Potential uses of underutilized sago to support the sustainability of food supply and bioeconomy

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Abstract

Various utilizations of sago need to be explored to support the local bioeconomy. The paper aims to review bioeconomy documents in the regions where sago mostly grows, and its potential uses. A document review of the bioeconomy strategy and a literature review to investigate the benefits of sago were performed. Sago provides advantages beyond food diversification, addressing household food insecurity and health while also promoting local/regional bioeconomy through the development of food and non-food industries, e.g. bioenergy. Sago forest conservation and development of its high value-added commodities are supported by the studied bioeconomy documents.

Keywords: sago, food diversification, non-wood forest products, underutilized, bioenergy, bioeconomy, sustainability

1. Introduction

Forests offer valuable forest ecosystem services and other benefits for the well-being of the people. The services provided include provisioning and regulating, as well as basic, supportive, and cultural services. Provisioning services cover the products obtained from forest ecosystems. Besides wood forest products, forests also provide food, water, medical sources, fiber, etc. (Krieger, 2001; Millennium Ecosystem Assessment, 2005a, 2005b). Forest products that exclude all woody raw materials were defined by the Food and Agriculture Organization (FAO) as non-wood forest products. Non-wood forest products play an essential role in economic, social, and environmental sectors depending on the type of the product and the place of origin (Dembner and Perlis 1999).

Sago palm is of the essential forest products from the genus *Metroxylon* belongs to the Palmae family, which can grow wildly in the forests. Tropical forest areas are a natural habitat of sago palm, mainly due to the similar environmental conditions (temperature, soil), food habits, and cultural value in consuming sago (Townsend 1974; Konuma 2018a; Bintoro et al. 2018). Sago palm achieves maturity at 9–12 years of age when starch in the trunk reaches the highest level (Bintoro et al. 2018). The palm has enormous benefits in the food sector and as a raw material for agroindustry, such as bioethanol (Jonatan et al., 2017; Girsang, 2018; Thangavelu et al., 2019). In comparison to other starchy foods, for instance, potato or cassava which yields about 40 kg per plant, sago produces the highest amount of dry starch by approximately 400 kg per tree (Zhu, 2019). Concurrently, sago waste is used as livestock feed (Dwyer and Minnegal, 1994; Girsang, 2018).

Due to its natural existence, which clustered in the specific region, sago was never promoted as an essential commodity on a larger scale. The enormous potency of sago has not been properly addressed. Moreover, awareness has been raised concerning the decrease of the total sago forest area over time that has changed to monoculture, cash crop, or other food crop production (Letsoin et al., 2020). This condition can threaten the food diversification supply and environmental sustainability.

To optimize the utilization of the sago plant, a comprehensive mapping of potency needs to be conducted with a thorough analysis from the point of view of implementing circular bioeconomy and ensuring sustainability. The circular bioeconomy encompasses the sago as a bio-based commodity that can be exploited optimally from its leaves to the trunk and from producing starch to bioethanol. Furthermore, the focus on decreasing waste can also be achieved by sago through its use as feed and fertilizer. Ensuring its sustainability is essential to enable sago plant to compete with other commodities in terms of utilization, which will also affect the land-use change. Innovation in creating value-added sago-based products, therefore, plays an important role in ensuring the sustainable supply of sago and bioeconomy.

In addition to developing value-added products, the policies at the international or national levels are crucial for implementing programs to preserve sago forest areas and promote sago utilization. At the global level, the preservation of sago areas supports the 15th goal (Life on land), especially Target 15.2 (End deforestation and restore degraded forests) of the Sustainable Development Goals (SDG), while promoting of sago applications into high value-added products in agreement with the bioeconomy principles, e.g., the European Bioeconomy (European Commission 2012; 2018). Additionally, through the promotion of sustainable agriculture and local biodiversity, the FAO supports food diversification for improving the well-being of the community (FAO, 2012). Furthermore, at the regional and national level, legislation regarding the bioeconomy in Southeast Asia, such as Malaysia (Bioeconomy Corporation, 2013) and Thailand (National Science and Technology Development Agency (NSTDA)., 2021) potentially put the promotion of sago as the source not only for food but also for non-food resources and renewable energy. Thus, the first objective of the paper is to review documents related to the bioeconomy in the region where sago primarily grows, which supports the utilization of sago. Secondly, a review of the potential uses of sago was also comprehensively done.

2. Materials and Methods

To answer the first research objective, a document review analysis concerning the related strategies that support the sago utilization, sago forest area conservation, and bioeconomy (local, regional, or global) was performed. In this paper, terminology bioeconomy is defined as an economy underlining the sustainable production of renewable resources and their conversion into products, such as food, feed, bio-based commodities, and bioenergy to replace fossil-based fuels (European Commission, 2018, 2012). Grouping the themes related to the topic of interest (provision of sustainable sago and its utilization) in the selected documents was done using thematic analysis (Vaismoradi et al., 2013). In the areas where sago thrives (Southeast Asia and Papua New Guinea), there has been no common policy or an agreement on the definition, principles, and strategic measures of the bioeconomy. Only Malaysia and Thailand possess a national bioeconomy strategy, while in the other countries, like Indonesia and the Philippines, the principles were included in different ministries. Furthermore, in 2020, a Southeast Asian conference on bioeconomy strategies in this region has been held in Thailand; however, the bioeconomy policy, especially a document concerning the management of sago forest and utilization, is still not available. Therefore, the principal documents under study were the Malaysian (Bioeconomy Corporation, 2013) and and Thailand bioeconomy strategies (NSTDA., 2021).

Secondly, a literature review methodology was used to understand the potential of sago in food products, as its primary provision, which was based on food processing, from simple technology to more advanced methods. The keywords “sago” AND “food” were used for the literature search. Hence, the potential of sago in the non-food industry was related to the food sector in this review paper, e.g., the waste derived from sago starch processing. In July–August 2021, a literature search was done in the Scopus and PubMed databases using the assigned keywords. Next, the articles were selected based on the criteria: (1) online accessibility of the full text from published articles in a journal or conference proceeding, downloaded using the University license, (2) written in English/German/Indonesian – the language proficiency of the authors, (3) the relevancy of the article’s content to answer the research objectives.

3. Results and Discussions

The sago palm area stretches from Melanesia (in the east) to India (in the west) and from Mindanao, the Philippines (in the north) to Java island, Indonesia (in the south), as presented in **Figure 1**. Even though sago plants are spreading in the tropical forest, the distribution is still clustered in a specific region within the countries. Indonesia is the primary habitats of sago (wild-stands or cultivated), followed by Papua New Guinea with a total sago area of approximately 1.4 and 1 million hectares (ha) before 2000 (Konuma, 2018). Outside Indonesia and Papua New Guinea, the distribution of sago cultivation is very diverse, for example, in Malaysia (45,000 ha) or Thailand and the Philippines (each 3,000 ha). Furthermore, based on the Indonesian Statistics Bureau, the current total sago area is approximately 5 million hectares (ha), chiefly located in Papua, and includes all other sago plantation regions in the country, e.g., Mollucan islands, Sumatra, and Sulawesi, however, only about 318,563 ha is productively used to plant sago palm trees, or only about 6%, with average productivity of 1.48 tons/ha/year (Coordinating Ministry For Economic Affairs of the Republic of Indonesia, 2020). In Papua New Guinea, Sepik, Western, and Gulf provinces are the main areas of sago plantations (Toyoda, 2008). In this region, sago has a significant value for the traditional livelihood activities of the local community and in delivering household food security, both in quantity and quality (Sunderland et al., 2013; Ehara et al., 2018).

Sago palms grow across different soil conditions, for example mineral soil, or types of land use like barren land or forest area. Also, various geographical positions such as lowland or upland even merged with another environment, for instance, along the lakes, rivers, or even without proper runoff. In Southeast Asia, for example, Thailand, sago palm lives in the swampy forest, while in Indonesia, wild sago stands together with other vegetation, such as grass, swampy shrub, etc. (Jariyapong et al., 2021; Letsoin et al., 2020). The sago palm range in several provinces of Indonesia, as shown by **Table A.1 (Appendix),** particularly, Sulawesi, Riau, Aceh, Kepulauan Riau, Sumatera, and Kalimantan are mostly semi-cultivated stands from smallholders' sites; this number includes immature, mature, and mismanaged sago palms (Directorate General of Estate Crops, 2019). Based on sago production in 2019, Riau Province is the largest producer in Indonesia with around 261,112 tons/year. Unfortunately, it has not been investigated yet in Papua, nor in Papua Barat, which are mostly sago forests or wild sago stands. Almost the entirety of sago forest in this area comes from one genus, i.e., *Metroxylon*; likewise Kep Mentawai and Sarawak (Malaysia), another region of Indonesia, Papua New Guinea (PNG), etc. (Table A.1). Besides *Metroxylon*, there are more general, namely, *Arenga*, *Caryota*, *Corypha*, and *Eugeissona* (Kenneth, 1979).

Figure 1. *Location of sago area*

The majority of sago production in Malaysia is driven by the smallholders' sector, and hence, creating a sago plantation enterprise from unused farmland has been implemented through their program, namely Smallholder Satellite Estate Development Programme (SSED), which is focused on how to amplify their sago production, and transforming small sago farms into commercial plantations. As reported, 2,883 sago areas have been developed and have advantaged 4,875 sago farmers. This is one of the reasons why today Malaysia is the third sago producer in the world where even their sago area is not wider than PNG, or the starch yield per trunk is less than Indonesia (Ahmad et al. 1999; Naim, Yaakub, and Hamdan 2016). Nevertheless, exploring the utilization of sago through scientific research while finding more recent procedures for replanting, seeding, drilling, harvesting, etc., needs to be considered.

Southern Thailand has observed 437 sago forest areas along the canal area. Generally, the Indigenous population who live close to the area gain some advantages from this palm, such as the availability of foodstuff, i.e., sago steamed with meat or coconut milk, sago sweet pudding, or depending on each community needs, for instance, sago leaves for roofs and walls. However, the area tends to be damaged due to land-use changes for other purposes such as preparing a new irrigation system (Suntiniyompukdee et al., 2017). In Mindanao and Visayas, the Philippine region, the current sago area is around 914 ha, which is less than the previously reported. During 2012 and 2013, this area suffered a tropical storm, which brought a significant change to the sago palm area (Santillan and Makinano-Santillan, 2016).

The role of sago in bioeconomy

Globally, the environmental problems due to climate change and their consequences are increasing, of which human influence has been found to play a significant role (Intergovernmental Panel on Climate Change (IPCC), 2021). Many countries have directed their national policies into bioeconomy principles, such as in the European countries, where the Bioeconomy Strategy has been introduced earlier and is well documented. In the area where sago mainly grows (Southeast Asia and Papua New Guinea), there has been no common policy or an agreement on the definition, principles, and strategic measures of the bioeconomy. Only Malaysia and Thailand have introduced the bioeconomy principles. Nevertheless, all of the proposed definitions from the bioeconomy principles encompass the utilization of renewable resources. In this respect, the green commodities, which include food, feeds, renewable energy sources, and other usages and utilization of waste material to fulfill the needs of human beings and to increase the livelihood of surrounding communities with regards to their food security, household economic status, and environmental sustainability, need to be explored (Malaysian Biotechnology Corporation 2005; NSTDA 2021) (**Table 1**). Other countries that utilize a considerable amount of sago plants included the bioeconomy principles in their related strategies at the ministerial level (e.g., agriculture, energy, and environment), like Indonesia (FAO, 2014; Direktur Jenderal Pengelolaan Hutan Produksi Lestari, 2015; Direktorat Jenderal Energi Baru Terbarukan dan Konservasi Energi (EBTKE), Kementerian Energi dan Sumber Daya Mineral (ESDM), 2021), and the Philippines (FAO, 2021).

The utilization of sago can be seen as a potential implementation of the bioeconomy. The role of sago as food (as a carbohydrate source and food ingredients) and its value-added commodities (such as for health) and non-food products in promoting the bio-based manufactures is in agreement with the strategic measures of the bioeconomy in Malaysia and Thailand (Table 1). From the food security point of view, sago starch can be used as a substitute for rice or other staple foods, and thus the food could reduce the dependency on a single commodity. With regard to the sago plant, every part of sago palm can be utilized to produce beneficial commodities to increase the livelihood of society. The leaves can be developed into a roof. Sago leaf sheaths can also be used as rope, ceiling, temporary wall, flooring, and furniture. Moreover, the trunk is the part which produces starch as the main product from the sago palm. The starch can be used traditionally as staple foods and snacks and can be modified and industrially developed as bio thermoplastic, bio-cellulose, biopolymer, capsule coating, etc. (Singhal et al., 2008). The food produced can ensure the society has a sufficient intake of foods, while the sago-based commodity development could create new industry establishments and provide new job markets.

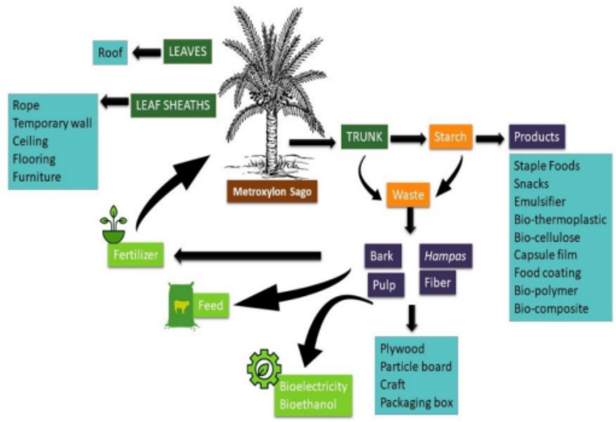

Figure 2. *The comprehensive description of the bioeconomy concept of sago*

Table 1. *Document review of the bioeconomy policies in Malaysia and Thailand*

Parameter	**The Malaysia National Biotechnology Policy** (Malaysian Biotechnology Corporation, 2005)	**The Thailand's Bio-Circular-Green Economy Model** (Ministry of Higher Education, Science, Research and Innovation (MHESI) of Thailand, 2019)
Goal	To further develop three economic sectors, namely agriculture, healthcare, and industrial manufacturing, as well as support the growth of an enabling eco-system throughout the scientific, academic, and business communities in Malaysia.	To use natural assets more efficiently with the least impact on the environment as possible. BCG applies a whole of society approach—where the government, private sector, academia, and society, collectively implement this principle, eventually putting Thailand on track to building back a healthier, greener, and more inclusive economy as the pandemic subsides
		Four drivers of the Thailand's Bio-Circular-Green Economy Model: 1. Food and Agriculture 2. Medical and Wellness 3. Bioenergy, Biomaterial and Biochemical Tourism and Creative Economy
Strategic measures where sago utilization can be promoted	**The 9 Thrusts of National Biotechnology Policy**	**The 2021-2026 Bio-Circular-Green Economy Strategic Plan** (National Science and Technology Development Agency, 2021)
• Sago-based diet as alternative carbohydrate source (staple food) • Advanced food technology in sago-based food, health, and non-food commodities • Utilization of sago as bioenergy, biomass, and bioethanol	Thrust 1: Agriculture. Enhance the value creation of agriculture sector Thrust 3: Increase opportunities for bioprocessing and manufacturing Thrust 2: Health. Commercialization of the discovery health-related natural products and bio-generic drugs	Strategy 2: Strengthening communities and grassroots economy by employing resource capital, creativity, technology, biodiversity, and cultural diversity to create value to products and services, enabling the communities to move up the value chain.
• Sustainable provision of sago and sago forest area conservation		Strategy 1: Promoting sustainability of biological resources through balancing conservation and utilization.

• Other strategic measures (education, research, and development)	Thrust 4: Establish centers of bioetechnology excellence, through research and development	Strategy 3: Upgrading and promoting sustainable competitiveness of Thai BCG industries with knowledge, technology, and innovation focusing on green manufacturing.
	Thrust 5: Build the nation's human capital through education, training, and research activities Thrust 6: Provide the right financial support via competitive lab to market funding and incentives Thrust 7: Reviewing ownership of intellectual properties and regulations relating to biotechnology processes and business Thurst 8: Build international recognition for Malaysian Biotechnology Thrust 9: Dedicated and professional Government agency to spearhead the development of the biotechnology industry with the incorporation of the Malaysian Biotechnology Corporation Sdn Bhd (BiotechCorp)	Strategy 4: Building resilience to global changes.

Sago waste, such as hampas from sago pith and bark, pulp, and fiber from the trunk that usually become problematic in other commodities, has the potency to be utilized. Such wastes can be used to produce bioelectricity and bioethanol. Moreover, it can also be processed into fertilizer, which can then be circularly used in sago palm cultivation. A comprehensive description of the bioeconomy concept of sago is presented in **Figure 2**.

By having the various perceived benefits for the society, the risk of overexploitation of sago should be anticipated, such as land-use competition of food, feed, and bioenergy, and also environmental sustainability on the land-use changes to fulfill the demand of certain products (Gawel et al., 2019). In this sense, Thailand has acknowledged the importance of environment conservation (including sago forest area) (Table 1). In this regard, regional, national, and international policy should play a critical role to ensure that the bioeconomy principles are implemented appropriately by considering nature's limits.

3.2. Literature review analysis on the potential role of underutilized sago

Using the keywords "sago" AND "food", the Scopus and PubMed literature search from mid-July to the end of August resulted in 361 and 121 papers, respectively, where 54 papers from PubMed were duplicates of those obtained from Scopus. Based on the more advanced criteria (i.e., the combination of keywords and accessibility) and thorough checking of the relevancy of the studies, the research objectives, and after pooling all selected articles, 25 papers in total were included in the analysis. Ten of them were included concerning sago utilization in food product development, while six and nine articles were reviewed concerning the health potential benefits of sago and bioenergy application, respectively.

Table 2. *Sago starch-based food product development*

No	Food product development	Descriptions	Ref.
1.	Sago cake, sago bread, sago brownies and doughy sago starch droplets used in cold drinks	Snack and delicacy products of Papua. Usually made with traditional processing method. Thus, guidance from the government and industry are needed to improve the quality.	(Mofu and Abbas, 2015)
2.	Local sago-meals namely	Snack and delicacy from Sulawesi. Dry sago-	(Ehime University

	kapurung, *Dange* or *Ruji* (sago bread), *barobbo* (mixed of sago-corn-vegetables),	based products are commercially available in the market, especially for tourist attraction	et al., 2017)
3.	Yellow soup fish *papeda*, *sagu lempeng*, various type of *bagea*, *sagu serut*, *sagu tumbuk*, *karkaru*,	Various sago-based local foods and delicacies in Moluccas, which potentially contribute as tourist attractions.	(Mahulette et al., 2021)
4.	Crackers	Modern food products developed from modified sago starch through cross-linking and succinylation	(Yusnita et al., 2017)
5.	Gelling agent	Native and modified sago starch as a gelling agent in various foods and delicacies, such as jam, jelly, patisserie, and sweetener.	(Javanmard et al., 2012; Hirao et al., 2021)
6.	Noodles	Native and modified sago starch used to produce noodles. In addition, fortification is often performed to enriched the nutritional content and improve the physicochemical properties. The fortificants such as mung bean, mushroom, sorghum, and tuna-fish meal flours.	(Tjokrokusumo et al., 2019; Azkia et al., 2021; Litaay et al., 2021),
7.	Vermicelli	Glass noodle/sohun/beehon produce using sago starch due to clarity-gel properties.	(Mogra and Midha, 2013)

3.2.1. Sago for traditional food production

The sago palm tree is mainly used for food production in the form of starch. The tree undergoes several processing steps to yield starch (Letsoin et al., 2022). The characteristics of ready-to-harvest sago palms can be seen from the changes in the leaves, thorns, shoots, and stems. Generally, sago plants are ready to harvest before flower primordia or flower buds have appeared but have not yet bloomed. As a result, the shoots become slightly swollen. In addition, the thorns decrease, and the leaf sheaths are cleaner and smoother than in the young trees. The appropriate trees are harvested by cutting, cleaning the bark, and collecting the trunks. Sago starch is traditionally extracted from the pith of the stem by crushing and kneading to release the starch and then washed and strained to release the starch from the fibrous residue. The raw starch is suspended in water and then collected, allowed to settle, and dried. Sago starch is consumed as a staple food in the diet and cooked traditionally using burnt stones in Papua New Guinea and Indonesia (Papua and Buol) (Townsend, 1974) or mixed with hot water (sago porridge, so-called *papeda*) (Metaragakusuma et al., 2016) (**Table 2**).

Sago starch has approximately a 90% carbohydrate content per 100 g, which is comparable to tapioca (89%) and sweet potato (86%) (Grace and Henry, 2020), yet considerably higher than white rice (34%) (Sonia et al., 2015) or wheat (59–71%) (Escarnot et al., 2012). The high carbohydrate content of sago indicates its potential as an alternative staple food. Sago starch has low protein and very low-fat content per 100 g (< 0.1% and < 0.01%) (Grace and Henry, 2020). Meanwhile, the more commonly consumed staple foods, white rice and wheat, are comprised of higher protein (3.9% and 10–16%, respectively) and fat (2.9% and 1.1–37%), respectively (Escarnot et al., 2012; Sonia et al., 2015). Sago was also found to have about 10 mg phosphorus/100 g. The phosphorus content was considered low compared to other staple foods, like sweet potatoes (Grace and Henry, 2020). Hence, to improve the protein and micronutrient content, a sago-based diet was later developed by combining it with animal and plant protein food sources (such as fish, soybean, or mungbean), or with mushroom as the source of fat and minerals (Mogra and Midha, 2013; Tjokrokusumo et al., 2019; Litaay et al., 2021; Azkia et al., 2021).

As a food with a high carbohydrate content recommended to be consumed as an alternative to staple foods, sago's role in the regular diet and household food staple is essential.

The use of sago starch can support food diversification (FAO, 2012). Meanwhile, modernization has taken place in the extraction of sago starch, indigenous products have been widely promoted globally, and various innovative food products have been developed to accelerate the utilization of indigenous or wild foods, including sago. Sago is currently used in traditional delicacies, for example, sago porridge, which is stirred in a small amount of cold water until a suspension with a specific viscosity forms. Other traditional sago-based snacks, for example, plate-formed sago, are known as *sagu lempeng*. Plate-formed sago is a dry food with a long shelf life and is usually moulded 8 × 8 cm wide and 0.5–1.0 cm thick.

3.2.2. *Sago for the Food Industry*

Based on its physicochemical properties, the report found that sago starch could be used as food ingredients due to its similar characteristics with cereal and potato starches. In addition, the x-ray diffusion of sago starch shows around a 35% similarity with bean starches (Ahmad et al. 1999), which indicated that the starch has limited solubility, a limited capability of swelling, and high stability of granules against mechanical shearing (Punia et al., 2019), which needs to be addressed in food product development.

Sago-based food production has considerable potential in culinary agro-industries due to the physicochemical properties that enable sago flour and sago starch to be used as ingredients for bakery products, mainly as a partial substitute for wheat flour. In the last decades, the progression of various bakery products such as bread, cake, croissant, cookies, and crackers has increased the demand for wheat flour. However, raising awareness of the adverse effect of gluten consumption on health creates an opportunity for sago for bakery products. As a gluten-free and rich starch source, sago can substitute for wheat flour in bakery products such as cake, bread, and brownies (Kumari, 2019).

The physicochemical characteristics of sago starch could be more suitable for producing biscuits or cookies. Sago starch plays a vital role in forming a structural network responsible for the crispness of biscuits (Yusnita et al., 2017; Konuma, 2018; Puspitasari et al., 2021). Meanwhile, a study on the characteristic of *keropok* crakers made of cassava starch with the addition of sago starch suggested that the increase of sago starch proportion is responsible for the decrease in the degree of gelatinization and expansion which can be improved by appropriate dough steaming conditions (Tongdang et al., 2008).

Foods that can be developed using sago starch are noodles and vermicelli. Sago starch is suitable for producing noodles and vermicelli due to its large starch granule, high retrogradation rate, and gel clarity properties. A report on noodles made of four different cultivars of sago starch revealed that sago starch could be processed to produce noodles. Nevertheless, heat moisture treatment is needed to obtain high-quality noodles (Tongdang et al., 2008). Furthermore, as polysaccharide carbohydrates containing linear (amylose) and branched (amylopectin) alpha-glucans, sago starch can potentially be used as a gelling agent (Tuan and Tuan, 2009).

Although sago starch applications in food and food products are widely known due to its lack of certain important nutritional content and unfamiliar sensory properties, sago starch is commonly fortified with various materials for food product development (Ansharullah et al., 2019; Maluku, 2016; Rasulu et al., 2021; Shanthamma et al., 2021; Sopade and Koyama, 1999; Suparmi et al., 2021).

In the native form, sago starch has limited functionality due to its nature of compact constituent structure which causes the low solubility of the starch granule, lower gel clarity, a shorter shelf life, and a limited capability as an emulsifier (Zhu, 2019). Therefore, chemical and physical modifications of sago starch have been widely formulated to achieve desirable physicochemical and rheological properties of the starch.

Chemical modification is the most common method to modify the starch structure and its properties due to the simple procedure and specific modification target responsible for starch's final characteristics (Sumardiono et al., 2021). The first modification is by substitution. Based on the specific starch properties needed, modification by substitution part of the chemical structure of starch by using added chemical compounds can be performed. For example, to decrease the crystallinity, increase the stability, and reduce the melting point of starch, modification through esterification was reported using vinyl laurate (VL) (Muljana et al., 2018) and benzyl chloride (Misman et al., 2015). Meanwhile, to decrease the gelatinization temperature, increase the solubility in cold water, and prevent syneresis and retrogradation, modification using propylene oxide was performed to yield hydroxypropylated sago starch (Aminian et al., 2013). Moreover, to increase the paste clarity and decrease the viscosity of sago starch, isopropanol can be used to produce carboxymethyl starch (Othman et al., 2015).

The second modification is by crosslinking. Crosslinking is a frequently investigated modification to increase the water absorption capacity and the desired particle size of starch granules. A crosslinking modification was performed using UV irradiation in the presence of cerium (IV) ammonium nitrate (Singh and Nath, 2012). Meanwhile, to obtain starch with higher thermal stability and swelling power, crosslinking was conducted with $POCl_3$ to yield sago starch phosphate with specific rheological properties (Tay et al., 2012).

Modification by degradation is the third method of chemical modification. Degradation-type modification can be done by alcoholic-alkaline solution, acid degradation, and enzyme degradation. To obtain sago starch with higher solubility in cold water, a larger granule size increased amylose content and lower viscosity in reported research using NaOH and ethanol to degrade the sago starch (Kaur et al., 2011). Modified starch using ozone oxidation in an alkaline environment with a long reaction duration tended to create more favorable properties of carbonyl and carboxyl content, swelling capacity, solubility, thermal profile, granule morphology, and functional groups (Sumardiono et al., 2021). Meanwhile, modification of sago starch can also be performed using a conventional acid hydrolysis method which usually uses sulfuric acid and hydrochloric acid. These hydrolysis methods produce a high yield of starch nanocrystals (SNC) of sago compared to other commercial starches, with a round polygon structure with a particle size distribution of around 20–100 nm that is more stable during storage and has the potential as an emulsifier in a Pickering emulsion system (Azfaralariff et al., 2020).

Modification of starch using enzymes is mainly conducted to produce glucose, of which α-amylase, glucoamylase, and pullulanase are the most commonly used enzymes for starch degradation. Unlike the alkaline and acid modification, the enzyme degradation consists of three steps: gelatinization of starch, partial degradation of starch by α-amylase, known as liquefaction to produce oligosaccharides, polysaccharides, or maltodextrin, and saccharification by glucoamylase or pullulanase to produce glucose and maltose (Okafor et al., 2019).

Both native and modified characteristics of sago starch can also be used in the human health and nutrition fields. The native sago is rich in starch (90% of starch per 100 g) (Grace and Henry, 2020), which makes the food rich in resistant starch. Sago also has a lower glycemic index value (40.7, low level) (Wahjuningsih et al., 2016) as compared to the other staple foods, for instance, white rice (61–87, medium to high level) and sweet potato (77, medium) (Osman et al., 2021). Hence, sago products can be used as alternative energy source and improve metabolic indices (Wahjuningsih et al., 2018; Setiawan et al., 2022). Furthermore, despite sago having a lower glycemic index, sago-based products provide a higher glycemic response that can improve physical performance during exercise (Ahmad et al., 2009; Ghosh et al., 2010; Matthan et al., 2016; Wahjuningsih et al., 2016).

3.2.3. Sago for Bioenergy and Other Uses

In addition to the food industry, sago can be converted into a variety of feedstock, fertilizer and bio-energy resources (Fetriyuna et al., 2022, inpress), which support the bioeconomy principles. Bioenergy uses are promoted due to its urgency in climate change mitigation. Bioenergy from sago, e.g., biomass (Abdul Aziz et al., 2013; Rambli and Khezri, 2019), biogas (Nururrahmah et al., 2018), bioelectricity (Jenol et al., 2019), bioethanol (Awg-Adeni et al., 2013; Praveenkumar et al., 2014; Wahida et al., 2021), and biohydrogen (Jenol et al., 2014; Nizzy et al., 2020), can be derived from the sago waste (such as bark, fiber, hampas, rough starch, and wastewater) (Letsoin et al., 2022). The strength points of sago waste in bioenergy provision are the higher quantity that can be produced compared to other food crops (e.g., cassava, sugarcane or maize) (Ahmad et al., 1999). It has approximately a 1.5 octanes rating more excellent than other types of gasoline, which makes the consumption less than gasoline and ecologically friendlier (Komarayati et al., 2011; Tuan and Tuan, 2009). A 2.92 g bioethanol fuel can be derived from 10 g dry matter sago pith waste (Jonatan et al., 2017). The following challenges of the biodiesel from food crops are the competition with a food consumption, and management of sago palm regeneration for maintaining the forest areas. Hence, the development of sago into bioenergy can be promoted as an alternative material for biofuel, too.

Hampas, "the starchy lignocellulosic by-product generated from the pith of sago palm after starch extraction" (Wardono et al., 2021), is the source of feedstock. Hampas has high fiber content, approximately 50–58% starch, 8-14.5% hemicellulose, 20–24% cellulose, and 6-8% lignin (Jenol et al., 2014; Vincent et al., 2015). Hence, various treatments are commonly used to improve the digestibility and palatability of the fodder (Stefanie et al., 2000; Vikineswary et al., 1994). In addition, the leftover remains of starch extraction (e.g., hampas, the pulp of the palm, and the bark) can be used as fertilizer and co-composting (Ch'ng et al., 2014; Supu and Jaya, 2018; Rasyid et al., 2020), which closing the lifecycle of sago production.

4. Conclusions

Document review analysis in this paper found that there has been no common policy established on the bioeconomy in the region or countries where sago *primarily grows. Only Malaysia and Thailand possess a national bioeconomy strategy, while in other countries, like Indonesia and the Philippines, the principles were included in different ministries. Promotion of sago utilization, and development of its value-added products, especially into bioenergy, is in line with the goal and strategic actions of the bioeconomy in Malaysia and Thailand. However, sustainable production of the biomass and the preservation of the forested landscape, including sago areas, as part of climate change mitigation are rarely discussed in the studied documents.

This literature review study revealed numerous potential uses of sago, beyond its original use as a food staple, that can be further developed. In the food industry, sago has undergone different processing methods that could improve palatability, nutrition, and physicochemical profiles. Furthermore, sago can also be beneficial in the non-food industry sector, especially bioenergy. The following challenges of the biodiesel from food crops are the competition with food consumption and management of sago palm regeneration for maintaining the forest areas. The potential uses and benefits of sago have prompted its utilization in food and non-food products. Thus, it encourages the sustainable production, conservation of sago forest areas, and promotion of the local bioeconomy.

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Appendix

Table A.1. *Estimation of world's sago area*

Province	Sago area (ha)	Sago productivity (tons/year)	Remarks	Reference
Indonesia	*5,224,235*		Sago forests	
	94,305		Cultivated-small holders	
Maluku (Moluccas)	64,205	1597		(Ehara et al., 2018)

Papua and Papua Barat (West Papua)	5,160,030		Wild stand-Semi	(Bintoro, 2019)
Aceh	6861	1745	Semi-cultivated	
Riau	62,257	261,112	Semi-cultivated	(Directorate General of Estate Crops, 2019)
Kepulauan Riau	5819	3364	Semi-cultivated	
Kalimantan	8204	1082	Semi-cultivated	
Sulawesi	11,163.75	8453.10	Semi-cultivated	
Sumatera	1461	1725		
Papua New Guinea,	*1,020,000*	82,962*		(Ehara et al., 2018); (Mohamad Naim et al., 2016)
Sepik Province	500,000	20	Wild stand	(Ehara et al., 2018);
Gulf Province	400,000	53	Wild stand	(Ehara et al., 2018);
Other provinces	100,000	11	Wild stand	(Ehara et al., 2018);
Sepik Province	5000		Semi-cultivated stands	(Ehara et al., 2018);
Gulf Province	5000		Semi-cultivated stands	(Ehara et al., 2018);
Other Provinces	10,000		Semi-cultivated stands	(Ehara et al., 2018);
Malaysia, in total	61,736	**		
Sabah	10,000			(Ehara et al., 2018);
Sarawak	46,736		Cultivated by smallholders and estate sago plantation	(Mohamad Naim et al., 2016)
West Malaysia	5000			(Ehara et al., 2018)
Thailand	5000	**	Sago forest, semi-cultivated	(Mohamad Naim et al., 2016)
Philippines	3000	**		(Ehara et al., 2018; Mohamad Naim et al., 2016)
ntries (Includes India)	5000	**		(Ehara et al., 2018)

* *In total*, Source: (Bourke and Harwood, 2009)
** unreporte

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