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Bangka Sago as A Superior Starch Source: Processing, Morphology, Chemical Properties, and Heavy Metal Content

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ABSTRACT

Indonesia has significant potential for food diversification through the development of sago as an alternative carbohydrate source. This study aims to analyze the processing methods, morphological characteristics, chemical properties, and heavy metal content of local sago in Bangka and Bangka Tengah Regencies. The research was conducted across six villages from November 2023 to March 2024, with chemical and heavy metal testing performed in accredited laboratories. The results indicate that modern processing methods produce high-quality starch with a starch content ranging from 79.06% to 83.73% and heavy metal levels such as tin (Sn), lead (Pb), and cadmium (Cd) below the established safety limits, making it safe for consumption. Morphologically, habitat differences influence the physical characteristics of sago, such as trunk height, bark thickness, and leaf area, which affect starch productivity. The study also identifies that environmental factors, including nutrient availability and soil moisture levels, influence the chemical composition of sago. This research provides a scientific foundation for the integrated management of sago, supporting national food diversification efforts and opening opportunities for the development of sago-based products that meet national quality standards (SNI) with an environmentally friendly approach. These findings are relevant for stakeholders in optimizing sago's potential as a strategic commodity contributing to national food security.

1. INTRODUCTION

Indonesia is known as a country with high biodiversity, including carbohydrate-producing plants such as rice, corn, and cassava (Sugeng & Fitria, 2023). The population's dependency on rice as a staple food is remarkably high, with consumption reaching 80.905 kg per capita in 2023 for a population of 278 million (BPS, 2023). However, rice production often faces challenges from extreme climate change, making food diversification an urgent necessity to maintain food security (Schneider & Asch, 2020; Sugeng & Fitria, 2023; Toromade *et al*., 2024). One promising alternative is sago (*Metroxylon* spp.), a local plant rich in starch, with a composition of 79.40%–80.77%, higher than cassava and maize (Rahmawati *et al*., 2019). With an area of 5.579 million hectares and annual production of 22.3 million tons (Djoefrie *et al*., 2014), sago has various development potentials, including as a raw material for value-added food products, High Fructose Syrup (HFS), and environmentally friendly products such as organic plastics (Syartiwidya, 2023).

The development of sago as an alternative food source is further supported by its wide geographical distribution, with Papua accounting for approximately 85.12% of the total national sago area. However, other regions, such as Bangka and Central Bangka, also have promising development potential, although data on their productivity remains limited (Babelprov, 2023). The favourable annual temperature conditions (20.2 – 34.4°C) make these regions viable for further exploration. Previous studies have shown that sago's morphological characteristics and starch composition vary, with high starch content being a significant advantage over other carbohydrate sources (Du *et al*., 2020; Sumardiono *et al*., 2021; Trisia *et al*., 2016). Therefore, identifying potential land and developing more standardized sago cultivation could be crucial for optimizing its contribution as a national food solution, especially in addressing future food security threats.

Despite its significant potential, sago in Indonesia still faces several challenges, including land area reduction due to conversion, overharvesting, and limited land accessibility (Octavia *et al*., 2022; Santoso, 2018; Sheil *et al*., 2021). On the other hand, sago management is mainly traditional, with low productivity and quality (Dewayani *et al*., 2024; Trisia *et al*., 2021). Demand for sago products is also predominantly local, weakening the supply side and the competitiveness of sago products in both national and international markets. The absence of consistent price and quality standards further hinders sago's competitiveness as an alternative staple food (Purbaningsih *et al*., 2019). In Bangka, for instance, although there are potential sago forest areas, their productivity has not been officially recorded (BPS, 2023). This condition indicates that sago has not been optimally utilized as an alternative food source to support national food diversification.

To address these challenges, the first step is to identify sago morphological characteristics, especially to discover varieties with high starch production. Additionally, an analysis of land potential for sago plantations in Bangka and Central Bangka, currently categorized as natural sago forests, is necessary. Sago processing must also be improved from traditional to modern, technology-based industrial scales to enhance quality and productivity. sago-based food diversification should be promoted extensively by developing value-added products such as sago rice and organic plastics. This effort requires synergy among the government, academics, and the private sector to develop efficient quality standards, markets, and processing technologies. The theory of food diversification serves as an essential foundation for this research, focusing on diversifying consumption, production, and food availability (Gaitán-Cremaschi *et al*., 2019; Ickowitz *et al*., 2019). This concept aligns with the theory of ecosystem adaptation, which posits that food sustainability requires the optimal utilization of local resources (Ickowitz *et al*., 2019). As a local plant, sago is highly adaptable to wetland environmental conditions, which is one of its advantages over other crops (Botanri, 2015). Within this framework, the development of sago can strengthen national food security, reduce reliance on rice, and stimulate local economic growth through food production diversification.

This research aligns with Li & Wei (2020) that focusing on morphological characteristics and chemical properties of starch. However, Li & Wei (2020) emphasizes starch ghost structure and its industrial applications, which refers to the insoluble remnants of starch granules that have undergone gelatinization after the release of amylose and amylopectin. Unlike resistant starch structure, which forms through retrogradation and enzymatic resistance, or remnant starch granules, which refer to native, insoluble starch, starch ghost is formed due to the partial degradation of the granule shell while retaining an amorphous yet structured morphology. This distinction is crucial for understanding its functional properties and applications in various industries. Both studies discuss the composition and properties of starch relevant to its potential applications. This research also aligns with Susanto *et al*. (2024) study, which explores the potential of local resources, identifying sago as a material with economic and ecological value, whether for renewable energy or as a superior starch source. Furthermore, this study relates to Ahmad *et al*. (2020) research on sago starch nanoparticles, particularly regarding morphology and potential applications. Both studies utilize sago as a primary material, highlighting its significant role in sustainable material innovations.

The primary difference between this research and Li & Wei's (2020) lies in the focus; this study explores local Bangka sago varieties to identify superior starch sources and analyze their heavy metal content, while Li & Wei (2020) study focuses on ghost starch derived from the gelatinization of non-waxy starch and its structural properties. Compared to Susanto *et al*. (2024) research, the difference lies in the objective, as Susanto *et al*. (2024) study utilizes sago waste for biomass energy, whereas this research emphasizes starch quality for food needs. The distinction with Ahmad *et al*. (2020) research lies in using sago starch in nanoparticle form for green composite reinforcement in material and biomedical applications. In contrast, this study prioritizes identifying chemical properties and heavy metal contamination analysis in sago starch from local varieties.

Thus, this study aims to analyze the processing process, morphology, chemical properties, and heavy metal content of sago starch in Bangka Regency and Central Bangka Regency. The uniqueness of this study lies in the holistic approach to local Bangka sago as a source of superior starch, which integrates studies starting from the sago Starch Processing process, morphology, chemical properties, and heavy metal content analysis. Different from previous studies, this study examines local varieties to identify varieties that have high starch production while ensuring consumption safety through heavy metal contamination analysis. This approach provides a new contribution to the development of sago as a quality and safe food source while enriching the literature on the potential of local Bangka resources. The main contribution of this study is to provide comprehensive information to support sago-based food diversification programs, increase the productivity and quality of sago products, and expand market opportunities for sago-based products at the national and international levels.

2. MATERIALS AND METHODS

The research was carried out from November 2023 to March 2024 in six villages: Lumut, Kimak, Kayu Besi, and Sempan Villages in Bangka Regency, as well as Air Mesu and Cambai Villages in Central Bangka Regency. The chemical composition of starch was tested at the Bina Sawit Makmur Testing Laboratory in Palembang. At the same time, the metal content analysis was conducted at the Balai Standarisasi dan Pelayanan Jasa Industri (BSPJI), Palembang. The materials used included sago trees collected through exploration for morphological characterization and sago starch samples for chemical and metal analysis. Reagents included chloroform, hydrochloric acid, sodium hydroxide, acetic acid, Luff-Schoorl solution, potassium iodide, sulfuric acid, sodium thiosulfate, starch solution, and ethanol. The equipment included GPS devices, cameras, diameter tape, calipers, digital scales, microscopes, ArcGIS software, Soxhlet apparatus, atomic absorption spectrophotometer (AAS), and microwave digester.

2.1. Research Procedure

2.1.1. Morphological Characteristics

Observations of the habitus included recording the crown shape, clumps, spines, and the number of suckers. Habitat conditions were observed directly to determine the type of land, such as dry land, non-permanent waterlogged areas (freshwater/brackish), or permanently waterlogged areas. Measurements of the stem included the height from the ground to the tip of the stem free of fronds, total stem height, the diameter of the parent stem after felling, and bark thickness at three points (base, middle, tip) using callipers. The colour of the bark and pith was identified using the Royal Horticultural Society Colour Chart (RHS 2015). Based on the RHS scale, leaf observations included petiole, rachis, leaflet, and midrib colours. The number of green leaves and leaflets was counted manually, while the petiole and leaf length were measured. Leaf area was calculated using the formula:

$$S_{leaf} = \frac{ab\pi}{8} + \frac{ac}{2} \tag{1}$$

where S_{leaf} is the leaf area, a is the rachis length, b is the total length of the left and right leaflets at the rachis midpoint, and c is the total length of the left and right leaflets at one-quarter of the rachis. The length and width of mature leaflets were measured on the second leaf from the apex for leaf dimensions. The leaflet area was calculated as follows:

$$S(\mathrm{e}) = 0.785 \times L_{leaflet} \times W_{leaflet} \tag{2}$$

where S(e) was the leaflet area, $L_{leaflet}$ was the leaflet length, and $W_{leaflet}$ was the leaflet width. Spine density was observed on the stems and leaves from juvenile to mature phases, including their arrangement and density.

2.1.2. Production Characteristics

- Production potential: This was observed using the line transect method with 50×50 m^2 sample plots. Samples were purposively selected based on sago habitats. Starch productivity was calculated using the formula:

$$\text{Productivity} = \text{starch yield per stem} \times \text{stand potential} \times \text{area size} \tag{3}$$

- Starch Production: Starch was extracted from sago trunks in 1-meter sections (1 tual). Extraction involved soaking in water, sedimentation for 12 h, and weighing the dry mass. Starch yield was calculated as the following:

$$\text{Starch yield per stem} = \frac{\text{stem volume}}{\text{sample volume}} \times \text{dry starch weight of the sample} \tag{4}$$

Stem volume was calculated as πr^2 × height, where π = 3.14 and r was the stem radius in cm.

- Potential Area Coverage: Sago clump locations were determined using geographic coordinates and linked into polygons using the Universal Transverse Mercator (UTM) method to calculate area coverage.

2.1.3. Chemical Analysis

- Moisture content: Moisture content (*MC*) was determined gravimetrically using oven at 130°C:

$$\text{Moisture Content} = \frac{W_2 - W_3}{W_2 - W_1} \times 100\% \tag{5}$$

where W_1 = the weight of empty dish, W_2 = the weight of the dish and sample before drying, and W_3 = the weight of the dish and sample after drying (Alemayehu *et al*., 2021).

- Ash content: Ash content was determined by combustion at 550°C using the formula:

$$\text{Ash Content} = \frac{W2_{ash} - W1_{ash}}{W}\ x\ 100\% \tag{6}$$

W_{1ash} = weight of the empty crucible, W_{2ash} = weight of the crucible with ash after combustion, W = weight of the sample before combustion.

- Crude fiber: Crude fiber was measured after acid-base extraction:

$$\text{Crude Fiber} = \frac{W_1}{W} \times 100\% \tag{7}$$

- Fat content: Fat was extracted using the Soxhlet method (W_1 and W_2 were weights before and after extraction):

$$\%\ \text{Fat} = \frac{\text{W} - W_1}{W_2} \times 100\% \tag{8}$$

- Protein content: Protein content was calculated using:

$$\text{Protein Content} = \frac{(V_1 - V_2) \times \text{N} \times 0{,}014 \times f_k \times f_p}{\text{w}} \tag{9}$$

where V_1 and V_2 were titration volumes, N was HCl normality, f_k was the conversion factor, f_p was the dilution factor, and w was the sample weight.

- Carbohydrate content: Carbohydrate content was determined by difference:

$$\text{Carbohydrate} = 100\% - (\%\text{Protein} + \%\text{Ash} + \%\text{Fat} + \%\text{Moisture}) \tag{10}$$

- Metal content: Metals (Pb, As, Cd, Sn) were tested using Atomic Absorption Spectrophotometry (AAS):

$$\text{Metal Content} = \frac{C_m}{W} \times V \times F \tag{11}$$

where C_m was the metal concentration from the calibration curve, W was the sample weight, V was the final solution volume, and F was the dilution factor.

2.2. Data Analysis

Data on morphological characteristic were analyzed descriptively using qualitative and quantitative methods with NTSYS-pc software. Descriptive statistics, such as the mean, standard deviation, standard error, and coefficient of variation, were calculated and used to analyze the data on chemical composition. A normality test was performed using the Shapiro-Wilk test to confirm the data distribution. The analysis's findings are displayed in a table.

3. RESULTS AND DISCUSSION

3.1. Descriptive Statistical Analysis

Table 1 presents the statistical analysis of various component levels in the sample, including moisture content, total fat, protein, ash, crude fiber, and carbohydrates. The average moisture content in the sample is 14.408%, with a standard deviation of 0.921% and a coefficient of variation of 6.394%, indicating a relatively low level of variation. The total fat content has an average of 2.030% with the highest coefficient of variation (37.417%), suggesting a significant variation among samples. The average protein content is 0.438%, ash content is 0.936%, crude fiber content is 0.846%, and carbohydrate content is 81.910% (the largest component in the sample). The coefficient of variation for crude fiber, fat, and ash content is relatively high, at 45.718%, 37.417%, and 30.391%, respectively, indicating substantial variation among samples. Overall, these data describe the sample composition with different levels of variation in each component.

Table 1. Descriptive statistical for measurement results of sago characteristic

Statistical Values	Moisture Content (%)	Total Fat Content (%)	Protein Content (%)	Ash Content (%)	Crude Fiber Content (%)	Carbohydrate Content (%)
Number of Data	8	8	8	8	8	8
Mean	14.408	2.030	0.438	0.369	0.846	81.910
Standard Deviation	0.921	0.760	0.133	0.038	0.387	1.710
Standard Error	0.326	0.269	0.047	0.014	0.137	0.605
Coefficient of Variation (%)	6.394	37.417	30.391	10.396	45.718	2.088

Table 2. Normality test results

Statistical Value	Moisture Content (%)	Total Fat Content (%)	Protein Content (%)	Ash Content (%)	Crude Fiber Content (%)	Carbohydrate Content (%)
Shapiro-Wilk's	0.850	0.887	0.902	0.983	0.868	0.907
p-value	0.095	0.219	0.302	0.977	0.144	0.337

3.2. Data Normality Test

Based on the normality test results using the Shapiro-Wilk test in the table 2, the *p*-values obtained for each variable are as follows: moisture content (0.095), total fat content (0.219), protein content (0.302), ash content (0.977), crude fiber content (0.144), and carbohydrate content (0.337). Using a 5% significance level (0.05), all variables have *p*-values greater than 0.05, indicating that the data are normally distributed. This suggests that the variables of moisture content, total fat content, protein content, ash content, crude fiber content, and carbohydrate content meet the normality assumption, which is essential for further parametric statistical analysis.

Table 3. Environmental conditions of sago growth

Habitat Type	Villages	RH (%)	Temperature (°C)	Soil pH (-)	Altitude (masl)
Dry	Sempan	70.0	32.9	5.85	18.25
Moist	Kayu Besi	80.0	30.0	5.90	24.00
Shallow Swamp (depth <50 cm)	Cambai, Kayu Besi, and Kimak	84.0	30.3	5.58	20.00
Moderate Swamp (depth 50–100 cm)	Air Mesu and Lumut	86.5	28.7	4.70	20.00

3.3. Morphological Characteristics of Sago

3.3.1. Habitat and Habitus

The sago habitat in Bangka and Central Bangka Regencies is classified into four categories: dry, moist, shallow swamp, and moderate swamp, each with significant differences in environmental conditions (Table 3). The dry habitat in Sempan Village has a relative humidity (RH) of 70%, a temperature of 32.9°C, a soil pH of 5.85, and an altitude of 18.25 meters above sea level. The moist habitat in Kayu Besi Village has an RH of 80%, a temperature of 30°C, a soil pH of 5.90, and an altitude of 24 m. The shallow swamp habitat, with a water depth of <50 cm, found in Cambai, Kayu Besi, and Kimak villages, exhibits an RH of 84%, a temperature of 30.3°C, a soil pH of 5.58, and an altitude of 20 meters. Meanwhile, the moderate swamp habitat, with a water depth of 50–100 cm in Air Mesu and Lumut villages, has the highest RH at 86.5%, the lowest temperature at 28.7°C, the lowest soil pH at 4.70, and an altitude of 20 meters. These data show that relative humidity increases with greater swamp depth while temperature tends to decrease. Swamp habitats have lower soil pH than dry and moist habitats, indicating that soil conditions become more acidic in environments with deeper water inundation. This pattern may influence sago growth, with optimal conditions seemingly found in shallow swamp habitats, where there is a balance between humidity, soil pH, and temperature.

3.3.2. Trunk

Table 4 presents the characteristics of sago tree trunks in Bangka and Central Bangka Regencies, including trunk length, diameter, bark thickness, and trunk condition. Sago trunk lengths range from 3.93 to 9.69 m, with an average of 6.34 m, while the average trunk diameter (excluding bark) is 49.82 cm. The bark thickness of sago trunks varies between 0.88 and 2.52 cm, with the thinnest bark found on the Kayu Besi C tree. Environmental factors, such as shading, soil nutrients, and water availability, influence trunk length, while trunk surface conditions are affected by dry or waterlogged environments. Thinner bark tends to yield more starch. Most sago tree trunks are covered with moss and broad-leaved climbing plants, indicating a humid and dense environment that supports optimal moisture levels of around 90%.

Table 4. Characteristics of sago tree trunks

Tree Location	Trunk Length (m)	Diameter (cm)	Bark Thickness (cm)	Trunk Condition
Lumut	8.82	38.69	1.67	Trunk covered with moss
Cambai	5.09	48.96	2.52	Trunk with moss and broad-leaved climbing plants
Air Mesu	3.93	43.82	1.35	Trunk with moss and broad-leaved climbing plants
Kimak	5.66	47.50	2.43	Trunk with moss and broad-leaved climbing plants
Kayu Besi A	5.01	63.00	2.46	Trunk with moss and broad-leaved climbing plants
Kayu Besi B	9.69	55.32	2.32	Trunk covered with moss
Kayu Besi C	6.85	49.32	0.88	Trunk with moss and broad-leaved climbing plants
Sempan	5.71	51.96	1.70	Trunk covered with moss
Average	6.34	49.82	1.92	
Standard Deviation	1.99	7.32	0.61	
Coefficient of Variation (%)	31.31	14.69	31.74	

Table 5. Color characteristics of sago tree bark and pith using the Royal Horticulture Society Colour Chart (RHS) 2015

No	Tree Location	Bark Color	Pith Color
1	Lumut	200C	N155D
2	Cambai	200D	156D
3	Air Mesu	200D	155B
4	Kimak	200D	155B
5	Kayu Besi A	N199C	155B
6	Kayu Besi B	N199C	157C
7	Kayu Besi C	N199C	158C
8	Sempan	200C	27B

Notes: 27B = Light Yellowish Pink; 155B= Yellowish White; N155D = Yellowish White; 156D = Yellowish White; 157C = Pale Yellow Green; 158C = Yellowish White; N199C = Moderate Yellowish Brown; 200C = Moderate Brown; 200D = Moderate Brown

Based on the data in Table 5, the bark and pith color characteristics of sago trees in Bangka and Central Bangka Regencies show considerable variation, as determined using the Royal Horticulture Society Colour Chart (RHS) 2015. The bark color is predominantly medium brown to medium brownish, such as Medium Brown (200C and 200D) and Medium Brownish (N199C). Meanwhile, the pith color exhibits a broader range of variations, from Yellowish White (N155D, 155B, and 156D), Medium Yellowish White (158C), Pale Yellow Green (157C), to Light Yellowish Pink (27B). Sago trees from Lumut Village have a bark color of Medium Brown (200C) with a pith color of Yellowish White (N155D). In contrast, trees from Cambai, Air Mesu, and Kimak Villages show a Medium Brown (200D) bark color with variations in pith color between Yellowish White (155B) and Yellowish White (156D). Trees from Kayu Besi Village have a Medium Brownish (N199C) bark color, with variations in pith color ranging from Yellowish White (155B) and

Medium Yellowish White (158C) to Pale Yellow Green (157C). Meanwhile, sago trees from Sempan Village have a bark color of Medium Brown (200C) with a unique pith color, namely Light Yellowish Pink (27B). This variation in pith color can be associated with the activity level of polyphenol oxidase (PPO). This enzyme plays a role in the color change of sago starch during oxidation. Additionally, environmental factors such as humidity, soil conditions, pH, and heavy metal content may also influence sago's morphological and chemical characteristics.

3.3.3. Leaf

The leaf characteristics of sago trees in Bangka and Central Bangka regencies exhibit significant variations (Table 6). The average number of leaves per tree is 16.00, with a coefficient of variation of 12.94%. The average number of leaflets on the right and left sides is 76.00 and 74.25 pieces, respectively, with an average leaf length of 6.75 m and an average rachis length of 5.42 m. Petiole length ranges from 32.0 cm to 283.0 cm, while petiole width varies between 7.2 cm and 13.0 cm. Leaf area ranges from 2.21 m² to 19.98 m², with an average of 13.74 m² and a coefficient of variation of 45.38%. The Kayu Besi B sago tree has the highest number of leaves (19 pieces) but the smallest leaf area (2.21 m²). Conversely, the sago tree from Kimak Village has the fewest leaves (13 pieces) but one of the largest leaf areas (15.24 m²). These variations are influenced by habitat conditions, soil nutrient content, and leaflet characteristics, including rachis length and the number of leaflets.

Table 6. Leaf characteristics of various sago trees

Tree Location	**Number of Leaves (pcs)**	**Number of Leaflets**		**Leaf Length (m)**	**Rachis Length (m)**	***Petiole* (cm)**		**Leaf Area (m²)**
		Right (pcs)	**Left (pcs)**			**Length**	**Width**	
Lumut	17	78	75	9.20	7.48	172.0	12.5	17.19
Cambai	13	75	72	7.64	6.59	105.0	9.3	18.19
Air Mesu	13	77	75	7.79	6.59	119.8	9.2	19.98
Kimak	17	89	87	8.66	5.83	283.0	12.0	15.24
Kayu Besi A	16	82	78	3.73	2.17	156.5	13.0	6.03
Kayu Besi B	19	59	62	1.14	0.82	32.0	7.2	2.21
Kayu Besi C	16	75	74	7.98	6.14	184.0	10.8	16.04
Sempan	17	73	71	7.86	7.76	210.0	9.5	15.07
Average	16.00	76.00	74.25	6.75	5.42	157.79	10.44	13.74
Standard Deviation	2.07	8.54	7.01	2.80	2.53	74.97	1.98	6.24
Coefficient of Variation (%)	12.94	11.23	9.43	41.48	46.69	47.51	19.02	45.38

Table 7. Characteristics of leaflets from various sago trees

Tree Location	**Length of Leaflet at ¼ Rachis (cm)**		**Length of Leaflet at ½ Rachis (cm)**		**Width of Leaflet at ½ Rachis (cm)**		**Leaflet Area (cm²)**
	Right	Left	Right	Left	Right	Left	
Lumut	122	123	128	133	10.1	9.6	1.009.06
Cambai	162	163	175	177	9.7	9.2	1.305.61
Air Mesu	164	165	176	177	6.9	8.3	1.052.99
Kimak	140	163	161	154	7.7	9.1	1.040.20
Kayu Besi A	152	135	161	159	9.2	9.0	1.144.75
Kayu Besi B	134	145	143	139	7.6	8.3	945.47
Kayu Besi C	140	135	151	151	8.2	8.6	941.29
Sempan	141	145	158	153	9.5	9.1	1.018.42

Based on the research findings presented in Table 7 regarding the characteristics of sago leaflets from various sago trees in Bangka and Central Bangka Regencies, it was found that the length of the leaflets at the ¼ rachis position ranged from 122 cm to 164 cm, while at the ½ rachis position, it ranged from 128 cm to 177 cm. The average width of the leaflets at the ½ rachis position was 8.26 cm (right) and 8.43 cm (left), with the lowest recorded variation at 7.7 cm and the highest at 10.1 cm. The largest leaflet area was found in a sago tree from Cambai, measuring 1.305.61 cm². In contrast, the smallest leaflet area was recorded in a sago tree from Kayu Besi C, measuring 941.29 cm². The interpolated data, marked with an asterisk (*), indicate significant variations in sago leaflet size, which are influenced by environmental conditions and the plant's genetic factors. Further analysis suggests that differences in leaflet size can be associated with habitat factors such as water availability, light intensity, and soil composition, which contribute to the morphological growth of sago trees in the region.

Table 8 illustrates the leaf color characteristics of mature and juvenile sago trees from various species in Bangka and Central Bangka regencies, based on the Royal Horticulture Society Colour Chart (RHS) 2015. Mature leaves exhibit variations in the color of petioles, leaflets, and midribs, such as Strong Yellow Green (144A) in the Lumut tree and Moderate Yellow Green (N144B) in the Kayu Besi C tree. The colors of leaflets and midribs in mature trees are predominantly shades of Deep Yellowish Green (141B and 141C). A wider variety of colors can be seen in young leaves, such as the Air Mesu tree's Moderate Reddish Orange (171A), the Cambai tree's Moderate Orange (173A), and the Kimak tree's Brownish Orange (165B). There are also unusual hues, like Moderate Reddish Brown (174A) in Kayu Besi C and Dark Pink (182C) in Kayu Besi B. While the Air Mesu tree's juvenile leaves range in color from Light Olive (152A) to Deep Greenish Yellow (153A), mature leaves are well documented with Moderate Yellow Green (144D) in petiole and Deep Yellowish Green (139B, 141B) in leaflet and midrib. Overall, the data show notable differences in leaf color, demonstrating the ecological flexibility of the several sago tree species found in the area.

Table 8. Leaf colors of mature and juvenile sago trees using the Royal Horticulture Society Colour Chart (RHS) 2015

Tree	Mature			Seedling		
	Petiole	Leaflet	Midrib	Petiole	Leaflet	Midrib
Lumut	144A	141B	141B	166D	166C	153A
Cambai	144D	139B	137B	172D	173A	173C
Air Mesu	144D	139B	141B	152A	171A	152B
Kimak	141C	141C	141B	165B	164A	144A
Kayu Besi A	145A	141B	141B	153B	165B	152C
Kayu Besi B	144B	141A	141A	182C	152B	143C
Kayu Besi C	N144B	141B	141B	174A	141C	143A
Sempan	144C	135A	135A	153A	165B	146C

Note: 135A = Dark Green; 137B = Moderate Olive Green; 139B = Moderate Yellowish Green; 141A = Deep Yellowish Green; 141B = Deep Yellowish Green; 141C = Strong Yellowish Green; 143A = Strong Yellow Green; 143C = Strong Yellow Green; 144A = Strong Yellow Green; 144B = Strong Yellow Green; N144B = Moderate Yellow Green; 144C = Strong Yellow Green; 144D = Light Yellow Green; 145A = Strong Yellow Green; 146C = Moderate Yellow Green; 152A = Light Olive; 152B = Light Olive; 152C = Dark Greenish Yellow; 153A = Deep Greenish Yellow; 153B = Strong Greenish Yellow; 164A = Brownish Orange; 165B = Brownish Orange; 166C = Brownish Orange; 166D = Moderate Orange; 171A = Moderate Reddish Orange; 172D = Moderate Orange; 173A = Dark Reddish Orange; 173C = Moderate Orange; 174A = Moderate Reddish Brown; 182C = Dark Pink.

3.3.4. Thorns

The thorns on the racis can be one of the prominent characteristics of the sago trees. Among the observed trees, the sago tree from Kayu Besi A is the only one with thorns characterized by a random arrangement. The distance between thorn rows is 4.61 cm on mature tree leaves and 1.24 cm on juvenile trees. In contrast, sago trees from other locations, including Kayu Besi B and C, Lumut, Cambai, Air Mesu, Kimak, and Sempan, do not have thorns. This indicates that thorns are unique to specific sago trees in the region.

3.4. Sago Starch Processing

Sago pith logs harvested are sent to processing facilities to turn them into sago starch ready for sale. Only one sago processing factory uses large-scale production and advanced processing methods, even though several are located throughout the Bangka Belitung Province. This firm in Sungailiat, Bangka Regency, has adopted the idea of a sustainable factory in addition to processing sago trunks using contemporary techniques. The trash is converted into biogas, animal feed, and even cleaned water during processing. Harvesters provide the factory with ready-to-process sago pith throughout the Bangka Belitung Islands Province.

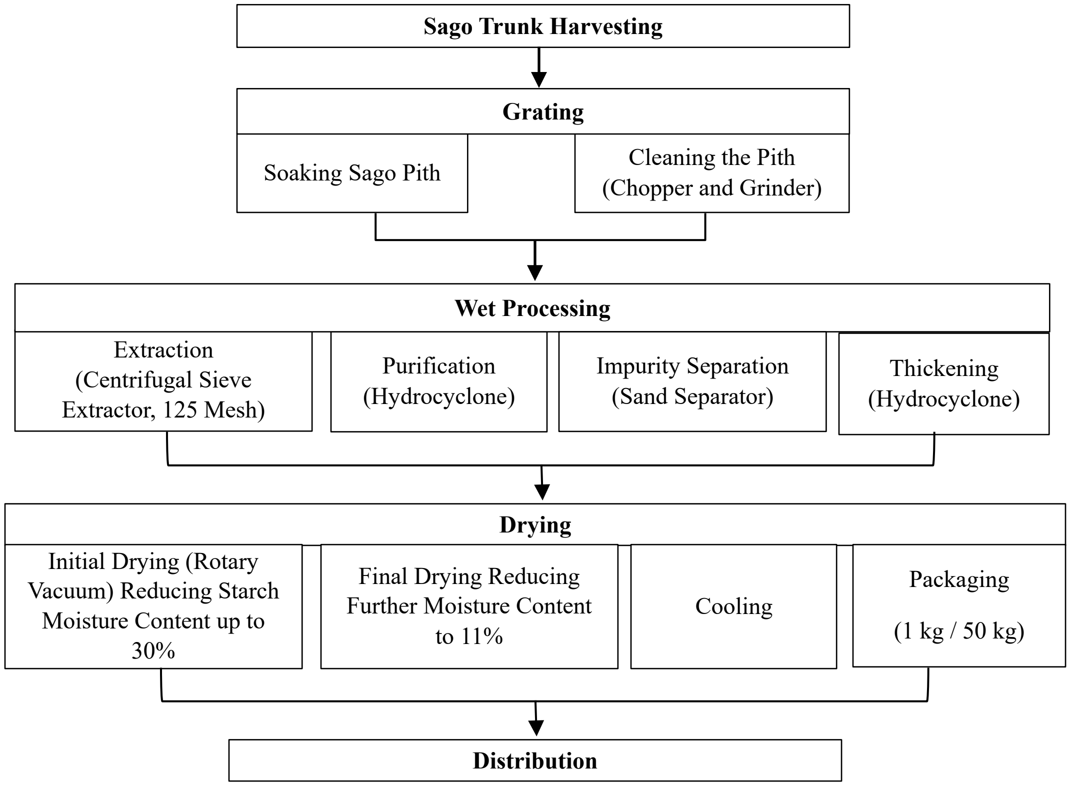

Figure 1. Sago starch processing

The sago processing into starch is divided into three stages: grating, wet processing, and drying (Figure 1). Grating is performed using choppers (shredders) and raspers (grinders for shredded material). Before grating, the sago pith is soaked in water to remove impurities such as mud and sand that may still adhere to the pith. This soaking process also serves to remove sap from the sago pith. After grating, the process continues to wet processing, which involves two stages: extraction and purification. Extraction is performed using a centrifugal sieve extractor of 125-mesh size. This process separates the starch liquid from the pulp. The remaining pulp, known as "onggok," consists of sago fibers. The starch liquid is then collected in sedimentation tanks. After the water is drained, the starch sediment undergoes purification using a hydrocyclone concentration machine. The purified starch is filtered through a sand separator to remove the remaining impurities. At this stage, starch thickening is conducted using hydrocyclone refining.

A rotary vacuum filter machine is used for the first and final drying stages of the drying process, where the purified wet starch moves on. The two-phase drying procedure guarantees that the wet starch will completely dry. The moisture content of the starch is further reduced to 11% after the final drying from 30% after the initial drying. A cooling system equipment is then used to cool the dried starch, reducing the possibility of moisture and bacterial growth and producing a smooth, clean, and cold product. As soon as the dried starch leaves the cooling system equipment, it is packaged in either 50-kg bulk or 1-kg little packaging.

The sago processing mill can produce 30 tons of sago pith every hour using 150 tons of machinery. However, to reach production capacity for effective processing, raw materials must be continually accessible, which means a waiting period of one to three days. To guarantee high-quality starch, the waiting period for processing sago pith must not exceed the allotted amount. Mold may grow on sago pith that is kept for more than three days, giving the starch a hazy appearance. 135 tons of dry sago starch are produced monthly when sago pith is processed for 2 to 3.5 hours to produce ready-to-distribute sago starch. The sago starch marketing area includes foreign markets like Malaysia as well as regions like Sumatra, Java, and Kalimantan.

3.1.5. Sago Production Characteristics

Table 9 shows that different sago tree species in Bangka and Central Bangka Regencies produce varied amounts of dry starch. The Sempan sago tree has the highest moisture content (54.92%), the lowest starch yield (14.82%), and the highest dry starch production per hectare annually (9.43 tonnes). This suggests excellent efficiency in converting biomass into starch and shows that Sempan sago productivity is still optimal despite its high moisture content. The Cambai sago tree, on the other hand, produces the least amount of starch (0.73 tonnes per hectare annually), although having a moisture level of 49.19 percent, which is not appreciably different from other varieties. This element would suggest that starch accumulation is not supported by the Cambai sago tree's genetic makeup or environmental circumstances. With a comparatively low moisture content (47.09%), the Kayu Besi B sago tree has the highest dry starch production per trunk (269.75 kg), underscoring the potential of this species for effective starch production. Plant management practices and environmental and genetic factors may all be responsible for these output variations. This study demonstrates that sago starch output can be maximized by choosing sago varieties with a high starch yield and a balanced moisture content.

During the study, the potential sago area in Bangka and Central Bangka regencies covers 96.360.23 hectares, with Bangka Regency accounting for 94.406.87 hectares, while Central Bangka Regency encompasses 1.953.36 hectares. Based on the potential sago area in Bangka and Central Bangka, which covers 96.360.23 hectares, the estimation of sago production potential is calculated by considering the average productivity per hectare. According to available data, sago productivity varies across locations, ranging from 0.73 to 9.43 tons per hectare per year, with an average productivity of 3.49 tons/ha/year and using the formula: Total Production Potential = Land Area × Productivity per ha. The total sago production potential is calculated to be 336.297.20 tons per year. This calculation indicates that Bangka and Central Bangka have a significant sago production potential, which can be optimized to support food diversification and sago-based industries.

Table 9. Production potential of various sago trees

Tree Location	Moisture Content (%)	Yield (%)	Dry Starch Production (kg per stem)	Harvestable Trees (trees per ha)	Dry Starch Production (tons per ha per year)
Lumut	61.06	16.40	119.51	48	5.74
Cambai	49.19	14.07	91.82	8	0.73
Air Mesu	44.13	16.03	68.37	24	1.64
Kimak	42.30	16.92	127.14	20	2.54
Kayu Besi A	60.79	11.56	143.17	12	1.72
Kayu Besi B	47.09	18.52	269.75	12	3.24
Kayu Besi C	48.32	20.18	144.81	20	2.90
Sempan	54.92	14.82	124.08	176	9.43

Table 10. Chemical composition of sago starch

No	Tree Location	Moisture Content (%)	Total Fat (%)	Protein (%)	Ash (%)	Crude Fiber (%)	Carbohydrate (%)
1	Lumut	15.80	2.48	0.66	0.38	1.62	79.06
2	Cambai	14.86	3.02	0.45	0.35	0.76	80.55
3	Air Mesu	14.22	3.15	0.47	0.40	1.19	80.57
4	Kimak	15.65	1.20	0.49	0.31	0.59	81.77
5	Kayu Besi A	13.55	1.38	0.47	0.38	0.49	83.73
6	Kayu Besi B	13.64	1.44	0.45	0.43	0.51	83.53
7	Kayu Besi C	13.57	1.68	0.29	0.37	0.72	83.37
8	Sempan	13.97	1.89	0.22	0.33	0.89	82.70

3.1.6. Chemical Properties of Sago Starch

Table 10 shows the chemical composition of sago starch from Bangka and Central Bangka regencies shows variations in moisture content, total fat, protein, ash, crude fibre, and carbohydrate content. The highest moisture content is found in Lumut starch (15.80%), while the lowest is in Kayu Besi C (13.57%). Total fat content ranges from 1.20% (Kimak) to 3.15% (Air Mesu). The highest protein content is recorded in Lumut (0.66%) and the lowest in Sempan (0.22%). All samples meet the ash content standard of SNI 3729:2008, ranging from 0.31% (Kimak) to 0.43% (Kayu Besi B). Only Kayu Besi A (0.49%) meets the standard for crude fibre, while the highest crude fibre content is found in Lumut (1.62%). Carbohydrate content in all samples exceeds the minimum standard of 65%, ranging from 79.06% (Lumut) to 83.73% (Kayu Besi A). These results indicate that environmental factors and processing methods influence the chemical quality of sago starch.

3.1.7. Metal Content in Sago Starch

The findings of metal testing indicate that the amounts of tin (Sn), lead (Pb), and cadmium (Cd) in sago starch in Bangka and Central Bangka regencies fall within the upper limits set by SNI 3729:2008, which are 40.00 mg/kg for Sn, 1.00 mg/kg for Pb, and 0.20 mg/kg for Cd." The Lumut sago sample had lower than 6.7 mg/kg of Sn, 0.5 mg/kg of Pb, and less than 0.1 mg/kg of Cd. However, information for Cambai, Air Mesu, Kimak, Kayu Besi (A, B, C), and Sempan is still missing from the table. One of the main reasons is that different regions have varying environmental conditions, which may affect the heavy metal level of sago starch and require further study due to differences in soil and water quality. Inaccurate test results or differences in analysis methods between locations are examples of technological issues with data processing that can also delay the results' delivery. However, according to test results, sago starch from these regions is safe to consume and meets food safety standards.

3.1.8. Relationship of Sago Morphological Characteristics

Based on cluster analysis using the SAHN clustering technique in the NTSYS 2.02 program, the genetic relationship among eight sago trees in Bangka and Central Bangka Regency exhibits varying degrees of similarity, with a phenotypic similarity coefficient (Kf) ranging from 0.43 to 0.69 (Table 11). The Kayu Besi B sago tree has the most distant genetic relationship compared to the other sago trees, while Air Mesu and Kimak have the closest relationship, with a Kf of 0.692. The dendrogram resulting from the clustering analysis divides the sago trees into two main groups at a Kf of 43%: Group A, which consists solely of Kayu Besi B, and Group B, which includes the remaining seven sago trees. Furthermore, at a Kf of 58%, Group B is further separated into two subgroups: Subgroup B1, consisting of Lumut, Air Mesu, Kimak, Kayu Besi C, and Kayu Besi A, and Subgroup B2, consisting of Cambai and Sempan. These findings indicate significant genetic variation among the analyzed sago trees, with some accessions exhibiting closer genetic relationships based on morphological and production traits.

Table 11. Similarity test values based on the morphological characteristics of sago

	Lumut	Cambai	Air Mesu	Kimak	Kayu Besi A	Kayu Besi B	Kayu Besi C	Sempan
Lumut	1.000							
Cambai	0.483	1.000						
Air Mesu	0.654	0.654	1.000					
Kimak	0.586	0.621	0.692	1.000				
Kayu Besi A	0.552	0.552	0.615	0.621	1.000			
Kayu Besi B	0.448	0.379	0.538	0.379	0.448	1.000		
Kayu Besi C	0.655	0.517	0.692	0.621	0.655	0.414	1.000	
Sempan	0.621	0.621	0.654	0.586	0.586	0.379	0.517	1.000

3.2. Discussion

The sago processing factory in Bangka Belitung successfully processes sago trunks into high-quality sago starch through modern methods, including grating, wet processing, and drying, with a production capacity of up to 135 tons per month for domestic and international markets. A sustainable approach is also implemented by recycling waste into animal feed, biogas, and clean water, enhancing production efficiency while maintaining environmental quality. This study shows that this plant grows naturally in various habitats, including mixed forests, oil palm plantations, and shallow and moderate swamps. The morphology of the sago trunk varies significantly, with a length ranging from 3.93 to 9.69 m, a diameter of 38.69 to 63.00 cm, and bark thickness of 0.88 to 2.52 cm. Growth habitats, such as moisture levels, light exposure, and swamp depth, significantly influence morphology, including the number of leaves and leaf area, which ranges from 2.21 to 19.98 m². Variations in trunk and pith colour, from light brown to yellowish-green, reflect differences in polyphenol oxidase (PPO) activity. This aligns with Selvarajan *et al*. (2018), stating that PPO affects the formation of brown pigments in plants. The highest starch production was found in Kayu Besi B, reaching 269.75 kg per trunk, supporting Ayulia *et al*. (2021) view that trunk size influences starch yield. Environmental factors such as nutrient availability and moisture were also identified as key factors in increasing sago productivity.

Chemical property analysis shows that starch content ranges from 79.06% to 83.73%, with the highest moisture content recorded in Lumut Village samples (15.80%). The lowest ash content was found in sago from Kimak Village (0.31%), consistent with Maherawati *et al*. (2011) findings that ash content increases with plant age. Although the crude fibre content of sago in the study area tends to be high, only samples from Kayu Besi A Village met the standards of SNI 3729:2008, indicating the potential for further processing. Heavy metal content, such as tin (Sn), lead (Pb), and cadmium (Cd) in sago starch, was below the SNI threshold, indicating the safety of sago as a food source in this region. These findings align with Polnaya *et al*. (2018), which shows that repeated washing of starch can reduce ash content and improve material quality. However, environmental contamination risks from tin mining require particular attention, as environmental management can affect crop quality (Zou *et al*., 2015). This study provides a scientific basis for optimizing sago potential as a food source while maintaining environmental sustainability.

This research has advantages over previous studies because it integrates the processing process, morphological studies, chemical properties, and heavy metal content analysis of sago, offering a holistic approach to the potential of sago as a superior starch source and safe food. Previous studies, such as Study by Li & Wei (2020), focused more on the structure and applications of starch, such as starch ghosts, in the food and non-food industries. In contrast, this study explores sago's nutritional content and food safety, including heavy metals. Study by Susanto *et al*. (2024) highlighted the use of sago for biomass energy but did not include food aspects or chemical analysis. Study by Ahmad *et al.* (2020) focused on sago starch nanoparticle innovation for green materials without discussing sago's full potential as a food source. Compared to these, this research provides deeper insights into sago's characteristics as a food ingredient, while previous studies were more specific to industrial applications. Nonetheless, this study aligns with Li & Wei (2020) in understanding starch properties, Susanto *et al*.'s (2024) study in utilizing sago as a natural resource, and Ahmad *et al.* (2020) in developing value-added sago products, demonstrating continuity in exploring sago's potential for various purposes.

The implications of this study indicate that integrated sago management can enhance its economic value as a superior food source while maintaining environmental sustainability. Morphological and chemical studies provide a scientific basis for selecting superior sago varieties for starch production, while heavy metal content analysis ensures food safety. This opens opportunities for developing sago-based products that meet national quality standards (SNI) while being environmentally friendly. By integrating agronomic, environmental, and food safety approaches, this study provides direction for more efficient sago resource management, including advancing processing technology to reduce ash and crude fibre content. Furthermore, attention to environmental contamination risks from tin mining emphasizes the importance of sustainable environmental management policies to maintain the quality of sago as a strategic food ingredient. These findings are relevant for stakeholders in the agriculture and food sectors and for industries and policymakers in developing sago's potential as a commodity that supports national food security.

4. CONCLUSION

Based on the research findings and discussion regarding the influence of attitudes on the intention of young The research findings show that the modern processing methods applied in sago factories can produce high-quality starch with a starch content ranging from 79.06% to 83.73%, while heavy metal content such as tin (Sn), lead (Pb), and cadmium (Cd) is below the threshold set by SNI, making it safe for consumption. From a morphological perspective, habitat differences affect the physical characteristics of sago, including trunk height, bark thickness, and leaf area, which influence starch productivity. The study also indicates that the chemical properties of sago are influenced by environmental factors such as nutrient availability and soil moisture levels. The research's limitations include the data scope, which does not fully cover the impact of tin mining on sago quality, and the need to improve processing efficiency. Further research is required to develop more efficient processing technologies, reduce crude fiber content, and identify superior varieties that can sustainably enhance sago starch production.

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