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Potential of Underutilized Sago for Bioenergy Uses

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***Abstract*— Sago is a plant that grows naturally in some areas in Southeast and South Asia. Despite having multiple advantages, the usage of the sago palm is primarily from its starch content and is commonly used as an alternative replacement for white rice and wheat flour, the two most prominent staple foods, in several regions. Additionally, people are now more aware of how the total area of sago forests has decreased as monoculture, cash crops, or other food crop development have replaced it. This condition may endanger the ecology and the sustainability of food diversity. To support the bioeconomy principles, various utilizations of sago by turning it into higher value-added biomass need to be explored. The paper aims to review the potential utilization of sago as biomass and bioenergy as a value-added product after processing it for food. A literature review method in Scopus and PubMed databases was used to answer the research objective. Sago palm can be converted into bio-energy resources like biomass-biogas, bioelectricity, bioethanol, and biohydrogen. Together with the advancement in the processing of sago starch, sago waste from bark, pulp, fiber, or *hampas* is transformed into different products, e.g., plywood and particle board, sago craft from sago bark and fiber; thus, sago waste or sago *hampas* is a prospective bioenergy commodity. In conclusion, sago provides advantages beyond food diversity, such as lowering household food insecurity and promoting sago's use for biomass and bioenergy.**

***Keywords*— sago; sago waste; underutilized; bioenergy; biomass.**

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I. Introduction

The Sago palm, a member of the Palmae family and belongs to the genus Metroxylon, is one of the forest products in tropical nations. One tree species that can spread out of control in forests is the sago. Sago palms naturally grow in tropical forest locations due to similar climatic factors (temperature, soil), dietary customs, and cultural significance of sago use [1]–[3]. Sago palm reaches maturity between the ages of 9 and 12 when the starch content of the trunk reaches its peak level [3]. The palm is very profitable for the food business and as a raw ingredient for agriculture-related industries, including bioethanol [4]–[6]. Sago produces the driest starch, over 400 kg per tree, compared to other starchy foods like cassava or potatoes, which yield around 40 kg per harvest tree [7]. Sago waste is sometimes used as livestock feed [8], [9].

From the north of Mindanao to the south of Java Island and from the east of Melanesia to the west of India, the sago plant naturally flourishes. The distribution of sago plants is still concentrated in a particular area within the countries, even though they spread throughout the tropical forest. Before 2000, Papua New Guinea had a total sago area of 1.4 and 1 million hectares (ha), making it the second-largest producer after Indonesia [2]. Sago cultivation is widely practiced outside of Indonesia and Papua New Guinea, such as in Malaysia (about 45,000 ha), Philippines and the Thailand (almost 3,000 ha for each). The present estimated total sago area is 5 million hectares (ha), mainly in Papua but also in all other places where sago is grown, including Sumatra, Sulawesi, and the Mollucan Islands. Nevertheless, only 318,563 ha, or just about 6%, are productively planted with sago palm trees, with productivity of 1.48 tons/ha/year in average [9]. Sago crops predominate in the Sepik, Western, and Gulf regions of Papua New Guinea [10]. Sago has a considerable importance in this area for the community's traditional livelihood activities and for providing both quantity and quality of food security for the home [11], [12].

Sago was never heavily promoted as a necessity, primarily because it is considered to have a lower economic value than other monoculture and cash crops (e.g., palm oil or timber) or other food crop production. Furthermore, in Indonesia, sago consumption as a staple food indicates the presence of food insecurity [13] which has discouraged the promotion of plant utilization in the country. The high potency of sago has not been sufficiently explored. Concern has also been expressed over the gradual loss of the entire sago forest as a result of farming conversion to monoculture, cash crops, or other food crops [14], which may jeopardize the sustainability of the ecosystem and the availability of a variety of food sources.

A detailed mapping of potency must be done together with a complete study from the perspective of implementing the circular bioeconomy and maintaining sustainability in order to maximize the use of the sago plant. The current review paper's main objective was to look into how best to use sago waste as a bio-based resource. The waste comes from its leaves to the trunk and is the by-product of starch production, which can provide bioethanol or bioenergy without direct competition with the food industry. Furthermore, by using sago as feed and fertilizer, the goal of lowering the environmental impact of waste can also be accomplished. The sago plant needs to be sustainable in order to compete with other commodities in terms of use, which will also have an effect on the shift in land use. Therefore, innovation in producing value-added sago-based products is crucial to assuring the sustainable supply of sago and the bioeconomy. The primary goal of the paper is to examine sago's potential as a biomass source. The second goal seeks to look at different sago usages to complement the review results.

II. Materials and Method

This study was a component of a literature review technique that sought to understand the potential of sago as a source for biomass and bioenergy. Therefore, a combination of keywords of "sago", “biomass”, “bioenergy”, “bioethanol” and “biohydrogen”. were used as search terms for the literature. This review study related the potential of sago in biomass and bioenergy to the food business in this regard, for instance, the byproduct of manufacturing sago starch. Using the specified keywords, a literature search was conducted in the Scopus and PubMed databases in July-August 2021 and continued to be updated until June 2023. The following criteria were used to choose the papers: (1) Online access to conference proceedings or journal articles in their entirety license; (2) written in English, German, or Indonesian – the authors' language proficiency; and (3) the relevance of the article's content to the research goals (Figure 1).

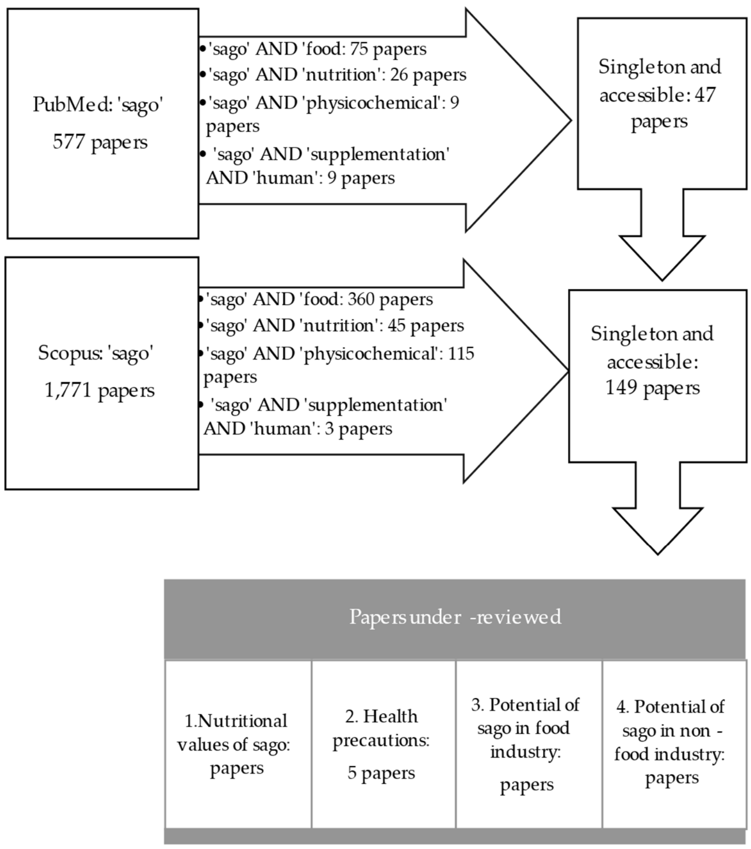

Fig. 1 Selection Process of Eligible Studies

III. Results and Discussion

The sago palm region stretches from Melanesia in the east to India in the west, from Mindanao, the Philippines, in the north to Java Island, Indonesia, in the south. Sago palms can thrive in a variety of soil types, such as mineral soil or areas that have been used as forests or barren land. As an example, wild sago trees can be found in Papua beside lakes, rivers, or even without sufficient drainage due to varied geographical situations, such as lowland or highland, merging with another ecosystem. Sago palms can be found throughout Southeast Asia, for instance in Thailand's marshy forest and in Papua, Indonesia, where they coexist with other plants including grass and swampy shrubs [14], [15]. In addition to Papua, the sago palm is also found in another Indonesian island including Sulawesi, Sumatera, and Kalimantan. The majority of the smallholders in these areas have semi-cultivated stands on their land, which include sago palms that are immature, mature, and neglected [16].

A. Review of Literature and Analysis of the Underutilized Sago

The mid-July to end-August 2021 Scopus and PubMed literature searches, updated in June 2023 returned 2340 and 813 papers, respectively, using the combination of keywords "sago", “biomass”, “bioenergy”, “bioethanol” and “biohydrogen”. Nine articles were reviewed regarding the potential of sago in biomass and bioenergy application after removing all the duplicate and using more sophisticated criteria (i.e., the combination of keywords and accessibility) and thoroughly checking the studies' relevancy and research objectives by reading the full articles. Regarding the use of sago as a feedstock and in food products, additional material from 25 and 5 selected studies was included and briefly presented.

The starch produced by sago palm trees is primarily utilized as food. To produce starch, the tree is processed through a number of stages. The modifications to the leaves, thorns, shoots, and stems reveal the features of sago palms that are ready for harvest. Before they are ready to be harvested, sago plants generally exhibit floral primordia, or flower buds that have opened but have not yet bloomed. The outcome is a little swelling of the shoots. In addition, there are fewer thorns and cleaner, smoother leaf sheaths than in juvenile trees.

By cutting, removing the bark, and gathering the trunks, the right trees are gathered. Traditional methods for obtaining sago starch include crushing and kneading the stem's pith to release the starch, followed by washing and straining the fibrous residue to separate the starch from it. After being suspended in water, the raw starch is collected, given time to settle, and dried. In Papua New Guinea and Indonesia (Papua and Buol), sago starch is taken as a staple food and traditionally prepared with burned stones [1] or mixed with hot water (sago porridge, also known as papeda) [17]. Figure 2 depicts traditional sago processing.

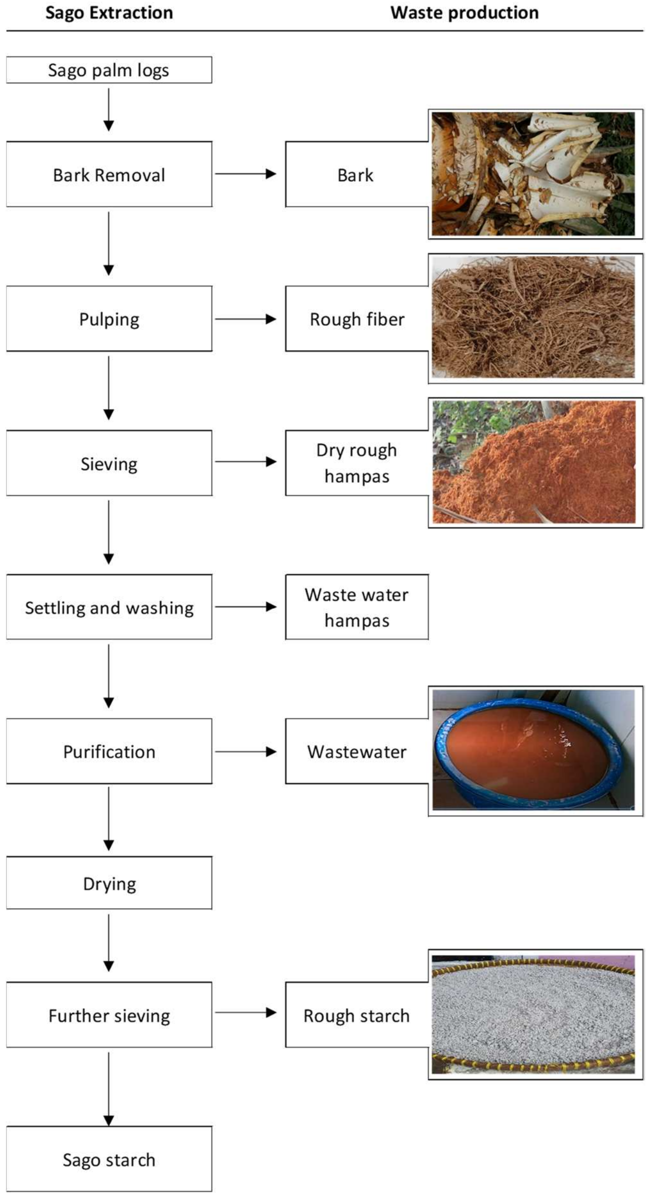

Fig. 2 Traditional sago starch production (courtesy of S.M.A. Letsoin)

Sago starch is comparable to sweet potato (86%) and tapioca (89%) and in terms of its carbohydrate content per 100 g [18], considerably higher than white rice (34%) [19] or wheat (59–71%) [20]. Due to its high carbohydrate content, sago may eventually take the place of other staple meals. Per 100 grams, sago starch has just 0.1% protein and 0.01% fat, respectively [18]. White rice and wheat, which are the most widely consumed staple foods, include greater proportions of fat (2.9% and 1.1-37%, respectively) and protein (3.9% and 10.1–16%) [19], [20]. Sago also contained roughly 10 mg of phosphorus per 100 g. When compared to other main foods such as sweet potatoes, the phosphorus concentration was deemed low [18]. As a result, a sago-based diet was later developed to boost the protein and micronutrient content by combining it with food sources of both plant and animal protein (such fish, soybeans, or mungbeans), as well as with mushrooms as a source of fat and minerals [21]–[24].

Sago is a food with a high carbohydrate content that is advised to be consumed as an alternative to staple meals, therefore its place in the typical diet and as a household staple are crucial. Dietary diversification can be aided by the use of sago starch [25]. To increase the consumption of native or wild foods, such as sago, contemporary sago starch extraction has been created, as well as widespread global promotion of indigenous products. Sago is still used in traditional dishes today, such as sago porridge, which is made by combining sago with a little cold water until a sticky suspension forms. Sagu *lempeng* is another name for classic sago-based delicacies like plate-shaped sago. Sago has a lengthy shelf life when it is formed into rectangular shapes that are 8 x 8 cm wide and 0.5–1.0 cm thick.

B. Sago for Biomass and Bioenergy Production

The starch of sago palm plays an essential role in supporting food security and the food agroindustry. During the starch processing, approximately the same amount of sago pith waste as starch can be produced [26], [27]. Sago waste can also be converted into various bio-energy resources like biomass-biogas, bioelectricity, bioethanol, and biohydrogen. Natural sago starch nowadays is undergoing specific genetic treatment for non-food industries, for instance, as an emulsifier in colloidal systems, bio-thermoplastics, bio-cellulose, hard capsules film, coating food products, biopolymers, biocomposites, acylated systems, and carboxymethylation. Together with the advancement in the processing of sago starch, sago waste from bark, pulp, fiber, or sago waste (*hampas)* is transformed into different products, e.g., plywood and particle board, sago craft from sago bark and fiber; thus, sago waste or sago *hampas* is a prospective bioenergy commodity.

Non-renewable energy is still the primary power and economic source in these regions. For instance, the Indonesian Government in Presidential Decree No 5/2006 states the target of 25% share of renewable energy (RE) by 2021; unfortunately, the RE production is only about 3%. The situation explains why bioenergy development in this country is supported and encourages the potentiality of waste from raw materials for energy utilization [28]. Currently, Indonesia has been producing and marketing biodiesel from palm oil. The competition with food products is the next obstacle for biodiesel made from palm oil, as palm oil is the country's most commonly utilized cooking oil, and the concern that many natural forests will be converted into palm oil plantations. As a result, developing sago into bioenergy could provide an alternate feedstock for biofuel.

Sago waste production includes solid waste (bark, fiber, hampas, rough starch) and wastewater (Figure 1), which also supports the implementation of a circular economy. As an illustration, the harvest area of sago starch is around 2,000–3,000 kg/ha/year. It could be two times higher when compared to cassava or three times higher than maize. The annual crop area of ethanol from four carbohydrate producers – sago, cassava, sugarcane, and maize- is 9.5 kL/ha, 4.0 kL/ha, 6.7 kL/ha, 3.2 kL/ha, respectively. To achieve this ethanol production, the harvested land of each crop, for example, sago land area is 60 trunks, while cassava is 23 tons of roots and 70 tons of sugarcane. Starch yield per trunk could reach 180 kg or more, depending on the geographical condition; for example, in Malaysia, around 180 kg to 385 kg starch/trunk, and in Indonesia, approximately 250 kg to 550 kg starch/trunk [29]. Added to this, gasohol E10 or 10% ethanol/gasoline fuel mixture has been introduced to reduce climate impact and promote petroleum conservation, as experimented in some Asian countries such as Vietnam, although it is not reported in detail about the particular substrate of ethanol, this study has investigated the possibility of bioethanol as gasohol blends in deriving specific vehicles. They are rated as having 2 or 3 octanes greater than conventional gasoline, as in Indonesia, ethanol from sago starch has a superior 1.5 octane rating over other types of gasoline. The fuel usage is lower than that of gasoline and is more environmentally friendly [30], [31]. The production of ethanol can be made from food crops that contain carbohydrate or starch components, such as fresh sugarcane like in Brazil or sugarcane molasses mostly used in India; nonetheless, the higher production of ethanol requires a significant feedstock of cropland, which could be adjusted to the availability of food crops. Hence, other ethanol feedstocks from lignocellulosic biomass, industrial residues, and agricultural wastes such as sago waste have been established [32]. Considering bioethanol feedstocks, categorized as (1) starch ingredients such as sago, cassava, and sweet potatoes, then (2) sugary ingredients, for example, sugarcane, sweet sorghum, and also from (3) cellulose materials or agricultural waste such as rice straw, sago waste, or banana stems, and presently, from macroalgae and microalgae waste [33]. In the case of sago, a 10 g dry matter sago pith waste can produce 2.92 g bioethanol fuel [4].

Bioethanol production from sago waste requires some processing; first, sago waste preparation or pretreatment, including hydrolysis to obtain cellulose and glucose, and then fermentation to improve the substrate, for example, by using the enzyme. Bioethanol low concentrate is achieved from the fermentation of sugar ingredients, followed by distillation and purification to get a higher level of ethanol [4]. Nevertheless, the efficacy of energy production should be assessed based on a particular value or reference to the nationwide specification and global market policy. Scientific modification scientifically in bioenergy production has been widely established, not only for fuels such as bioethanol and biogas but for other prospects, as shown in Table 1. The dry weight of sago waste consists of starch, cellulose, and lignin. While sago bioethanol liquid waste (SBLW) roughly contains glucose, glycerol, and lactic acid, the content of dried sago hampas is mostly starch, around up to 45%, then moisture, ash, protein, fiber, and fat. For bioethanol fermentation, microorganisms such as saccharomyces can be used; thus, analytical and quantifying methods are implemented using a spectrophotometer, High - Performance Liquid Chromatography (HPLC), and an Iodine starch calorimeter. However, viscosity and appropriate solvent or diluted ratio should be taken into account [34]. Sago biomass can be transformed into fuel through specific thermochemical procedures, for example, carbonization, gasification, direct combustion, liquefaction, and pyrolysis. Although sago biomass is ecologically sound for fuel, the specified HHV result showed higher when converted to biochar through the pyrolysis process [35]. Pyrolysis itself can be derived into (1) char, used for all of the solid products, including organic matter such as high carbon and ash, (2) gases, for example, methanol or ammonia, and (3) liquids, including bio-oil. Then, three types of pyrolytic reactions, differentiated by the heating range and temperature of substances [36], affect bio-oil production, for example, slow pyrolysis using a microwave reactor type of sago waste to get bio-oils in different heating times between two to ten mins. Sago waste values may show a positive rate in bio-oil production. However, based on the calorific values, the results tend to be smaller than other fuel oils, such as petroleum, gasoline, or diesel fuel [37]. From a bioelectricity perspective, microbial fuel cells (MFC) transform the chemical reactivity into bioelectricity through electrochemically active bacteria to the electrode, such as *Clostridium beijerinckii*. Some substances are recognized for bioelectricity, such as organic acids (acetate, lactate), fermentable sugars (glucose), and carbohydrates (starch); however, the market price and environmental impact due to the production process need to be considered [38], [39]. In other locations of Asia, for example, India, biohydrogen is produced by using microorganisms like bacteria and algae. Principally, biohydrogen is a type of biofuel like bioethanol, biodiesel, bio-oil, etc., and can be generated through chemical and biological processes using microorganisms. Hydrogen has three times greater energy than petrol or diesel; and also, can be used as a transport fuel and less gaseous pollutant. To support these advantages, the National Hydrogen Program of the United States projects the total hydrogen market at around 8–10% by 2025. Although biological hydrogen is considered a future fuel due to high energy density, zero-emission of CO_2, enhanced hydrogen manufacturing with a minimal substrate, and cost development need to be noted [40], [41]. Understanding the potential role of sago beyond its daily use also supports the importance of promoting the possible uses of sago, especially throughout the wild-stand palms, and encourages its alternative uses in the local economy.

TABLE I
POTENTIAL OF SAGO IN BIOENERGY PRODUCTION

No.	Product	Method and result	Application	Ref
1.	Bioethanol	The acid pretreatment method was used to handle sago waste. Microorganism *Saccharomyces cerevisiae* was used to ferment. Ethanol production in fungal saccharification was up to 3.02 g/l from 5 g/l of sago waste. To support the ethanol result, the Iodoformtest and litmus test were applied.	Bioproduction of ethyl alcohol	[34]
		The study aimed to increase the glucose rate in sago hampas in three sequences that were hydrolyzed by the enzyme. The glucose in sago hampas was tested using yeast. 40.30 g/ liter of ethanol was produced from the fermentation process. Glucose obtained from the hydrolysis process in sago hampas was adequate to primary sago starch.	Glucose production, feedstock for bioethanol production	[42]
		Sago fiber was used as feedstock for the bioethanol process. Saccharomyces as microorganism bioethanol fermentation was used. SBLW consists of glucose, glycerol, lactic acid, and ethanol ±0.08 g/liter measured using HPLC.	Fermentation feedstock, biocatalyst industry	[43]
2.	Biomass	This study focuses on two different treatments for sago biomass and sago biochar. Various methods were applied, for example, pyrolysis OFAT, proximate analysis, Scanning Electron Microscopy (SEM), and Brunauer-Emmer-Teller (BET). The values of sago biomass were significantly greater when it became sago biochar as indicated through their Higher Heating Value (HHV). HHV referred to the potential thermal energy produced, which was measured as a unit of energy per unit mass or volume of the substance.	Solid fuel	[35]
		Sago waste produced bio-oils using microwave within medium temperature, i.e., smaller than 400 °C, and different heating ranges. They were classified as slow pyrolysis for liquid. The calorific value was around 21 MJ/kg calculated by the bomb calorimeter. This value was lower than gasoline, diesel fuel, or petroleum. Numerous methods and equipment were used, such as Gas chromatography-mass spectroscopy, mass spectrometer, Fourier Transform Infra-Red (FTIR) analysis, evaporator, and microwave.	Chemical feedstock, Liquid fuel	[37]
3.	Biogas	Different sago wastes, such as hampas and wastewater were used to find out their chemical characteristics for biogas purposes. Atomic absorption spectroscopy was used to measure minerals and other content using spectrophotometry, followed by an analytical method to evaluate the C/N ratio and Chemical Oxygen Demand (COD).	Biogas feedstock	[44]
		Sago waste performance in biogas production was evaluated. The parameter advanced by Central composite design (CDC) and Response Surface Methodology (RSM) such as COD, Biochemical Oxygen Demand (BOD), Total Organic Carbon (TOC). The results confirmed that the RSM was an appropriate predictor of biogas production throug waste recycling.	Biogas complement	[45]
4.	Bioelectricity	Granulated Sago hampas as a carbon substrate was fermented using *C.beijerinckii*, then compared to other substances, namely profitable starch, hydrolyzed sago hampas, and non-hydrolyzed sago within the results of 78.92 mW/cm^2, 56.5 mW/cm^2, 73.78 mW/cm^2, respectively. It explained how sago hampas, without being further hydrolyzed can be used as a feedstock of bioelectricity using MFCs.	Direct bioelectricity	[38]
5.	Biohydrogen	Sago wastewater as the substrate was fermented using bacteria, i.e., *Clostridium sartagoforme* and *Enterobacter cloacae.* Although the results of both bacteria were comparable, *C. sartagoforme* showed relatively better results	Biofuel	[40]

C. Sago for feed and fertilizer production

For many years, sago has been used as animal fodder. Initially, the exposed starch from a cut sago trunk can be fed directly to poultry or pigs. Alternatively, the harvested pith can be dried and milled to produce sago high-energy pith meal comparable to corn in poultry diets. During starch extraction, the wet form of sago pith is produced, and starch granules can be collected while producing large quantities of sago waste. This sago waste (*hampas*) is the common source of feed. *Hampas* is "the fibrous residue left behind after most of the starch has been washed out of the rasped pith of the sago palm" [46], consisting of roughly 58–66% starch, 5–21% lignin, 20–23% cellulose [47], [48], which makes it a great fodder due to its high content of fiber. Because of its high fiber content, *hampas* have commonly undergone various treatments to improve its digestibility and palatability, for instance, ensiling [49][50]. In the same way and organically closing the life cycle, sago waste for animal feeds can also be used as a natural fertilizer. For the most part, the leftover remains of starch extraction are used as fertilizer, e.g., *hampas*, the pulp of the palm, and the bark [48], [51]. The sago waste is usually mixed with the poultry (or other livestock) waste to introduce something called "co-composting", a technique that allows the decrease of fertilizer expenses, as well as regulates the excesses in the amount of carbon and nitrogen in the soil, which could be detrimental to plants when excessive [52].

IV. Conclusion

Beyond its original use as a staple food, this literature review study indicated the prospective uses of sago in a variety of bio-energy resources such biomass-biogas, bioelectricity, bioethanol, and biohydrogen that can be further expanded. Sago can be a substitute feedstock in the production and marketing of biodiesel from palm oil in Indonesia. Sago is now used in both culinary and non-food products due to its prospective uses and advantages. This in turn promotes local bioeconomy development, sago forest preservation, and sustainable production.

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