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Review article

Sago Wastes and Its Applications

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ABSTRACT

The sago starch industry is one of the major revenue sources of the Malaysian state of Sarawak. This state is currently among the world's leading producers of sago starch, exporting more than 40,000 tons every year to different Asian countries. This number is expected to rise since starch production and export value have been increasing 15.0%–20.0% each year. Sago palm is subjected to various processes to obtain starch from its trunk. During processing, a huge amount of residual solid wastes is generated, such as bark and *hampas*, and in general, is burned or washed off to nearby streams. Along with the rising sago starch demand, the sago starch industry is now facing waste management problems, which have resulted in environmental pollution and health hazards. These wastes comprise starch, hemicellulose, cellulose, and lignin; hence, can be valorized into feedstock as value-added products. To date, these wastes have been utilized in the production of many materials like adsorbents, sugars, biofuels, nanomaterials, composites, and ceramics. This review article aims to summarize the various methods by which these wastes can be utilized besides to enlighten the major interest on sago *hampas* and bark.

Keywords: Adsorbent, biofuel, sago bark, sago *hampas*, waste utilization

INTRODUCTION

Sago is a Javanese term that means starch-containing palm pith. Scientifically, it is known as *Metroxylon sago,* whereby *metra* means parenchyma or pith and *xylon* means xylem (Singhal et al., 2008). Sago palm is a starch crop par excellence, as it has a higher starch production capacity, between 20–25

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tons/ha/year, than that of cassava, rice or corn (Flores, 2008). In Malaysia, Sarawak has the largest sago palm plantation areas, particularly in the Mukah division. Currently, it is known as one of the world's largest exporter of sago starch, exporting more than 40,000 tons annually to different countries, including to Peninsular Malaysia. Nevertheless, this value is expected to rise every year, corresponding to the world demand and will subsequently increase the amount of waste generated. The three main types of wastes from the sago industry are sago *hampas*, bark, and wastewater. These wastes predominantly comprise starch and lignocellulosic compounds, namely, lignin, cellulose, and hemicellulose. Sago wastes have been neglected despite its high value. The wastes are not fully utilized as higher value-added products. Moreover, current improper disposal practices of these wastes, such as washed off into nearby rivers, pose harmful effects to the environment.

Waste lignocellulosic biomass is typically an abundant nonedible plant material that has been discarded across the world. This carbon neutral material is generated naturally from available carbon dioxide, water, and sunlight via the photosynthesis process. Therefore, it is considered the only sustainable source of organic carbon and the perfect equivalent of fossil resources. Unlike lignocellulosic carbons, the high dependency of industrial chemicals and synthetic polymers on depleting fossil resources will cause a lethal threat to human beings (Isikgor & Becer, 2015). Hence, elevating concerns regarding this issue has turned researchers' attention to valorize the starchy-lignocellulosic compounds present in sago wastes. Many studies have been carried out to investigate the conversion of this waste into useful products or its use as a raw material in other industries. Wastes produced from the sago industry can be utilized in the production of adsorbents, sugars, biofuels, nanomaterials, composites, and ceramics. Therefore, in this present study, efforts have been made to compile and discuss the recent methods employed to utilize solid wastes from the sago industry, i.e. *hampas* and bark. Besides that, this review will also elucidate the major interest in both wastes.

SAGO PALM

Sago palm belongs to the genus *Metroxylon*, under the order Arecales, family Palmae, and subfamily Calamoidae (Awg-Adeni et al., 2010). It is a hapaxanthic or monocarpic plant that flowers only once in a lifetime and dies shortly thereafter (Bujang, 2006; Flach & Schuiling, 1988). The plant is believed to convert all of its stored nutrients into starch and fill its trunk during the vegetative stage just before flowering (Abd-Aziz, 2002). Sago palm's vegetative phase lasts 7 to 15 years, during which the pith will be saturated with starch, from the base of the stem upwards (Karim et al., 2008). This plant is extremely hardy and is the only starch crop that thrives and grows with minimum care in swampy, acidic peat soils with a low level of nutrients, where very few crops can survive (Flach & Schuiling, 1988; Singhal et al., 2008).

Generally, the sago plant reproduces via suckers that emerge from roots or lower trunks of parent plants, unlike other plants of the same genus that usually propagate by seeds. Nonetheless, propagation from suckers is usually limited in number, hence, an in vitro technique is most suitable to produce a vast amount of materials for extensive planting and to improve the quality and vigor of palms (Singhal et al., 2008). Apart from suckers, sago palm may also propagate from seedlings (Karim et al., 2008). A full-grown plant can grow up to 25.0 m tall, and typically reach a height of around 10.0–12.0 m and a diameter of about 0.800–1.00 m when matured (Bujang, 2006). A matured sago produces the highest starch content of 25 tons per hectare, compared to other starch crops like rice, corn, wheat, and potato, which only produces 6.00, 5.50, 5.00, and 2.50 tons, respectively (Awg-Adeni et al., 2010).

There are several remarkable environmental benefits of sago palm highlighted in previous studies. Firstly, its large fibrous root system helps to trap silt loads and removes pollutants, fecal contaminants, and heavy metals. This feature also makes the plant resistant to floods, drought fires, and strong winds. Next, the sago forest acts as an excellent carbon sink for carbon sequestration (Chew et al., 1999), by assimilating carbon dioxide for starch conversion. Thus, it is a very good tool for offsetting the greenhouse effect and a potential plant resource for bioremediation (Flores, 2008).

The sago palm flourishes in a moist environment and is therefore found along riverbanks, water holes, and swampy areas. It is an indigenous species of the Southeast Asia region, specifically Malaysia, Indonesia, Papua New Guinea, and the Philippines. As such, there are similarities in the terminologies used. In these countries, sago is either known as *saksak*, *rumia*, *lumbia*, or *unod* or the food ingredient *landang* or *kinugay* (Flores, 2008; Naim et al., 2016). Besides that, the sago palm's center of diversity is in the island of New Guinea.

SAGO INDUSTRY

Papua New Guinea, Indonesia, and Malaysia are the three leading producers of sago, whereby sago is primarily grown for sago starch. In Malaysia, more than 90.0% of all sago-planting areas are in the state of Sarawak, which is one of the world's largest sago exporter, exporting about 25,000–40,000 tons of sago products annually to Peninsular Malaysia, Japan, Taiwan and Singapore (Bujang, 2006; Singhal et al., 2008). Currently, Malaysia is the third main sago producer in the world after Indonesia and Papua New Guinea and combined, the three countries produce approximately 94.6% of the world's sago (Naim et al., 2016). Although Indonesia and Papua New Guinea produce more sago than Malaysia, the sago industry in this country is well established and has become one of the important industries contributing to export revenue (Karim et al., 2008). In Malaysia, sago starch ranks fifth in terms of highest agricultural revenue after pepper, palm oil, cocoa, and rubber (Abd-Aziz, 2002).

Sago is cultivated in wild and semi-wild conditions in Sarawak and covers approximately 19,702 ha. The production capacity of sago palm varies from 2.00–5.00 tons of dry starch/ha in the wild to 10.0–25.0 tons/ha in the case of cultivated plants (Abd-Aziz, 2002). Realizing sago's potential, the Sarawak government appointed the Land Custody and Development Authority (LCDA) to kick-start the commercial cultivation of sago and implement management techniques. A large-scale sago palm plantation was initiated in 1986, with the opening of three precedent plantations, namely Mukah Sago Plantation (MSP), Sebakong Sago Plantation (SSP), and Dalat Sago Plantation (Aziin & Rahman, 2005). In fact, Malaysia is the first country that introduced estate plantation for sago (Naim et al., 2016). Based on the latest data by Department of Agriculture Sarawak (DAS), (Department of Agriculture Sarawak, 2013) the total estimated area of sago plantation in 2013 was 54,087 ha, with the largest area found in Mukah division with 46,924 ha. Although estate plantations have been introduced, small-holdings still amount to a huge area, i.e. 37,028 ha.

SAGO STARCH

Processing of Sago Starch

Sago palms are usually felled about 10 to 15 years after planting, depending on the fertility of the terrain. Due to the rapid decline of starch content in the trunk after fruiting, palms at a height between 7.50 to 9.00 m will be felled right after flowering and immediately before fruiting (Singhal et al., 2008). The sago trunk is then cut into about 10–12 sections, with each section measuring 75.0 to 90.0 cm long. Cut sago logs are tied together in the form of rafts and tugged by boats to sago factories for processing. Otherwise, the logs will be kept in ponds prior to processing to reduce deterioration (Vikineswary et al., 1994). Other than that, the logs may also be delivered by land to the factories, in which independent agents will collect and transport the logs for a fee. Since sago factories are invariably situated along river banks, floating of sago logs along the canals and rivers is the most typical form of transportation. However, when the canals become dry, lorries will be used instead (Chew et al., 1999; Chew et al., 1998).

The sago palm pith mainly consists of starch, which has to be separated from the cellulosic materials and thus, will undergo several stages of processing to extract a good quality and quantity of starch (Awg-Adeni et al., 2010). Generally, sago starch extraction can be categorized into two types, traditional and modern. For the traditional method, it is further classified into two levels, namely, domestic and small-scale processing plant. Unlike the small-scale processing plant level, the domestic level is practiced by individual farmers, in which sago palms are felled and processed in the garden without the need to transport the heavy trunks to factories. On the other hand, for modern method, several modifications to the small-scale processing plant level are involved. Mostly, large-scale factories in Sarawak have adopted this technique whereby they are fully mechanized and capable to reduce most laborious tasks (Karim et al., 2008). Nevertheless, the principles and methods of starch extraction are similar in both traditional and modern methods, differing only in scale of operation (Kamal et al., 2007)

During processing, the bark-like layer of the palm is first stripped off followed by maceration using a rasper. The rasping process is done either manually or mechanically to pulverize the pith and loosen the starch particles within the fiber. Next, the starch is removed from the fiber either by kneading with hand, trampling by feet or spraying with water. Then, the starch is passed through a series of centrifugal sieves for removal of coarse fibers. It is later extracted using cyclone separators and then dried with a rotary drum dryer, followed by hot air drying (Chew et al., 1998; Kamal et al., 2007; Vikineswary et al., 1994). A simplified sago starch extraction process is shown in Figure 1.

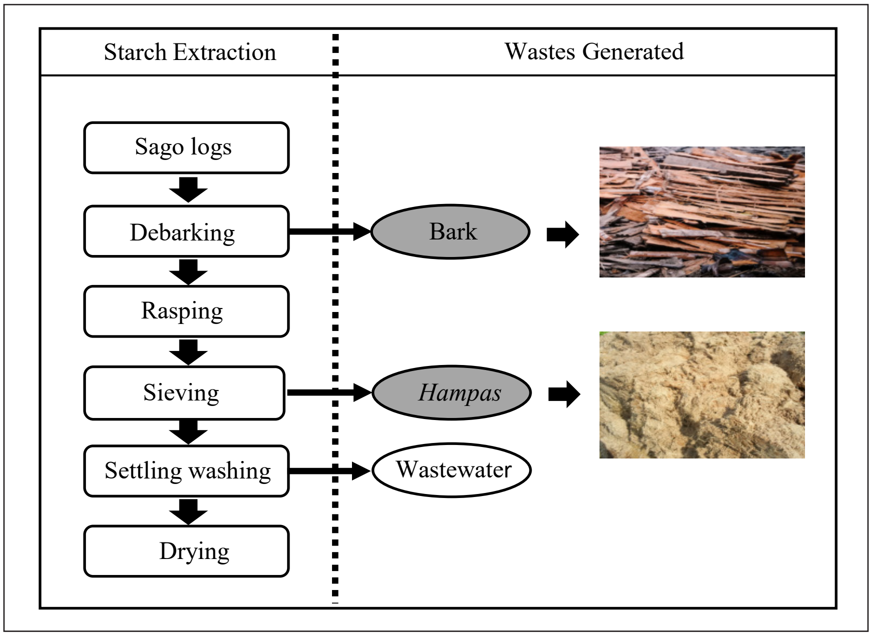

Figure 1. Schematic flow diagram of sago starch extraction

Starch Production Statistics

The Malaysian sago palm industry is one of the crucial sago exporters in the world, exporting more than 40,000 tons of sago starch since 2004. It was reported that the production and export value of sago starch has been increasing 15.0% to 20.0% every year (Jenol et al., 2014; Mohamad et al., 2011). Figure 2 illustrates the 10 years sago starch export trend from 2008 to 2017, as reported by DAS. The sago starch export was at peak, with the export value of more than 47,000 tons from 2011 to 2013, before it dropped to approximately 40,000 tons in four subsequent years, 2014 to 2017. Nonetheless, the export value in 2017 rose a bit which shows the tendency of sago starch export to increase in the future. The displayed trend indicates the global demand for sago starch. When the demand increases, so will sago production, which consequently contributes to the significant amount of waste generated. Hence, the sago industry is facing waste disposal and management problems.

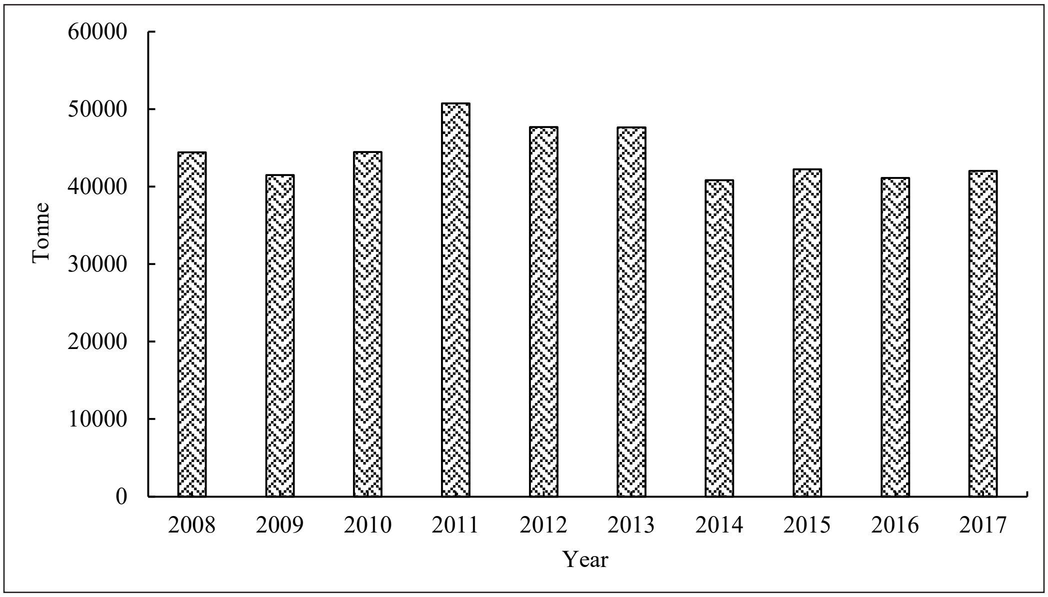

Figure 2. Ten (10) years Malaysia sago starch export statistics, 2008 - 2017

SAGO WASTES

During the processing of sago starch, three major by-products are generated, namely bark of sago trunk, fibrous pith residue, which is also known as *hampas*, and wastewater (Figure 1). Bark and *hampas* are classified as solid residues whereas wastewater is a liquid residue (Awg-Adeni et al., 2010). Sago wastes consist of non-starch polysaccharides (NSP) or lignocellulosic materials, i.e. cellulose, hemicellulose, and lignin. In a day, 15.6 tons of woody bark, 238 tons of wastewater, and 7.10 tons of fibrous pith residue are generated from approximately 600 logs of sago palm (Ngaini et al., 2014a).

Solid Residue

Sago *Hampas.* Sago *hampas* is an inexpensive fibrous residue left behind after the starch extraction process, particularly from crushing and sieving (Figure 1). It is also known as sago pith residue, a starchy lignocellulosic by-product. In Sarawak, mainly in Sibu and Mukah divisions, about 50.0 to 100 tons of sago *hampas* are produced daily (Awg-Adeni et al., 2010). Previous studies have revealed that a large number of starch granules, approximately 60.0%–70.0% starch per gram dry weight of *hampas*, are still trapped within the lignocellulosic matrix (Singhal et al., 2008; Vikineswary et al., 1994). Since a significant amount of starch is left within the *hampas*, it has been used as feedstuffs for swine around sago processing areas.

Hampas is a refuse from sago starch extraction process and is usually discarded into nearby streams together with the factory wastewater (Vincent et al., 2015a). Eventually, the streams' oxygen content, which supports higher life forms, decreases due to the high consumption of dissolved oxygen for degradation of the wastes via microbial activity. Indubitably, this will negatively affect the environment, whereby a severe drop in water quality can endanger aquatic lives (Lai et al., 2013). Due to the presence of lignocellulosic fibrous materials (Table 1), *hampas* has been used as animal feed, compost for mushroom culture, substrate in hydrolysis process to produce confectioners syrup, and for particleboard manufacture (Phang et al., 2000). Apart from that, sago *hampas* is also applied as a cheap carbon source for production of several enzymes via fermentation like laccase (Kumaran et al., 1997), α-amylase, and cellulase (Khan & Husaini, 2006).

Table 1
Chemical composition of sago hampas and SB

Item	**Sago *Hampas***			**SB**		
Reference	Ozawa et al. (1998)	Lee et al. (2014)	Jenol et al. (2014)	Mohamad et al. (2011)	Ethaib et al. (2016)	Erabee et al. (2017)
Starch (%)	49.7	37.0	49.5	-	-	-
Cellulose (%)	20.2	40.0	26.0	44.1	40.8	44.1
Hemicellulose (%)	7.9	13.0	14.5	21.1	22.3	21.1
Lignin (%)	3.3	5.0	7.5	23.3	25.9	23.3

Sago Bark. Basically, there are two types of sago bark (SB) wastes, which are peeled and shredded. Most of the peeled types come from the lower part of a sago tree and are manually peeled using a parang due to its uneven shape. It has a thicker peripheral, approximately 2.00 to 3.00 cm thick. On the other hand, shredded types are produced during the debarking process using machine (Aziin & Rahman, 2005). The bark accounts for about 17.0% of the processed logs and approximately 5.00–15.0 tons of bark per day is produced from a factory (Vikineswary et al., 1994). Annually, more than 20,000 tons of SB are discarded from Malaysia's sago industry.

A lot of SB wastes left behind during the starch extraction process are destroyed through open or controlled burning. This practice poses several serious problems such as threat to the environment through air pollution and furnace chimney corrosion. Discarding SB into rivers is also inappropriate as it could cause the rivers to become shallow. Likewise, leaving tones of SB to naturally degrade would consume time and space besides creating an unpleasant odor and view. Furthermore, only less than 15.0% of SB is used as fuel in sago processing mills due to the corrosion problem caused by SB since the compound is acidic in nature (Wahi et al., 2014). Nevertheless, due to its woody nature, locals usually use SB wastes to build a platform around the factory, footpaths of houses, wall materials, and fences. Moreover, numerous interior decoration products, such as wall tiles, furniture, and flower pots or containers, have been successfully recycled from SB, ascribing to the natural features and beautiful surface of SB (Aziin & Rahman, 2005). Not only that, an eco-friendly material, glulam, from SB is used in combination with less used wood species, *pulai* and *binuang*, in an effort to maximize SB utilization (Wahyudi & Arifudin, 2017). The detailed chemical composition of SB is tabulated in Table 1.

APPLICATION OF SAGO WASTES

Due to the high amount of residual wastes generated every year from the sago industry, efforts have been made to resolve this plaguing issue by valorizing the wastes into value-added materials. The wastes have been widely used as feedstocks or raw materials in industrial applications owing to the large quantity of carbon neutral still embedded within its complex lignocellulosic matrix. Hence, use of sago wastes is one of the solutions to the impending petroleum shortage crisis and a way to address environmental issues by making full use of sustainable resources. The following sections discuss the applications pertinent to the utilization of sago wastes.

Adsorbents

Heavy Metals Adsorbent. Low-cost adsorbents made from agricultural wastes are now gaining more interest than conventional adsorbents to remove harmful contaminants from watercourses because it is abundantly available and economically attractive. Sago *hampas* is largely composed of cellulose and lignin and thus has potential to be used directly as a biosorbent (Vikineswary et al., 1994). Ground, dried, and sieved untreated sago *hampas* has been used to remove metal ion pollutants like copper, Cu(II), and lead Pb(II) in aqueous solution (Quek et al., 1998). The findings showed that sago *hampas* adsorbed Pb(II) better than Cu(II), with a higher initial sorption rate and greater sorption capacity. On the other hand, chemically activated sago *hampas* using H_2SO_4 and $(NH_4)S_2O_8$ efficiently removed both Cu(II) (Maheswari et al., 2008) and Pb(II) (Karthika et al., 2010). In general, a lower pH is more favorable for effective adsorptions of Pb(II) and Cu(II). Nonetheless, a higher pH was found optimum for Zn adsorption by sago waste compared to pH 7 (Wahi et al., 2010). Besides, it was proven that sago *hampas* had the potential to be used as a low-cost biosorbent for mercury removal (Saman et al., 2014). A better adsorption was found for inorganic mercury (Hg(II)) than that of organic mercury ($CH_3Hg(I)$), with a maximum adsorption capacity of 0.288 and 0.213 mmol/g, respectively. Adsorption of mercury ions was highly dependent on the solution's pH in which Hg(II) adsorption was higher at pH > 4, while $CH_3Hg(I)$ adsorption was higher at pH < 5.

Activated Carbon (AC). Various agricultural wastes, including sago *hampas*, have been used for activated carbon (AC) preparation using concentrated sulfuric acid (Kadirvelu, 2003). Sago *hampas* AC significantly adsorbed different dye and metal ion components from aqueous solutions as early as 1 h and registered a more than 90.0% removal in 24 h. Specifically, it effectively adsorbed mercury (Hg(II)) (Kadirvelu et al., 2004) and Rhodamine-B (Kadirvelu et al., 2005) with a 55.6 mg/g and 16.1 mg/g adsorption capacity, respectively, for a particle size range of 125–250 µm at approximately pH 5. Meanwhile, physiochemical activation of SB via $ZnCl_2$ produced a higher surface area AC compared to commercial AC made from coconut shells (Erabee et al., 2017). Low ash and high carbon and oxygen content in waste feedstocks positively affect the production of a good adsorbent

Oil Adsorbent. Oil pollution negatively impacts both the economy and environment and remains a serious concern in Malaysia. Natural organic sorbents, particularly those made from agricultural wastes, have many advantages like having a comparable density with synthetic sorbents, chemical-free, and highly biodegradable (Annunciado et al., 2005). Some are also able to significantly absorb more oil than commercial sorbents made of polypropylene (Adebajo & Frost, 2004). However, most of the cellulose portions are covered by the hydroxyl groups, causing the cellulose to behave more hydrophilic than hydrophobic (Said et al., 2009), hence, will adsorb water and reduce the oil sorption capacities (Ali et al., 2012). In response, numerous studies have been conducted to improve the hydrophobicity and oleophilicity by means of alkalization, salt treatment, surfactant treatment, and esterification (Wahi et al., 2013).

Esterification of SB (Ngaini et al., 2014a) and sago *hampas* (Ngaini, et al., 2014b) using stearic acid (SA) resulted in a higher used engine oil (UEO) sorption capacity and lesser water uptake in an aqueous environment compared to untreated ones. Besides that, the findings also highlighted a higher buoyancy (able to remain afloat for 7 days) and sorption capacity in esterified sago bark (ESB) than other natural sorbents. To enhance ESB's adsorption ability, various parameter relationships were examined (Wahi et al., 2014). ESB with a preparation condition of 1:1 SB:SA, 15.0% catalyst (CaO), and 8 h refluxing time produced a maximum oil removal efficiency of up to 95.5% compared to untreated SB (45.4%). Later, this optimized ESB's capability to remove oil, particularly from palm oil mill effluent (POME), was tested (Wahi et al., 2017). After a systematic investigation of various parameters, ESB was revealed to be a potentially better palm oil sorbent with a consistent 88.0%–89.0% oil removal efficiency and had excellent reusability of up to six cycles. Interestingly, ESB has also demonstrated its capability in removing oil spilled in a dynamic seawater environment (Ngaini et al., 2017). The oil sorption capacity after 60 min was 5.70 g/g in the dynamic seawater system compared to 3.30 g/g in deionized water. This suggests that ESB is a promising low-cost natural sorbent that works best in dynamic seawater conditions.

Sugar Sources

Sago waste can also be utilized to produce fermentable sugars. Sago *hampas* was analyzed to determine its carbohydrate content using cold and hot water extraction and acid hydrolysate (Akmar & Kennedy, 2001). All sago *hampas* hydrolysates showed a significantly higher total monosaccharides content, especially in glucose, compared to oil palm trunk wastes. This makes sago *hampas* a potential fermentation substrate candidate. Optimum glucose production from sago *hampas* through acid and enzymatic hydrolyses were also systematically investigated using H_2SO_4 and glucoamylase, respectively (Kumoro et al., 2008). A maximum of 0.565 and 0.623 g glucose/g waste were generated via enzymatic and acid hydrolyses, respectively. Likewise, hydrolysis of sago *hampas* using microbial enzymes containing 24.0 IU β-glucosidase produced by *Aspergillus fumigatus* UPM2, gave a higher reducing sugar production of 20.8 g/L (Linggang et al., 2012). Meanwhile, a local fungus, *Trichoderma* sp. KUOM0001 was found suitable to be applied on sago *hampas* for reducing sugar conversion via solid substrate fermentation (SSF) (Shahrim et al., 2008). The optimized condition during SSF after 96 h incubation further maximized the generation of reducing sugar i.e. from 24.0 mg/L obtained without optimization to 46.0 mg/L.

In addition, several pre-treatment methods for sago *hampas* were developed for bio-convertible polysaccharides recovery prior to employing enzymatic hydrolysis (Janggu & Bujang, 2009). Steaming treatment produced a significant starch concentration in liquid fraction with a relatively high solid fraction recovery of 50.6%, high convertibility degree of cellulose fiber at 42.0%, and high lignin reduction. This makes it the best pre-treatment compared to the other two alkaline pre-treatments examined in the study. Furthermore, another study demonstrated that ionic liquids could have dual-functions, namely, biomass dissolution and structural disruption, which facilitated maximum recovery of reducing sugars from sago *hampas* (Lee et al., 2014). A maximum reducing sugars recovery of 90.0% was achieved via incorporation of the ionic liquid pre-treatment, solid acid, and enzymatic saccharification, using 1-butyl-3-methylimidazolium chloride ([BMIM]Cl), Amberlyst 15 (A15), and *Trichoderma viride* cellulase, respectively.

Recently, several studies were conducted on SB to test its potential to be used as a raw material for production of sugars. Due to the presence of complex lignocellulosic components, microwave-assisted dilute acid pre-treatment was introduced prior to commencing enzymatic hydrolysis (Ethaib et al., 2016). After the pre-treatment, there was a 32.0% reduction in lignin content, an increased crystallinity from 29.0% to 47.0%, and clear damage and fragmentation to the surface structure of SB. The enzymatic hydrolysis showed that 24.0 FPU/g cellulase and 50.0 U/g β-glucosidase were sufficient to obtain a higher sugar yield from pre-treated SB. Apart from glucose, monosaccharide xylose was also produced from SB. Xylose is a carbon source for microorganism growth to produce xylitol. The xylose concentration achieved was 22.8 g/L under optimum hydrolysis time and acid concentration of 60 min and 8%, respectively (Mohamad et al., 2011).

Biofuels

Bioethanol. The current dependency on starchy biomass to produce ethanol has raised concerns regarding food shortages, fuel conflicts, and serious destruction of soil resources (Balat & Balat, 2009; Kennes et al., 2015). Hence, extensive research efforts have focused on the potential of using inedible feedstocks as alternatives to starchy biomass (Sun & Cheng, 2002). In this regard, lignocellulosic biomass, which does not compete with food production or animal feed, was determined to be an appropriate substrate for bioethanol production (Limayem & Ricke, 2012). Sago *hampas*, which is mainly composed of lignocellulosic materials, has been subjected to three cycles of enzymatic hydrolysis, whereby the hydrolysate is reused, prior to bioethanol production (Awg-Adeni et al., 2013). This method has shown great improvement in sugar concentration and produced a higher ethanol yield of 93.3% per total glucose existing in the fermentation media.

Simultaneous co-saccharification and fermentation (Sc-SF) was also carried out on sago *hampas* using two different enzymes, amylase and cellulase (Vincent et al., 2015b). During the Sc-SF process, both enzymes were added together into the culture for starch and fiber co-saccharification, while *Saccharomyces cerevisiae* was used to ferment the sugars in hydrolysate. A maximum of 37.9 g/L glucose and 80.5% theoretical ethanol yield were obtained from 5.00% sago *hampas* loading. On the other hand, another study introduced a modified version of sago *hampas* Sc-SF called sequential saccharification and simultaneous fermentation (SSSF) (Vincent et al., 2015a). Distinct from Sc-SF, this technique was performed in two steps, i.e. Stage 1 (amylolytic step) and Stage 2 (cellulolytic step). Cellulase was added into the culture sequentially after amylase during the designated 5 days experiment. Although the highest ethanol yield from SSSF of 77.4% was lower than that of Sc-SF, both techniques converged the idea of producing a high ethanol yield when different enzyme mixtures and *S. cerevisiae* were combined in a culture.

Besides that, a recent study had demonstrated the effect of acid hydrolysis on sago *hampas* and compared it with conventional enzymatic hydrolysis (Bukhari et al., 2017). Dilute acid hydrolysis resulted in a substantial amount of fermentable sugars with 96.0% hydrolysis conversion compared to 79.0% achieved using enzymatic approach. Furthermore, the highest yield of 98.0% ethanol was also attained from acid hydrolysate without supplementation of nitrogen and nutrients. Considering the environmental aspect, time consumption, and cost issues posed by both enzymatic and acid hydrolysis methods, production of ethanol has switched towards utilizing emerging advanced technology. For instance, microwave technology has been applied in bioethanol production from sago *hampas* (Thangavelu et al., 2014) and SB (Kannan et al., 2013). These studies have reported promising ethanol yield and limited by-products.

Biobutanol/Bio-Oils/Biohydrogen/Co-Firing Material. Besides bioethanol, biotechnological production of biobutanol has also gained increased interest for use as alternative biofuel. Fermentable sugars from enzymatic hydrolysis of sago *hampas* were converted to acetone-butanol-ethanol (ABE) by *Clostridium acetobutylicum* ATCC 824 (Linggang et al., 2013). This process produced approximately 8.84 ± 0.200 g/L ABE (5.41 ± 0.100 g/L butanol). Bio-oils can also be produced from sago *hampas* via microwave pyrolysis (Mona et al., 2013). A high colorific value of 22.0 MJ/kg was recorded and a significant hydrocarbon quantity was identified from sago *hampas*, enabling it to be used as a liquid fuel. In addition, a higher biohydrogen yield (2.65 mol H_2/mol glucose) was achieved when sago *hampas* was fermented with *Clostridium butyricum* A1, compared to using synthetic glucose as the substrate (1.90 mol H_2/mol glucose) (Jenol et al., 2014). Furthermore, SB has been utilized as a co-firing fuel along with commonly used biomass wastes (Chong et al., 2014). SB recorded a competitive heating value (HV) of 19.0 MJ/kg in the dry state and hence is suitable for co-firing during coal power generation. In a techno-economic study, SB was found to be feasible for use as feedstocks for a combined heat and power (CHP) system. A maximum of 472 kW of net electricity was generated with a payback period of 3.51 years and carbon saving of 5475 kg CO_2/d (Kin et al., 2015).

Nanomaterials

Along with the rising global awareness of creating sustainable communities via waste minimization, sago wastes were found to be reliable low-cost precursors in preparing silica, a material that possesses a strong luminescent property. Nanocrystalline silica xerogel (NSX) powder was produced from an amorphous silica xerogel (ASX) extracted from sago *hampas* ash. The crystalline silica xerogel (CSX) was derived from ASX via calcination process using an electric furnace with a heating rate of 2°C/min and retention time of 8 h at 1,200°C (Aripin et al., 2013). It was discovered that NSX transformed into a stable form at 1,200°C. Likewise, sago waste was also successfully converted into highly fluorescing carbon dots (C-dots) via a simple thermal hydrolysis method without any surface passivation (Tan et al., 2014). The C-dots can be dispersed in aqueous media and it will portray a significant fluorescent property in the presence of various metal ions that can be observed by the naked eye under a UV light source. Moreover, a better quenching effect was observed on both Cu(II) and Pb(II).

Apart from that, SB has been utilized as a carbon precursor in the synthesis of catalyst-free carbon nanospheres (CNs) using a simple one-step pyrolysis technique (Hegde et al., 2015). Synthesized CNs displayed a porous nature and it was revealed that more than 95.0% of the carbon particles were 40.0–70.0 nm in size. The specific capacitance value of 180 Fg^{-1} at 2.00 mVs^{-1} and the cycling stability of up to 1,700 cycles have made the obtained CNs suitable for use in supercapacitor applications. Besides its high supercapacitance value, a continuity study had demonstrated that SB CNs significantly enhanced the tensile strength of basalt fiber via homogenous distribution in the epoxy matrix (Mengal et al., 2016). The results showed a significant improvement in tensile strength when 0.600 wt% and 1.00 wt% of CNs particles were included in the basalt fiber-reinforced epoxy composite laminate. Nevertheless, the particle loading of 1.00 wt% showed the best result when 80.6% tensile strength increment was recorded (679 MPa) in comparison to neat basalt fiber-reinforced epoxy composite laminate (376 MPa).

Ceramics

The abundance and availability of agricultural by-products with high silica content and low levels of inorganic compounds have made them a promising raw material for synthesizing silica xerogel (SX). This was confirmed when CaO and Si_2O were the major compounds found in sago pith waste ash (SPWA) and increased in value with the rise of calcination temperature (Rashid et al., 2016). These by-products are usually inexpensive and their effective utilization is highly desirable from an environmental point of view. SX can be produced using either synthetic or natural materials. Numerous studies have demonstrated that a great number of natural resources were effectively utilized to produce SX (Kalapathy et al., 2000; Okoronkwo et al., 2013; Sudiana et al., 2015). Silica-glass ceramic is produced from SX through the heat treatment process known as sintering (El Hamzaoui et al., 2010; Rao et al., 1999). Intensive studies have been done on SX extracted from sago *hampas* ash used for manufacturing ceramics.

Silica-glass ceramic was successfully produced, using SX extracted from sago *hampas* ash, via microwave thermal treatment using a sub-millimeter wave gyrotron (300 GHz) as the radiation source (Aripin et al., 2011a). SX was found to crystallize in the cristobalite phase at 800°C sintering temperature, which is about 200°C lower than the one observed in the conventional process. This ceramic material reached a bulk density at 900°C (about 2.20 g/cm^3), which is probably the same as that of vitreous silica. In a structural and microwave properties study on SX glass-ceramic subjected to different radiation frequencies (8.20 to 12.4 GHz), the reflection losses decreased as the sintering temperature increased. This was due to the formation of fully crystallized silica-glass ceramic under sufficiently high temperature as it became more transparent to the microwaves (Aripin et al., 2012). Hence, SX's high transparency and good chemical durability to irradiation exposure have made it a good candidate for non-linear optics applications such as optical waveguides (Kim et al., 2005; Xu et al., 2010).

Nonetheless, the applicability of SX is limited by its brittleness and certain structural reliability issues, for instance, poor chemical stability at high temperatures in the presence of water, which results in the formation of surface hydroxyls. Thus, incorporating other properly selected oxides into SX helps to improve its properties. For example, incorporation of TiO_2 into SX gives an appreciable effect on the crystallite size of TiO_2 and formation of Si-O-Ti bonds at 900°C (Aripin et al., 2016a). On the other hand, inclusion of SnO_2 increased the bulk density of silica-based glass ceramics and its crystallization, while simultaneously reducing its porosity (Aripin et al., 2016b). Different compositions of Al_2O_3 mixed with SX substantially influenced mullite crystallization of ceramics (Aripin et al., 2013). Results showed that the intensities of cristobalite peaks gradually reduced, while those of the characteristics peaks of mullite amplified with increasing Al_2O_3 content. In addition, another study had demonstrated that the mixture of sago waste ash with clay had successfully produced highly porous ceramics (Aripin et al., 2011b). The results showed 10.0 wt% ash could be incorporated into the clay material without any adverse effects on the bulk density and porosity of the samples sintered at 1,000 °C. Clay ceramic with a high porosity can be applied for particulates removal from hot gas stream and catalyst recovery from off-gases and, hence, is suitable for industrial application.

Composites

Most biodegradable plastics rely on cheap and abundant by-products from the agro-industry, which have a faster biodegradable rate and are relatively hydrophilic in nature and somewhat crystalline in structure. Based on preceding works, renewable biodegradable polymer used alone tends to cause performance and processing problems; hence, blending it with synthetic polymers such as polyvinyl alcohol (PVA) is highly desirable. PVA is the world's largest synthetic water-soluble and biodegradable polymer (Ramaraj, 2007) with an outstanding chemical resistance, tensile strength, flexibility, and barrier properties. Due to its high price, PVA has been restricted from being substantially used in applications (Schellekens & Bastiaansen, 1991). Nonetheless, in a different compounding methods study, incorporation of sago *hampas* into PVA yielded the highest value of tensile strength and elongation at break, particularly for dry-blending PVA with sago *hampas* (PVA/SPW) and pre-plasticized PVA and sago *hampas* (pPVA/pSPW) (Toh et al. 2011a). In addition, another study (Toh et al., 2011b) showed that blending sago *hampas* with a high PVA loading created great molecular force interactions that could overtake those of PVA itself. This outcome indicates that the interaction between PVA and sago *hampas* is reactive, thus inducing synergistic effects.

In accordance with the high starch content in sago *hampas*, plasticization of this waste is believed to produce biodegradable composite materials without the addition of any synthetic plastics as a binder. This characteristic makes the sago *hampas* a unique and special material compared to other fibrous wastes. With glycerol and water as plasticizers, sago *hampas* waste was successfully plasticized to form a natural fiber filled thermoplastic using a twin screw extruder (Lai et al., 2013). Plasticization causes the disruption of the original C-type crystallinity. However, V_H and B types of crystallinities were developed due to the reorganization of amylose, amylose-lipid complex (very fast), and amylopectin chains (slow). Nevertheless, increasing glycerol content adversely affected the tensile strength of the plasticized sago *hampas*, while elongation at break remained unchanged (Lai et al., 2014). Phase separation and fiber agglomeration were determined to be responsible contributors to this trend. Distinct molecular restructuring took place in plasticized sago *hampas* upon ageing, which was reflected in the bulk properties leading to an increase in the tensile strength and a decline in elongation at break (Lai et al., 2016). Glycerol and fiber were the two compounds that restrained the retrogradation process of plasticized sago *hampas*. Besides that, a study was also conducted to investigate the potential of SB as a reinforcement material for a natural fiber composite (Abral et al., 2012). Treated SB using 5.00% NaOH after mercerization revealed not only an elastic area but also a plastic zone. The strength of treated bark fiber significantly increased whereby the average ultimate strength was 163 MPa compared to 46.0 MPa of the untreated bark fiber. Similarly, a greater elastic modulus was recorded for treated bark fiber than untreated bark fiber.

A Summary of Sago *Hampas* and SB Applications

Table 2 summarizes and differentiates all the discussed sago wastes applications. Several studies on solid sago wastes have been done recently, indicating the increase in awareness to fully utilize them as value-added materials. Nevertheless, more rigorous researches were conducted on sago *hampas* than SB. Such a difference emphasizes the lower amount of complex lignocellulosic materials and higher starch content in sago *hampas* compared to SB, which had likely drawn much of the researchers' attention. Despite that, there are many studies (Table 2) that have successfully utilized SB with outcomes that are comparable to sago *hampas*.

Table 2
Summary of recent sago wastes applications

Sago waste	Application	Source
Sago *hampas*	**1. Adsorbents**	
	Heavy metals	Karthika et al. (2010); Maheswari et al. (2008); Quek et al. (1998); Saman et al. (2014); Wahi et al. (2010)
	Activated carbon (AC)	Kadirvelu (2003); Kadirvelu et al. (2005, 2004)
	Oil	Ngaini et al. (2014b)
	2. Sugar sources	Akmar and Kennedy (2001); Janggu and Bujang (2009); Kumoro et al. (2008); Lee et al. (2014); Linggang et al. (2012); Shahrim et al. (2008)

Table 2 *(continue)*

Sago waste	Application	Source
Sago *hampas*	**3. Biofuels**	
	Bioethanol	Awg-Adeni et al. (2013); Bukhari et al. (2017); Thangavelu et al. (2014); Vincent et al. (2015b); Vincent et al. (2015a)
	Biobutanol	Linggang et al. (2013)
	Bio-oil	Mona et al. (2013)
	Biohydrogen	Jenol et al. (2014)
	4. Nanomaterials	Aripin et al. (2013); Tan et al. (2014)
	5. Ceramics	Aripin et al. (2011b); Aripin et al. (2013, 2012); Aripin et al. (2011a); Aripin et al. (2016a); Aripin et al. (2016b); Rashid et al. (2016)
	6. Composites	Lai et al. (2016, 2013, 2014); Toh et al. (2011a); Toh et al. (2011b)
Sago bark	**1. Adsorbents**	
	Activated carbon (AC)	Erabee et al. (2017)
	Oil	Ngaini et al. (2017); Ngaini et al. (2014a); Wahi et al. (2017, 2014)
	2. Sugar sources	Ethaib et al. (2016); Mohamad et al. (2011)
	3. Biofuels	
	Bioethanol	Kannan et al. (2013)
	Co-firing	Chong et al. (2014); Kin et al. (2015)
	4. Nanomaterials	Hegde et al. (2015); Mengal et al. (2016)
	5. Composites	Abral et al. (2012)

CONCLUSIONS

Sago wastes are receiving more attention because these residual solids are a viable and utilizable resource for conversion into value-added products. Sago *hampas* and bark have high potential to be used as sustainable feedstocks due to its availability and significant content of starchy-lignocellulosic compounds. When chemically-treated, the sago wastes were able to be a good adsorbent for both heavy metals and oils. Enzymatic and acid hydrolysis approached capable of extracting sugars from the polysaccharides matrix of the sago wastes. Also, the fermentable sugars produced i.e. glucose were used to generate bioethanol, bio-butanol and bio-hydrogen via fermentation using different bacteria accordingly. Meanwhile, high temperature thermal treatment enhanced the special nature of sago wastes, hence producing good nanomaterials products i.e. C-dots and CNs. The high silica content and low level of inorganic compounds contained in sago wastes have made it as a promising source in producing silica-glass ceramic. Therefore, it can be deduced that conversion of sago wastes into useful products is a promising approach to mitigate environmental pollution while concurrently reducing the dependency on petroleum resources. However, among the solid sago wastes generated, emphasis should also be given to SB, parallel with the rigorous studies done on sago *hampas,* due to its high cellulose and hemicellulose content, regardless of the presence of lignin. Newer chemical syntheses and technological adaptations should be considered to overcome the strong lignin structure that is strongly bound with precious neutral carbon, i.e. hemicellulosic materials.

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