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Review

Industrial production, processing, and utilization of sago palm-derived products

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Abstract

With a deep concern over the probable global food shortage in the years to come, underutilized plant resources are now being extensively tapped by scientists throughout the world. In this regard, sago palm is gaining much importance as a crop par excellence and a starch crop of the 21st century, due to its being an extremely sustainable plant with an ability to thrive in most soil conditions. The review focuses on sago palm as an invaluable resource of starchy foods and of innumerable other products of significant commercial value such as modified starches, lactic acid, cyclodextrins, and ethanol. Several important aspects of the properties and applications of sago palm-derived products that could be exploited commercially are also covered.

Keywords: Sago palm; Sago pith; Starch; Ethanol; Sugars; Lactic acid; Kojic acid; Cyclodextrin; Modified starch; Sap; Fronds; Hampas; Waste water

1. Introduction

The sago palm (*Metroxylon sagu*) (Fig. 1) is a crop par excellence for sustainable agriculture. The word 'sago' is originally Javanese, meaning starch-containing palm pith. The scientific name is derived from 'metra', meaning pith or parenchyma and 'xylon' meaning xylem. It is considered as the 'starch crop of the 21st century' by many scientists (Jong, 1995). Sago palms are economically acceptable, environmentally friendly, and promote a socially stable agroforestry system (Flach, 1997). It is an extremely hardy plant, thriving in swampy, acidic peat soils, submerged and saline soils where few other crops survive, growing more slowly in peat soil than in mineral soil (Flach & Schuilling, 1989; Hisajima, 1994). The palm is immune to floods, drought, fire and strong winds. The large fibrous root system traps silt loads and removes pollutants, faecal contaminants and heavy metals. Sago forest acts as an excellent carbon sink for carbon sequestration, thereby mitigating the greenhouse effect and global warming arising from the release of carbon dioxide into the atmosphere due to industrialization, and an increase in the number of motorized vehicles (Stanton, 1991).

Starch can accumulate in the trunk of the sago palm until the flowering stage with maximum starch content occurring just before the onset of the palm flowers. A 25-ton ha^{-1} y^{-1} of starch productivity from sago plantation is under development in the Malaysian state of Sarawak (Ishizaki, 1997). It is so far the highest in productivity among the starchy crops of the world (Ishizaki, 1997). The two primary uses of the species of *Metroxylon* are for the production of edible starch and durable leaf thatch.

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Fig. 1. Sago palms (*Metroxylon sagu*) in Sarawak, Malaysia.

M. sagu is a staple food crop in the Sepik and Gulf provinces of lowland Papua New Guinea, where most of the sago grows in wild, uncultivated areas.

2. The sago palm

The sago palm is a species of the genus *Metroxylon* belonging to the Palmae family. It is a socio-economically important crop in South-East Asia and its centre of diversity is believed to be New Guinea (Rauwerdink, 1986) or the Moluccas (Ehara et al., 2002). The sago palm grows well in humid tropical lowlands, up to an altitude of 700 m. Temperatures above 25 °C and relative air humidity of 70% are favorable. Incidental light should preferably be above 800 k/cm^2 per day and salinity should not exceed 10 S/m, which is equivalent to one-eighth of the salt concentration of sea water.

The sago palm is hapaxantic, that is, it flowers once and dies shortly thereafter. During the vegetative stage, just before flowering, the plant converts its stored nutrients into starch, which fills the trunk (Abd-Aziz, 2002). At the mature stage, it possesses a huge trunk and may reach a height of 6–10 m, with a circumference of 1.2 m (Flach, 1977). The plant reaches commercial maturity at 9–12 years of age, when the fruit starts to develop, and starch accumulation in the trunk reaches a maximum (Yatsugi, 1986). Sago reaches a maximum height of 25 m and a diameter of 40 cm, grows in clumps, has pinnate leaves about 6–9 m long, and very thick stems similar to those of the buri palm (*Corypha elata*). It is easily distinguished by the robust size of the inflorescence branches, which are massive compared with other species. The stem of a full-grown sago is 20 m long and the fruits, in clusters, which take about 24 months to mature are depressed-globose to obconical, 3 cm to 2 inches in diameter, and covered with 18 vertical rows of rhomboid greenish-yellow scales. Sago produces both pollinated (seeded) and parthenocarpic (non-pollinated) fruits. Seeded fruits contain a hard stony white endosperm and brown testa. Parthenocarpic fruits are smaller and contain a spongy mesocarp. The leaflets are linear-ensiform, up to 1.5 m in length. The spadix is 3.5–4.5 m long, with the spathes quite spineless. The spikes are 10–12 cm long and about 1 cm in diameter. The sago palm-derived products have a number of applications as shown in Fig. 2.

Metroxylon sagu undergoes four stages during its life cycle. Flach's (1997) model has a 11–12 years life cycle from seed to seed under optimum ecological conditions. The stages are:

- *Rosette stage of 45 months from seeding*: A period characterized by relatively little growth, the plant forms a total of 90 leaves.
- *Bole formation stage of 54 months*: During this period, the bole elongates to a maximum height and produces one leaf per month. Plants during this stage have a total of 24 leaves and 54 leaf scars on the bole and produce a high amount of starch.
- *Inflorescence stage of 12 months*: The plant forms two leaves per month and the rate of starch accumulation starts to decrease and the starch moves from the lower to the upper bole. Palms are harvested for starch during this and the next period.
- *Fruit ripening stage of 24 months*.

All *Metroxylon* species are propagated by seeds. An exception to this is *M. sagu*, which for the most part is sterile, reproducing *via* vegetative suckers emerging from roots or lower trunks of parent plants. Several researchers report that germinating sago seeds are rare (Barrau, 1960; Rauwerdink, 1986). The species also reproduces by stolons, often meters in length (Schuilling & Jong, 1996). Suckers with unopened buds are the best planting materials which grow into adult palms. A sago holding can virtually produce palms in perpetuity eliminating the need for recurring expensive establishment costs after every harvest of the adult palms. Propagation of sago palm plant by plant tissue culture is also reported (Hisajima, 1994).

2.1. Clonal propagation of sago palm

Although sago palms can be propagated from suckers, the number is limited; hence clonal propagation through *in vitro* techniques is most suitable both for producing the vast amount of planting material required for extensive plantations, and for improving the quality and vigor of palms (www.krishiworld.com). Since 1983, research is being conducted at the Department of Biotechnology, Faculty of Food Science and Biotechnology, University Perta-

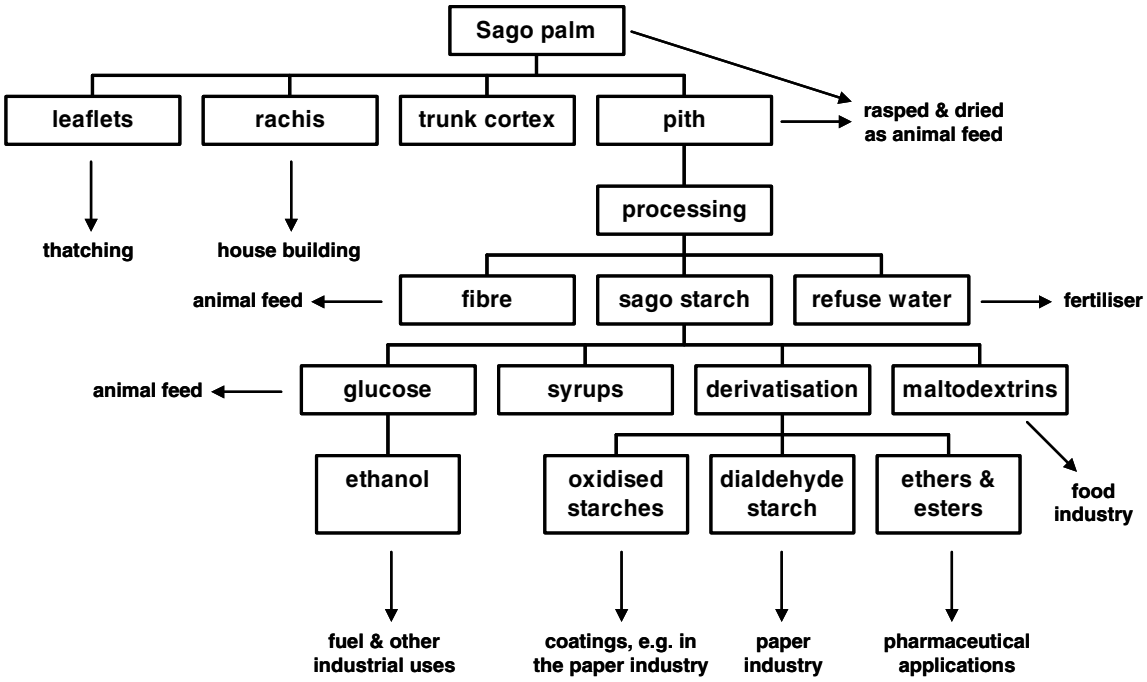

Fig. 2. Applications of sago palm (Flach, 1983; www.ipgri.cgiar.org).

nian Malaysia, Serdang, Selangor, towards clonal propagation of sago palm. Several hundreds of clonal plantlets have been produced over a period of 18–24 months from culture initiation; the protocol for inducing embryogenesis from explants and developing embryoids into plantlets is being improved (www.krishiworld.com).

3. Sago production statistics

Sago grows in the hot humid tropics of Southeast Asia (Indonesia, Thailand, Philippines and Vietnam) and Oceana (Papua New Guinea and Oceanian Islands), with the probable center of diversity in New Guinea and the Melanesian Islands. The sago palm abounds in fresh-water swamps at low altitudes in Mindanao, and has been planted in some parts of Cebu, Bohol, Siquijor, Mindanao (Agusan, Surigao, Misamis, Zamboanga, Cotabato, Davao), Basilan, and Sulu. *M. sagu* is also found in Guam, Palau, Nukuoro, Kosrae, and Jaluit, which is most likely the result of human introduction (Fosberg, Sachet, & Oliver, 1987). The palm has been introduced to Bangladesh, Costa Rica, Brazil and Zaire.

The three leading world producers are Malaysia, Indonesia, and Papua New Guinea, where sago is grown commercially for the production of sago starch and/or conversion to animal food or to ethanol. Indonesia has large forests (>7,00,000 ha) of wild sago palms, in which a $5 million plant for processing palm pulp into sago flour and by-products has been set in Halmahera Island. The plant capacity is around 11,000 tons sago flour/year (Magda, 1993). In many countries of South East Asia, except Irian Jaya, *M. sagu* is mainly found in semi-cultivated sands. Irian Jaya has about 6 million ha of *M. sagu*. Papua New Guinea has an estimated 1 million ha of wild, and 20,000 ha (49,400 ac) of semi-cultivated *M. sagu*. The Pidie District in East coast of Aceh has 2012 ha area for sago production with 527 tons of sago being produced.

The importance of starch production by sago palm is mainly focused in the Asia-Pacific region (Stanton, 1993) and South East Asia (Wang, Powell, & Oates, 1996). Sago starch is the main carbohydrate source in Malaysia (Douglas & William, 1984). Compared to other starches, sago starch has a low cost of production and high yields (Fasihuddin & Williams, 1996) ranging from 15 to 25 tons of air-dried starch/ha (6.7–11.1 tons/acre) of *M. sagu* at the end of an 8-year growth cycle (Flach, 1997). *M. sagu* is considerably more productive for starch production compared with other *Metroxylon* species. Sago produces higher amount of starch compared to other crops, around 2–3 tons starch per ha per year, compared to cassava, for which it is 2 tons and maize, 1 ton (Stanton, 1993).

The largest sago-growing areas in Malaysia are outside the Peninsula, in the state of Sarawak, which is now the world's biggest exporter of sago, exporting annually about 25,000–40,000 tons of sago products to Peninsular Malaysia, Japan, Taiwan, Singapore, and other countries (Malaysian Agricultural Economics Association, www.econ.upm.edu). Since 1984, there has been an upturn in the export of sago starch, earning the State of Sarawak 11.4 million dollars in revenue (www.krishiworld.com). In Sarawak, sago palms are grown commercially on small-holdings. The production capacity of the sago palm varies from 2 to 5 tons of dry starch/ha in the wild regions to l0–25 tons/ha in the case of cultivated plants (Abd-Aziz, 2002). A clump density of 590 palms/acre, or 1480 palms/ha, allows an annual har-

vest of 125–140 palms/year. The Land Custody and Development Authority of Sarawak (PELITA; a government statutory body) has started the development of two sago plantations, the Dalat Sago Plantation (1600 ha) located on the border between Oya and Igan, and the Mukah Sago Plantation (20,000 ha) located in the Mukah District. The underlying aim in these plantations is the application of modern, scientific agricultural technology and a large-scale institutional organization to exploit the cultivation of sago (Abd-Aziz, 2002).

4. Sago pith

The inner portion of the trunk, after the removal of the outer bark-like layer, is the pith. Sago starch accumulates in the pith of the sago palm stem from the base upwards. At maturity, the trunk is fully saturated with starch almost to the crown (Lang, Mohamed, & Karim, 2006). The starch content increases as the palms mature from *plawei* (mature vegetative growth) to *angau muda* (flowering) stage, and decreases from *angau tua* (fruiting) to late *angau tua* stage. The total and insoluble non-starch polysaccharides decreases as the palms mature to *angau muda* and *angau tua* stages, and increases as the palms age into late *angau tua* stage (Lang et al., 2006). In all the growth stages, the amount of phenolic compounds is less than 1%, whereas the lignin content ranges from 9% to 22%. Lignin is strongly associated with hemicelluloses in the pith cell walls. Xylose and glucose are the major components of hemicelluloses, together with arabinose and galactose, and lower levels of rhamnose, mannose, fucose and uronic acids (RunCang, Jones, Tomkinson, & Bolton, 1999). The lignins in the cell walls contain high proportions of non-condensed syringyl units, low levels of non-condensed guaiacyl units and very low levels of non-condensed *p*-hydroxyphenyl units.

4.1. Sago starch

4.1.1. Production

4.1.1.1. Production of sago starch. Recently, interest in the production of sago palm starch has increased considerably. The starch content of the pith obtained from commercially harvested logs varies between 18.8% and 38.8% (fresh weight) for *M. sagu* (Wina, Evans, & Lowry, 1986). Starch accumulation in the trunk of the sago palm can reach up to 250 kg (dry weight per plant) (Flach, 1997). After fruiting, the starch content declines rapidly. Hence, the trees are felled when about 7.5–9 m high, after flowering and immediately prior to fruiting. The trunks are stripped of leaves and cut into lengths of about 1 m for easy handling. After removing the cortex, rachis, and leaflets from the pith, which is probably the most labor-intensive operation in sago palm processing, starch has to be extracted from the pith by a process referred to as 'rasping'. The 50 mm thick outer woody rind is slit lengthways, and the soft but fibrous pith removed with a wooden hoe or rasped, usually by means of bush knives or an adze armed with a sharpened piece of hardwood at its end. The carbohydrates of the sago palm trunk waste obtained after removal of starch are not readily hydrolysable. In order to utilize the carbohydrates, especially as fermentation substrate, one needs an efficient method of hydrolysis for a higher sugar yield (Akmar & Kennedy, 2001). Glucose is the major monosaccharide in the sago palm trunk waste.

In the traditional method of starch extraction, the starch in the pith has to be separated from the cellulosic cell walls of the trunk. The starchy pith is grated into a material resembling sawdust, kneaded with water and filtered through sieves to extract the relatively large (20–60 μm) starch granules (Shipman, 1967). The pith is subjected to several washings and strainings, and the starch milk is allowed to run into troughs. The starch settles in the troughs, which is subsequently sun- or kiln-dried. One trunk generally results in 600–800 lb of pith yielding 200–400 lb of sago starch (Shipman, 1967). The traditional, small-scale cottage mills, which produce a type of inferior, wet sago called "lementak" for the local markets are slowly being wiped out due to competition from the high-quality, dry sago flour produced by the modern factories.

The traditional, manual method of extraction of sago starch has been replaced by a commercial process (Stanton, 1993) involving a sequence in Fig. 3. Palm logs are rafted to the mill and stored in the river to reduce deterioration (Fig 4). In the mill yard, the bark-like layer is stripped from each log with an axe or bush knife and the logs split into 6–8 battens which are then rasped by a diesel-powered, home-made rasping wheel which rotates at high speed. The wheel is mounted on a platform to permit the rasped pith to drop into one end of a cylindrical washing reel that rotates on a central shaft. A perforated water pipe sprays water into the body of the reel and flushes the rasped pith as it is passed along the inside by perpendicular splines arranged in a spiral pattern along the central shaft of the reel. This loosens starch grains from the stem fiber and washes them out in suspension. Waste fibers fall from the lower end of the washing cylinder. Starch-laden water then flows through the coarse wire screen that encases the reel and is led off by a conduit through a coarse sieve which removes most of the fiber prior to sedimentation in cement tanks or wooden troughs. The starch may be separated using cyclone separators and dried on a rotary vacuum drum drier, followed by hot air drying. When dry, it is known as *chong hoon*. The mill extracts wet flour mechanically and produces three grades of dry flour, which, from low to high are known as *chong hoon*, *thai hoon*, and *siong hoon*. To produce *thai hoon*, the middle grade, it is sieved after drying. Crude dry flour can be rewashed, dried again and then sieved to produce the highest grade of flour, *siong hoon*.

Improvements in quality have been achieved by preventing microbial degradation prior to processing, and by inhibiting enzymes to prevent the oxidative browning of phenolics. DL-Epicatechin, D-catechin, and procyanidin

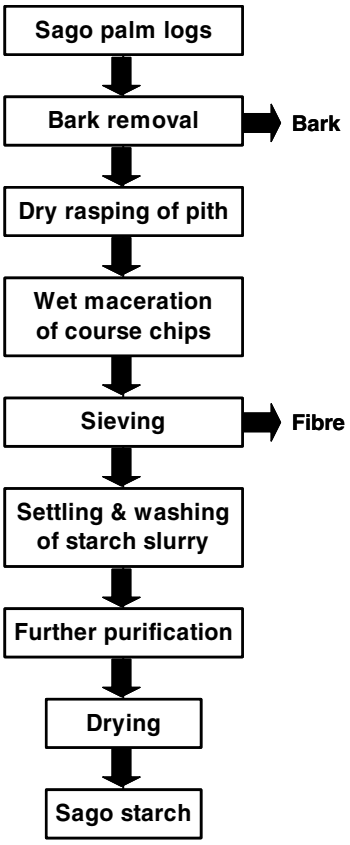

Fig. 3. Production of sago starch (Knight, 1969).

Fig. 4. Sago logs arriving at a starch factory in Mukah, Sarawak, Malaysia.

are responsible for the browning of sago starch (Okamoto, Ozawa, Imagawa, & Arai, 1986). Two membrane-bound peroxidases mPOD-I and mPOD-II, of molecular masses, 51.2 and 43.8 kDa, respectively are able to oxidize the phenols naturally present in sago logs. The food-compatible enzyme inhibitors, metabisulfite, L-cysteine, *p*-coumaric acid and ascorbic acid are effective against the isoenzymes (Onsa, Saari, Selamat, & Bakar, 2004).

The crude starch usually referred to as 'sago flour' is essentially a raw material, which is refined, purified, or slightly bleached by oxidation with small quantities of hypochlorites (0.25–6% chlorine on dry starch basis) using modern processing machinery for sieving, dewatering and drying (Radley, 1976b). There are currently 11 modern sago processing plants in Sarawak, each processing 200–600 metric tons of dry sago flour per month (Chew & Shim, 1993).

There are some precautions to be taken for the efficient production of starch from sago. Harvesting of immature trunks should be avoided, as the starch grains then may be too small for easy separative settling. Logs should not be stored for more than 2–3 days at the very most, and preferably in water; both longer and dry storage lead to deterioration of starch quality, through microbial activity, and to a diminishing quantity of starch. The bark should be removed as sparsely as possible, as the inner layers still contain a considerable amount of starch (www.ipgri.cgiar.org). Before sedimentation, the starch slurry should be passed through a screen no coarser than 120 mesh (125 microns). Settling tanks should be extensive and shallow, rather than compact and deep. In this way, small starch grains can also be captured. Starch should not be kept wet for more than 24 h; if longer, it may be treated with SO_2.

Theoretical economic calculations by Hoogland (1986) show large-scale production to be quite profitable. A 30,000 tons dry starch factory could give a rate of return on investment of over 10%. The starch produced by small factories is usually of varying quality, not completely white, and contains remnants of fiber, with the starch grains often being spoilt through microbial activity, a limitation in international markets. The commercial production aims at a consistently high level of production per unit time and area (Riezebos, 1986). There is need for market promotion, a standardized grading system, and quality regulation of sago flour, as the prospects of the sago industry in the international market depends on consistent quality and a reliable supply of sago flour (www.krishiworld.com).

4.1.1.2. Sago pearls. Moist sago starch is used to make a popular native food, pearl sago. In its preparation, the moist starch cake is pressed through a perforated sheet of iron or coarse screen (Radley, 1976b). The pellets of starch are put into a shallow hammock-like contrivance to which a circular swinging motion is imparted. Swinging this contraption in the correct manner imparts a rotary motion to the pellets which, provided the moisture content is correct, assume a roughly spherical shape. The process is rather akin to pin-rolling. The pearls are sieved for removal of fine particles and large aggregates and roasted in shallow metal pans, which partly gelatinize and dry the sago pellets. These are then graded into large and small 'bullet' or 'pearl' sago. A more modern method is to extrude sago starch through small orifices in an iron plate, tumbling

the products so obtained in a revolving steam-heated jacket until vitreous in appearance (Radley, 1976c).

In West Malaysia, sago pearls are prepared from slightly wet starch, which is pressed through a sieve. The small particles of wet starch are then rolled around and heated in a pan with a round bottom until the outside has been gelatinized. The pearls are subsequently dried, sorted and sold. These pearls are often used to prepare the 'three palm pudding': sago pearls, cooked in coconut milk, and topped with sugar from the sugar palm (*Arenga pinnata*). In Sarawak, some pearls are prepared from sago palm starch mixed with rice bran.

4.1.2. Physicochemical characteristics of sago starch

The chemical composition of sago starch is shown in Table 1. Sago starch contains 27% amylose and 73% amylopectin (Ito, Arai, & Hisajima, 1979). However, amylose content of the starch from the lower part of the trunk is higher than that from the upper part of the trunk, which further increases with growth. Gelatinization onset temperature of starch from the upper part of the trunk is in the range of 65.3–68.2 °C with a gelatinization conclusion temperature of 75–76 °C. Starch from the lower part of the trunk has a lower gelatinization onset temperature and a higher gelatinization conclusion temperature. Relative crystallinity of starch is higher in a 14.5-year-old palm than a 9-year-old palm, and this also holds true for the upper part of the trunk compared to the lower part (Tomoko, Tamao, Shoon, Keiji, & Setsuko, 2000). The starch granule properties and gelatinization characteristics are shown in Table 2. The sago starch behaves more like waxy corn, even though it is an amylose-containing starch (www.niir.org). The starch will set to firm gels if the starch is degraded with acids (fluidity starches).

The starch storage positions differ in palms grown in acidic and mineral soils. In plants grown in mineral soil, most starch is accumulated below the 600 cm height, with the maximum at the position of 300–350 cm, and almost no starch is present in the top portion (850–920 cm) (Nozaki et al., 2004). Conversely, the starch concentration of plants grown in acidic soil is higher at the top, with the maximum amount at a height of 700–780 cm. Fig. 5 shows the micrograph of starch granules obtained from sago palms grown in mineral and acid sulfate soils. There are no morphological differences in the starch granules among the soil conditions and the positions (Nozaki et al., 2004). The granules are ellipsoidal and clearly divided into two groups according to size. The large granules are 8–15 μm, and the small ones are less than 8 μm in lengthwise diameter.

Table 1
Chemical composition of sago starch (Swinkels, 1985)

Constituent	Dry wt. basis (%)
Amylose	27
Amylopectin	73
Lipids	0.1
Protein (nitrogen content × 6.25)	0.1
Ash	0.2
Phosphorus	0.02

Table 2
Starch granule properties and gelatinization characteristics of native sago starch (Swinkels, 1985; www.niir.com)

Characteristics	
Starch granule properties	
Type/origin	Pith
Size (diameter in μm)	
Range	5–65
Average	30
Shape	Oval, truncated
Gelatinization characteristics	
Kofler gelatinization temperature range (°C)	60–72
Brabender pasting temperature (8% starch concentration, °C)	65–70
Brabender peak viscosity (8%, Brabender units)	1100
Swelling power at 95 °C (%)	97
Cook characteristics of native starch (cooked, 1 part in 15 parts water at neutral pH)	
Hot-cook body	Stringy-cohesive
Hot-cook viscosity	Moderately high
Viscosity on prolonged cooking	Thinning
Gel formation on cooling	Moderate
Clarity (cold)	Fairly clear

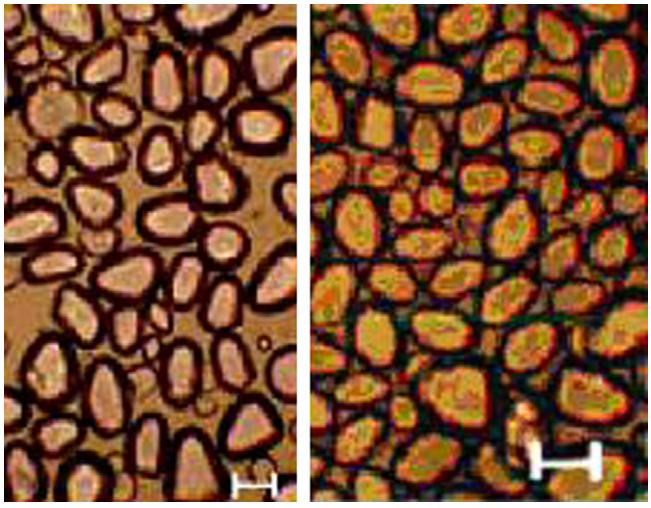

Fig. 5. Micrograph of iodine-stained starch granules grown in mineral soil and acid sulfate soil, respectively, from a plant height of 300–350 and 700–780 cm, respectively. Bar indicates 6.9 μm (Nozaki et al., 2004).

4.1.3. Processing and utilization of sago starch

Sago starch has a multitude of uses. It is used as a stabilizer and thickener, and as a substitute for modified corn starch (www.agnet.org). Besides its use as a foodstuff, sago starch can also be utilized to produce adhesives for paper, textiles, and plywood; as a stabilizer in pharmaceuticals; or

converted to other types of foods. Sago starch is also widely employed together with other starches in the production of monosodium glutamate and fructose syrup for non-alcoholic drinks. The starch is now used as an economically viable feedstock for conversion to industrial sugars, and the market for sago is set to expand both as a domestic food and as a trade crop.

4.1.3.1. Extrusion of sago starch. During extrusion processing, starch undergoes depolymerization (Gray & Chinnaswamy, 1995). Extrusion destroys the organized crystalline structure either partly or completely, depending on the amylose–amylopectin ratio and on the extrusion variables such as moisture content and shear. Liquefaction of starch occurs without the use of enzymes due to the development of high pressure and shear. In a study on the effect of barrel temperature (81–149 °C) and screw speed (315–486 rpm) on extrusion processing of sago starch in a corotating twin-screw extruder (Govindasamy, Campanella, & Oates, 1996), thermomechanical processing of sago starch in the twin-screw extruder at high moisture (34–47%) led to shear-induced limited degradation and starch phase transition (a composite melting gelatinization process). Gelatinization was found to be the fundamental mechanism in the high-moisture system rather than dextrinization. A low water solubility index (WSI) (4.5–18.1%) was ascribed to either granular crystallite remnants or rearrangement of bonds during extrusion.

4.1.3.2. Production of ethanol. Ethanol is gaining importance as a fuel additive, or as a conventional non-renewable fuel replacement (Abd-Aziz, 2002). Ethanol can significantly reduce the amount of oil imported by developing countries, allowing large savings in import costs or increased revenues from export of the country's own oil, both of which will contribute significantly towards strengthening of foreign currency reserves (Doelle, 1994). The production of fuel ethanol by fermentation requires the ability to produce high ethanol concentrations rapidly while maintaining good yields (Ratnam, Narasimha, Damodar, Subba, & Ayyanna, 2003). Rapid fermentation and high alcohol levels are desirable to minimize capital costs and energy required for distillation, while good yields are necessary for process economics. The substrate is the main cost component for industrial ethanol production, and it is essential that ethanol production should be carried out with cheap substrates such as starch or cellulose (Elisson, Hofmeyr, Pedler, & Hahn-Hagerdal, 2001; Lee & Woodward, 1983).

Recently, there has been active research aimed at increasing the ethanol yield by immobilized biocatalyst techniques. In a study on simultaneous saccharification and fermentation (SSF) of ethanol from sago starch with coimmobilized amyloglucosidase (AMG) (immobilized on powdered chitin) and *Zymomonas mobilis* MTCC 92 by submerged fermentation, a maximum ethanol concentration of 55.3 g/L was obtained using a starch concentration of 150 g/L (Bandaru, Somalanka, Menduc, Madicherla, & Chityala, 2006). Continuous ethanol production from sago starch was also carried out using immobilized amyloglucosidase (AMG) and *Z. mobilis* cells in a packed-bed reactor (Lee, Kim, Abidin, Han, & Rhee, 1987). Chitin was used for the immobilization in sodium alginate beads. The maximum ethanol productivity was 37 g/L h amounting to 84% of the theoretical yield. The use of sago starch hydrolyzate (by enzyme saccharification) as a carbon source (instead of pure glucose) and natural rubber waste as a nutritional source for ethanol fermentation by *Z. mobilis* resulted in a specific glucose uptake rate, specific ethanol production rate and ethanol yield comparable to those on pure glucose-yeast extract medium (Ayaaka & Sudarut, 1995).

Unsterile conditions may be used in the efficient production of ethanol from sago starch. Direct ethanol production from raw sago starch as substrate using a mixture of a mold strain *Aspergillus niger* N-10 (which produces the raw sago starch – hydrolyzing enzyme), and the ethanol-producing yeast, *Saccharomyces cerevisiae* IFO 0309 (Pranamuda, Kamogawa, Ozawa, & Tanaka, 1995), under unsterile conditions, i.e., with no sterilization of the medium and the apparatus, produced an ethanol yield from raw sago starch of 0.4 g ethanol/g starch at a concentration of ca. 30 g ethanol/L. Alcoholic fermentation from heat-treated (below gelatinization temperature at low pH) sago starch granules using a raw starch-digesting enzyme from *Aspergillus* sp. No. 47 and *cerevisiae* No. 32 resulted in 48.4% conversion yield of starch to ethanol (Nadirman, 1995).

4.1.3.3. Production of fermentable sugars. In view of its abundance, sago may be utilized for the production of fermentable sugars. Glucose from sago starch is used as a substrate in the fermentation industry and for the production of high-fructose syrup (Arbakariya, Asbi, & Norjehan, 1990). Sago starch pretreated by heating at 60 °C for 2 h in sodium acetate buffer (pH 3.5) is hydrolyzed using commercial glucoamylase-AMG (EC 3.2.1.3), α-amylase-BAN, Fungamyl and Termamy1 (EC 3.2.l.1), debranching amylase-Promozyme (EC 3.2.1.41), and their mixtures in sodium acetate buffer at pH 5 and 35 °C (Wang et al., 1996). Raw sago starch can however be a poor substrate for enzyme action compared to corn and tapioca starches, although pretreating the starch increases the extent and rate of hydrolysis.

Amylolytic enzymes secreted by a recombinant DNA *S. cerevisiae* strain YKU 107 can rapidly hydrolyze gelatinized sago starch to produce fermentable sugars (Ang et al., 2001; Uchiyama et al., 1995). The highest α-amylase action and reducing sugar production are obtained at pH 6 and a low operating temperature of 30 °C.

4.1.3.4. Production of lactic acid. Over the last decade, lactic acid production has attracted considerable attention owing to its use as a raw material for the synthesis of polylactic acid, a biodegradable plastic material (Datta, Tsai,

Bonsignore, Moon, & Frank, 1995; Marchall, 1987; Yin, Yahiro, Ishigaki, Park, & Okabe, 1998). Presently, of the 80,000 tons of lactic acid produced annually worldwide about 90% is produced by lactic acid fermentation (Hovendahl & Hahn-Hagerdal, 2000). Fermentative production has an advantage that an optical pure product can be obtained by choosing a microbial strain to produce only the isomer of interest (Fig. 6), whereas synthetic production always results in a racemic mixture of lactic acid. Sago starch is a cost-effective and remarkable substrate for lactic acid fermentation. Process yield of L-lactic acid from sago starch is about 100%.

A continuous culture system with high cell density of a novel amylolytic lactic acid bacterium *Enterococcus faecium* No. 78 isolated from *puto* (fermented raw rice in Philippine), showed higher lactic acid productivity ($3.04\ g\ l^{-1}\ h^{-1}$) than batch culture ($1.105\ g\ l^{-1}\ h^{-1}$) and conventional continuous culture ($1.56\ g\ l^{-1}\ h^{-1}$) (Shibata, Flores, Kobayashi, & Sonomoto, 2007). In the direct L-lactic acid fermentation carried out with various starches, yields of lactic acid from sago starch were higher than that from glucose and other starches.

An efficient bioreactor, termed 'synchronized fresh cell bioreactor' developed by Cirilo, Toshiyuki, Genta, Kenji, and Ayaaki (2002), consists of a pH-dependent substrate feed system coupled with crossflow filtration and turbidity control (Cirilo et al., 2002). Using this system, high specific productivities can be obtained, which guarantees high commercial productivity at economical costs. At a cell concentration of 15 g/L and a feed glucose concentration of 53 g/L, volumetric lactic acid productivities of 8.2, 19.3, and 33.1 g/L h were obtained in continuous culture by *Lactococcus lactis* IO-1 in enzyme-hydrolyzed sago starch medium.

4.1.3.5. Production of kojic acid. Kojic acid (5-hydroxy-2-(hydroxymethyl)-4-pyrone) (Fig. 6) continues to attract much attention due to its economical potential in the field of medicine, food science, cosmetics and agriculture (Gomes, Lunardi, Gonzales, & Tedesco, 2001; Kayahara et al., 1990; Le Blanch & Akers, 1989; Smith & Lindsay, 2001). It has increasingly been used as a skin-depigmenting agent in skin-care products marketed in Japan since 1988 (Mikio, Keiichi, & Kyozo, 1995). However, there are contradictory reports on the genotoxicity of kojic acid (Satoko, Yu, Satomi, Masataka, & Minako, 2006).

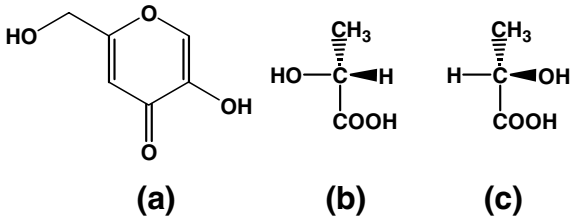

Fig. 6. Structures of (a) kojic acid, (b) L-lactic acid and (c) D-lactic acid.

Kojic acid can be produced by aerobic fermentation of *Aspergillus* sp. using various carbon sources such as glucose, sucrose, acetate, ethanol, arabinose and xylose (Beelik, 1956; Presscot & Dunn, 1959). Gelatinized sago starch has been investigated as a carbon source to produce high yields of kojic acid by *Aspergillus flavus* Link 44-1 in different fermentation modes (batch and fed-batch with different feeding modes) in an 8-L stirred tank fermentor (Rosfarizan et al., 2002). The addition of a large volume of concentrated sago starch (140 g/L) 2 days after the start with an initial starch concentration of 60 g/L produced 16.43 g/L of kojic acid, which was about four times higher than that for batch fermentation of 100 g/L sago starch. Further improvement of kojic acid production was obtained by adding small amounts of concentrated starch (140 g/L) intermittently at 2-day intervals to the culture.

4.1.3.6. Cyclodextrin (CD) from sago starch. Sago starch is an interesting substrate for the production of CD (Kim, Kim, & Lee, 1997), an important polysaccharide due to its unique hydrophobic interior cavity and hydrophilic surface. CD can encapsulate hydrophobic organic substances and aid its solubilization in water. This property is useful in food, pharmaceutical, cosmetic, and agricultural applications (Szejtli, 1988; Tombs & Harding, 1998). CD can be synthesized enzymatically by cyclodextrin glycosyltransferase (1,4-α-D-glucopyranosyl transferase (cyclization), EC 2.4.1.19; CGTase) produced by various microorganisms, particularly *Bacillus* sp. (Larsen et al., 1998) which converts starch into CD. In one study, the productivity of CD from sago starch was unaffected when CGTase, crude or partially purified from *Bacillus* circulans by ammonium sulfate precipitation, was used. The optimum pH and temperature for CD production were found to be in the range of 4.5–5.0 and 55–60 °C, respectively. β-CD was the predominant product, constituting 65% of all CD products (Charoenlap, Dharmsthiti, Sirisansaneeyakul, & Lertsiri, 2004). Mechanical sieving of sago starch is beneficial compared to the use of pullulanase, a debranching enzyme, in the conversion of sago starch into CD (Solichien, 1995).

Transgenic sago plants may be produced by expressing a gene for cyclodextrin glycosyltransferase (CGTase) to convert the starch reserves to CD (Stalker, Shewmaker, & Oakes, 1991).

4.1.3.7. Modified sago starches for improved functionality. Modification is usually carried out to overcome the unstable properties of native sago starch and improve its physical properties during processing. Like other native starches, sago starch needs to be modified to improve its quality. Sago starch shows a breakdown in viscosity during heating and shearing, and this breakdown further increases under acidic conditions. Furthermore, the native starch exhibits higher retrogradation, forming a long cohesive gel with increased syneresis (Wattanachanta, Muhammad, Hashim, & Rahman, 2003).

4.1.3.7.1. Hydroxypropylated and acetylated starches. Chemical modification improves the physicochemical properties of sago starch. Structures of hydroxypropylated starch, cross-linked starch and acetylated starch are shown in Fig. 7. Cross-linking reinforces the granule of starch to be more resistant towards acidic medium, heat and shearing while hydroxypropylation improves their freeze-thaw or cold-storage stability (Tuschhoff, 1986; Wurzburg, 1986; Yeh & Yeh, 1993). Acetylation of starch provides sol stability and functional properties such as hydrophobic, cationic or anionic character at relatively low cost (Rutenberg & Solarek, 1984). Acetylation increases the gelatinization temperature (Tp) but reduces the enthalpy while hydroxypropylation cross-linking reduces both the Tp and enthalpy, indicating that hydroxypropylation cross-linking and acetylation loosen the structure of starch granules and gelatinize starch with lower heat requirements (Aziz, Daik, Ghani, Daud, & Yamin, 2004). Acetylation also increases the thermal stability of sago starch. The introduction of acetyl groups reduces the interaction between starch molecules and thereby increases the swelling power and solubility of the starch granule, and also decreases the coagulation of the starch and gives improved clarity and freeze-thaw stability. Clarity, viscosity, and stability of acetylated starches are of value in food, paper, and textile applications.

In order to overcome the inherent deficiencies of native starches, a dual-modification, hydroxypropylation, and cross-linking, is practiced commercially (Lopez, 1987; Tessler, 1975; Tuschhoff, 1986; Wurzburg, 1986; Yeh & Yeh, 1993). In a dual-modified starch, cross-linking reduces the degree of subsequent hydroxypropylation, and hydroxypropylation increases the degree of subsequent cross-linking. Starches with high amylose content can be stabilized by initially reacting them with propylene oxide and this reaction is inhibited by adding cross-linking agents to yield modified starches having outstanding high temperature and short time retort properties (Tessler, 1975). In a study on dual-modification of sago starch, hydroxypropylation using propylene oxide at levels ranging from 6% to 12% was followed by cross-linking using three different types of cross-linking agents: a mixture of sodium trimetaphosphate (STMP) and sodium tripolyphosphate (STPP), phosphorus oxychloride and epichlorohydrin (Wattanachanta et al., 2003). Through hydroxypropylation, it was found that there was a significant increase in molar substitution which in turn induced an increase in cross-linking. This was accompanied by a significant decrease in paste clarity, swelling power, and solubility compared to that of the native starch. Starch that was hydroxypropylated with 10–12% propylene oxide, and further cross-linked by a mixture of 2% STMP and 5% STPP produced a modified starch that exhibited no viscosity breakdown, high acid

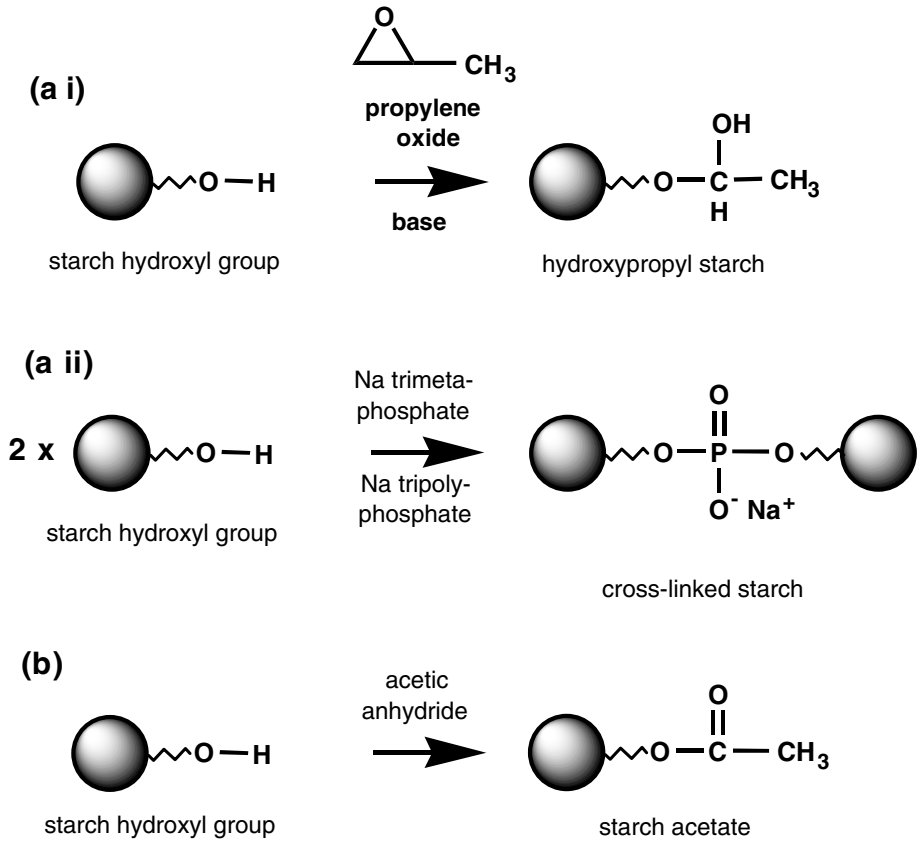

Fig. 7. Structures of (a i) hydroxypropylated starch, (a ii) cross-linked starch, and (b) acetylated starch (Aziz et al., 2004).

resistance, high freeze-thaw stability and improved gel texture.

4.1.3.7.2. Carboxymethylated starch. Starch becomes cold-water soluble by substituting the hydroxyl groups with sodium monochloroacetate (SMCA) to give carboxymethyl starch (CMS) (Zainal, Alias, & Tjoon, 2005). CMS is a water-soluble polysaccharide that finds many applications in the food and non-food industries (Bhattacharya, Singhal, & Kulkarni, 1995). The carboxymethyl group is hydrophilic in nature, and when introduced into starch granules weakens or strains the internal bond structure holding the granule together. The reduction in bond strength is reflected in lower starch-pasting temperatures. The higher the level of modification, the lower the pasting temperature, until the starch granules are rendered soluble or swell up in water at room temperature.

Carboxymethylation can be performed in water as a solvent or in a water-miscible organic solvent containing a small amount of water such as ethanol, isopropanol, methanol, or toluene (Zainal et al., 2005). The use of organic solvents preserves the final product in the granular form, and the side product can be washed away easily (Tijsen, Kolk, Stamhuis, & Beenackers, 2001). CMS with a degree of substitution (DS) ranging from 0.1 to 0.32 prepared from sago starch using isopropanol as a solvent exhibited excellent dispersibility and cold-water solubility as judged by the absence of peak viscosity in the pasting profile. The pasting profile of CMS was qualitatively similar to pregelatinized starch. CMS at higher substitution levels (DS 0.27 & 0.32) showed significantly lower retrogradation as judged by lower setback, absence of DSC endotherm upon storage at 4 °C and lower syneresis upon repeated freeze-thaw cycles. Retrogradation was effectively retarded by the presence of the bulky carboxymethyl group (Zainal et al., 2005).

4.1.3.7.3. Ethersuccinylated hydroxyl polymers. Native starch may be depolymerized with α,β-unsaturated dicarboxylic acid or salts, hydrogen peroxide, and metal catalyst, and then without isolation be submitted to ethersuccinylation reaction. Alternatively, the starch can be ethersuccinylated, and then depolymerized with hydrogen peroxide under alkaline conditions (Wayne, 2006). Applications involving viscosity modification include thickeners for use in foods, pharmaceuticals, latex paints, personal care products, and petroleum fracturing. For thickener applications, the ethersuccinylated starch hydroxyl polymer may have a DS of 0.05–0.7 and have a MW > 500,000. Granular ethersuccinylated starch hydroxyl polymer in the calcium form may be particularly advantageous, since it retains its granular nature until the calcium is removed either by a sequestrant or acid, and rapidly swells thereafter. The swelling properties of ethersuccinylated starch hydroxyl polymer allow its use as a disintegrant in tablets, for which a DS of 0.05–0.5 is appropriate.

4.1.3.7.4. Graft polymerization of sago starch. Graft copolymerization of starch with acrylic acid has found extensive commercial applications, especially as hydrogels for personal care products, in the construction of buildings, in food packages, medical applications and agricultural applications (Athawale & Lele, 2001). Starch graft copolymers can be achieved, primarily, by free radical-initiated processes. As with other free radical polymerizations, starch-graft-poly(acrylic acid) [*S*-gpoly(AA)] copolymer can be prepared through either chemically initiated or radiation-induced process. In free radical-initiated graft copolymerization involving starch, a free radical produced on starch reacts with a monomer to form a grafted copolymer (Kiatkamjornwong & Meechai, 1997). A photoinitiator is required in UV-radiation curing to absorb a photon from the UV light source, and to form the initiator radical. The initiator radical then reacts with starch to create a free radical for grafting. Photografting by UV works at a rapid grafting rate compared to the conventional chemical process. In the UV-initiated graft copolymerization of sago starch with acrylic acid (AA) at low level (2.5%, 5%, 7.5%, and 10% w/w), as investigated by Lee, Kumar, Rozman, and Azemi (2005), the UV curing technique successfully produced starch-graft-poly (acrylic acid) [*S*-g-poly-(AA)]. *S*-g-poly-(AA) showed higher peak viscosity, peak time and setback than native untreated starch and lower swelling power and solubility than the native sample.

Radiation grafting also prevents the retrogradation process of starch (starch recrystallization (Senna, Zaman, Ghazali, & Hashim, 2005). In a study on γ radiation-induced grafting of methacrylic acid monomer (MAA) onto sago starch films, the highest grafting yield was obtained within the irradiation dosage level of 10–20 kGy and by using monomer concentration range of 15–20 wt%. The highest tensile mechanical properties were observed for sago starch films having 66% graft yield of MAA. The DSC thermograms indicated a decrease in the gelatinization temperature of sago starch as a result of grafting.

The suitability of sago starch as a paper additive has been demonstrated using both unmodified and modified sago starch (sago starch blended with acrylamide, sago starch grafted with acrylamide in an acidic medium and adjusted to alkaline conditions) (Yeng, Tahir, Yunus, Zin, & Zakaria, 2004). The starches were used to coat lab handsheets made from recycled pulp fibers. The incorporation of acrylamide in to sago starch through grafting significantly reduced viscosity of the solution. Generally, coating the handsheets with unmodified sago starch significantly improved some properties compared to the uncoated handsheets. Among the types of sago starch modification methods, blending gave superior performance when coated on the handsheets except for smoothness and air permeance.

4.1.3.7.5. Sago hydrogel films. Sago hydrogel sheets are used for wound dressing applications and may be produced by radiation process using high-energy electron beam (3 MeV) or low-energy electron beam, Curetron (200 keV) (Kamaruddin & Norzita, 2004). Cross-linking of sago hydrogel depends on the thickness of the material

exposed to the electron beam. Thinner samples give higher degrees of cross-linking compared to thicker samples, at a specific dose and beam current.

4.1.3.7.6. Sago-based gelling starches. Sago-based gelling starches are prepared by bleaching and converting sago starch to a required Brabender viscosity, then cross-linking the starch with 0.02% phosphorus oxychloride (Trksak & Ford, 2005). The starch product recovered is washed with water and air-, or drum-dried. The pregelatinized starch obtained may be ground until 85% of the starch passes through a 200-mesh screen. Stronger gels are obtained when the starch is cross-linked with over 0.03% $POCl_3$. Such starches can be used to prepare pie fillings with no syneresis.

4.1.3.7.7. Linear long-chain dextrins from sago starch. The use of sago starch for bioconversion is limited by high paste viscosity and resistance of the raw granule to enzyme digestion (Sakano, Aoyagi, & Kobayashi, 1986; Takao, Sasaki, Kurosawa, Tanida, & Kamagata, 1986). The debranching enzyme, pullulanase can produce linear long-chain dextrins (LLD) from sago starch that is either heat-gelatinized or pretreated with acid (Barker & Somers, 1987). Depending on the degree of polymerization, the linear long-chain dextrin so produced may act as amylose. A starch suspension of 5% (w/v) sago starch was heated at 100 °C for 45 min and cooled, and the gelatinized sago starch was hydrolyzed with 2% (v/w) pullulanase (Promozyme 400L, Novozyme A/S, Denmark) for 12 h to maximize the amount of LLD. The enzyme-modified sago starch, with a higher amount of LLD has the ability to impede migration of air between the environment and food, and is suitable for use as a coating for fresh fruits and vegetables thereby inhibiting browning (Wong, Muhammad, Dzulkify, Saari, & Ghazali, 2007).

4.1.3.7.8. Pyrodextrins from sago starch. Dextrins formed by heat are known as pyrodextrins, and are mixtures of various products of hydrolysis and recombination. Pyrodextrins are generally classified into three groups: white dextrins which are prepared from starch in the presence of an acid catalyst activity for a relatively short period of time (3–8 h) at a relatively low temperature (79–120 °C); yellow, or canary dextrins which are prepared from starch in the presence of an acid catalyst for a more moderate period of time (6–18 h) at a relatively high temperature (150–220 °C); and British gums which are prepared from starch without any catalyst for long periods of time (10–20 h) at a relatively high temperature (130–220 °C) (Kasica, Choe, Kouba, & Styer, 2001). White dextrins and British gums are conventionally up to 95% soluble in water, while canary dextrins are conventionally 95–100% soluble in water. British gums form viscous solutions as the name indicates, while white and canary dextrins form relatively less viscous solutions.

Pyrodextrins which are substantially 100% water-soluble in water and hydratable in solution have low free water at ambient temperature. They have a high viscosity relative to canary dextrins, and are preferably prepared by acidifying the sago/tapioca starch, and dextrinizing under substantially anhydrous conditions at 170–210 °C (Kasica et al., 2001). In the early stages of dextrinization, hydrolysis is the major reaction due to the presence of high moisture. During hydrolysis, the molecular weight of the starch decreases and water is used up. Although some recombination is possible during this phase, it is minor until the temperature rises and the water (moisture) level decreases. As the moisture is driven out of the process and temperature continues to increase, the rate of hydrolysis tends to slow down, especially during the latter stages of dextrinization. The processing conditions in the latter stage, namely, high temperature and low moisture, promote recombination of starch molecules which releases water. As recombination occurs, the molecular weight and branching of the starch increase relative to the hydrolysis product. Further, water is released allowing for further hydrolysis (Kasica et al., 2001). With time, an equilibrium state is reached between the two reactions, hydrolysis and recombination. The dextrins, so obtained can be used in a variety of industrial applications including adhesives, pharmaceuticals, foods, paper, glass fibers, binders, insecticides, dyes, paints, thickeners, sizing agents, agricultural products, coatings, water treatment products, cosmetics, and textiles. In particular, they are useful for coating and film applications, encapsulation, emulsification, and in confectionery products (Kasica et al., 2001).

4.1.3.7.9. Amylose products. A normal tablet gives a rapid release of the drug from the tablet. However, the properties of the tablet may be modified for sustained release of the drug, e.g. in the gastrointestinal tract. This is referred to as programmed release, controlled release and/or sustained release. Important aims of programmed release systems are the reduction of side effects of the drug and the enabling of a lower dosing frequency. This can be realized by providing for sustained and gradual release of the drug from the release system (Bergsma, Te Wierik, Aten, & Arends, 2005). Thus, the drug is absorbed in the blood more gradually, and there is a higher probability that the plasma concentration of the drug is higher than the minimum effective concentration.

For the said application, amylose products may be prepared from all starch types containing at least 15 wt% (on dry substance) of amylose such as does sago starch. In the general preparation of the amylose products, an aqueous starch solution is treated with α-amylase (EC 3.2.1.1.) and a debranching enzyme such as an isoamylase (EC 3.2.1.68) or a pullulanase (EC 3.2.1.41). These treatments take place simultaneously, or in the order of first α-amylase and then the debranching enzyme. α-Amylase partially depolymerizes the starch, and the debranching enzyme converts the amylopectin molecules into short-chain amylose.

4.1.3.7.10. Granular boiling-stable resistant (to digestion by enzymes in the small intestine) starch (RS). In present times, there have been increased interests in the nutritional implications of resistant starch (RS), not only due to its

decreased caloric content but also for its physiological effects very similar to those of dietary fibers. Resistant starch is resistant to digestion by α-amylase, and is not absorbed in the small intestine, although, it may be fermented in the large intestine by the colonic microflora (Thompson & Brumovsky, 2002). A boiling-stable granular resistant sago starch can be made by subjecting starch to acid hydrolysis followed by hydothermal treatment (Thompson & Brumovsky, 2002). The granular product may be used in formulating low-fat, high-fiber food products, as a tableting aid, and as an inhibitor of excessive ice crystal formation in frozen products.

4.1.3.7.11. Other hydrolyzed starches. As tablet filler, sago starch needs to be modified by acid hydrolysis at ambient temperature to form highly crystalline starch, the high crystallinity of starch providing high hardness to the starch tablet. Sago starch can also be employed as a flavor encapsulating agent (Varavinit, Luangpituksa, Shobsngob, & Nuyim, 2000). To achieve this, sago starch is hydrolyzed partially by thermostable α-amylase, and then reacted with stearic acid to give pregelatinized-hydrolyzed sago starch stearate which can be used as an encapsulating agent for both water-soluble and insoluble flavors.

Sago starch capsules may be used to protect various entities such as living microbes or enzymes against the effect of the environment or the intestine (Paivi, Pirkko, & Kaisa, 1999). In an attempt to demonstrate the effectiveness of such starch capsules, sago starch granules which had been hydrolyzed with α-amylase were able to stabilise storage of *Lactobacillus rhamnosus* for long periods at ambient temperature.

Fluidity starches are made by hydrolyzing the starch in dilute acid below the gelatinization temperature of the starch. The range of fluidities is 20–90, with a 90 fluidity starch being very much thinner than a fluidity of 20 (www.niir.org). Sago fluidity starches with a water fluidity of 40–80, a gelation temperature of 5–7 °C higher than a comparable corn fluidity starch and a gel strength 100% greater than a comparable corn fluidity starch are manufactured from conversion of a chemically or physically modified sago starch (e.g. by acid hydrolysis using HCl or oxidation using $KMnO_4$) for use in confectioneries (Hanchett, Kasemsuwan, Light, & Tan, 2001).

4.1.3.8. Sago starch, as a nutraceutical. Sago starch in the diet may be useful to keep the *in vivo* oxidative status at a low level. In a study on the effect of sago starch content in diets on the status of lipid peroxidation and antioxidative enzyme activities in rats fed cholesterol-free and cholesterol-enriched diets (Kazuka & Kiharu, 2003), the value of the plasma thiobarbituric acid reactive substance was lower in rats fed the diet with a high ratio of sago starch. Liver superoxide dismutase and catalase activities and serum and liver α-tocopherol concentrations were higher in rats fed the cholesterol-free and enriched diets with a high sago starch content.

4.1.3.9. In food delicacies

4.1.3.9.1. Pearl sago. In Sarawak, sago is widely used to produce sago pearls, which can be boiled, either alone or mixed with other foods, and consumed directly as a carbohydrate source (www.agnet.org).

4.1.3.9.2. Biscuits and cookies. Sago starch mixed with water may be baked to form a product analogous to bread or a pancake. In Sarawak, sago is widely used to produce '*tabaloi*', a local biscuit delicacy (www.agnet.org). It is common to bake sago starch into *lempeng*, which are moulded forms (*forna*). The *lempengs* are usually made entirely of starch, but they may occasionally contain other ingredients such as ground peanuts or other pulses. They are dipped in tea, coffee or other fluids before consumption. In the Moluccas, during festive periods, a kind of cookie, *bagea* is made from sago starch combined with ground seeds of the *kenari* tree (*Canarium commune*).

4.1.3.9.3. Noodles. Sago starch is a potential source of flour for noodles. However, noodles made from sago starch have limitations due to the absence of gluten and lack of desired functional properties. Heat moisture treatment is a promising technique for improving the quality of sago noodle and is performed by exposing the starch to high temperatures (110 °C, 16 h) at a moisture content of 25% (Purwani, Widaningrum, Thahir, & Muslich, 2006). In a study, sago starch was processed into noodles by forming a dough from the starch and a binder (completely gelatinized starch and additive) and pressing it manually through a container with holes. Noodles were steamed for 2 min and dried at 50 °C in a convection drier. Non-heat moisture-treated sago starch was used as the control. Noodles from the heat moisture-treated sago starch showed higher firmness and elasticity, and lower stickiness compared to those from non-treated starch. The starch exposed to heat-moisture treatment changed its pasting profile from an initial type A before treatment to type B after treatment. In general, three types of starches, designated as type A, type B, and type C, have been identified based on X-ray diffraction patterns. These depend partly on the chain lengths making up the amylopectin lattice, the density of packing within the granules, and the presence of water (Wu & Sarko, 1978). Cereal starches are shown to exhibit the typical A-type X-ray pattern, whereas, the tuber starches show the B-form and legumes, the mixed state pattern 'C' (Singh, Singh, Kaur, Sodhi, & Gill, 2003).

Sago, together with rice, corn, and potatoes, is widely used in the manufacture of noodles. The incorporation of alkaline salts (mainly carbonates) into noodle formulations has a great impact on the color, flavor, and texture of the finished noodles (www.aaccnet.org). Cross-linked sago starch can be used for the partial substitution of wheat flour in the production of alkaline noodles. Instant noodles which have low levels (0.1–0.3%) of alkaline salts added as a texture improver are not classified as alkaline noodles because they lack the strong alkaline flavor and color associated with the addition of high levels (0.5–1.5%) of alkaline salts (www.aaccnet.org).

4.1.3.9.4. In puddings/as thickeners. Sago can be made into steamed puddings such as sago plum pudding, or used for making cream-type and fruit puddings (Radley, 1976c). It can be ground into a powder and used as a thickener for other dishes, or used as dense glutinous flour.

4.1.3.9.5. Jelly confections. As a high fluidity product, sago starch is used in jelly confections, similar to maize starch, which becomes cloudy on storage (Radley, 1976c).

4.1.3.9.6. Rice cake. Rice cake may be prepared using 10 wt% waxy corn starch with the addition of 5–95 wt% (based on the main materials) processed starch containing 10 wt% acetylated and/or hydroxypropylated sago or potato starch (Sato & Matsubara, 1993). The rice cake manufactured is free of surface cracks on drying.

4.1.3.9.7. Fish crackers – keropok. In the Peninsular Malaysian states of Kelantan, Terengganu, and some parts of Pahang, fish is processed into snacks called 'keropok' (dried fish crackers), with more than 100 small-scale processors being engaged in the business (www.agnet.org). The crackers are made by mixing minced fish meat with sago flour, tapioca flour, salt, and monosodium glutamate. The mixture is then moulded into cylinders, steamed, cooled, sliced, and sun-dried. Before consumption the slices are fried in hot oil, whereupon the *keropok* expands into a porous low-density product. Crispness is the most important parameter governing the quality of keropok (Siaw, Idrus, & Yu, 1985). The quality of expanded foods is judged from their crispness, which in turn is determined by their expanded volume (Chinnaswamy & Hanna, 1988). Linear expansion, a measurement of crispness, is the most important sensory attribute in fish crackers (Yu, 1992).

Linear expansion is positively correlated to the swelling power and solubility of starch. The average length and width of swollen gelatinized sago starch granules are significantly higher than that of wheat starch and consequently the linear expansion of 'keropok' with wheat starch is lower than that of 'keropok' made with tapioca or sago starches (Cheow, Kyaw, Howell, & Dzulkifly, 2004).

4.1.3.9.8. Bread. Sago starch is used in the production of white bread, the consumption of which is rapidly rising in Indonesia. The starch can be used to make up 40% of the content of white bread (Clarke, Sim, & Tan, 1980).

4.1.3.9.9. Fortified sago. Sago starch forms the basis for many traditional foods in Papua New Guinea such as karamap saksak. Fortification of sago starch solution (representing karamap saksak) with peanut paste can increase protein levels without altering the thinning behavior of sago starch. Fortified sago starch may have potential to combat malnutrition, particularly among children (Sopade & Koyama, 1999).

4.1.3.10. For textile sizing. The practice of sizing cotton, linen, or viscose rayon in the form of hank or warp has the primary objective of causing the fiber to absorb an adhesive-like starch or an allied product. This treatment imparts a much greater tensile strength to the fiber, and also resistance to the abrasive action of the parts of the various forms of machinery that are employed in making the yarn into a woven fabric. Starches differ in viscosity characteristics and when first made, potato starch and farina have the highest viscosity followed by sago, tapioca, and maize (Radley, 1976a). On prolonged boiling, the viscosities of all fall so that after 2 h, the viscosity of farina and tapioca are approximately the same, at about relative viscosity of 150, while that of maize falls to 60+ and sago to 50. Farina is unstable in viscosity, which makes it unsuitable to be used on its own, but it may be mixed with another starch to obtain a stable paste, e.g. sago. The effect of stirring or mechanical shear, or working on the pastes have a distinct effect on the viscosity, with farina pastes having high initial viscosity which fall rapidly, while sago pastes have a low initial viscosity and a less rapid rate of fall (Radley, 1976a). Pastes of higher acidity appear to be subject to a rapid fall in viscosity due to some hydrolysis. The stable pH region for sago is 7–8, while farina has its optimum at pH 5, and maize at 4.5–6.5. The effect of neutral salts on starch pastes is also interesting, possibly more in connection with textile finishing, dressing, and textile printing than with sizing. Farina pastes are very sensitive to the effect of neutral salts, although the effect on sago pastes is slight (Radley, 1976a).

4.1.3.11. In biodegradable polymers. In a comparison of the mechanical, morphological, and biodegradation properties of two types of polycaprolactone/sago starch composites, dried granulated sago starch functioned better as fillers in terms of mechanical properties and ease of biodegradation, compared to undried thermoplastic sago starch (Ishiaku, Pang, Lee, & Mohamad, 2002). However, the undried thermoplastic sago starch imparted better yield strength to the composites. While the rigid granular starch retained its shape in the composites, thermoplastic starch surrounded by microvoids was easily deformed due to plasticization.

In Malaysia, an international team of scientists have developed an efficient production process based on starch derived from the sago palm for polylactic acid, a polymer which has numerous applications in pharmaceutical and packaging fields as a biodegradable polymer.

4.1.3.12. As a tablet binder. Sago starch can be used as a tablet binder in formulations of which dissolution is not the prime concern or in formulations which contain sufficient disintegrants (Nuttanan, Wichan, Sansanee, & Ampol, 1995). Evaluation of the binding property of sago starch in comparison with various commercial binders such as corn starch, tapioca starch, pregelatinized starches and polyvinylpyrrolidone showed sago starch to prolong the disintegration by 19.3 min as compared to about 5 min for other samples.

4.1.3.13. As a binder in charcoal briquettes. Combustible carbonaceous briquettes may be made from 85 to 96 wt% carbonaceous material, 2–8 wt% organic binder, e.g. a starch or starch derivative (from sago), and a 1–5 wt% water-swellable clay, e.g. bentonite (Dell, 1992). The binder and the clay, mixed together as slurry is added to the carbonaceous material, which is then shaped, dried, and compressed under high pressure to the desired briquette shape. The briquettes have a much smoother surface, are more uniform in size and shape, and have higher customer appeal.

Table 3
BIS requirements for sago (*sabudana*)

Characteristics	Requirements
Moisture, % by weight, max	11
Total ash (dry basis), % by weight	0.4
Acid insoluble ash (dry basis), % by weight, max	0.10
Starch (dry basis), % by weight, max	98
Protein (N × 6.25) (dry basis), % by weight, max	0.30
SO_2, ppm, max	100
Crude fiber (dry basis), % by weight, max	0.20
pH of aqueous extract	4.5–7.0

4.2. Flavonoids

Two water-insoluble flavans were isolated from the pith of the sago palm and identified to be (2*S*)-7-hydroxy-5-methoxyflavan and (2*S*)-5,7-dimethoxy-4′-hydroxyflavan (Okamoto et al., 1986). HPLC of crude procyanidin, isolated from the pith of the sago palm revealed the presence of epicatechin (Ozawa, Hiroto, & Imagawa, 1990) one of the catechins, the most widely recognized properties of which are their antioxidant activities.

5. Artificial sago

Artificial sago in Germany is made from other starches such as potato or maize starch (Radley, 1976b). Moist starch is pressed through circular orifices in a plate, which is vibrated to detach the extruded starch in the form of noodles. These small cylinders are next rounded by tumbling them in a revolving barrel with a little powdered starch to prevent sticking, graded to size and then subjected to hot moist air or steam on trays for a short time, at about 74 °C to produce a thin surface film of gelatinized starch. Hot air is then passed over the trays to dry the gelatinized layer. The simulation of real sago is carried still further by slightly tinting the pearls to a brown shade by roasting or to a yellow or by the use of a trace of caramel.

In India, *sabudana* 'sago' is manufactured from the starch obtained from the tubers of tapioca (*Manihot Utilisima Pohl, Mesculenta*) (Aneja, Mathur, Chandan, & Banerjee, 2002) and is a processed food starch marketed in the form of small globules or pearls. *Sabudana*, intended to be used as an ingredient in foods should be tested for processing quality by the method prescribed in Appendix A of IS: 899–1971. The Bureau of Indian Standards requirements for *sabudana* are shown in Table 3 (Aneja et al., 2002). The tapioca sago is used in a variety of dessert puddings like *payasam*, *kheer*, various starchy food products, and some bakery products such as bread and pastries. A blend of milk or cream with soft-boiled sago granules and sometimes fruit juice topped with ice cream make a rich beverage called *falooda*, quite popular in Mumbai.

Gomuti sago, from the Gomuti palm (*Arenga pinnata*) is of brownish color and is used as food in Japan. 'White' sago is also produced, especially in Japan, and sells at relatively high prices. Some American sagos are made from the batato (*Convolvulus batatos*) and the areca palms (*Areca oleracea*) (Radley, 1976b). Sago starch is also prepared from the pith of the cycads of the genus, *Cycas*. *Cycas revoluta* is referred to as 'sago palm', 'Japanese sago', or 'king sago' and *Cycas rumphii* as 'tree sago' or 'queen sago' (www.hawaiiag.org). Cycads are not palms and are members of the family, Cycadaceae. Cycads are gymnosperms, while palms are angiosperms.

6. Sago sap

An inflorescence stalk of the sago palm may be beaten with a wooden mallet each day for 2–3 weeks to loosen the sap and the exuding sap is caught in the hollow joint of a bamboo (Zuniga, 2000). A thin slice is removed from the base end of the stalk once or twice each day as the sap flows. Sap yield varies depending on the climatic condition, the age of the tree and the length of time the sap has been flowing out. The flow gradually diminishes from 10 to 2 L a day after 2½ months (Hines, 1914). Sap fermentation begins in the bamboo nodes and tuba is a fermented sago sap.

Sugar can be produced from sago by boiling the sweet unfermented sap. Generally, the sap is thickened into a desirable consistency by boiling it in an open kettle. The right mixture is attained if the liquid solidifies easily when dropped on to a cold surface. The sugar produced is brown, similar to the sugar produced from buri palm. The sap of the palm can also be made into wine and vinegar.

7. Sago fronds

Fronds of the palm sago can be used for thatching. To make a thatch, the leaflets are taken off the rachis and are folded over a wooden or bamboo lathe and sewn together. The rachis of fronds is often used for walls, fastened between horizontal posts. The leaf sheaths sometimes are used for mats, and fiber from young leaves may be used for mats. The strong leaves can be woven into bags, baskets, cages, ropes, spoons and food wrappers (Singapore Zoological Gardens Docents, www.szgdocent.org).

Sago palm fronds have been assessed for their potential as a pulp and papermaking raw material using the anthraquinone (I)-soda pulping process (Jamaludin, Paridah,

Hamami, & Yin, 1995) resulting in 45% pulp yield and rape with a low shives content – 0.07%, κ number – 18, tensile index – 82 Nm/g, and bursting strength – 7 kPa m^2/g.

8. Sago hampas

Sago 'hampas' is an inexpensive, copious fibrous residue left behind after most of the starch has been washed out of the rasped pith of the sago palm. Microscopic examination revealed a large number of starch granules to be trapped within the lignocellulosic matrix (Chew & Shim, 1993). Dried hampas contains about 60–70% starch on a dry weight basis (Vickineswary, Shim, Thambirajah, & Blakebrough, 1994) (Table 4). The hampas may be used as animal feed, compost for mushroom culture, for hydrolysis to confectioners' syrup and for particleboard manufacture (Phang, Miah, Yeoh, & Hashim, 2000). The rice-straw mushroom (*Volvariavolvacea*), considered a delicacy in the Moluccas can be cultivated on the sago waste (Chang, 1980; Chang & Buswell, 1996; Chang & Miles, 1989). Another important application lies in its use as an additional carbon in anaerobic digesters for the production of biogas (Abd-Aziz, 2002).

8.1. As substrate for production of enzymes

Apart from its reuse as an animal feed supplement and organic fertilizer, sago hampas is a potential substrate for microbial conversion *via* solid substrate fermentation into value-added products such as enzymes. The thermophilic fungus *Myceliophthora thermophila* and the mesophilic fungi *Chalara* sp. and *Neurospora sitophila* all produce economically significant amounts of enzymes such as cellulases, amylases, and the raw starch degrading enzyme, glucoamylase (www.cebar.um.edu.my) from a variety of substrates including sago hampas.

Sago hampas can also be used as a substrate for the production of laccase by solid substrate fermentation (SSF) with *Pleurotus sajor-caju* (Kumaran, Sastry, & Vickineswary, 1997). The fungus grown on the hampas with a C:N ratio of 35:1 exhibited high laccase activity together with variable cellulase and xylanase activities. *Pycnoporus sanguineus* also showed good growth during solid state fermentation of sago hampas, which was supplemented with urea as nitrogen source, (Rifat, Paramaswari, Abdullah, & Sekaran, 2003) again producing large amount of laccase.

Table 4
Composition of sago hampas

Component	%
Starch	65.7
Crude fiber	14.8
Crude protein	1
Fat	n.d.
Ash	4.1
Moisture	59.1

Ref. Abd-Aziz, 2002.

8.2. As adsorbents

The fiber residues from sago waste largely composed of celluloses and lignins have some potential as a biosorbent (Vickineswary et al., 1994). They may be produced by grinding sago waste in a food processor, drying in an oven at 105 °C for 24 h, and then screening through sieves to give adsorbents with a known particle size range, which can be used to adsorb lead and copper ions from solution (Quek, Wase, & Forster, 1998). Sago waste is a better adsorbent for lead than for copper, having higher initial sorption rate and greater sorption capacity.

Increasing awareness of the environmental impact of heavy metals has prompted a demand for the purification of industrial waste waters prior to discharge into natural waters. This has led to the introduction of a more strict legislation to control water pollution, such as the Environmental Quality (Scheduled Wastes) Regulation, 1989, in Malaysia (Yeoh & Chong, 1991), which will probably affect metal-related industries. The preparation of activated carbon (AC) from sago industry waste is promising to produce a useful adsorbent for chromium (VI) and mercury (II) removal from industrial effluents (Kadirvelu, Kavipriya, Karthika, Vennilamani, & Pattabhi, 2004; Vennilamani, Kadirvelu, Sameena, & Pattabhi, 2005). A flow diagram for the preparation of activated carbon is shown in Fig. 8. Surface modification of the carbon adsorbent with strong oxidizing agents such as conc. sulphuric acid generates more active adsorption sites on the solid surface and pores for metal ion adsorption.

Effluents discharged from dyeing industries are highly colored and they can be toxic to aquatic life in receiving waters (Lee, Low, & Gan, 1999). Color removal from textile effluents has been given much attention in the last few years because of its potential toxicity. Adsorption onto activated carbon is superior to other techniques for adsorbing a broad range of chemical entities efficiently, and also

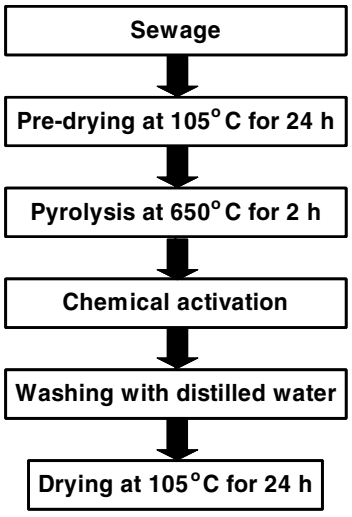

Fig. 8. Process flow diagram of activated carbon preparation from sewage (Reddy, Kottaiah, Reddy, & Velu, 2006).

because of the simplicity of design involved. However, commercially available activated carbons are still considered expensive (Chakraborty, De, DasGupta, & Basu, 2005). The use of cheap adsorbents is an alternative substitution of activated carbon for the removal of dyes from waste water (Azhar, Liew, Suhardy, Hafiz, & Hatim, 2005). Sago waste-prepared carbon is reported to be effective in adsorbing 100% Rhodamine B from an aqueous solution (Kadirvelu, Karthika, Vennilamani, & Pattabhi, 2005).

9. Processing and utilization of sago waste water

After the separation of starch from the pith, the wastes are in the form of bark, the solid component known as *hampas* and waste water. The waste water is usually discharged into the rivers, each factory producing about 10–22 tons waste water per day (Phang et al., 2000). The effect of treated sago effluent on the fish tissues of the Indian carp *Cirrhinus mirigala* is such that histologically tissues showed varied degrees of damage suggesting the study to be useful as an indicator of water pollution (Nagarajan & Suresh, 2005).

There are newer possibilities for the design of low-cost and compact, on-site waste treatment systems with very short retention periods. A hybrid reactor which combines the advantages of both fixed-film and up-flow anaerobic sludge blanket systems for the treatment of sago waste water for reduction of Chemical Oxygen Demand (COD) was operated at organic loading rates varying from 10.4 to 24.6 kg COD/m^3d (Banu, Kaliappan, & Dieter, 2006). After 120 days of start-up, an appreciable decrease in COD and efficient removal of solids were evident. The COD removal varied from 91% to 83%, while the removal of total solids was in the range of 56–63% and that of volatile solids varied from 67% to 72%. This was considered a step in the right direction for the treatment of waste water in the prevention of pollution.

An indigenous strain of *Rhodopseudomonas palustris* strain B1 isolated from rice–noodle factory waste water was grown in 50% sago effluent in an attempt to utilize the sago starch processing waste water to produce biomass (Vickineswary et al., 1997). A high biomass concentration of 2.5 g/L with a pigment content of about 1.1 mg carotenoid per g cell mass was achieved after 96 h of growth in anaerobic-light culture system together with a 77% reduction in the COD of the sago effluent. This was considered to be of value since carotenoids are nutraceuticals having a huge market worldwide.

Waste water arising from the production of sago starch has a very high carbon to nitrogen ratio (105:0.12), but it has been made more suitable for fermentation by anaerobic fermentation in an upflow packed bed digestor (Phang et al., 2000). The digested effluent with an average C:N:P ratio of 24:0.14:1 supports growth of *Spirulina platensis* (*Arthrospira*). The highest crude protein, carbohydrate and lipid content of the biomass were 68%, 23%, and 11%, respectively. The reduction in COD, ammoniacal-nitrogen and phosphate levels of the digested effluent reached levels of 98.0%, 99.9%, and 99.4%, respectively.

10. Miscellaneous uses of the sago palm

The pith is used to make porridge and bread. Ground pith sometimes is used as an animal feed, especially for pigs. When dried, it is also used for horses and chickens. The starch is eaten as raw chunks of pith or as baked pieces of pith. The non-pith parts of the sago palm trunk are utilized as an excellent building material for local and urban houses, sheds, or other buildings (El-Nawawy, 1992; Zadrazil, 1992), as a resource for composting (biofertiliser), a resource for gasification and energy production, and as an animal feed. Whole logs are baked and taken as sea-provisions on long canoe voyages.

The woody leaf petioles of *M. sagu* are used to make walls, ceilings, and fences (Schuilling & Jong, 1996). The decaying trunks of the sago palm are a source of the sago palm beetle grubs (*Rhynchophorous ferrugineus/bilineatus*), an excellent source of protein; however the protein is deficient in tryptophan (Mitsuhashi & Sato, 1994). Grubs, especially *Rhynchophorus* sp. are considered a delicacy by sago growers. Sometimes, parts of trunks are left in the field by the Asmat tribe to be infested by the grubs, which are eaten fresh or roasted or mixed with sago flour and steamed. New uses for sago include its use in the manufacture of biodegradable plastics, alcohol, ethanol, and citric acid (www.unu.edu).

11. Conclusions

The sago palm will become a key crop in the near future, as it can not only survive adverse environmental conditions but also serve as a countermeasure to the green house effect. It is an excellent starch resource with a myriad of possible applications in the food, polymer, pharmaceutical, and textile industries. Sago hampas offers much scope for utilization as a substrate for microbial conversion *via* solid substrate fermentation into value-added products such as enzymes. Furthermore, the preparation of activated carbon from sago wastes is a promising way to produce useful adsorbents for the removal of metals ions. The importance of the sago palm being well recognized, special considerations on strategies for materializing its potential are essential.

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