical properties of sago starch is crucial for optimizing its use in various applications. Exploration of various chemical aspects of sago starch to improve its function and utility. Hydroxypropylation and cross linking of sago starch produce a modified starch with desired properties. The effect of cationization on the thermal profile, pasting, and emulsifying properties of sago starch, indicating changes in its chemical characteristics (Siau et al., 2004). A thorough understanding of sago starch's chemical properties is critical for optimizing its functional properties and enhancing its performance across a broad range of industrial and technological applications. Various chemical modification strategies have been developed to improve its functional performance. Hydroxypropylation, for example, enhances swelling capacity while decreasing gelatinization temperature and retrogradation behavior (Paramitasari et al., 2024). Cross linking treatments enhance thermal stability and resistance to viscosity degradation (Punia Bangar et al., 2024). In addition, cationization alters crystalline structure and granule morphology, thereby affecting thermal behavior (DSC) and pasting properties, while also enhancing emulsifying activity and stability (Nasir et al., 2020; Zhang et al., 2024). The high content of resistant starch in sago starch indicates its potential as a source of resistant starch (Zailani et al., 2023). The synthesis of graft copolymers and phosphorylated sago starch has shown improvements in adhesiveness, water absorption, and biodegradability, demonstrating the chemical versatility of sago starch (Sondari and Iltizam, 2018; Ng et al., 2018).

Currently, 75% of sago starch production is concentrated in Riau province (Statistik-Perkebunan, 2023), which is distributed both locally and internationally. This sago starch meets the chemical specifications required by consumers. While demand for sago starch continues to rise, production, particularly in Riau, has not kept pace. In contrast, Indonesia's sago plantation potential outside of Riau remains largely untapped. Despite the significant potential of Indonesian sago starch, its comprehensive characterization, hinders its use in both local and international markets. The effects of geographic and environmental factors on the chemical characteristics of sago starch are not well understood. One critical aspect that has received little attention is the presence of heavy metals, such as Pb, Cd, Hg, and As, which can come from soil, water, or processing methods. These heavy metals pose health risks and may affect the competitiveness of sago products in the global market. Therefore, strict monitoring is essential to ensure safety and compliance with international food standards.

An in-depth analysis of the chemical composition of sago starch from various regions in Indonesia is essential. This study will assess the proximate content, the proportions of starch, amylose, amylopectin, and the levels of metal contamination. These factors will indicate the quality and safety of sago starch sourced from several sago-producing regions in Indonesia. The novelty of this research lies in its comprehensive profile of chemical composition and metal contamination, which aims to enhance the utilization and export potential of Indonesian sago starch through clustering.

This study's theoretical foundation is bolstered by a conceptual framework that distinctly delineates exposure, vulnerability, and resilience concerning the quality and safety evaluation of sago starch. In this study, exposure refers to the measurable physicochemical and contaminant attributes of sago starch, including proximate composition, amylose–amylopectin ratio, pH, and heavy metal concentrations. These indicators represent observable conditions derived from laboratory analysis. Vulnerability refers to the susceptibility of starch quality to deterioration, regulatory non-compliance, or safety risks arising from intrinsic compositional characteristics (such as elevated moisture or ash content) and external environmental or processing factors.

Resilience refers to the capacity of regional sago production systems to maintain consistent and acceptable quality and safety standards despite variations in geography, environment, and processing methods. This study concludes that there is resilience because the performance of the indicators is the same across regions and the clustering outcomes stay the same no matter how the weights are set. By clarifying these dimensions, the clustering methodology surpasses simple statistical classification and is anchored in a unified theoretical framework of quality exposure patterns, vulnerability gradients, and regional resilience characteristics.

2. EXPERIMENTAL SECTION

2.1 Materials

The sago starch examined in this study was sourced from 17 prominent sago producing districts in Indonesia, encompassing 10 provinces with significant sago plantations. The regions encompass Banda Aceh, Meranti, Indragiri Hilir, Lingga, North Luwu, Luwu, Central Moluccas, Banjarmasin, Kendari, Mamuju, Biak, Sentani, Timika, and Pontianak. The choice of these sites was determined by their geographic diversity and substantial production capacity, deemed essential for obtaining representative samples. Each region has unique environmental conditions and production methods that may affect the attributes and quality of sago starch. Consequently, sampling from several areas was aimed at capturing the heterogeneity of sago starch produced across Indonesia. Furthermore, these locations function as significant hubs for sago processing, predominantly operated by Micro, Small, and Medium Enterprises (MSMEs). Thus, the sago starch samples sourced from MSMEs in these regions are deemed indicative of the overall conditions of sago starch production in Indonesia. The research assessed several physicochemical characteristics of the starch, including proximate composition, pH, total starch content, amylose and amylopectin levels, and heavy metal concentrations. The analytical techniques were generally conducted in line with the Indonesian National Standard (SNI). The SNI is the national standards system established by the National Standards Agency of Indonesia (BSN) to ensure the quality, safety, and reliability of products, processes, and services.

2.2 Methods

2.2.1 Determination of Proximate Composition

Moisture content was determined using the oven-drying method according to ISO-1666 (1996) at 130 °C for 1.5 h, followed by cooling in a desiccator prior to weighing. Protein content was analyzed using the Macro-Kjeldahl method (AOAC, 1995), with nitrogen content converted to protein using a factor of 6.25. Ash content was determined by dry ashing, and fat content was analyzed by Soxhlet extraction, both following AOAC (1995) procedures. All analyses were conducted in triplicate, and the results were expressed as percentages.

2.2.2 Determination of pH

The pH was analyzed using a magnetic stirrer to mix 0.1 g of the sample with 100 mL of distilled water in a glass beaker. The suspension was then measured with a calibrated pH meter at room temperature. The reading displayed on the pH meter was subsequently recorded (Sabirin et al., 2024).

2.2.3 Determination of Starch Content (SNI-3729, 2008)

Starch content was determined using the Luff–Schoorl method. A 5 g starch sample was hydrolyzed with 200 mL of 3% HCl under reflux for 3 h, then cooled, neutralized with 30% NaOH, and slightly acidified with 3% acetic acid. The solution was diluted to volume (500 mL), filtered, and an aliquot of 10 mL was reacted with 25 mL of Luff–Schoorl reagent and distilled water, heated to boiling for 10 min. After cooling, 25 mL of 25% H_2SO_4 and 15 mL of 20% KI were added, and the liberated iodine was titrated with 0.1 N sodium thiosulfate using starch as an indicator. Glucose content was calculated based on sodium thiosulfate consumption using the Luff–Schoorl table, and starch content was calculated as 0.90 × glucose content.

2.2.4 Determination of Metal Content of Sago Starch

2.2.4.1 Determination of Cd and Pb Content (SNI-3729, 2023)

A 10 g starch sample was dry-ashed in a furnace at 450 ± 5 °C until carbon-free. The ash was dissolved in 6 M HCl, evaporated to dryness, redissolved in 0.1 M HNO_3, and diluted to 50 mL with distilled water. Metal concentrations (Pb and Cd) were determined by Atomic Absorption Spectroscopy (AAS) at 283.3 nm and 228.8 nm, respectively, using calibration curves. Metal content was calculated from sample weight and the final solution volume.

2.2.4.2. Determination of Hg Content (SNI-3729, 2023)

A 0.5 g starch sample was digested with concentrated HNO_3 and H_2O_2 at 180 °C for ≥20 min, cooled, and diluted to 50 mL with distilled water. Mercury (Hg) concentration was determined by Atomic Absorption Spectrometry at 253.7 nm using reagent blanks and calibration standards. Hg content was calculated using the calibration curve, the final volume, and the sample weight.

2.2.4.3. Determination of As Content (SNI-3729, 2023)

A 0.5 g sample was digested with concentrated HNO_3 and H_2O_2 at 180 °C for ≥20 min, diluted to 50 mL, and an aliquot was dried, ashed at 450 ± 5 °C, and redissolved in 8 M HCl with KI addition. Arsenic (As) concentration was determined by Atomic Absorption Spectrometry at 253.7 nm using calibration curves, and results were calculated based on final volume and sample weight.

2.2.4.4. Determination of Sn Content (SNI-3729, 2023)

A 0.5 g starch sample was digested with HNO_3-HCl followed by H_2O_2 using microwave digestion at 180 °C for 20 min, cooled, and diluted to 50 mL. Tin (Sn) concentration was determined by Atomic Absorption Spectrometry at 286.3 or 235.5 nm using calibration curves, with analyses performed in duplicate.

2.2.5 Clustering Analysis and Composite Index Validation

2.2.5.1. Clustering Analysis

Clustering effectively classifies observations into homogeneous groups based on similarities in quantitative charac-teristics (Marhamah et al., 2023). Clustering was performed using the K-means algorithm to group observations into K clusters by minimizing within-cluster variation and maximizing between-cluster separation (Everitt and Hothorn, 2011).

2.2.5.2. Data Structure and Preprocessing

The dataset consisted of n sago starch samples and p measured variables arranged in a data matrix by calculating using Equation 1.

$$X = [x_{ij}], \quad i = 1, 2, \ldots, p \tag{1}$$

where x_{ij} denotes the value of the variable j for sample i. Range standardization was applied to account for differences in measurement scales, with calculations using Equation 2.

$$Z_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \tag{2}$$

where $\min(x_j)$ and $\max(x_j)$ represent the minimum and maximum of the variable j, and Z_{ij} are standardized values scaled to the 0-1 range to prevent dominance by larger numerical values.

2.2.5.3. K-Means Clustering Algorithm

The K-means algorithm partitions n samples into K clusters by

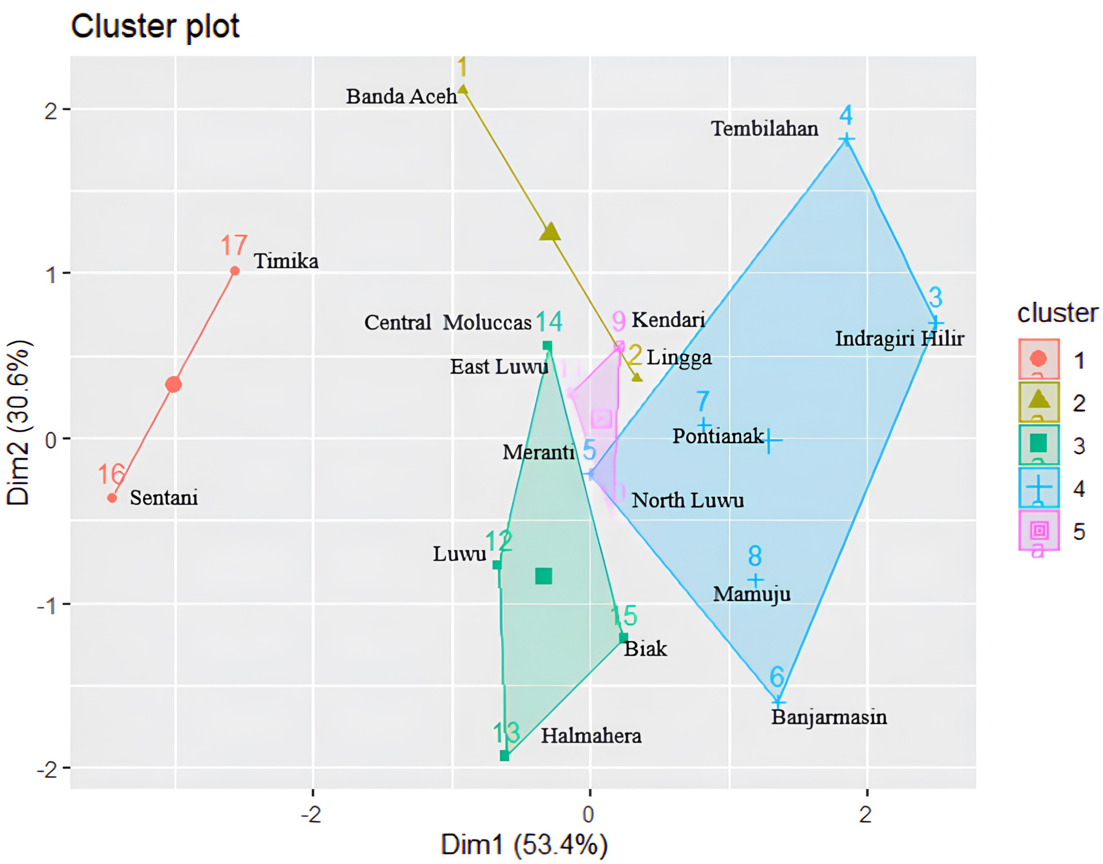

Figure 1. Clustering of Starch, Amylose, and Amylopectin Content Sago Starch

minimizing the within-cluster sum of squares (WCSS) using Equation 3 and Equation 4.

$$WCSS = \min_{C_1,\ldots,C_K} \sum_{k=1}^{K} \sum_{i \in C_k} \|Z_i - \mu_k\|^2 \quad (3)$$

where:

- Z_i is the p-dimensional standardized vector for sample i,
- μ_k is the centroid (mean vector) of cluster k,
- $\|\cdot\|^2$ denotes the squared Euclidean distance:

$$\|Z_i - \mu_k\|^2 = \sum_{j=1}^{p} (z_{ij} - \mu_{kj})^2 \quad (4)$$

The cluster centroid k is calculated using Equation 5.

$$\mu_k = \frac{1}{|C_k|} \sum_{i \in C_k} Z_i \quad (5)$$

where C_k denotes the observations in cluster k, and the algorithm iteratively assigns data to the nearest centroid and updates centroids until cluster assignments stabilize or WCSS changes minimally.

2.2.5.4. Determination of Optimal Number of Clusters

The optimal number of clusters K was determined before final partitioning by minimizing total within-cluster variance to ensure robust separation using Equation 6.

$$\text{Total WCSS} = \sum_{k=1}^{K} \sum_{i \in C_k} \|Z_i - \mu_k\|^2 \quad (6)$$

The elbow method was used to identify the optimal K by examining WCSS reductions, and cluster separation was further evaluated using the between-cluster sum of squares (BCSS) (Steinley, 2008). BCSS calculation using Equation 7.

$$BCSS = \sum_{k=1}^{K} |C_k| \|\mu_k - \mu\|^2 \quad (7)$$

where μ is the overall mean vector of the dataset. A larger BCSS relative to total variance indicates better defined clusters.

Table 1. Starch, Amylose and Amylopectin Content of Indonesian Sago Starch

Origin Sago Starch	Starch Content (%)	Amylose (%)	Amylopectin (%)
Banda Aceh, Aceh	83.55 ± 0.50^{fg}	32.01 ± 0.08^{g}	51.54 ± 0.42^{b}
Lingga, Riau Islands	84.54 ± 0.25^{cdef}	35.33 ± 0.27^{ef}	49.21 ± 0.52^{cd}
Indragiri Hilir, Riau	82.59 ± 0.25^{gh}	37.35 ± 0.12^{bc}	45.24 ± 0.37^{b}
Tembilahan, Riau	81.63 ± 0.50^{h}	35.44 ± 0.33^{ef}	46.19 ± 0.18^{gh}
Meranti, Riau	85.02 ± 0.25^{abcde}	35.64 ± 0.30^{ef}	49.38 ± 0.80^{c}
Banjarmasin, South Borneo	85.53 ± 0.25^{abc}	38.67 ± 0.17^{a}	46.86 ± 0.42^{fgh}
Pontianak, West Borneo	83.86 ± 0.50^{defg}	36.26 ± 0.45^{cde}	47.60 ± 0.95^{defg}
Mamuju, West Sulawesi	84.53 ± 0.25^{cdef}	37.72 ± 0.18^{ab}	46.81 ± 0.07^{fgh}
Kendari, Southeast Sulawesi	83.45 ± 0.25^{fg}	35.10 ± 0.22^{f}	48.35 ± 0.47^{cdef}
North Luwu, South Sulawesi	84.52 ± 0.25^{cdef}	36.21 ± 0.33^{de}	48.31 ± 0.08^{cdef}
East Luwu, South Sulawesi	83.72 ± 0.25^{efg}	35.08 ± 0.15^{f}	48.65 ± 0.40^{cde}
Luwu, South Sulawesi	85.12 ± 0.25^{abcd}	35.65 ± 0.30^{ef}	49.47 ± 0.05^{c}
Halmahera, North Moluccas	86.25 ± 0.25^{a}	37.00 ± 0.05^{bcd}	49.26 ± 0.21^{cd}
Central Moluccas	83.11 ± 0.25^{g}	34.63 ± 0.20^{f}	48.48 ± 0.05^{cdef}
Biak, Papua	84.61 ± 0.25^{bcdef}	37.19 ± 0.38^{bcd}	47.42 ± 0.13^{efg}
Sentani, Papua	85.96 ± 0.25^{ab}	32.21 ± 0.30^{g}	53.76 ± 0.57^{a}
Timika, Papua	83.68 ± 0.49^{efg}	31.68 ± 0.40^{g}	52.00 ± 0.10^{b}

Notes: The numbers followed by the same letter in the same column indicate no significant difference by Tukey test ($p < 0.05$).

2.2.6 Validation and Robustness Assessment of the Composite Quality Safety Index

To ensure that clustering results were statistically robust and interpretable, the composite quality–safety index underwent multiple validations and robustness checks.

2.2.6.1. Internal Consistency

Internal consistency of the composite quality safety index was evaluated using Cronbach's alpha to assess the reliability of the aggregated standardized indicators. A Cronbach's alpha value of 0.70 indicated acceptable internal consistency, supporting the robustness of the composite index structure.

2.2.6.2. Multicollinearity Diagnostics

Along with testing for reliability and sensitivity, multicollinearity among the standardized indicators was formally checked before combining the indices. For each physicochemical and contaminant variable used in the clustering and index construction process, we calculated the Variance Inflation Factor (VIF). All VIF values were below the widely accepted limit of 5, indicating no multicollinearity and no indicators with excessive linear dependence on others. This result shows that each variable adds unique information to the composite quality-safety index and that the weighting scheme does not introduce unnecessary variance. The lack of significant multicollinearity makes the aggregated index more statistically valid and easier to understand.

2.2.6.3. Uncertainty Estimation

To improve interpretability and inferential robustness, the uncertainty associated with the composite quality safety index was quantified by computing 95% confidence intervals for each regional index score. Using a non-parametric bootstrap resampling procedure (1,000 iterations), we estimated confidence intervals for the standardized and weighted indicators before they were combined. This method accounts for sampling variability and potential instability in the weighting structure, without requiring strict normality assumptions. This makes it a more reliable way to show how spread out the index is.

2.2.6.4. Sensitivity to Alternative Weighting Schemes

A sensitivity analysis was conducted using different objective weighting methods to ensure that the clustering results weren't based solely on the MCDA based weights assigned at the start. First, an equal-weighting scheme was used, meaning all standardized indicators were given the same weight. This method works as a neutral baseline model, assuming that physicochemical and contaminant variables are equally important. Second, we used an entropy-based weighting method to obtain objective weights based on each variable's spread across samples. Indicators with more variability provided more information, so they got higher weights. After range standardization, entropy weights were calculated to enable comparison of the indicators. We then used the same K-means method to cluster the data again, but this time with different weighting schemes. Cluster stability was assessed by analyzing cluster membership consistency, within-cluster sum of squares (WCSS), between-cluster separation, and the overall grouping structure. This method made it possible to assess the reliability of the clustering results without altering the original variable structure or reducing the number of dimensions.

2.2.6.5. Robustness Check

To evaluate the robustness of the clustering results, supplementary analyses were performed utilizing different data normalization methods and outlier diagnostics. In addition to range (min–max) standardization, z-score normalization was used, yielding very consistent clustering structures with only minor changes at the sample edges. This shows that the choice of normalization method did not affect the clustering results. Outlier detection was performed using standardized scores and interquartile range (IQR) criteria prior to clustering. No substantial outliers were identified that could significantly influence centroid estimation or cluster association. The re-evaluation, after excluding borderline observations, produced analogous cluster patterns and variance metrics, thereby confirming the stability and robustness of the findings.

2.2.7 Composite Index Computation and Validation

The composite quality safety index (CI) for each sample was calculated as a weighted aggregation of standardized indicators using Equation 8.

$$CI_i = \sum_{j=1}^{p} w_j z_{ij} \tag{8}$$

where w_j is the assigned weight for indicator j. Confidence intervals were used to rigorously compare regions: samples within the same cluster had overlapping intervals, indicating internal homogeneity, while clusters were clearly separated, affirming discriminative validity.

All statistical analyses, including clustering, weighting, and validation, were performed in (R Development Core Team, 2011), ensuring transparency and reproducibility. Data were analyzed with a one-way analysis of variance. The significant differences among the origin sago starch means were determined using the Tukey test at the 5% significance level.

3. RESULTS AND DISCUSSIONS

Sago (*Metroxylon sp.*) is a plant found abundantly in Indonesia and produces sago starch, which can be used as both a food and an industrial ingredient. Sago starch has various characteristics, including functional (starch, amylose, and amylopectin content), chemical/proximate (moisture, fat, protein, and carbohydrate content), pH, and metal content. These characteristics influence its quality and usefulness in various applications, both in the food and industrial sectors.

3.1 Characteristics of the Functional Properties of Sago Starch

The functional characteristics of sago starch include its starch, amylose, and amylopectin content, which significantly influence its rheological properties and applications across various industries. Sago starch, derived from the Metroxylon species, has attracted considerable attention for its high starch content and versatile uses (Chua et al., 2022). The physicochemical and mechanical performance of starch-based materials is governed by the chemical composition of sago starch (Kusumawati et al., 2025). Several factors affect sago starch yield, including the harvest stage, traditional varieties, environmental conditions, and cultivation methods (Chua et al., 2022). Notably, sago starch exhibits unique properties, including lower peak viscosity, higher setback, and excellent gel-forming properties, positioning it as a potential food stabilizer (Du et al., 2020). In this study, the sago starch content from different regions in Indonesia varied, ranging from 81.63% in Tembilahan, Riau, to 86.25% in Halmahera, North Moluccas (Table 1). The high starch content in sago makes it a valuable energy source in the food industry and other applications. Specifically, sago varieties from Halmahera (86.25%), Banjarmasin (85.53%), and Luwu (85.12%) demonstrate particularly high starch content. Furthermore, the starch content in sago is significantly influenced by the harvesting time; for instance, sago harvested at 12.5 years can yield up to 97.9% starch (Litaay et al., 2022).

The amylose content of sago starch, typically around 21.7%, significantly influences its physicochemical properties (Yadav and Garg, 2013). Sago starch has a type C crystal structure with a crystallinity of approximately 28.13%. Notably, it contains higher levels of amylose and resistant starch than corn and potatoes (Yadav and Garg, 2013). This unique composition offers significant potential for sago starch as a food stabilizer. Additionally, the growth stages of Metroxylon sagu plants affect both the resistant starch content and amylose levels, impacting the physicochemical properties of type III resistant starch (Bunyasetthakun et al., 2020). Research indicates that the amylose and amylopectin content in sago starch greatly influences its characteristics and applications in the food and other industries (Setiawan et al., 2022; Trisia et al., 2021). In various regions of Indonesia, the amylose content of sago starch ranges from 32.01% to 38.67%, indicating a relatively high amylose value. Higher amylose content generally results in a more complex and denser texture. This is due to amylose's linear structure, which forms hydrogen bonds and denser crystals, enhancing the final product's strength.

In this study, the amylopectin content ranged from 45.24% and 53.76% (Table 1). This is comparable to the amylopectin content of sago starch, which ranges from 43.69% to 48.4% (Dewayani et al., 2022). The structure of amylopectin plays a crucial role in determining starch viscosity. Low-viscosity amylopectin is characterized by a smaller molecular size and slightly longer chain length than high viscosity amylopectin (Fadhallah et al., 2023).

Clustering the functional properties of sago starch is highly beneficial for identifying potential areas for developing processed sago products intended for industrial applications. It also aids in helps standardize sago product quality and regulations at national and international levels. By averaging clustering results, the industry and government can develop more effective strategies to utilize Indonesia's sago resources to meet various needs. Figure 1 displays the clustering of sago starch producing regions in Indonesia, based on key components: starch, amylose, and amylopectin.

Clustering analysis can be used to assess chemical varia-

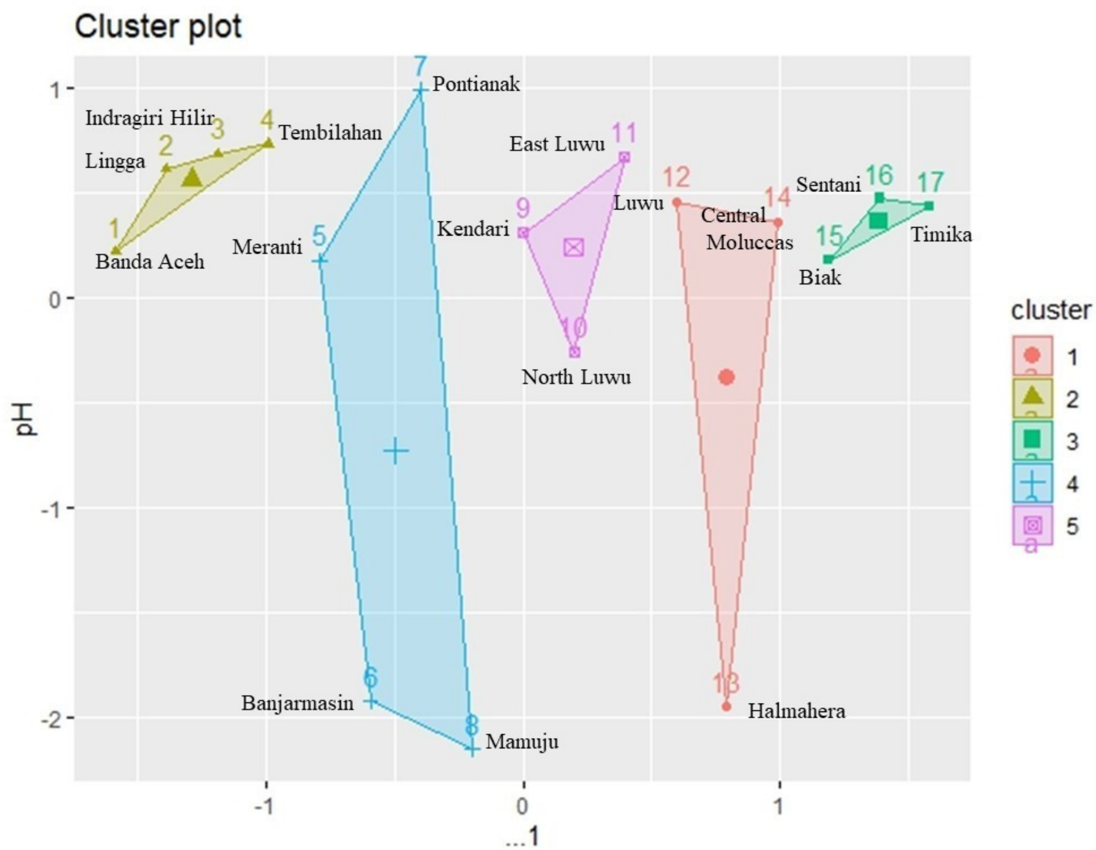

Figure 2. Clustering of pH Sago Starch

tion in starch materials from different geographical sources (Oliveira et al., 2020; Santos et al., 2021). The first two principal dimensions, Dim1 and Dim2, explain approximately 84.0% of the total variance, indicating a strong representation of the differences in starch chemical characteristics among the samples.

The characteristics of sago starch, including its amylose and amylopectin content, can be grouped into five distinct clusters based on their geographical origins (Figure 1). Cluster 1 (Red) includes the Timika and Sentani regions. This cluster exhibits similarities in chemical composition and is closely related in terms of sago starch properties. The high amylose content in this cluster contributes to products with a denser texture and greater structural complexity, such as sago crackers, which require structural integrity (Sulaiman et al., 2023), cookies, and snacks (Burakorn et al., 2024). Cluster 2 (Yellow) encompasses the Banda Aceh and Lingga regions. This cluster has a relatively high amylose content and moderate amylopectin levels. The unique properties of sago starch from this region result in products with a well-balanced texture, being neither too hard nor too soft. Traditional foods like pempek and sago cakes are particularly well-suited to these qualities, as they offer a pleasing combination of chewiness and softness (Romero-Rosales et al., 2025; Hu et al., 2024; Horstmann et al., 2017).

Cluster 3 (Green) includes the Central Moluccas, Biak, Halmahera and Luwu regions. Sago starch from this cluster has a higher amylopectin content, which affects its viscosity. This increased amylopectin content is ideal for creating softer and chewier products, making it perfect for sweet sago porridge and soft sago cakes (Romero-Rosales et al., 2025; Horstmann et al., 2017). The viscosity of amylopectin contributes to achieving the desired texture in these applications (Burakorn et al., 2024). Cluster 4 (Blue) comprises regions such as Pontianak, Mamuju, Banjarmasin, Meranti, Indragiri Hilir and Tembilahan. This cluster exhibits relatively high starch content with a balanced amylose amylopectin composition, contributing to good functional stability and suitability for food products such as noodles, vermicelli, starch-based snacks, sauces, and instant soups (Romero-Rosales et al., 2025; Hu et al., 2024; Horstmann et al., 2017).

Cluster 5 (Purple) includes East Luwu, North Luwu and Kendari. This cluster exhibits a balance between amylose and amylopectin, making it suitable for food products that require good elasticity, such as sago noodles and traditional cakes. It is characterized by regions with higher water and very low fat content. The increased water content and softer texture make it ideal for soft-textured foods like sago porridge and wet sago cake (Novianti et al., 2024).

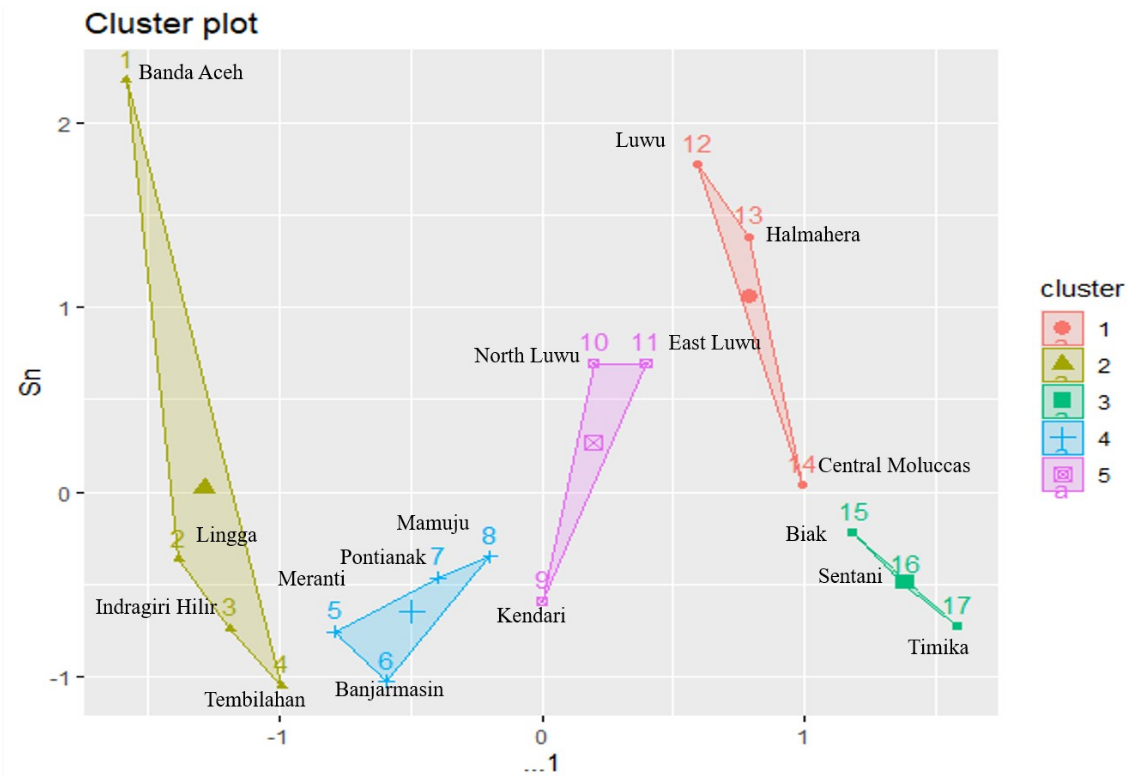

Figure 3. Clustering of Sn Analysis Sago Starch

3.2 Characteristics of the pH of Sago Starch

The pH is an important parameter in characterizing sago starch. Sago starch pH influences the chemical and functional properties, as well as the quality of the final product. Sago starch has a relatively neutral to slightly acidic pH. Studies show that the natural pH of sago starch ranges from 4.35 to 6.97 (Table 2). Variations in sago starch pH depend on the region and environmental conditions in which sago palms grow. This pH value is influenced by the mineral content, such as phosphate and sulfate, found in the starch. pH affects the solubility and swelling power of sago starch. Starch solubility tends to increase at a low pH (more acidic), but swelling power may decrease. Conversely, swelling power may increase at a higher pH (more alkaline), but solubility may decrease. A pH value that is too low or too high can disrupt the gelatinization process and affect the final texture of products containing sago starch. At a neutral to slightly acidic pH, the viscosity of sago starch paste is usually more stable. However, viscosity can decrease at extreme pHs due to damage to starch molecules.

Cluster 1 (red) consists of sago starch samples from Luwu, Halmahera, and Central Moluccas, characterized by moderate to high pH levels (Figure 2). Cluster 2 (yellow) includes sago starch from Banda Aceh, Lingga, Indragiri Hilir, and Tembilahan, which display lower pH characteristics. Cluster 3 (green) encompasses samples from Biak, Sentani, and Timika, showing a reasonably stable pH that tends to be higher. Cluster 4 (blue) contains samples from Meranti, Banjarmasin, Pontianak, and Mamuju, each with distinct pH values that suggest unique chemical properties. Cluster 5 (purple) comprises the Kendari, North Luwu, and East Luwu samples, reflecting varying pH values but remaining within certain limits. Adjacent clusters such as Clusters 1 and 3 may share overlapping chemical characteristics, including similar pH levels or nutrient content. In contrast, distant clusters, such as Cluster 2 and Cluster 4, demonstrate significant differences in pH values and other chemical properties. A lower pH in Cluster 2 may indicate higher acidity, which can impact the starch's resistance to enzymatic degradation or fermentation. A high pH (Cluster 3 or 4) indicates that a material is more basic, which may be associated with a higher mineral content. A pH range from slightly acidic to neutral can improve water retention and enhance system stability, making it suitable for applications such as sauces (Seet Chi et al., 2021). Conversely, elevated pH levels may promote enzymatic activity and alter the pathways of starch conversion during fermentation (Lin, 2025). Sago starch performs best at a neutral to slightly acidic pH, improving viscosity stability and a final product that aligns with consumer expectations for quality and taste (Puspantari et al., 2023). Moderate pH levels promote reasonable solubility while allowing adequate swelling, which is essential for achieving the right texture and moisture retention, especially in sweet applications (Miao et al., 2015). Although a more alkaline pH offers higher swelling power, it reduces solubility, making it suitable for both traditional culinary practices and contemporary food trends emphasizing texture

(Ismail and Zaaba, 2014).

Table 2. The pH of Indonesian Sago Starch

Origin Sago Starch	pH
Banda Aceh, Aceh	6.28 ± 0.01^{fg}
Lingga, Riau Islands	6.63 ± 0.01^{bc}
Indragiri Hilir, Riau	6.70 ± 0.01^{b}
Tembilahan, Riau	6.74 ± 0.04^{b}
Meranti, Riau	6.24 ± 0.01^{g}
Banjarmasin, South Borneo	4.37 ± 0.03^{i}
Pontianak, West Borneo	6.97 ± 0.02^{a}
Mamuju, West Sulawesi	4.17 ± 0.03^{j}
Kendari, Southeast Sulawesi	6.36 ± 0.01^{efg}
Halmahera, North Moluccas	4.35 ± 0.04^{h}
North Luwu, South Sulawesi	5.86 ± 0.02^{b}
East Luwu, South Sulawesi	6.69 ± 0.01^{bc}
Luwu, South Sulawesi	6.49 ± 0.08^{i}
Central Moluccas	6.41 ± 0.01^{def}
Biak, Papua	6.24 ± 0.01^{g}
Sentani, Papua	6.50 ± 0.08^{b}
Timika, Papua	6.47 ± 0.01^{i}

Notes: The numbers followed by the same letter in the same column indicate no significant difference by Tukey test ($p < 0.05$).

3.3 Metal Contamination

The content of heavy metals such as Cd, Pb, Hg, As, and Sn in sago starch poses a health risk to humans. These heavy metals can contaminate food products and pose serious health risks, including neurotoxicity, carcinogenic effects, and other systemic toxicities (Tchounwou et al., 2012; Genchi et al., 2020). Sn is the most dominant heavy metal contaminant (Table 3). Pb content is also found in sago starch from North Luwu, Luwu, Central Moluccas, Banda Aceh, and Timika. Meanwhile, cadmium, mercury, and arsenic were not detected in sago starch from 17 locations in Indonesia. The heavy metal content of Sn and Pb in sago starch remains below the maximum thresholds set by the Indonesian National Standard (SNI), namely Cd ≤ 0.05 ppm, Pb ≤ 0.25 ppm, Hg ≤ 0.03 ppm, As ≤ 0.1 ppm, and Sn ≤ 40 ppm (28). Accumulation of heavy metals in food products, including sago starch, can occur through environmental pollution, agricultural practices, and industrial waste disposal (de Almeida et al., 2022; Pandiangan and Audah, 2022). The presence of metals in sago starch can also be influenced during the production process (Uthumporn et al., 2014). In addition, sago pith, a component of the sago tree, is known to contain starch, soluble solids, and ash, which may contain metal components (Pinyo et al., 2017).

There are five clusters of sago starch in Indonesia based on stannum contamination (Figure 3). This clustering is based on the stannum (Sn) content in sago starch from several regions, as Pb, Cd, Hg, and As were undetected. This clustering process groups sago producing regions into several clusters, each with similar Sn value characteristics. In general, a higher Sn value indicates a more digestible sago starch. Conversely, a lower Sn value indicates a more difficult to digest sago starch, which slows digestion. Based on the clustering results, five main clusters of sago starch are produced from various regions in Indonesia. The first cluster, which includes regions such as Luwu, Halmahera, and Central Moluccas, shows high Sn values, indicating that sago starch from these regions is easily digested and suitable for food products that require rapid absorption. The second cluster, consisting of Lingga, Indragiri Hilir, Banda Aceh, and Tembilahan, showed lower Sn values, making sago starch from these regions more difficult to digest and more suitable for food products that do not require rapid digestion. The third cluster, which includes Biak, Sentani, and Timika, had moderate Sn values, indicating that this sago starch is suitable for food products that require normal digestion speeds. Meanwhile, the fourth cluster, Pontianak, Mamuju, Meranti, and Banjarmasin, had relatively low Sn values, making it more suitable for food products requiring slower digestion or longer shelf life. The fifth cluster, including Kendari, East Luwu, and North Luwu, showed high Sn values, making it suitable for food products that are easily digested and quickly absorbed by the body. By understanding this clustering, the food industry can more accurately select sago starch suitable for the food products they want to produce, whether for rapid or slower digestion.

3.4 Proximate Content

Sago starch has excellent potential as a sustainable carbohydrate source (Yusuf et al., 2019). This starch plays a significant role in food security, especially in certain regions in Indonesia where sago consumption is a tradition. Proximate content measures the main nutrient composition of a food ingredient, including water, ash, protein, fat, and carbohydrates (including starch). The proximate content of Indonesian sago starch is presented in Table 4.

The moisture content of sago starch ranges from 10.63-15.37% (Table 4), whereas the SNI standard for sago starch 3729: 2023 is a maximum of 13%. The moisture content of the sago starch produced has largely met the SNI standard except for the Banda Aceh, Mamuju, and Kendari areas. Based on a statistical analysis of moisture content in sago starch from various regions in Indonesia, the average moisture content is 12.75%, which is below the maximum limit established by SNI 3719:2023 (13%). There is a significant variation in moisture content, with a standard deviation of 1.61%. Approximately 64.7% of the samples meet the SNI standard, indicating that some areas must improve their extraction or storage methods to achieve the required standards. The differences in moisture content among sago starch products can be attributed to varying standards and drying processes in different sago starch-producing industries. Inadequate drying methods often result in moisture content exceeding 13%. A starch product with more than 13% moisture usually has a shorter shelf life. Additionally, higher moisture content can negatively impact product quality,

Table 3. Metal Contamination of Indonesian Sago Starch

Origin Sago Starch	Cd	Pb	Hg	As	Sn (ppm)
Banda Aceh, Aceh	nd	0.0019	nd	nd	2.87 ± 0.03^{a}
Lingga, Riau Islands	nd	nd	nd	nd	1.37 ± 0.03^{h}
Indragiri Hilir, Riau	nd	nd	nd	nd	1.15 ± 0.01^{k}
Tembilahan, Riau	nd	nd	nd	nd	0.97 ± 0.01^{l}
Meranti, Riau	nd	nd	nd	nd	1.14 ± 0.01^{k}
Banjarmasin, South Borneo	nd	nd	nd	nd	0.98 ± 0.01^{l}
Pontianak, West Borneo	nd	nd	nd	nd	1.31 ± 0.01^{i}
Mamuju, West Sulawesi	nd	nd	nd	nd	1.38 ± 0.00^{h}
Kendari, Southeast Sulawesi	nd	nd	nd	nd	1.24 ± 0.01^{j}
North Luwu, South Sulawesi	nd	0.0013	nd	nd	1.98 ± 0.01^{e}
East Luwu, South Sulawesi	nd	nd	nd	nd	2.81 ± 0.01^{b}
Luwu, South Sulawesi	nd	0.0009	nd	nd	2.61 ± 0.00^{c}
Halmahera, North Moluccas	nd	nd	nd	nd	2.38 ± 0.00^{d}
Central Moluccas, Moluccas	nd	0.001	nd	nd	1.61 ± 0.02^{f}
Biak, Papua	nd	nd	nd	nd	1.45 ± 0.01^{g}
Sentani, Papua	nd	nd	nd	nd	1.28 ± 0.02^{i}
Timika, Papua	nd	0.0014	nd	nd	1.16 ± 0.01^{k}

Notes: The numbers followed by the same letter in the same column indicate no significant difference by Tukey test ($p < 0.05$), nd: no detected

accelerating spoilage. Several factors influence the moisture content of sago starch, including processing methods and environmental conditions. Traditional drying methods tend to result in higher moisture levels, which limit market potential and affect quality (Kamal et al., 2019). Lower moisture content in dried sago starch results in more resistant starch and a higher water absorption index, but it also reduces solubility index and swelling capacity (Kamal et al., 2019). The harvesting stage, traditional varieties, the surrounding environment, and cultivation practices significantly influence sago starch yield and water content (Chua et al., 2022). Understanding the moisture content of sago starch is essential for optimizing its production and quality in Indonesia. Recognizing the importance of maintaining low moisture content can positively impact the industry. Consistent processing standards and strict quality control measures are needed to ensure that sago starch meets national standards and can be safely and efficiently used in various food applications.

The ash content of sago starch in Indonesia varies between 0.03% and 0.61% (Table 4), with a maximum allowable ash content of 0.3% as established by SNI-3729 (2023) for sago starch. Most regions in Indonesia produce sago starch that meets this standard, except for Banda Aceh, Mamuju, and Kendari. Several factors influence sago starch's ash content and composition, including the harvesting stage, variety, environmental conditions, and cultivation methods (Chua et al., 2022). A statistical analysis of the ash content in samples from various regions shows that approximately 82.4% comply with the SNI standard. While many regions produce sago starch with acceptable ash levels, some need improvements in their processing methods. The processing of sago starch significantly affects the ash content of the final product. Factors such as the quality of raw materials, cleaning methods, drying techniques, milling, and refining can influence the ash content (Cammerata et al., 2021). Improper processing, such as the use of contaminated raw materials or uncontrolled drying, may increase the ash content of sago starch (Baasandorj et al., 2021).

The fat content of sago starch in Indonesia ranges from 0 to 0.14% (Table 4). Several factors influence the fat content and overall composition of sago starch. Fat content in sago starch is influenced by various factors, including harvesting stage, local varieties, environment, and cultivation methods (Chua et al., 2022). Processing techniques such as lintnerization and autoclaving can alter the physicochemical properties of sago starch, including its fat content (Pratiwi et al., 2015). Based on statistical analysis, the average fat content of sago starch (0.042%) is very low, making it a nearly fat-free carbohydrate source. Variation in fat content is relatively slight, with a standard deviation of 0.038%, indicating consistency in fat composition across most samples.

The protein content of sago starch in Indonesia ranges from 0.15-0.27% (Table 4). Sago starch derived from Metroxylon sagu is a promising crop with high carbohydrate but low protein content (Sarungallo et al., 2021). The protein content of sago starch can vary significantly, with one study reporting a range of 0.015% to 0.06% (Rickard et al., 1991). Other factors that influence the characteristics of sago starch include processing time, which can affect color, mineral content, solubility, and rheological properties (Rickard et al., 1991). Based on statistical analysis, the average protein content of sago starch (0.225%) indicates that it has a very low protein content. The variation in protein content is relatively slight, with a standard deviation of

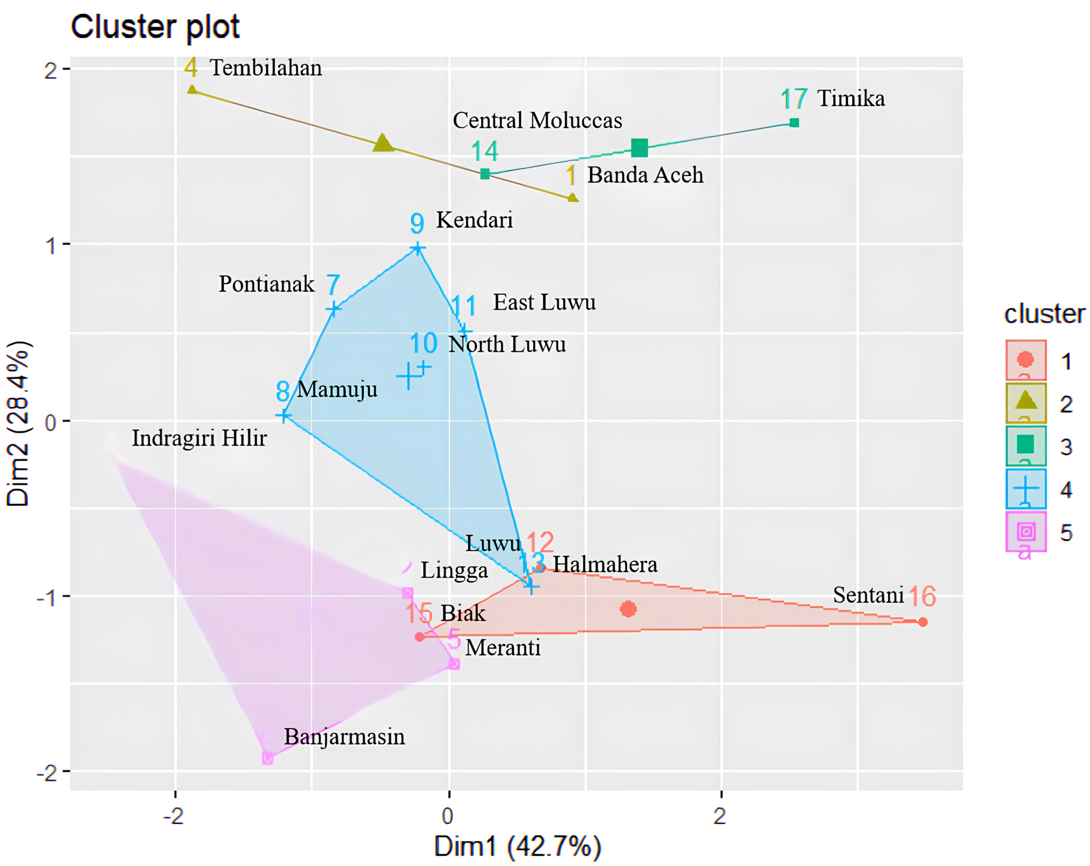

Figure 4. Clustering of Proximate Sago Starch

0.036%, indicating consistency in protein composition across most samples.

The carbohydrate content of sago starch in Indonesia ranges from 84.26% to 94.93% (Table 4). Carbohydrate is an important component of sago starch. The carbohydrate content of dry sago starch ranges from 84% to 89% of its composition (Jading et al., 2017). Based on statistical analysis, the average carbohydrate content of sago starch (87.86%) indicates that it is a very high-carbohydrate source. The variation in carbohydrate content is quite significant, with a standard deviation of 3.54%, indicating that some regions produce sago starch with very high carbohydrate content, while others produce lower levels.

Proximate composition studies indicate that sago starch has a high carbohydrate content, ranging from 96.95% to 97.72% (Sarungallo et al., 2021). This high carbohydrate content makes sago starch a highly valuable raw material for various food products and industrial applications. Furthermore, sago starch is also utilized as a carbon source in producing kojic acid, further confirming its potential as an abundant carbohydrate source (Devi et al., 2015). With its exceptionally high carbohydrate content, sago starch is a versatile ingredient in the food industry and plays a vital role in various industrial processes, further emphasizing its strategic value as a high-value carbohydrate source.

Clustering based on similar content has identified five distinct clusters (Figure 4). Cluster 1 (red) encompasses the Biak, Halmahera, and Sentani regions. The sago starch from this cluster is better suited for products with a shorter shelf life, as indicated by studies on its physicochemical characteristics (Sumardiono et al., 2021). Cluster 2 (yellow) includes Banda Aceh and Tembilahan, where the sago starch exhibits significantly different chemical properties. These variations are likely influenced by local processing techniques and the specific types of sago used, resulting in unique starch characteristics. As a result, this cluster's sago starch is ideal for fresher food products, such as cakes and other quickly consumed culinary delights (Novianti et al., 2024). Cluster 3 (green) consists of regions such as the Central Moluccas and Timika. Sago starch from this area has a notably higher carbohydrate content, which is advantageous for producing high-carbohydrate foods like noodles and pastries. This increased carbohydrate potential confirms that sago can be an adequate substitute for conventional raw materials in high-energy food products (Simatupang and Simbolon, 2023). Cluster 4 (blue) includes Pontianak, Kendari, Mamuju, East Luwu, Luwu, and North Luwu. These areas share similar chemical compositions, with stable nutrient content. Sago starch from this cluster is particularly well-suited

Table 4. Proximate Content of Indonesian Sago Starch

Origin Sago Starch	Moisture (%)	Ash Content (%)	Fat Content (%)	Content Protein (%)	Carbohydrate Content (%)
Banda Aceh, Aceh	11.64±0.01^{i}	0.61±0.01^{a}	0.14±0.03^{a}	0.26±0.00^{ab}	87.35±0.07^{f}
Lingga, Riau Islands	15.37±0.03^{a}	0.09±0.01^{ghi}	0.03±0.00^{def}	0.26±0.00^{ab}	84.26±0.03^{m}
Indragiri Hilir, Riau	14.07±0.01^{d}	0.035±0.01^{i}	0.035±0.01^{def}	0.24±0.03^{abcd}	85.62±0.09^{i}
Tembilahan, Riau	14.34±0.02^{c}	0.215±0.01^{cd}	0.055±0.01^{cde}	0.26±0.00^{ab}	85.13±0.01^{h}
Meranti, Riau	14.34±0.04^{bc}	0.07±0.01^{hi}	0.04±0.01^{cde}	0.18±0.01^{abcd}	85.36±0.03^{j}
Banjarmasin, South Borneo	11.35±0.06^{j}	0.05±0.01^{hi}	0.025±0.01^{def}	0.15±0.04^{d}	94.93±0.10^{a}
Pontianak, West Borneo	11.45±0.06^{j}	0.21±0.01^{cd}	0.065±0.02^{bcd}	0.27±0.02^{a}	88.01±0.06^{d}
Mamuju, West Sulawesi	10.63±0.02^{m}	0.33±0.03^{c}	0±0.00^{f}	0.16±0.02^{cd}	93.82±0.02^{b}
Kendari, Southeast Sulawesi	14.42±0.02^{c}	0.435±0.02^{b}	0.035±0.01^{def}	0.24±0.02^{abc}	84.87±0.03^{l}
Halmahera, North Moluccas	11.15±0.08^{l}	0.23±0.03^{fgh}	0.01±0.01^{ef}	0.20±0.03^{abc}	94.79±0.02^{c}
North Luwu, South Sulawesi	10.95±0.04^{b}	0.1±0.01^{ghi}	0.015±0.01^{ef}	0.25±0.01^{abcd}	88.68±0.04^{jk}
East Luwu, South Sulawesi	14.51±0.01^{e}	0.09±0.03^{ef}	0.02±0.00^{bc}	0.21±0.05^{abc}	85.17±0.04^{h}
Luwu, South Sulawesi	12.96±0.01^{k}	0.16±0.01^{d}	0.085±0.01^{ef}	0.25±0.01^{abcd}	86.53±0.01^{a}
Central Moluccas	12.55±0.05^{f}	0.255±0.01^{d}	0.04±0.00^{def}	0.25±0.01^{abc}	86.90±0.04^{g}
Biak, Papua	12.16±0.02^{g}	0.14±0.03^{fg}	0.015±0.03^{ef}	0.24±0.03^{abcd}	87.45±0.03^{f}
Sentani, Papua	11.93±0.06^{h}	0.06±0.01^{hi}	0.07±0.01^{def}	0.18±0.00^{bcd}	87.80±0.04^{e}
Timika, Papua	11.09±0.03^{e}	0.06±0.01^{hi}	0.1±0.01^{ab}	0.24±0.02^{abc}	88.50±0.06^{c}

Notes: The numbers followed by the same letter in the same column indicate no significant difference by Tukey test ($p < 0.05$).

for industrial applications that require consistent quality, such as producing sago flour for baby food, sago chips, or ready to eat meals (Kamal et al., 2019). Cluster 5 (purple) comprises Indragiri Hilir, Banjarmasin, and Meranti, where sago starch is produced. The starch from this region is characterized by high carbohydrate and low ash content, making it significant for local diets and industrial food production, especially as a carbohydrate source in various processed foods (Grace and Jeyakumar Henry, 2020).

The 95% confidence intervals obtained from bootstrap resampling, along with the composite index scores, further substantiate the robustness of the clustering results. The confidence intervals for regions in the same cluster usually overlapped, indicating that their combined quality and safety performance was statistically consistent. On the other hand, clusters with different composite index levels had, little overlap in intervals, suggesting that the groups are significantly different from each other. These results confirm that the regional patterns we saw are not just the result of how we weighted the data. Instead, they show that there are statistically stable differences in the quality of sago starch and the types of contaminants present.

The clustering results provide a structured classification of exposure patterns based on measurable indicators; however, the policy implications of these results require meticulous analysis. The exposure categories identified in this study are derived from the analytical grouping of observed factors and are not associated with actual cyber event data. So, the clusters don't show real events or confirmed risk outcomes. Instead, they show different kinds of exposure based on the underlying signs.

The suggested exposure framework is not intended to serve as a guide for predicting or explaining cyber incidents. It is meant to be an exploratory, risk-informed tool that helps prioritize strategies, compare evaluations, and monitor initiatives. The data may help policymakers and practitioners identify which areas need more attention or research, especially when exposure indicators appear simultaneously and consistently.

Nonetheless, establishing a direct empirical correlation between exposure categories and recorded cyber incidents necessitates longitudinal incident datasets and integrated event-level analysis, which exceed the parameters of the current study. Subsequent research must explicitly connect exposure-based classifications with authenticated incident records to substantiate and enhance the policy significance of the proposed framework.

4. CONCLUSIONS

The results of this study indicate that the chemical characteristics of Indonesian sago starch vary across provinces. The carbohydrate content ranges from 84.26% to 94.93%, while fat and protein levels are low. There are also variations in the amylose, amylopectin, and crude fiber content. Furthermore, Indonesian sago starch has low metal levels of contamination and meets international safety standards, making it suitable for consumption. Sago starch from Indragiri Hilir, Banjarmasin, and Lingga exhibits characteristics such as starch, amylose, amylopectin, crude fiber, digestibility, pH, metal contaminants, and proximate composition that are comparable to those of sago starch from Meranti. This finding suggests that sago starch from Indragiri Hilir, Banjarmasin, and Lingga can substitute for that from Meranti, which is regarded as Indonesia's primary source of sago starch. The balance between amylose and amylopectin in the sago starch from these areas makes it particularly suitable for food products that require good elasticity.

5. ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the National Research and Innovation Agency (BRIN) for providing analytical research services and technical support that significantly contributed to the completion of this study.

REFERENCES

Abbas, B., M. Dailami, B. Santoso, and M. Munarti (2017). Genetic Variation of Sago Palm (*Metroxylonsagu* Rottb.) Progenies with Natural Pollination by Using Rapd Markers. *Natural Science*, **9**(4); 104–109

AOAC (1995). *Official Methods of Analysis of AOAC International*. AOAC International, 16 edition

Azman, W. M. F. B. W., R. Shamsudin, M. Z. M. Nor, and A. Hamzah (2021). Evaluation and Optimization of Disc Grating Machine for Sago Starch Production (*Metroxylon spp.*). *Advances in Agricultural and Food Research Journal*, **2**(2); 1–12

Baasandorj, T., J. B. Ohm, and S. Simsek (2021). Physicochemical and Bread-Making Characteristics of Millstreams Obtained from an Experimental Long-Flow Mill in Hard Red Spring Wheat. *Cereal Chemistry*, **98**(3); 517–531

Budiyanto, A., M. Hadipernata, M. Ainuri, W. Supartono, A. Arif, and T. Sulistiyani (2023). Variations of Washing Agent on The Physicochemical And Microbiology Properties of Sago Starch. In *IOP Conference Series: Earth and Environmental Science*, volume 1246. IOP Publishing, page 012049

Bunyasetthakun, T., Q. Huang, K. Sureepisan, M. Suphantharika, N. Tangsrianugul, and R. Wongsagonsup (2020). Effects of Dual Pullulanase-Debranching and Temperature-Cycling Treatments on Physicochemical Properties and In Vitro Digestibility of Sago Starch and Its Application in Chinese Steamed Buns. *Starch/Stärke*, **72**(9–10)

Burakorn, J., P. Pinthong, M. Aimkaew, P. Tongbai, and K. Srithai (2024). The Effect of Glucose Syrup on Rheological Properties of Sago Starch. *Trends in Sciences*, **21**(3); 7253–7253

Cammerata, A., R. Marabottini, E. Allevato, G. Aureli, and S. R. Stazi (2021). Content of Minerals and Deoxynivalenol in the Air-Classified Fractions of Durum Wheat. *Cereal Chemistry*, **98**(5); 1101–1111

Chua, S. N. D., E. P. Kho, S. F. Lim, and M. H. Hussain (2022). Sago Palm (*Metroxylon sagu*) Starch Yield, Influencing Factors and Estimation from Morphological Traits. *Advances in Materials and Processing Technologies*, **8**(2); 1845–1866

Cipto and D. Parenden (2022). Sago Extraction Machine Design. *MATEC Web of Conferences*, **372**; 01002

de Almeida, C. C., D. d. S. Baião, P. d. A. Rodrigues, T. D. Saint'Pierre, R. A. Hauser-Davis, K. C. Leandro, V. M. F. Paschoalin, M. P. da Costa, and C. A. Conte-Junior (2022). Toxic Metals and Metalloids in Infant Formulas Marketed in Brazil, and Child Health Risks According to the Target Hazard Quotients and Target Cancer Risk. *International Journal of Environmental Research and Public Health*, **19**(18); 11178

Devi, K., P. Vijayalakshmi, V. Shilpa, and B. Kumar (2015). Optimization of Cultural Parameters for Cost Effective Production of Kojic Acid by Fungal Species Isolated from Soil. *British Microbiology Research Journal*, **7**(5); 255–268

Dewayani, W., Suryani, R. Arum, and E. Septianti (2022). Potential of Sago Products Supporting Local Food Security in South Sulawesi. In *IOP Conference Series: Earth and Environmental Science*, volume 974. IOP Publishing, page 012114

Du, C., F. Jiang, W. Jiang, W. Ge, and S. K. Du (2020). Physicochemical and Structural Properties of Sago Starch. *International Journal of Biological Macromolecules*, **164**; 1785–1793

Ehara, H., Y. Toyoda, and D. V. Johnson (2018). *Sago Palm: Multiple Contributions to Food Security and Sustainable Livelihoods*. Springer

Everitt, B. and T. Hothorn (2011). *An Introduction to Applied Multivariate Analysis with R*. Springer Science & Business Media

Fadhallah, E. G., S. E. R. Rinjani, A. K. S. Anantasya, A. Pranata, R. Triharto, and A. H. Dameswary (2023). Potency of Betacyanin from Beetroot (*Beta vulgaris*) Peel Waste as Chicken Meat Freshness Indicator in Sago Starch-Based Biodegradable Smart Packaging. *MOJ Ecology & Environmental Sciences*, **8**(5); 186–190

Genchi, G., M. S. Sinicropi, G. Lauria, A. Carocci, and A. Catalano (2020). The Effects of Cadmium Toxicity. *International Journal of Environmental Research and Public Health*, **17**(11); 3782

Grace, N. C. and C. Jeyakumar Henry (2020). The Physicochemical Characterization of Unconventional Starches and Flours Used in Asia. *Foods*, **9**(2); 182

Hammado, N., S. Utomo, and Budiyono (2020). Characteristic Lignocellulose of Sago Solid Waste for Biogas Production. *Journal of Applied Engineering Science*, **18**(2); 157–164

Horstmann, S. W., K. M. Lynch, and E. K. Arendt (2017). Starch Characteristics Linked to Gluten-Free Products. *Foods*, **6**(4); 29

Hu, A., Y. Liu, and S. Wu (2024). A Review on Polysaccharide-Based Jelly: Gell Food. *Food Chemistry: X*, **23**; 101562

Ismail, H. and N. F. Zaaba (2014). Effect of Unmodified and Modified Sago Starch on Properties of (Sago Starch)/Silica/PVA Plastic Films. *Journal of Vinyl and Additive Technology*, **20**(3); 185–192

ISO-1666 (1996). Starch – Determination of Moisture Content – Oven-Drying Method

Jading, A., N. Bintoro, L. Sutiarso, and J. N. W. Karyadi (2017). Artificial Neural Network-Based Modelling and Optimization to Estimate the Fineness Modulus of the Drying Process of Sago Starch Using a Pneumatic Conveying Recirculated

Dryer. *International Journal of Engineering and Technology*, **9**(4); 3281–3291

Jahiding, M., M. Mashuni, F. H. Hamid, W. O. S. Ilmawati, and R. Hamdana (2024). The Production of Renewable Fuels Sago Dregs and Low-Density Polyethylene by Pyrolysis and Its Characterization. *Science and Technology Indonesia*, **9**(3); 565–576

Kamal, M. M., R. Baini, S. Lim, M. Rahman, S. Mohamaddan, and H. Hussain (2019). Drying Effect on the Properties of Traditionally Processed Sago Starch. *International Food Research Journal*, **26**(6); 1861–1869

Kusumawati, R., Syamdidi, A. H. D. Abdullah, R. C. Nissa, B. Firdiana, R. Handayani, I. Munifah, F. R. Dewi, J. Basmal, and S. Wibowo (2025). Physical Properties of Biodegradable Chitosan-Cassava Starch Based Bioplastic Film Mechanics. *Science and Technology Indonesia*, **10**(1); 191–200

Lee, J.-S., J. H. Akanda, S. L. Fong, C. K. Siew, and A. L. Ho (2022). Effects of Annealing on the Properties of Gamma-Irradiated Sago Starch. *Molecules*, **27**(15); 4838

Lin, S.-D. (2025). Effects of Processing and Cooking on Physicochemical, Sensory, and Functional Properties of Food

Litaay, C., A. Indriati, N. K. I. Mayasti, R. I. Tribowo, Y. Andriana, R. C. E. Andriansyah, and Others (2022). Physical, Chemical, and Sensory Quality of Noodles Fortification with Anchovy (*Stolephorus sp.*) Flour. *Food Science and Technology*, **42**; e75421

Marhamah, S. Surono, and E. Darmawan (2023). The Risk Cluster in Type 2 Diabetes Mellitus Based on Risk Parameters Using Fuzzy C-Means Algorithm. *Science and Technology Indonesia*, **8**(1); 17–24

Miao, M., B. Jiang, S. W. Cui, T. Zhang, and Z. Jin (2015). Slowly Digestible Starch-A Review. *Critical Reviews in Food Science and Nutrition*, **55**(12); 1642–1657

Nasir, N. M., E. Abdulmalek, and N. Zainuddin (2020). Preparation and Optimization of Water-Soluble Cationic Sago Starch with a High Degree of Substitution Using Response Surface Methodology. *Polymers*, **12**(11); 1–13

Ng, J. Q., C. K. Siew, H. Mamat, P. Matanjun, and J. S. Lee (2018). Effect of Acid Methanol Treatment and Heat Moisture Treatment on In Vitro Digestibility and Estimated Glycemic Index of Raw and Gelatinized Sago (*Metroxylon sagu*) Starch. *Starch/Stärke*, **70**(9–10)

Novianti, F., N. Mayasti, A. Indriati, C. Litaay, R. Andriansyah, E. Br Ketaren, and T. Widiantara (2024). Techno-Economic Analysis of Dry Noodle Products Based on Sago Flour Enriched with Anchovy Flour. In *IOP Conference Series: Earth and Environmental Science*, volume 1338. IOP Publishing, page 012068

Oliveira, D. C. d., H. A. Maieves, C. Bernardo, I. C. Bellettini, B. B. Remor, R. Moresco, et al. (2020). Evaluation of Cassava Starch as Raw Material According to the Characteristics of the Granules. *Research, Society and Development*, **9**(12); e8491210879

Pandiangan, F. I. and K. A. Audah (2022). Heavy Metal Contamination Status in the Soil-Water-Rice System near Coal-Fired Power Plants in Cilacap, Indonesia. *Jurnal Ilmiah Pertanian*, **19**(3); 145–154

Paramitasari, D., M. Musa, O. N. Putra, S. Suparman, Y. S. Pramana, S. Elisa, T. Hidayat, A. E. Tjahjono, D. P. Meidiawati, and K. Pudjianto (2024). Hydroxypropylation for Functional Enhancement of Sago Starch: The Effects of Low Propylene Oxide Concentration Using Response Surface Methodology. *Journal of Agriculture and Food Research*, **15**; 100933

Pinyo, J., P. Luangpituksa, M. Suphantharika, C. Hansawasdi, and R. Wongsagonsup (2017). Improvement of Sago Starch Extraction Process Using Various Pretreatment Techniques and Their Pretreatment Combination. *Starch/Stärke*, **69**(9–10)

Pratiwi, W. S. W., A. K. Anal, and S. R. Putra (2015). Production by Lintnerization-Autoclaving and Physicochemical Characterization of Resistant Starch III from Sago Palm (*Metroxylon sagu* Rottb). *Indonesian Journal of Chemistry*, **15**(3); 295–304

Punia Bangar, S., K. Sunooj, M. Navaf, Y. Phimolsiripol, and W. S. Whiteside (2024). Recent Advancements in Cross-Linked Starches for Food Applications-A Review. *International Journal of Food Properties*, **27**(1); 411–430

Puspantari, W., P. T. Cahyana, A. Saepudin, Budiyanto, I. Kurniasari, A. D. Kusumasmarawati, et al. (2023). Sago Rice as an Environmentally Sustainable Food. In *BIO Web of Conferences*, volume 69. EDP Sciences, page 03012

R Development Core Team (2011). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria

Rickard, J. E., M. Asaoka, and J. M. V. Blanshard (1991). The Physicochemical Properties of Cassava Starch. *Tropical Science*, **31**; 189–207

Romero-Rosales, M., H. E. Romero-Luna, D. Cantú-Lozano, I. Andrade-González, and G. Luna-Solano (2025). Functionality and Modifications of Food Hydrocolloids: An Approach to Starch. *Starch-Stärke*, **77**(9); e70083

Sabirin, A. B. Sitanggang, S. Budijanto, M. B. Kusarpoko, A. Darussalam, A. S. Purwoto, and Y. S. Pramana (2024). Characteristics of Partially Pregelatinized Sago Starch from Bangka, Riau, and Papua Extruded Using Twin-Screw Extruder. *Journal of Food Measurement and Characterization*, **18**(5); 3793–3805

Santos, T. B. d., C. W. P. d. Carvalho, L. A. d. Oliveira, E. J. d. Oliveira, F. Villas-Boas, C. M. L. Franco, and D. W. H. Chávez (2021). Functionality of Cassava Genotypes for Waxy Starch. *Pesquisa Agropecuária Brasileira*, **56**; e02414

Sarungallo, Z. L., B. Santoso, and A. M. Puspita (2021). Physicochemical and Functional Properties of Spineless, Short-Spines, and Long-Spines Sago Starch. *Biodiversitas*, **22**(1); 137–143

Seet Chi, Y., H. Kamilah, Y. Nor Shariffa, and U. Utra (2021). Phosphorylation of Sago (*Metroxylon sagu*) Starch Cross-Linked with Sodium Triphosphate and the Physicochemical Properties of the Potential Application in Batter. *Journal of*

Food Processing and Preservation, **45**(6); e15491

Setiawan, B., F. Fetriyuna, S. M. A. Letsoin, R. C. Purwestri, and I. R. A. Jati (2022). A Sago Positive Character: A Literature Review. *A Sago Positive Character: A Literature Review*, **11**(2); 145–155

Siau, C. L., A. A. Karim, M. H. Norziah, and W. D. Wan Rosli (2004). Effects of Cationization on DSC Thermal Profiles, Pasting and Emulsifying Properties of Sago Starch. *Journal of the Science of Food and Agriculture*, **84**(13); 1722–1730

Simatupang, D. F. and M. Simbolon (2023). Fabrication of Biobriquettes from Mixture of Palm Fronds and Palm Shells with Varying Binders of Tapioca and Sago Flour. *International Journal of Applied Research and Sustainable Sciences*, **1**(4); 319–330

SNI-3729 (2008). Sago Starch. National Standardization Agency

SNI-3729 (2023). Sago Starch. National Standardization Agency

Sondari, D. and I. Iltizam (2018). Karakteristik Edible Coating dari Modifikasi Pati Sagu Dengan Metoda Cross Link. *Jurnal Teknologi Industri Pertanian*, **28**(3); 286–294

Statistik-Perkebunan (2023). *Statistik Perkebunan Jilid I (2022–2024)*

Steinley, D. (2008). Stability Analysis in K-Means Clustering. *British Journal of Mathematical and Statistical Psychology*, **61**(2); 255–273

Sulaiman, T. N. S., W. Wahyuono, A. N. Bestari, and F. N. Aziza (2023). Preparation and Characterization of Pregelatinized Sago Starch (PSS) from Native Sago Starch (NSS) (*Metroxylon* sp.) and Its Evaluation as Tablet Disintegrant and Filler-Binder on Direct Compression Tablet. *Indonesian Journal of Pharmacy*, **33**(2)

Sumardiono, S., B. Jos, I. Pudjihastuti, A. M. Yafiz, M. Rachmasari, and H. Cahyono (2021). Physicochemical Properties of Sago Ozone Oxidation: The Effect of Reaction Time, Acidity, and Concentration of Starch. *Foods*, **10**(6); 1309

Susanto, B., Y. T. Tosuli, H. Nami, A. Surjosatyo, D. Alandro, A. D. Nugroho, M. I. Rashyid, and M. A. Muflikhun (2024). Characterization of Sago Tree Parts from Sentani, Papua, Indonesia for Biomass Energy Utilization. *Heliyon*, **10**(1)

Tabari, M. (2017). Effect of Carboxymethyl Cellulose on the Mechanical and Barrier Properties of Sago Starch Based Films. *academia. edu*, **1**; 1–7

Tchounwou, P. B., C. G. Yedjou, A. K. Patlolla, and D. J. Sutton (2012). Heavy Metal Toxicity and the Environment. *Molecular, Clinical and Environmental Toxicology*, **101**; 133–164

Trisia, M. A., M. Tachikawa, and H. Ehara (2021). The Role of the Sago Supply Chain for Rural Development in Indonesia. *Reviews in Agricultural Science*, **9**; 143–156

Uthumporn, U., N. Wahidah, and A. Karim (2014). Physicochemical Properties of Starch from Sago (*Metroxylon sagu*) Palm Grown in Mineral Soil at Different Growth Stages. In *IOP Conference Series: Materials Science and Engineering*, volume 62. page 012026

Wardono, H. P., A. Agus, A. Astuti, N. Ngadiyono, and B. Suhartanto (2021). Potential of Sago Hampas for Ruminants Feed. In *E3S Web of Conferences*, volume 306. EDP Sciences, page 05012

Yadav, R. and G. Garg (2013). A Review on Indian Sago Starch And Its Pharmacuetical Applications. *International Journal of Pharmaceutical and Life Sciences*, **2**(3); 99–106

Yusuf, M., M. Romli, Suprihatin, and E. Wiloso (2019). Potential of Traditional Sago Starch: Life Cycle Assessment (LCA) Perspective. In *IOP Conference Series: Materials Science and Engineering*, volume 507. IOP Publishing, page 012014

Zailani, M. A., H. Kamilah, A. Husaini, A. Z. R. A. Seruji, and S. R. Sarbini (2023). The Digestibility and Bacterial Growth Rates of Microwave Treated Sago (*Metroxylon sagu*) Starch. *Pertanika Journal of Science and Technology*, **31**(5); 2283–2290

Zhang, W., R. He, Z. Yu, G. Zhao, H. Zhang, C. Hou, and L. Yang (2024). Preparation Conditions Optimization and Functional Characteristics Investigation of Cationic-Acetylated Glutinous Rice Starch. *Lwt*, **201**; 116239

