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Integrating Fermentation into Eco-Design of Sago Flour Processing: Enhancing Water-Energy Efficiency and Functional Properties

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ABSTRACT

Sago (*Metroxylon sagu* Rottb.) represents a strategic carbohydrate resource for wetland regions; however, conventional sago starch processing is characterized by high water and energy consumption, limiting its environmental sustainability. This study proposes an eco-design approach for sago flour production by integrating controlled microbial fermentation using a mixed starter dominated by lactic acid bacteria and low-temperature drying to redesign the conventional processing pathway. The proposed system eliminates water-intensive rasping and sedimentation stages, thereby improving water–energy efficiency while enhancing product quality. Experimental results demonstrate that the eco-design process reduced water consumption from 5–20 times to 2–3 times the weight of raw material and decreased mechanical power requirements from 54 HP to 40 HP. Fermentation pretreatment using the microbial starter induced partial modification of starch granule structure, increased flour yield by approximately 10%, reduced antinutritional tannin content, and improved functional properties, including water-holding and oil-holding capacities. Physicochemical analyses indicated that the resulting sago flour maintained high carbohydrate content and brightness while exhibiting enhanced functionality for food applications. Overall, this study presents a viable eco-design paradigm for sustainable and value-added sago flour production.

1. INTRODUCTION

Sago (*Metroxylon sagu* Rottb.) is an indigenous starch-producing palm widely cultivated and utilized across the Southeast Asia–Pacific region, particularly in Indonesia, Papua New Guinea, and Malaysia. It represents a strategic carbohydrate resource due to its exceptional adaptability to marginal wetland ecosystems, including peatlands and periodically flooded areas, where conventional food crops are unable to thrive. Under optimal management, sago palms are capable of producing 20–40 tons of dry starch per hectare annually, which is substantially higher than the average yields of cassava, potato, and maize cultivated under comparable conditions [1]. This high productivity, combined with minimal agricultural input requirements, positions sago as a climate-resilient and resource-efficient crop with strong potential to strengthen regional food security.

Beyond its agronomic advantages, sago plays a critical socio-economic role in rural and remote communities. In Indonesia, approximately 75% of sago production is carried out by smallholder farmers, who utilize not only the starch as a staple food but also other plant components—such as bark and fronds—for housing materials and household needs. Sago trunks are often regarded as a “living savings system” because they can be harvested at any time to meet household financial needs, providing livelihood security for wetland-dependent communities [2]. Consequently, the development of sustainable sago processing technologies has implications that extend beyond food production, encompassing rural development, environmental conservation, and socio-economic resilience.

Despite this potential, conventional sago starch extraction practices remain resource-intensive and environmentally burdensome. The dominant processing sequence—rasping, washing, sieving, sedimentation, and drying—requires substantial amounts of water and mechanical energy and often leads to starch losses during unit operations. Water consumption in traditional sago starch extraction has been reported to reach 10–20 L per kilogram of dry starch, while the drying stage alone contributes significantly to total energy demand and greenhouse gas emissions [2, 3]. In rural processing systems, particularly in Papua New Guinea, sago extraction remains highly labor-intensive and relies on large volumes of water for pith maceration and washing [4]. These inefficiencies not only increase production costs but also generate wastewater containing suspended solids and organic matter, which is frequently discharged without treatment, contributing to local environmental degradation.

In the broader context of sustainable agro-industrial development, excessive water and energy consumption are widely recognized as major barriers to environmental performance. Eco-design has therefore emerged as a strategic approach to mitigate these challenges by integrating environmental considerations into the early stages of process and system design. Within agro-processing systems, eco-design emphasizes process flow redesign, reduction of unit operations, minimization of resource inputs, and enhancement of material efficiency while maintaining or improving product quality. Previous studies in the starch and flour industries have demonstrated that cleaner production, process intensification, and biologically assisted pretreatments such as fermentation, as well as optimized drying strategies, can substantially reduce environmental burdens [5].

However, technological innovation in sago processing has largely focused on mechanical improvements in starch extraction equipment, with limited attention given to process-level eco-design strategies that integrate biological modification. Most existing systems continue to produce wet starch, which inherently requires high water input and energy-intensive drying. In contrast, flour-based processing of sago pith offers a promising alternative pathway, as it enables direct conversion of raw material into a stable, shelf-ready product while retaining nutritionally relevant non-starch components such as dietary fiber. Previous studies have reported that food products formulated with sago flour, such as noodles, can contain up to 13.16% total dietary fiber, indicating opportunities for functional food development [6].

Fermentation represents a particularly attractive core technology within an eco-design framework, as it offers multiple, simultaneous benefits. Beyond facilitating downstream processing through partial degradation of cell walls and starch granules, fermentation can reduce antinutritional compounds (e.g., tannins), improve flavor characteristics, and enhance functional properties such as water- and oil-holding capacities. These effects contribute to improved product quality while lowering mechanical resistance during drying and milling, thereby achieving a synergistic improvement in both processing efficiency and functional performance—a "quality and efficiency" win–win scenario [7].

In addition to food applications, the valorization of sago processing by-products (sago hampas) through starch recovery, glucose production, and subsequent bioethanol fermentation has been demonstrated, highlighting opportunities for circular bioeconomy integration and improved process sustainability [8]. These findings further suggest that process redesign incorporating fermentation can simultaneously support resource efficiency, product diversification, and waste minimization.

In this study, eco-design is defined as the systematic redesign of the sago processing pathway to minimize water and energy consumption, reduce environmental impact, and enhance resource efficiency through process integration. The proposed eco-design approach integrates controlled microbial fermentation and low-temperature drying to eliminate water-intensive rasping and sedimentation stages characteristic of conventional starch extraction. This integration is expected not only to reduce operational inputs but also to improve starch functionality, reduce antinutritional compounds, and increase overall flour yield.

Therefore, the objective of this study is to evaluate an eco-design approach for sago flour processing that integrates fermentation and drying technologies to improve water and energy efficiency while enhancing the physicochemical and functional quality of the resulting flour. By aligning process innovation with sustainability principles, this work aims to contribute to the development of environmentally responsible sago-based agro-industrial systems suitable for small- and medium-scale implementation in wetland regions.

2. MATERIALS AND METHODS

2.1 Raw material

Fresh sago trunks (*Metroxylon* sp.) were obtained from smallholder farmers in the Sukabumi region, West Java Province, Indonesia. Mature trunks aged approximately 7–10 years were selected to ensure optimal starch accumulation. The outer bark was manually removed, and the inner pith was separated and cut into small pieces prior to fermentation. All chemicals used for analysis were of analytical grade.

2.2 Eco-design of sago flour processing

An eco-design processing approach was implemented by integrating controlled fermentation and low-temperature drying to redesign the conventional sago processing pathway. Unlike traditional starch extraction, this method eliminates rasping, intensive washing, and sedimentation stages, thereby reducing water and energy consumption (Figure 1).

The sago pith was cut into pieces measuring approximately 1–2 cm and subjected to controlled fermentation using a mixed microbial starter dominated by lactic acid bacteria (LAB). The starter consisted of a commercial food-grade fermentation culture containing *Lactobacillus* spp., supplemented by naturally occurring fermentative microorganisms present in the sago pith (mixed-culture fermentation). Prior to inoculation, the starter was activated in warm potable water (35–37°C) for 15 min to ensure microbial viability. Fermentation was conducted for 0 (control), 1, 2, 3, and 4 days at ambient temperature (28–30°C) in closed plastic containers. The ratio of sago pith to water was maintained at 1:2 (w/v). Starter concentrations were applied at 0%, 1%, 2%, and 3% (w/w), based on fresh pith weight, to evaluate their effects on process efficiency and flour quality.

Following fermentation, the material was dried in a forced-air oven at 45–50°C until the moisture content reached ≤ 12%. The dried product was subsequently milled using a hammer mill and sieved through a 120-mesh screen to obtain sago flour.

For comparison, a conventional sago starch extraction process commonly practiced in the Meranti Islands Regency, Indonesia, was used as a reference system for water and energy efficiency evaluation. The conventional process involved mechanical rasping using a diesel-powered rasping machine (approximately 20 HP), followed by 3–5 washing cycles with a water-to-pith ratio of approximately 1:5–1:10 (w/v). The starch slurry was allowed to settle for 6–12 h in sedimentation tanks before decantation and subsequent drying using sun drying or hot-air drying, as reported in previous field surveys and literature [9, 10]. These parameters were adopted as representative benchmarks for traditional small-scale sago processing systems in Indonesia.

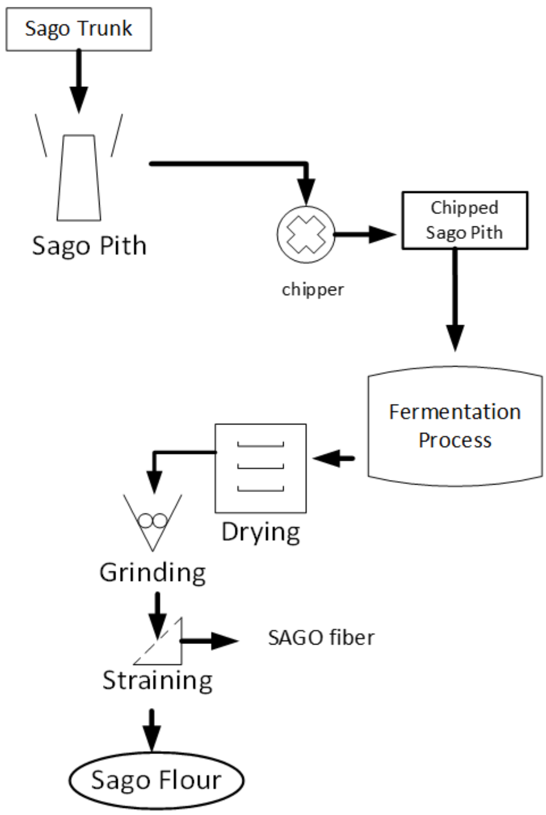


Figure 1. The overall eco-design process flow for fermentation-based sago flour (FM) production

Mechanical energy consumption was estimated based on the rated power (HP) of each processing unit and its operating duration. Actual real-time power draw was not directly measured; therefore, a standard load factor of 0.7–0.8 was applied to account for partial equipment loading, as commonly used in agro-industrial energy assessments. This approach allowed comparative evaluation between conventional and eco-design processing systems.

Drying energy consumption was calculated using the mass of water removed and the latent heat of evaporation of water (2,257 kJ kg^{-1}). A thermal efficiency of 60% was assumed for the forced-air dryer based on typical performance reported for small-scale industrial drying systems. Energy calculations were therefore semi-theoretical and intended for comparative assessment rather than absolute energy auditing. These assumptions were consistently applied to both processing systems to ensure methodological comparability.

2.3 Experimental design

The experiment followed a completely randomized design (CRD) with two factors: (1) Fermentation time (0, 1, 2, 3, and 4 days), and (2) Starter concentration (0%, 1%, 2%, and 3%). Each treatment combination was performed in duplicate. The experimental unit consisted of 2 kg of fresh sago pith. A non-fermented sample (0 day, 0% starter) served as the control to assess the effects of fermentation and starter addition.

2.4 Measurements and analyses

2.4.1 Water and energy consumption

Water consumption was quantified as the total volume of water used per kilogram of fresh sago pith. Mechanical energy requirements were estimated based on the HP and operating duration of each processing unit. Drying energy demand was calculated using the mass of water removed and the latent heat of evaporation, supported by field observations and literature-based estimations.

2.4.2 Physicochemical properties

Proximate composition (moisture, ash, fat, protein, carbohydrate, and crude fiber) was determined following the AOAC (2019) standard methods. Amylose content was analyzed using the iodine-binding method, while tannin content was quantified spectrophotometrically. Color attributes were expressed as the whiteness index (L*) measured using a HunterLab colorimeter (USA).

2.4.3 Particle size distribution and microstructure

Particle size distribution (PSD) was evaluated using a multi-stage sieve analysis. Microstructural characteristics were examined using scanning electron microscopy (SEM; Hitachi SU3500, Japan) at 500× magnification after gold sputter-coating.

2.4.4 Functional properties

Functional properties, including water-holding capacity (WHC), water solubility index (WSI), oil-holding capacity (OHC), and swelling power (SP), were determined using standard analytical procedures commonly applied in flour characterization.

2.5 Statistical analysis

All results are expressed as mean ± standard deviation. Statistical analysis was conducted using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test at a significance level of $p < 0.05$, using SPSS software (IBM Corp., USA). Although the number of replications was limited, the study was designed as an exploratory assessment of eco-design performance in sago processing. Future studies with higher replication are recommended to enhance statistical robustness.

3. RESULTS AND DISCUSSION

3.1 Physicochemical properties

The fermentation treatments applied in the eco-design processing system resulted in significant variations in the physicochemical characteristics of sago flour, which are closely related to both processing efficiency and product performance. The physicochemical properties of fermented sago flour are presented in Table 1. Moisture content ranged from 5.92% to 10.63%, indicating that fermentation influenced water retention within the flour matrix. This effect can be attributed to microbial acid production during fermentation, which promotes partial disruption of cell wall polysaccharides and facilitates moisture release during drying, thereby potentially reducing drying energy requirements.

Carbohydrate content remained relatively stable (88–90%), confirming that controlled fermentation did not substantially degrade the primary starch fraction. This suggests that microbial metabolism preferentially targets non-starch components rather than extensive starch hydrolysis, consistent with previous reports on LAB–dominated fermentation systems [11, 12]. Maintaining high carbohydrate content is essential for preserving the functional role of sago flour in starch-based food applications.

Fermentation-induced changes in protein and fat contents were also observed. Protein content ranged from 0.50% to 0.70%, while fat content varied between 0.52% and 0.65%. These variations are likely associated with microbial enzymatic activity, particularly proteolytic and lipolytic enzymes, which can partially hydrolyze macromolecules and alter their extractability during analysis. Similar trends have been reported in fermented cereal- and tuber-based materials, where fermentation modifies macromolecular structures without substantially increasing total nutrient levels [13].

A notable reduction in tannin content was observed across fermentation treatments (Table 1). This decrease can be explained by the acidic environment generated during fermentation and the action of microbial tannase and esterase enzymes, which are known to degrade polyphenolic compounds. The reduction of tannins is particularly important from a nutritional perspective, as tannins can bind proteins and minerals, thereby reducing their bioavailability.

Amylose content exhibited a slight decreasing trend with increasing fermentation duration, declining from 30.88% in the non-fermented control to 27.38% in the longest fermentation treatment. This reduction may be attributed to limited enzymatic hydrolysis of amorphous regions within starch granules, which can influence pasting behavior and textural properties relevant to food processing applications [14]. Importantly, flour brightness (L*) values remained relatively unchanged, indicating that fermentation did not negatively affect visual quality.

From an eco-design perspective, these physicochemical changes demonstrate that fermentation not only improves product quality but also supports process efficiency by reducing moisture retention and antinutritional factors, thereby facilitating downstream drying and milling operations.

Table 1. Physicochemical properties of sago flour as affected by fermentation time and starter concentration under an eco-design processing system

	Moisture Content	Fat Content (%)	Protein Content (%)	Crude Fiber Content (%)	Ash Content (%)	Carbohydrate Content (%)	Amilosa Content (%)	Brightness (L*)	Tannin Content (mg/100 g)	Yield (%)
F0H1	5.92 ± 0.69^{A}	0.65 ± 0.04^{C}	0.63 ± 0.01^{BC}	3.03 ± 0.05^{A}	2.48 ± 0.14^{B}	89.13 ± 0.06^{Ab}	30.88 ± 0.48^{Aa}	92.02 ± 0.32^{Aa}	66.66 ± 0.74^{Aa}	39.45 ± 0.69^{Aa}
F0H2	7.58 ± 0.66^{A}	0.59 ± 0.02^{A}	0.68 ± 0.01^{A}	0.68 ± 0.01^{A}	2.48 ± 0.01^{B}	88.84 ± 0.05^{Ad}	30.29 ± 0.23^{ABa}	92.25 ± 0.16^{Aab}	56.19 ± 0.09^{Ba}	40.41 ± 0.66^{Aa}
F0H3	8.02 ± 0.08^{A}	0.52 ± 0.01^{D}	0.65 ± 0.01^{B}	0.65 ± 0.01^{B}	2.98 ± 0.01^{A}	88.32 ± 0.35^{Ba}	29.21 ± 0.64^{Ba}	92.09 ± 0.97^{Aab}	52.39 ± 0.33^{Ca}	40.65 ± 0.08^{Aa}
F0H4	6.86 ± 0.97^{A}	0.58 ± 0.01^{B}	0.62 ± 0.01^{C}	0.62 ± 0.01^{C}	2.39 ± 0.08^{B}	88.11 ± 0.02^{Bb}	29.04 ± 0.01^{Ba}	91.89 ± 0.04^{Ab}	52.29 ± 1.21^{Ca}	39.27 ± 0.97^{Aa}
F1H1	6.62 ± 0.44^{B}	0.59 ± 0.01^{B}	0.66 ± 0.01^{B}	0.66 ± 0.01^{B}	2.70 ± 0.08^{A}	90.51 ± 0.51^{Aa}	28.18 ± 0.01^{Ab}	92.34 ± 0.13^{Aa}	64.62 ± 0.71^{Ab}	34.34 ± 7.44^{Ba}
F1H2	8.61 ± 0.30^{AB}	0.57 ± 0.01^{C}	0.5 ± 0.02^{A}	0.5 ± 0.02^{A}	2.70 ± 0.13^{A}	89.30 ± 0.06^{Bb}	26.78 ± 0.15^{Bb}	91.87 ± 0.69^{Aa}	49.05 ± 0.11^{Bb}	35.09 ± 7.30^{Aa}
F1H3	7.57 ± 0.81^{B}	0.56 ± 0.01^{A}	0.67 ± 0.01^{A}	0.67 ± 0.01^{A}	2.19 ± 0.15^{A}	88.98 ± 0.00^{Bab}	25.58 ± 0.57^{Cb}	91.83 ± 0.83^{Ab}	42.31 ± 0.60^{Ca}	35.63 ± 7.81^{Aa}
F1H4	10.03 ± 0.84^{A}	0.56 ± 0.04^{B}	0.66 ± 0.04^{C}	0.66 ± 0.04^{C}	2.23 ± 0.08^{A}	88.11 ± 0.07^{Cb}	25.17 ± 0.06^{Cd}	91.86 ± 0.01^{Ab}	38.14 ± 0.04^{Db}	36.27 ± 6.84^{Aa}
F2H1	7.85 ± 0.15^{A}	0.58 ± 0.01^{AB}	0.67 ± 0.01^{A}	0.67 ± 0.01^{A}	2.04 ± 0.18^{A}	90.11 ± 0.06^{Aa}	30.40 ± 0.21^{A}a	92.30 ± 0.07^{Ca}	66.31 ± 0.02^{Aa}	32.87 ± 9.15^{Aa}
F2H2	7.66 ± 0.25^{A}	0.53 ± 0.01^{A}	0.67 ± 0.01^{B}	0.67 ± 0.01^{B}	1.93 ± 0.06^{A}	89.75 ± 0.04^{ABa}	30.33 ± 0.30^{ABa}	93.22 ± 0.12^{Aa}	48.62 ± 0.71^{Bb}	34.32 ± 7.25^{Aa}
F2H3	7.08 ± 0.59^{A}	0.55 ± 0.00^{B}	0.69 ± 0.01^{B}	0.69 ± 0.01^{B}	2.00 ± 0.13^{A}	88.65 ± 0.61^{ABa}	29.44 ± 0.06^{Ba}	93.34 ± 0.23^{Aa}	42.66 ± 0.46^{Cb}	34.61 ± 7.59^{Aa}
F2H4	7.90 ± 0.52^{A}	0.53 ± 0.01^{B}	0.67 ± 0.02^{C}	0.67 ± 0.02^{C}	2.03 ± 0.06^{A}	89.19 ± 0.02^{Ba}	28.35 ± 0.38^{Cb}	92.74 ± 0.07^{Ba}	39.16 ± 0.03^{Db}	35.34 ± 5.52^{Aa}
F3H1	10.63 ± 0.86^{A}	0.57 ± 0.02^{A}	0.68 ± 0.01^{A}	0.68 ± 0.01^{A}	1.82 ± 0.01^{A}	88.16 ± 0.02^{Ab}	30.38 ± 0.69^{Aa}	92.38 ± 0.07^{Aa}	64.08 ± 0.20^{Ab}	32.34 ± 11.86^{Aa}
F3H2	9.40 ± 0.73^{A}	0.56 ± 0.01^{BC}	0.69 ± 0.01^{A}	0.69 ± 0.01^{A}	1.79 ± 0.01^{A}	88.65 ± 0.14^{Ac}	30.39 ± 0.33^{Aa}	91.34 ± 0.06^{Bb}	43.91 ± 0.28^{Bc}	34.14 ± 8.73^{Aa}
F3H3	9.47 ± 0.97^{A}	0.54 ± 0.02^{AB}	0.70 ± 0.01^{B}	0.70 ± 0.01^{B}	1.78 ± 0.01^{A}	88.17 ± 0.00^{Bb}	28.88 ± 0.15^{Ba}	91.24 ± 0.00^{Bb}	41.45 ± 0.18^{Cb}	35.26 ± 6.97^{Aa}
F3H4	10.63 ± 0.43^{A}	0.52 ± 0.01^{C}	0.68 ± 0.01^{B}	0.68 ± 0.01^{B}	1.81 ± 0.04^{A}	88.20 ± 0.49^{Bb}	27.38 ± 0.08^{Ca}	91.45 ± 0.57^{Ba}	37.72 ± 0.79^{Db}	33.80 ± 7.43^{Aa}

Notes: FnHm indicates treatment combinations, where F is the starter concentration (0–3%), and H is the soaking time (1–4 days). Values followed by different uppercase letters differ significantly for the effect of starter concentration, while different lowercase letters indicate significant differences for soaking time, based on ANOVA followed by Duncan's multiple range test ($p < 0.05$).

3.2 Functional properties of sago flour

The functional properties of sago flour produced under the eco-design processing system were significantly influenced by fermentation time and starter concentration, as summarized in Table 2. Key functional parameters evaluated included WHC, WSI, OHC, and SP.

WHC

The WHC of fermented sago flour increased markedly compared to the non-fermented control, with the highest value observed in treatment F3H3. This enhancement can be attributed to fermentation-induced structural loosening of starch granules and partial depolymerization of cell wall components, driven by microbial enzymatic activity and organic acid production. These biochemical changes increase the availability of hydrophilic sites, thereby improving the ability of the flour matrix to bind water. Improved WHC is advantageous for food applications requiring moisture retention, such as noodles and dough-based products.

Table 2. Functional properties of sago flour as affected by fermentation time and starter concentration under an eco-design processing system

	WHC	WSI	OHC	SP
F0H1	131.78 ± 3.6	7.76 ± 0.8	78.98 ± 11,1	7.03 ± 0.4
F0H2	130.75 ± 4.5	7.8 ± 0.5	82.31 ± 7.4	7.39 ± 0.6
F0H3	139.38 ± 8.4	8.45 ± 0.8	94.2 ±13.4	7.54 ± 1.1
F0H4	137.13 ± 7.6	8.72 ± 0.7	83.22 ± 2.6	7.59 ± 0.8
F1H1	148.15 ± 1.6	8.05 ± 0.5	85.63 ± 22.8	8.01 ± 0.72
F1H2	152.76 ± 10.4	8.53 ± 0.8	103.09 ± 1.94	6.11 ± 0.43
F1H3	162.14 ± 13.7	10.51 ± 0.8	109.41 ± 9.24	6.61 ± 0.43
F1H4	152. 98 ± 9.7	13.11 ± 0.8	121.59 ± 1.57	7.58 ± 1.05
F2H1	137.13 ± 7.6	9.82 ± 0.5	107.52 ± 8.19	4.75 ± 0.43
F2H2	142.67 ± 4.3	11.32 ± 0.9	110.32 ± 10.2	4.09 ± 0.37
F2H3	162.34 ± 5.9	12.57 ±1.1	122.83 ± 2.99	4.81 ± 0.61
F2H4	130.18 ± 6.7	15.7 ± 1.4	125.75 ± 7.48	3.96 ± 0.23
F3H1	134.63 ± 11.4	9.67 ± 0.7	116.36 ± 9.09	5.11 ± 0.75
F3H2	139.71 ± 14.6	16.77 ± 1.4	121.12 ± 1.84	4.54 ± 0.48
F3H3	167.62 ± 13.44	18.49 ± 1.1	122.26 ± 2.35	5.01 ± 0.38
F3H4	148.79 ± 11.5	19.07 ± 1.7	123.48 ± 2.35	4.91 ± 0.13

Notes: Values are mean ± SD (n = 3). Different uppercase letters indicate significant differences among starter concentrations, whereas different lowercase letters indicate significant differences among fermentation times ($p < 0.05$). WHC: water-holding capacity, WSI: water solubility index, OHC: oil-holding capacity, SP: swelling power.

WSI

WSI increased progressively with fermentation duration, reaching its maximum in treatment F3H4 (Table 2). Elevated WSI values reflect increased solubilization of low-molecular-weight carbohydrates and partially hydrolyzed starch fractions, resulting from enzymatic activity during fermentation. This behavior enhances flour dispersibility and is desirable for liquid and semi-solid food formulations [15].

OHC

OHC also increased substantially following fermentation, with the highest values observed in treatments with longer fermentation times. The increased OHC is likely associated with fermentation-induced exposure of hydrophobic groups in starch–protein complexes, enhancing oil adsorption capacity. Such properties are beneficial for improving flavor retention and mouthfeel in processed food products.

SP

SP showed moderate variation among treatments, with optimal values observed at intermediate fermentation durations. This suggests that controlled fermentation can enhance starch hydration behavior without causing excessive granule degradation, thereby preserving swelling capacity while improving overall functional performance.

Overall, the improvements in functional properties are closely linked to the biochemical transformations induced by fermentation, confirming its role as a core technology that simultaneously enhances product functionality and processing efficiency within an eco-design framework.

3.2.1 Response surface interpretation of fermentation time and starter concentration

To visually interpret the combined effects of fermentation time and starter concentration on key performance indicators, response surface plots were constructed based on experimental trends observed across treatments. Rather than serving as predictive optimization models, these plots are intended to illustrate interaction patterns and identify practical process windows that balance functionality and resource efficiency within the eco-design framework.

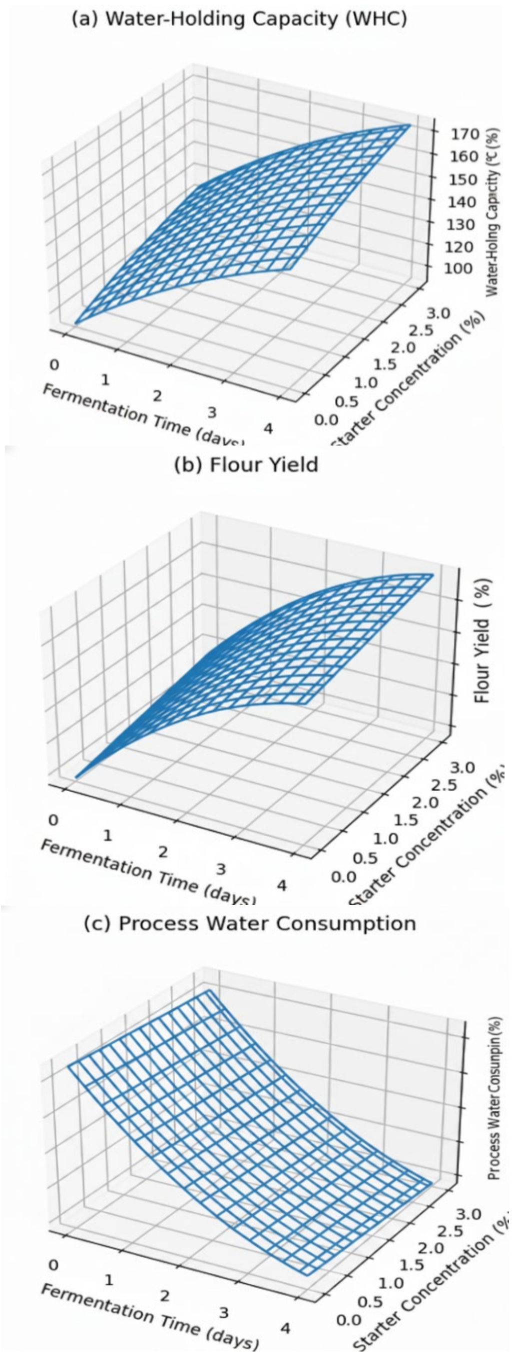


Figure 2. Response surface plots illustrating the combined effects of fermentation time and starter concentration on (a) WHC, (b) flour yield, and (c) process water consumption in fermentation-based eco-design sago flour processing

Figure 2(a) presents the response surface of WHC as influenced by fermentation time and starter concentration. WHC increased progressively with fermentation duration, particularly at starter concentrations between 2–3%. The response surface indicates a synergistic interaction, where extended fermentation enhances starch–fiber matrix loosening and microbial enzymatic modification, thereby increasing hydrophilic binding sites. The region corresponding to treatment F3H3 represents an optimal zone, where WHC is maximized without excessive degradation of starch structure.

Figure 2(b) illustrates the response surface for flour yield, showing that yield improvement is primarily driven by fermentation time, with moderate enhancement from starter concentration. The surface suggests that fermentation durations of 3–4 days coupled with 2–3% starter addition promote improved starch liberation and reduced material loss during drying and milling. Beyond this region, yield gains tend to plateau, indicating diminishing returns from prolonged fermentation.

Figure 2(c) depicts the response surface for process water consumption, highlighting the eco-design advantage of fermentation-based processing. Water consumption remains low and relatively stable across all starter concentrations, with a slight decrease observed at longer fermentation times due to improved moisture release and reduced reprocessing requirements. This confirms that fermentation does not introduce additional water burdens and instead contributes positively to overall process efficiency.

Collectively, these response surface visualizations demonstrate that the eco-design processing window centered around 3 days of fermentation and 2–3% starter concentration (F3H3) offers a balanced compromise between functional performance (WHC), material efficiency (yield), and resource conservation (water use). Importantly, the response surfaces are used here as qualitative decision-support tools, aligning with the exploratory nature of the study and avoiding over-interpretation beyond the experimental resolution.

3.3 Particle size distribution and microstructure

PSD and microstructural characteristics provide important insights into the physical behavior and functional performance of sago flour produced using different processing methods. As shown in Figure 3, variations in PSD were observed among sago flour non-fermented (TS), sago flour with metabisulfite treatment without fermentation (SM), and sago flour fermented (FM).

The relationship between particle size fraction and crude fiber content (Figure 3) indicates a consistent decrease in fiber as particle size becomes finer. Coarser fractions (40–80 mesh) retained substantially higher crude fiber, while the finest fraction (<200 mesh) contained markedly lower fiber levels. This trend reflects the mechanical fractionation occurring during milling and sieving, where rigid fibrous tissues tend to resist fragmentation and remain in coarse fractions, whereas brittle starch-rich particles are more easily disintegrated and pass through finer sieves. Fermentation likely weakened cell wall structures in FM, further facilitating particle breakdown and reducing fiber content in the finer fractions. These differences in fiber distribution are relevant for the development of sago flour-based noodles. Finer fractions, dominated by starch and lower fiber, promote better hydration, dough cohesiveness, and extrusion stability, leading to improved structural integrity of noodle strands. In contrast, coarse fiber-rich particles may disrupt the starch matrix and reduce dough continuity. Therefore, controlling PSD and minimizing coarse fibrous fractions are important strategies to improve the processing performance and textural quality of noodles produced from sago flour.

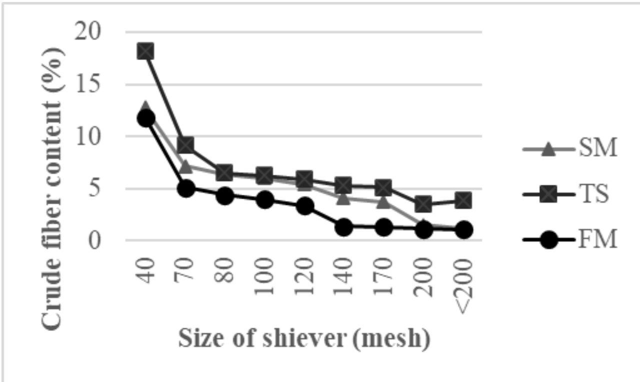
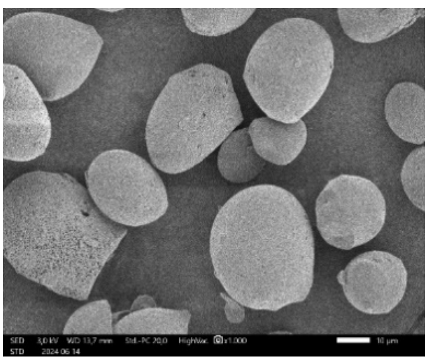
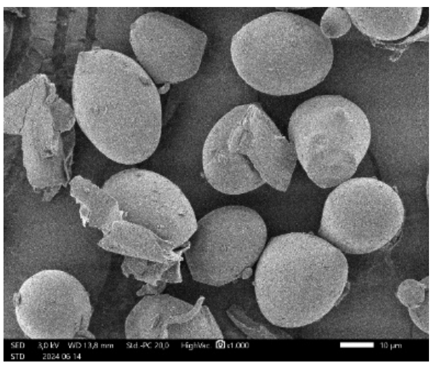


Figure 3. Particle size distribution (PSD) of sago flour produced by different processing methods: Sago flour non-fermented (TS), metabisulfite-treated sago flour (SM), and sago flour fermented (FM)

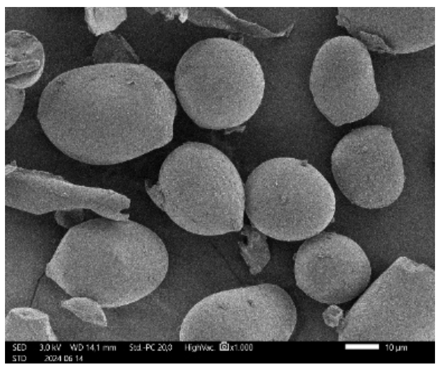
Microstructural analysis using SEM further confirmed the effects of processing treatments on starch granule morphology (Figure 4). Conventional sago starch (PS) displayed smooth, round-to-oval granules with relatively uniform dimensions, characteristic of native starch. In contrast, SM exhibited partial surface modification, suggesting chemical-induced alteration of starch granules. FM showed more pronounced structural disruption, with irregular surfaces and slightly reduced particle dimensions, indicating partial degradation of starch granules due to microbial activity.



(a) Sago starch - PS



(b) Sago flour - SM



(c) Sago flour fermented - FM

Figure 4. SEM (500× magnification) of sago particles: (a) PS, (b) SM, and (c) FM

These microstructural changes are consistent with the observed improvements in functional properties and suggest that fermentation plays a key role in modifying starch morphology in a manner that enhances milling efficiency, hydration behavior, and overall flour performance. From an eco-design perspective, the production of finer particles through biological pretreatment reduces mechanical energy requirements during milling, thereby contributing to overall process efficiency.

3.4 Process flow redesign, resource efficiency, and environmental implications

Conventional sago starch extraction involves multiple mechanical and hydraulic unit operations, including rasping, washing, sieving, sedimentation, and drying, which collectively require substantial water and energy inputs. In traditional processing systems, sago pith is mixed with water at ratios ranging from 1:5 to 1:20 (w/v), followed by prolonged sedimentation and high-temperature drying stages. These practices result in high resource consumption, starch losses during processing, and significant wastewater generation, particularly in small-scale production units [9].

A comparative overview of the conventional starch extraction system and the proposed fermentation-based eco-design process, including key differences in material flow, unit operations, and resource consumption, is summarized in Table 3. This comparison highlights how process flow redesign directly translates into reductions in water use, energy demand, and environmental burden.

Table 3. Comparative analysis of conventional and fermentation-based eco-design sago processing in terms of process flow, resource consumption, and environmental implications

Parameter	Conventional Starch Extraction	Eco-Design Fermentation-Based Flour Processing	Eco-Design Implication
Primary product	Wet starch	Sago flour	Direct production of a shelf-stable product
Main unit operations	Rasping, washing, sieving, sedimentation, drying	Fermentation, low-temperature drying, milling	Reduced process complexity
Number of unit operations	6–7	4	Process flow simplification
Water-to-raw material ratio	1:5 – 1:20 (w/v)	1:2 (w/v)	60–80% water reduction
Total water consumption	150–200 m^3 ton^{-1} pith	20–30 m^3 ton^{-1} pith	120–170 m^3 water saving
Mechanical power requirement	54 HP	40 HP	≈ 25% power reduction
Estimated energy consumption	700–900 kWh ton^{-1} pith	520–650 kWh ton^{-1} pith	180–250 kWh energy saving
Drying temperature	60–80°C	45–50°C	Lower thermal load
Drying time	48–72 h	24–36 h	Shorter
Fermentation stage	Not applied	Ambient temperature (28–30°C)	No external heat input
Fermentation water discharge	Not applicable	None (retained in system)	Reduced wastewater generation
Starter material input	Not applicable	1–3% (w/w) pith	Minor material cost
Estimated CO_2 emissions*	570–740 kg CO_2 ton^{-1} pith	365–535 kg CO_2 ton^{-1} pith	**150–205 kg CO_2 reduction**
Starch/flour yield	Baseline	+ ≈10%	Improved material efficiency
Tannin content	Higher	Reduced	Improved food functionality
Functional properties	Limited	Improved WHC & OHC	Added functional value
Wastewater generation	High	Low	Reduced environmental burden

The fermentation-based eco-design approach proposed in this study fundamentally reconfigures the conventional process flow by integrating fermentation prior to drying and milling, thereby eliminating water- and energy-intensive rasping and sedimentation stages. This redesign reduced the total number of unit operations from seven to four, leading to shorter processing times, lower operational complexity, and reduced resource demand. Quantitative analysis showed that water consumption decreased from approximately 50–200 L kg^{-1} pith in conventional processing to 20–30 L kg^{-1} pith in the eco-design system, while mechanical power requirements were reduced from 54 HP to 40 HP. In addition, drying time was shortened from 48–72 h to 24–36 h, reflecting improved moisture removal efficiency following fermentation [10].

To illustrate the environmental implications at a practical scale, processing 1 ton of fresh sago pith using the proposed eco-design system would result in an estimated water saving of approximately 120–170 m^3 compared to conventional starch extraction. Based on a conservative reduction of 20–25% in combined mechanical and thermal energy demand, the eco-design system is estimated to save approximately 180–250 kWh of electricity per ton of processed pith. Using an electricity emission factor of 0.82 kg CO_2 kWh^{-1} for Indonesia's power grid, this corresponds to a reduction of approximately 150–205 kg CO_2 emissions per ton of sago processed [16].

From an ecodynamics perspective, these reductions are not achieved solely through equipment downsizing, but through material–energy–function coupling, in which fermentation functions as a biological pre-treatment that partially substitutes mechanical and thermal work [17]. Microbial activity during fermentation softens cellular structures and weakens starch–fiber interactions, thereby facilitating moisture diffusion during drying and reducing mechanical resistance during milling.

The resource consumption associated with the fermentation stage itself was explicitly considered in the overall assessment. Fermentation was conducted at ambient temperature (28–

30°C) and therefore did not require external thermal energy input. The water-to-pith ratio during fermentation was maintained at 1:2 (w/v), which is substantially lower than that used in conventional washing and sedimentation stages. Starter addition ranged from 1–3% (w/w) of fresh pith, and its associated material cost was relatively minor compared to the savings achieved in water, energy, and processing time. Importantly, the fermentation water was retained within the system and contributed to the final drying load, rather than being discharged as wastewater, further reducing environmental burden.

Although the energy and emission estimates presented in this study are based on semi-theoretical calculations and standard assumptions, they provide a meaningful order-of-magnitude comparison that highlights the environmental relevance of the proposed eco-design approach [18]. Future work incorporating direct energy metering and life cycle assessment (LCA) is recommended to further quantify cradle-to-gate environmental impacts.

Overall, the results confirm that integrating fermentation into sago flour processing delivers measurable gains in water and energy efficiency while maintaining product quality. This study demonstrates that process-level eco-design can effectively transform traditional sago processing into a more sustainable and resource-efficient agro-industrial system.

4. CONCLUSIONS

This study demonstrates that integrating controlled fermentation and low-temperature drying into sago flour processing provides a viable eco-design paradigm for reducing water and energy consumption while enhancing material efficiency and functional quality. The redesigned process successfully eliminates water-intensive rasping and sedimentation stages, resulting in substantial reductions in water use and mechanical power demand, alongside improved flour yield, reduced tannin content, and enhanced functional properties relevant to food applications. These findings confirm that biological pre-treatment can partially substitute mechanical and thermal inputs, thereby strengthening material–energy–function coupling within sago-based agro-industrial systems.

Despite these promising results, this study has several limitations that should be acknowledged**.** The experimental work was conducted at laboratory scale with a limited number of processing batches, and energy and environmental benefits were estimated using semi-theoretical assumptions rather than direct metering or a full LCA. In addition, starter culture composition and fermentation conditions were not yet optimized for industrial robustness, and product performance was evaluated primarily through physicochemical and functional indicators rather than end-use validation in diverse food systems.

Future research should therefore focus on pilot-scale implementation to verify process stability, resource efficiency, and operational feasibility under real production conditions. Comprehensive LCA studies are needed to quantify cradle-to-gate environmental impacts and confirm the net sustainability benefits of the proposed eco-design system. Further studies should also explore optimization of starter cultures and fermentation parameters to balance processing efficiency, functional quality, and cost, as well as application-oriented validation of the resulting sago flour in specific food products, such as noodles or bakery formulations.

Finally, the drier and more uniform by-products generated from the eco-design process show potential for further valorization within circular bioeconomy frameworks, although additional techno-economic and environmental evaluations are required before such pathways can be confirmed. Overall, this work provides a scientifically grounded foundation for advancing eco-design-driven innovation in sago processing, contributing to the development of more sustainable and resilient agro-industrial systems in wetland regions.

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