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Review Article

Recent developments in sustainable arrowroot (*Maranta arundinacea Linn*) starch biopolymers, fibres, biopolymer composites and their potential industrial applications: A review

J. Tarique [a], *S.M. Sapuan* [a,b,*], *A. Khalina* [c], *S.F.K. Sherwani* [a], *J. Yusuf* [a], *R.A. Ilyas* [d,e]

[a] *Advanced Engineering Materials and Composites Research Centre (AEMC), Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400, UPM, Serdang, Selangor, Malaysia*

[b] *Laboratory of Biocomposite Technology, Institute of Tropical Forest, and Forest Products (INTROP), Universiti Putra Malaysia, 43400, UPM, Serdang, Selangor, Malaysia*

[c] *Department of Biological and Agricultural Engineering, Universiti Putra Malaysia, 43400, UPM, Serdang, Selangor, Malaysia*

[d] *School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, UTM, Johor Bahru, Johor, Malaysia*

[e] *Centre for Advanced Composite Materials (CACM), Universiti Teknologi Malaysia, 81310, UTM, Johor Bahru, Johor, Malaysia*

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ABSTRACT

Raising environmental awareness had forced researchers to explore the potential and implementation of environmentally friendly materials as alternatives for conventional materials. Environmentally friendly materials are biodegradable, safer, non-toxic, lightweight, cheap, and readily available. Arrowroot starch has a high content of amylose (~35.20%) which makes it suitable for better film production. Starch extracted from arrowroot rhizomes can be blended, plasticized with other polymers, or reinforced with fibres to improve their properties. The melt blended glycidyl methacrylate-grafted polylactide (PLA-g-GMA) and treated arrowroot fiber (TAF) treated with coupling agent developed PLA-g-GMA/TAF composite, which showed better properties than the PLA/AF composite. To the best of our knowledge, no comprehensive review paper was published on arrowroot fibres, starch biopolymer, and its biocomposites before. The present review focuses on recent works related to the properties of arrowroot fibres and starch, and their fabrication as biocomposites. The review also reveals the vast potential of arrowroot fibres

* Corresponding author.
E-mail address: sapuan@upm.edu.my (S.M. Sapuan).

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and starch for food industries, medicines, textiles, biofuel, pulp, and paper-making industries, bioenergy, packaging, automotive, and many more.

1. Introduction

Current environmental pollution is getting more serious, and it is making us more vulnerable to various crises. The growing awareness of climate change and the enactment of more stringent laws and regulations are forcing the industries to seek environmentally friendly alternatives are the use of fibre polymer biocomposites (100% green composites) in manufacturing and processing [1]. Green chemistry and eco-friendly engineering are being viewed as key options for the growth of the upcoming new generation of goods, technologies, and processes in response to the progression of detailed environmental concerns, philosophies of ecology, manufacturing ideologies, and ecosystem effectiveness [2]. The conventional methods for manufacturing and processing are using synthetic polymer composites, where the fibre and polymer sources are from synthetic materials [3]. To support the effort, scientists and engineers have moved towards developing fibre-reinforced polymer biocomposites that utilize biodegradable, non-toxic, and edible natural fibres [4,5]. Bio composite is used in food packaging where it is non-toxic and biodegradable, and it is significant because of environmentally friendly, renewable, sustainable, biodegradable, cheap, abundantly available, and comparable physical and mechanical properties to synthetic composite parts [6,7]. Using natural polymers for packaging rather than conventional petroleum-based polymers [8–11] is one solution to reducing the environmental effects. Biodegradable polymers are those that are destroyed by the enzymatic activity of living organisms (such as microbes, leaves, fungi) when exposed to the bioactive environment, and converted to CO_2, H_2O, and biomass under aerobic conditions at the end of the process, and hydrocarbons, methane and biomass under anaerobic conditions [12]. Fakhouri et al. [11], reported that, both starch and gelatin are natural polymers in this respect, which have been extensively used in the preparation of polymeric matrices for food industry applications such as edible and biodegradable films coatings [13].

Arrowroot (*Maranta arundinacea*) has a pivotal role in the development of biodegradable products such as biocomposites. The rhizome of arrowroot is the main origin of starch and fibre [14]. It has long fibrous roots with tuberous rhizomes [15]. The arrowroot plant is mainly found in the West Indies (Jamaica), Indonesia, Philippines, India, and Sri Lanka [14]. About 95% of the world's demand for arrowroot is fulfilled by St. Vincent (West Indies) [16]. The arrowroot is a high starch content rhizome. The extracted starch is known to be easily digested [17] and it also has an excellent gelling property [18]. It has a high content of amylose (35.20%) which makes it suitable for the production of films [14]. The technical properties of films, in particular when it comes to mechanical strength and barrier properties, are usually stronger than those of amylopectin [14,19–22]. Recently, there has been a growing interest in the use of rigid nanoscale particles as reinforcement materials in polymeric matrices, composites, and nanocomposites. Carbon nanotubes and cellulose nanowhiskers are two examples of such particles [23]. In that way, arrowroot fibres are biomass residues derived from agribusiness, which provide a good source of cellulose nanowhiskers. However, the arrowroot rhizome is hydrophilic [24,25]. The arrowroot fibre is small in diameter. Hence tear resistance of this fibre is high which makes it useful for packaging and suitable for tissue paper purposes. It can be blended with biopolymers like polylactic acid (PLA), polyvinyl alcohol (PVA), polyhydroxyalkanoate (PHA), and polyethylene glycol (PEG) to create more useable biocomposites and biomaterials, as well as to boost the versatility of arrowroot starch [26]. Recently, a number of work have been done on arrowroot starch based composites including.

The biodegradability of arrowroot fibre can be prolonged by blending the fibre with PLA [27]. The arrowroot rhizome product can also be used for packaging materials, biomedical materials, and agricultural purposes [28,29]. In reviewing the literature, no significant data was found on the characterization of arrowroot fibres. A considerable amount of literature has been published on arrowroot starch as can see in Table 7. This study seeks to obtain data that will help to address these research gaps. Also, highlights a clear review of the recent developments, advancements, and properties of arrowroot fibre, biopolymer, biofilms and biocomposites which will help the industry and engineering sector in developing advanced bio-based composites for potential applications.

Currently, there is no review on arrowroot fibre, starch, and biocomposites. Therefore, there is a need for this review because many people are interested in the most recent developments in arrowroot research.

2. Arrowroot (*M. arundinacea Linn*)

2.1. Arrowroot plant

Arrowroot (*M. arundinacea*) represents the *Marantaceae* family and mostly found in the tropical forest [14]. Arrowroot is a perpetual plant with a height of 90–150 cm [30]. It has white flowers, big green leaves with a length of 10–20 cm, and white fleshy cylindrically rhizomes with 2.5–3 cm width and 20–40 cm length [31]. Usually, arrowroot rhizomes either are found in a bunch of two to three or single. Fig. 1 shows the Arrowroot plant which has long green leaves as well as the fresh rhizome. The arrowroot rhizome is an important source of starch, bagasse fibre as well as husk fibre.

Fig. 1 – Arrowroot (*Maranta Arundinacea*) plant and rhizome.

2.2. Nutrients of arrowroot

Tubers are a part of some plant species that are enlarged so that they can store energy, nutrients, and vitamins. As a result, plants with tuber can live for the following season, and as a means of asexual reproduction [32]. Several critical biological nutrients such as carbohydrates, fats, and proteins are found in arrowroot starch, which plays significant roles in nourishing the human body as well as in the development of life [33]. Table 1 shows the nutritional properties of unensiled and ensiled arrowroot fractions. For comparison purposes, similar values for different silages are also included. Unless otherwise mentioned, all values are listed moisture-free. Meanwhile, when ensiled aerial (EA) plant biomass was compared to equivalent control samples, ether extract, crude protein, In vitro dry matter digestibility (IVDMD) level, and nitrogen-free extract were considerably lower. On the other hand, EA plant biomass had slightly higher amounts of crude fibre, ash, acid detergent fibre (ADF), neutral detergent fibre (NDF), and lignin [34]. EA biomass and coarse and fine arrowroot extraction residues contained 10.8–21.1% crude protein, 11.1–30.2% crude fibre, 38.5–60.3% IVDMD and 3.8–17% ash. In addition, the amount of all nutrients in ensiled and yeast-supplemented ensiled arrowroot fractions were comparable to sugar beet silage, but ash amounts were 2.9–3.2 times higher in the arrowroot silages. According to Erdman et al. [34], the coarse residue can be suitable for tear-resistant especially quality papers such as wrapping paper as well as bags. Also, the use of arrowroot by-products can result in increased cultivation of this species as a fruit, feed, fuel and fibre resource. Besides, by-product utilization can also help to reduce environmental issues caused by the direct discharge of unused by-products.

3. Arrowroot starch

Industrial needs are satisfied mostly by food sources which include tubers like (potatoes, sweet potatoes) cereals include (rice, wheat etc.) roots (cassava, yam, etc.) and legumes (bean, green pea, etc). Arrowroot contains a strong standard starch and is widely used in the food industry in various viscosities or textures, as well as in several other applications. Starch is a polysaccharide composed primarily of two basic elements, amylopectin, an anhydroglucose molecules with an especially branched structure, and amylose, a non-branched glucose element as displayed in Fig. 2. Amylose is basically a linear molecule composed of glucose units linked by an α-1-4 linkage, while amylopectin is highly branched and composed of several short chains of (1–4)- α -D- glucans linked by an α -1-6 linkage. These α -1-6 linkages are responsible for ramifications. The nature of amylose and amylopectin is especially affected by molecular weight, shape, and scale. Because of differences in unit weight distribution and composition, these two units exhibit distinct pasting, retrogradation, viscoelastic, and rheological properties [35].

Arrowroot starch has many advantages such as versatile, non-poisonous, ecological, blood-adaptable, and bio-accumulate [29,36]. Therefore, arrowroot starch is a potential novel alternative. In the food industry, it has been used for making biscuit, cake, pudding, porridge, as well as pie filling.

Table 1 – Nutrient characteristics of unensiled and wiled arrowroot fractions [34].

Sources	Treatment	Crude protein (%)	Crude fibre (%)	Nitrogen free extract (%)	Acid detergent Fibre (%)	Lignin (%)	Ash (%)	Ether extract (%)	Neutral detergent fibre (%)	Gross energy (cal/gm)
Aerial plant	Control	17.48	20.68	45.65	29.15	2.69	13.97	2.2	60.27	3716.32
	Ensiled	12.05	27.84	41.93	43.184	7.154	16.194	1.99	66.54	3723.90
	Ensiled with yeast	10.790	30.234	42.21	42.40	5.68	14.81	1.96	67.75	3778.69
Coarse residue	Control	3.34	18.45	70.09	28.94	3.93	7.43	0.49	70.99	3587.87
	Ensiled	3.99	20.16	67.44	3120	5.16	7.731	0.681	50.35	3749.98
	Ensiled with yeast	4.414	21.09	65.89	34.68	5.92	7.89	0.724	58.93	3740.45
Fine residue	Control	3.37	11.12	81.58	17.20	2.05	3.77	0.16	77.75	3545.09
	Ensiled	4.350	15.39	75.64	26.15	4.07	4.07	0.55	56.58	1645.65
	Ensiled with yeast	6.41	16.664	71.41	30.16	6.72	4.95	0.574	56.4	3792.43
Corn silage		7.0	25.5	59.3			5.3	2,8		
Alfalfa silage		17.3	33.1	37.1	43.2		8.9	3.7	52.3	
Sugar beet silage		12.5	32.0	48.5			5.1	1.9		

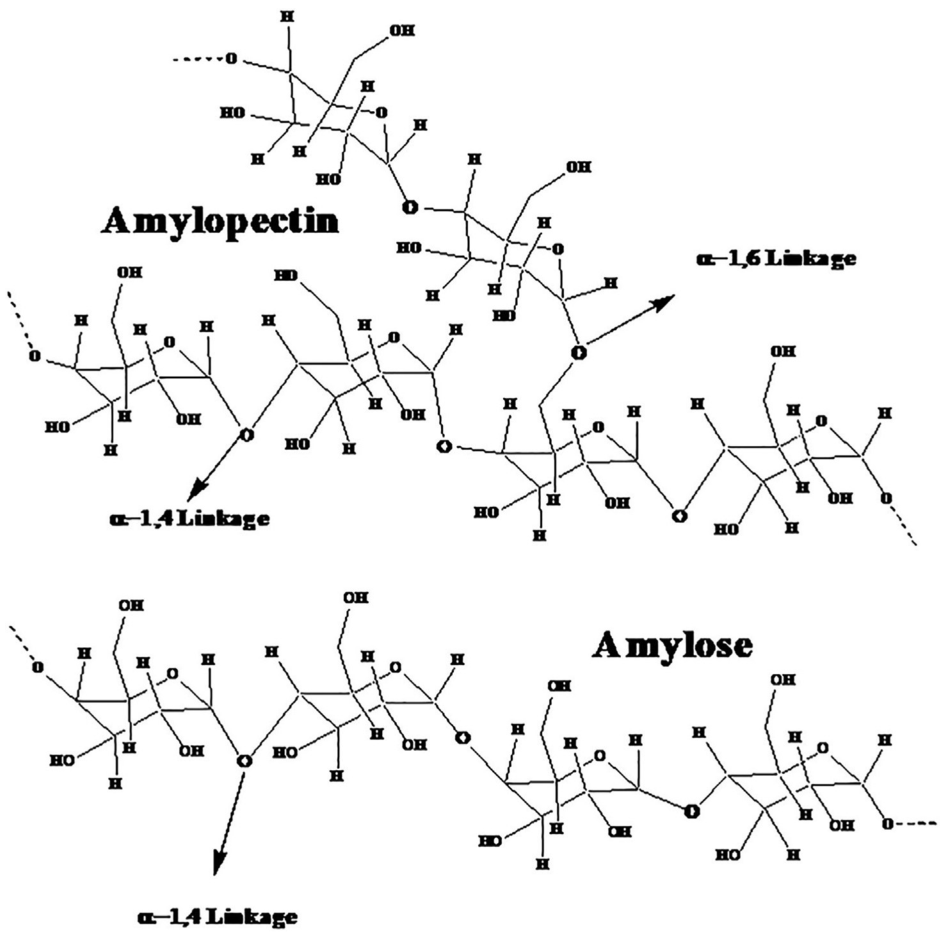

Fig. 2 – Structure of amylose and amylopectin adopted from ref. [35].

In certain food preparations, it is used as a thickener and/or stabilizer and for therapeutic purpose. According to Kay et al. [18], arrowroot starch could be used for children, convalescent or with organic weakness because of its high digestibility. Additionally, It has a high content of amylose (35.20%), which makes it suitable for the production of films [37]. This high amount of amylose has a fundamental importance in its choice as film-forming material, as it interferes directly with its final characteristics. Therefore, the technological properties of amylose films are generally better than those of amylopectin, especially when it comes to mechanical strength and barrier properties [21].

3.1. *Processing of starch extraction from arrowroot rhizomes*

Arrowroot is mostly harvested for its starch from the rhizomes. Leonel et al. [38] reported that, at 14 months, arrowroot rhizomes showed the highest value of the dry mass and starch in a fresh form that is 61.17% and 25–30% respectively. But, in literature, this value reported in the range of 68%–75% of moisture [39–41]. The required unit operations including disintegration, extraction, filtration, concentration and, finally drying for arrowroot starch extraction are the same as for other roots, and tubers. Sajeev et al. [42] reported that, disintegration by grating/milling is the most essential as it opens up the walls of the plant cells and reveals the granules of starch within the plant [43]. Graters are used extensively in both large-scale and small-scale industries. According to Sajeev et al. [42] graters consist of revolving cylindrical containers mounted side by side with multiple saw blades, divided longitudinally by 10 mm. This form of grater facilitates size reduction by friction and shearing and must be routinely replaced or sharpened to ensure that the high efficiency of breakdown keeps rising.

In small-scale application with the same concept Sheriff and Balagopalan et al. [44] developed a multipurpose raw material grater for extracting starch, with a capacity of 75–125 kg.h-1. They measured the productivity of different tuber and root crops such as yam, cassava and potato and found the capability of machine ranged, depending on the crop, from 120 to 200 kg.h-1 of raw material. The arrowroot farmers in the province of Marinduque are effectively practising two methods of starch extraction. One is by the conventional process, known locally as ilod, the other using a grinder system powered by a motor. In Barangay Malbog, Buenavista, Marinduque, arrowroot farmers use the conventional process. This technique utilizes a large timber that allows the arrowroot rhizomes to crush when rolled over two

Fig. 3 – Conventional method of arrowroot rhizomes grinding using a coconut trunk known locally as "Ilod" in Marinduque Philippines. Adapted from ref. [48], copyright 2018, Alexander Pascua.

other large timbers at both ends Fig. 3. Because of the laborious and time-consuming process of the conventional method farmers discovered the use of motor-operated arrowroot grinder designed machines. Besides, Barth et al. [45] also reported that more physical labour is needed for handmade starch extraction, which is often correlated with unhealthy and non-ergonomic practices.

In 1993, Tan and Gayanilo [46], experimented with four different arrowroot starch extracting processes such as (a) Grinding of rhizomes using a conventional machine known as "ilohan" (b) Grating of the rhizomes using grater equipment (c) Grinding of wet chips using attrition grinder and (d) Grinding of dried chips. It was experienced that, grinding of dry chips produced high starch recovery of 1.97 kg/man-hr but showed high ash content of 3.97% with coarse and poor particle colours while grater machine performance was 1.47 kg/man-hr with high starch quality. In 2012, Malinis et al. [41] designed an industrial arrowroot machine and processes to determine at Rejano's Bakery in Brgy. Banahaw, Sta. Cruz, Marinduque, Philippines. After processing it was found that the machine operated using a 1 hp electric motor has a capability of 200 kg/h and a starch recovery of 12–18%. Capina et al. [47] also developed arrowroot machines but with the low recovery of starch about 13% out of the 3 kg fresh rhizomes.

The extracted compounds from the arrowroot are composed of mostly water and fibre, and a low amount of starch as shown in Table 2. Carbohydrate is one of the most valued ingredients found in arrowroot starch, which is used to produce medicine, biscuits, pastries cakes, and other bakery products whereas the waste rhizome fibre is commonly used to make paper, flours, tissue paper and cardboard [47].

The flowchart depicted in Fig. 4 shows the process of extracting starch from the arrowroot. Initially, fresh arrowroot

Table 2 – Extracted materials from fresh Arrowroot rhizomes [47].

S.N.	Sample	Composition (%)
1.	Water content	59
2.	Starch	13
3.	Waste rhizome fibre	28
	Total	100

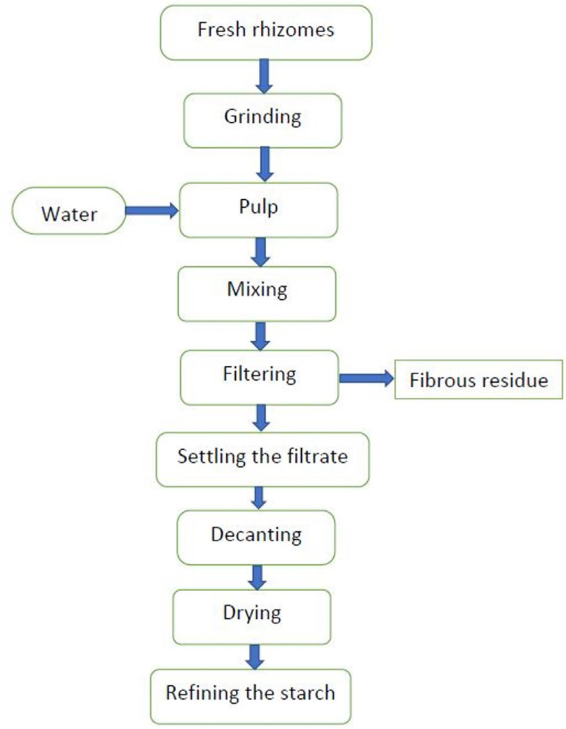

Fig. 4 – Flow diagram of starch extraction from arrowroot rhizomes [47].

rhizomes were washed, sliced, and ground in a wet milling machine until the smallest desired fraction was obtained and water was added to the arrowroot pulp. After mixing, the mixture was filtered through a cheesecloth to remove the fibrous residue. Finally, the remaining solution which contains the extractives was decanted, dried, and stored.

3.2. *Properties of arrowroot starch*

3.2.1. *Chemical composition of arrowroot from different origin*

The composition of fibre plays a significant role in defining the functional properties. Table 3(a) indicates the chemical composition of the arrowroot. Based on several considerations, such as the method of extraction, origin, crop age, environmental factors, etc., the arrowroot is usually accompanied by other ingredients, including fibre, lipids, proteins, and minerals. Some of these impart favourable characteristics to the starch, while others control the quality. Table.4 illustrates that arrowroot rhizomes cultivated in Venezuela showed the highest protein (5.96%) and moisture content (79.88%) on a dry basis [26]. Higher moisture levels can lead to microbial damage and subsequent quality degradation. In deciding the moisture content, temperature variables also play a role. The total ash (%) in arrowroot was reported to vary from (0.31 ± 0.02 to 2.41 ± 0.37%). It can also be observed that arrowroot has high carbohydrate varied from 52.20% to 98.65%. It is commonly used as a stabilizing agent in food, condiments, soup, sweets, pudding and ice cream as a carbohydrate source [49]. Starchy carbohydrates are found in the mature arrowroot rhizomes along with β-carotene, niacin, and thiamine so that they become very

Table 3a – Chemical composition of arrowroot (g/100 g dry weight) from the different origin are shown.

Material	Origin	Protein (%)	Moisture (%)	Ash (%)	Crude fat (%)	Crude fibre (%)	Carbohydrate (%)	Reference
Arrowroot starch	Palmira city, Colombia	0	15.05 ± 0.22	0.64 ± 0.15	0.32 ± 0.01	0.29 ± 0.03	98.65 ± 0.01	Valencia et al. [30]
	Yogyakarta, Indonesia	1.88 ± 0.45	7.52 ± 0.28	1.53 ± 0.66	1.47 ± 0.55	23.25 ± 0.04	52.20	Herawati et al. [31]
	Venezuela	5.96	79.88	2.84	–	7.49	78.25	Perez et al. [61]
	Mysore, India	0.8 ± 0.01	8.1 ± 1.21	1.5 ± 0.20	1.0 ± 0.09	1.7 ± 0.02	81.6 ± 0.24	Madineni et al. [27]
	Mandalay, Myanmar	–	8.3	2.7	–	–	–	Nyo et al. [28]
	Palmira city, Colombia	0.00	13.20 ± 0.20	0.31 ± 0.02	–	0.17 ± 0.04	59.14 ± 0.58	Gordillo et al. [29]
	Semarang, Indonesia	6.14	7.12	4.14	0.63	6.76	81.97	Wahjuningsih et al. [62]
	Kerala, India	0.06	9.82 ± 0.50	0.45 ± 0.03	0.88 ± 0.00	–	86.67 ± 1.0	Raja et al. [63]
	St. Vincent, West Indies	0.27 ± 0.01	14.85	2.41 ± 0.57	0.28 ± 0.03	–	–	Erdman et al. [64]
	Kerala, India	12	7.4	1.2	–	–	72	Jayakumar et al. [33]
	Brazil	0.40 ± 0.03	15.24 ± 0.19	0.33 ± 0.01	0.12 ± 0.01	–	83.91	Nogueira et al. [54]
	Indonesia	0.93	13.95	1.00	1.79	4.56	73.53	Hasibuan et al. [65]

* All values were expressed as main ± standard error ($n = 3$).

digestible and nutritional foods when they have been peeled and cooked [50]. This can be a basis for further study and product development for food and animal feeds.

3.2.1.1. *Chemical composition of arrowroot starch.* Gordillo et al. [29] examined the properties of AS to explore their potential as a novel alternative polymer. Table 3 (b) displayed that Arrowroot starch registered superior amylose content (35.20%) when compared to other starches such as tapioca (17%), sago (24–27%), potato (20–25%), wheat (26–27%) and maize (26–28%) [51]. Because of its high amylose content, the starch of arrowroot may be used to make films with good technical properties, particularly in terms of mechanical strength and barrier properties [19,20,22]. According to Wang et al. [52], the high amount of amylose in starch reduced film solubility and improved film integrity. Whereas Zhang et al. [53] reported that, samples with low values of amylose improves structural and absorption properties and can be used to produce superabsorbent materials such as baby diapers, adults pads, as well as clinical dressings. As for amylopectin, it is a highly branched polysaccharide component of starch that consists of hundreds of shorts chains formed of α-D- glucopyranosyl residues with (1 → 4) linkages. AS have low protein and fat contents of 0.40% and 0.12% (w/w), respectively [54].

3.3. *Water absorption index and water solubility index of arrowroot starch*

There are several functional properties of arrowroot starch which include water absorption index (WAI), water solubility index (WSI), an oil absorption index (OAI) of starch. The amount of water occupied by the granule or starch polymer after swelling in more water is determined by WAI, while WSI measures the number of polysaccharides or polysaccharide discharge from the granule when additional water is added [66]. According to Seena et al. [67], oil absorption index of flours and proteins is an essential functional property in food. Besides, OAI influences taste, texture, mouthfeel, as well as product yield. In a study conducted by Jyothi et al. [68], dry powdered starch was thoroughly mixed with a sufficient amount of purified water and placed in the refrigerator for 7 days, with intermittent mixing to correct the distribution of

Table 3b – Chemical composition of Arrowroot starch and other commercial starches.

Starch	Moisture content (%)	Density (g/cm^3)	Amylose (%)	Ash (%)	Reference
Arrowroot	15.24	–	35.20	0.33	[37]
Potato	18–19	1.54–1.55	20–25	0.4	[55,56]
Wheat	13	1.44	26–27	0.2	[51,55,56]
Sugar palm	15	1.54	37.60	0.2	[57]
Maize	12–13	1.5	26–28	0.1	[51,55,56]
Sago	10–20	–	24–27	0.2	[58,59]
Tapioca	13	1.446–1.461	17	0.2	[56,60]

Table 4 – Difference between functional properties of native starch and extrudates [68].

Types of starch	Water Absorption Index (WAI)	Water Solubility Index (WSI)
Native Starch	1.81 ± 0.56 g gel/g	1.16%
Extrudate Starch	8.85 ± 0.67 g gel/g	15.92%

* "g gel/g" means the weight of the wet sediment (g)/initial weight of the dry starch(g).

moisture in the sample. Afterwards, the sample was extruded. The extruded starch would have different functional properties as compared to the native starch [68]. The study revealed that the extrudate had higher values of water absorption index and water-soluble index than the native starch as shown in Table 4. The highest WAI of 8.85 ± 0.67 g gel/g dry sample was observed at 160 °C with 16% moisture. This phenomenon indicated higher cold paste viscosities for the extrudates [69]. According to Badrie and Mellowes et al. [70], the extruded cassava flour has high WAI and WSI than unmodified flour.

Granados et al. [71], stated that starch granules do not swell significantly at temperatures below 60 °C. This gradual increase in swelling power with the temperature implies that the internal associative forces that sustain the granule structure of the bead were still high and powerful, thereby resisting swelling [72]. Nogueira et al. [14] also reported that the swelling power of arrowroot starch had increased from 2.17 ± 0.21 g/g to 11.32 ± 0.53 g/g as the temperature was raised from 60 °C to 90 °C as the graph shown in Fig. 5. This might be attributed to the continuous heating of water temperature triggers a strong vibration of starch granule molecules, resulting in the rupture of intermolecular hydrogen bonds in amorphous regions. In Fig. 5, the solubility of arrowroot starch was observed, where the value had increased from 1.59 ± 0.60% to 17.22 ± 1.43%. Similar results have been reported by Perez et al. [73], that solubility of arrowroot starch was 2.09% at 60 °C and 13.22% at 90 °C.

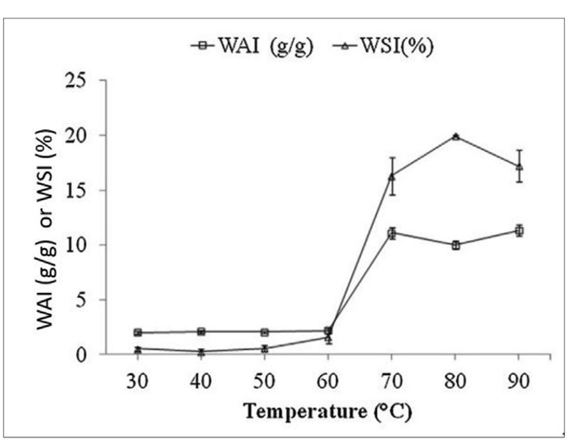

Fig. 5 – Water absorption index (WAI), water solubility index (WSI) for arrowroot starch [14], copyright 2018, Elsevier.

3.4. *Morphological and structural studies of arrowroot starch*

Generally, a scanning electron microscope (SEM) is used to observe the morphological properties of the fibre or starch granules. According to Charles et al. [74], the controlled arrowroot starch was visibly observed as a smooth and spherical structure with a size of around 7–16 μm. After acid hydrolysis, it became irregular in shape and enlarged to around 11 μm–22 μm size granules whereas no structural change was observed [75]. Besides, Erdman et al. [64] observed the shape of arrowroot starch round, oval, and polygonal and size ranged 10–16 μm. Fakhouri [37] reported that a combination of cranberry powder in starch will result in a rough and uneven film surface. According to Astuti [75], no substantial deviations were found in the arrowroot starch granules morphology after acid hydrolysis.

The SEM images of arrowroot starch are shown in Fig. 6. It displayed uneven and circular geometries from ellipsoid to oval of starch particles. The surface of arrowroot starch granules was smooth, without cracks sign. In another study, results revealed that the arrowroot starch granules have circularity ranges from 0.74 to 0.99, roundness values from 0.39 to 0.96 and elliptical values from 1.05 to 2.54, which confirms the existence of spherical and elliptical shapes [30]. Several authors also found a circular and semi-circular shape of 8.6–42.02 μm size for similar starch [27,64,72,73,76].

3.5. *X-ray diffraction (XRD) analysis of arrowroot starch*

The crystallinity (%) of a sample is defined by the intensity ratio of the diffraction peaks and of the sum of all measured intensity. X-ray diffractometry technique was used to determine the arrowroot starch's crystal structure. Commonly, starch has a semi-crystalline structure consecutive to various polymorphs, that can be categorized into several groups of allomorphs. The grouping depends on various X-ray patterns and their features [77].

Villas-Boas et al. [78] revealed A-type crystallinity in arrowroot native starch, with principal peaks at $15^{0,}$ $17^{0,}$ 18^{0} and 23^{0}, by Moorthy et al. [79], who recorded type A crystalline structure in arrowroot, cassava, and other tuber starches such as yams. According to Valencia et al. [30], the arrowroot starch was characterized as a B-type crystal structure with diffraction peaks around 5.61^{0}, 17.12^{0}, $22.3^{0,}$ and 24.11^{0} accompanied by an interplanar distance' is equal to 1.58, 0.52, 0.40 and 0.37 nm. Furthermore, 29.1% of crystallinity was recorded in the arrowroot starch. The study by Nogueira et al. [14], stated that the crystal structure of arrowroot starch was a C-type pattern by the peaks of $2\theta = 5.68^{0}$, 17.42^{0} and 23.14^{0} as presented in Fig. 7. In summary, the B-type crystallinity pattern of arrowroot starch may be linked to the long branch chains of amylopectin [80], whereas A-type is specific to the short chains of amylopectin [81].

The arrowroot starch is a natural starch with a type A crystalline form of 20% crystallinity. Upon heating with polyvinyl alcohol (PVA) during film preparation, the arrowroot starch's crystalline structure had changed to an amorphous structure, which increases swelling and water adsorption. The citric acid was used to increase the crystallinity of PVA film,

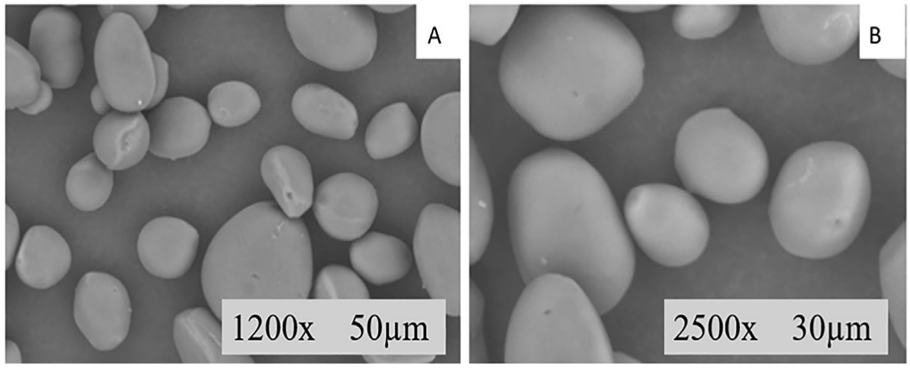

Fig. 6 – Morphological images of arrowroot starch granules with (A) 1200x and (B) 2500x magnification Adapted from ref. [14], copyright 2018 Elsevier.

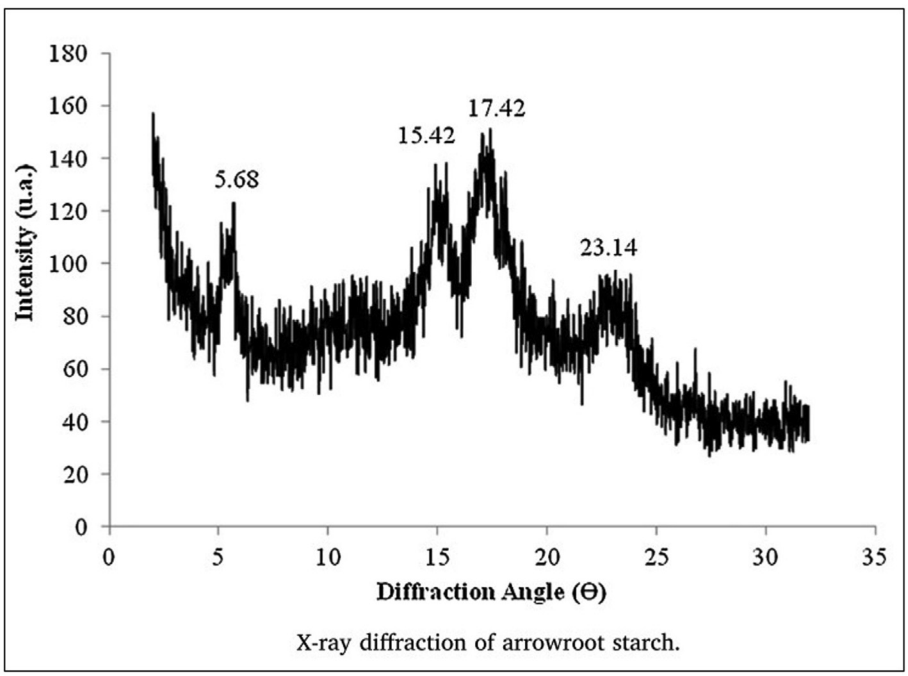

Fig. 7 – X-ray diffraction of Arrowroot starch [14], copyright 2018, Elsevier.

which increased the intermolecular interaction between arrowroot starch and polyvinyl alcohol. The intermolecular interaction between arrowroot starch and polyfunctional compound like PVA was increased due to cross-linking. PVA can react with the hydroxyl group of amylase which strengthens the hydrogen bonds in the starch chain [82].

3.6. *Pasting characteristics of arrowroot starch*

Pasting is a process of determining the swelling index of the starch kernel, the leaching of polysaccharides, as well as the change in viscosity and essential formation of amylose after the gelatinization process [83]. To calculate the viscosity of starch, a Viscoamylograph or a rapid Viscoanalyzer system could be used; in the meantime, the pasting temperature could be observed by raising the onset viscosity at the end of the cooling and heating period [84]. According to Zobel et al. [85], the pasting properties of arrowroot starch depends on the granule structure, the amylose, amylopectin content, porosity, and starch particle size. In a study done by Srichuwong et al. [86], the high pasting temperature starch indicates greater resistance to swelling and rupture. The starch gelatinization process of arrowroot starch breaks down the intermolecular bonds of starch molecules in the presence of water and heat, allowing the hydrogen bonding sites (the hydroxyl hydrogen and oxygen) to absorb more water. Consequently, the starch granules swelled, and this produces a pasting behaviour. The pasting viscosity of modified starch was calculated using a method proposed by Charles et al. [74].

Initially, the temperature of semi-solid starch was elevated to 95 °C and kept constant for 5 min. After that, the temperature was brought down to 50 °C and kept constant at that temperature for 2 min. The viscoamylographs was used to find out the maximum, constant, and final value of viscosity [74]. According to Madineni et al. [27], the starch was kept at a temperature of 92 °C with 14% humidity at a heat rate of 7.5 °C/min for 5 min. After that, the temperature was reduced to 50 °C and remained steady at this temperature for 1 min. According to the study, it was seen that the arrowroot starch attended a higher gelatinization temperature (74.8 °C) than other roots such as sago (68.28 °C) and another result showed that the viscosity of the starch dropped from 498 BU to 455BU within 5 min. The reduction of thickness shows that it could be used for frozen food application [27,87]. According to Franklin et al. [81], the pasting temperature of arrowroot starch had been detected at 77.8 °C.

3.7. *Thermal properties of arrowroot starch*

3.7.1. *Thermogravimetric analysis (TGA) of arrowroot starch*

The thermogravimetric analysis curve displays the weight degradation and weight derivative as the temperature is raised gradually [14]. There were two stages of decomposition in temperature between 25 and 600 °C as shown in Fig. 8. Franklin et al. [81] mentioned that the preliminary stage of degradation typically takes place at the 25–200 °C temperature range, which resembled the loss of moisture content from starch. After analysing this thermogram, it was found that 13% of total weight degradation occurred below 200 °C which was approximately the initial moisture content (15.24 ± 0.19%), and approximately 40% between 330 °C and 410 °C owing to depolymerization of starch macromolecules and around 600 °C it was completely decomposed. By these results, it can be mentioned that arrowroot starch is thermally stable and has favourable characteristics for the manufacture of biodegradable and bio packaging films.

3.7.2. *Differential scanning calorimeter (DSC) study of arrowroot starch*

A differential scanning calorimeter is used to analyse the thermal behaviour of arrowroot starch. In a study conducted by Valencia et al. [30], the recorded the gelatinization temperature at 65.50 ± 0.10 °C, which is considered a precise endothermal point. Besides, the value of the total enthalpy of arrowroot starch was found to be at 8.42 ± 0.57 J/g. Some previous studies reported that the value of the total enthalpy of arrowroot starch ranged from 10 to 19 J/g [64,73,76]. According to Cooke & Gidley et al. [88], the value of crystallinity is directly proportional to the gelatinization temperature and total enthalpy. Granule swelling, crystal melting, and amylose leaching are the processes involved during gelatinization. Higher heat is possible to reduce the amorphous portion of starch [89]. There was a movement of amorphous chains at a glass transition temperature ranging from 118.37 °C to 120.34 °C resulting from the heating of polymeric materials as shown in Fig. 9 [14]. Chuang et al. [90] reported that the thermogram of potato starch showed T_g of 161.72 °C and 141.91 °C with the moisture content of 3.7% m/m (UR 11%) and 18.8% m/M (UR 75%) respectively, while tapioca starch films presented T_g of 150.10 °C and 137.50 °C with the moisture content of 7.34% w/w (23% RH) and 19.52% w/w (75% RH), respectively [91]. There was an increase in contact between polymer chains in Arrowroot starch when the amount of water was low. As plasticizer was added in arrowroot starch-based films, it resulted in more spacing as well as increment of the movement of the polymer chain and dropped the temperature. In addition to humidity, the starch T_g also relies on its amylose and amylopectin content, the molecular interactions between starch and low molecular weight cosolutes, and the essence of the measuring protocol used [92].

3.8. *Rheological characteristics of arrowroot starch*

Rheological characteristics analysis is used to evaluate the substantial gel performance of arrowroot starch. Elastic modulus (G′), viscous modulus (G″), and phase angle (δ) of arrowroot starch gels were resolution with frequency ranging from 0.1 to 100 Hz which is within the range of viscoelastic. After analysis of arrowroot starch gels, it was found that as the frequency was increased from 0.1 Hz to 100 Hz, the value of elastic modulus (G′) had increased whereas the viscous modulus (G″) had decreased [27]. Two different gel compositions were analyzed: 10% and 12% of starch content. The study revealed that the gel formulated with 12% starch content, which contains around 4% sucrose and 1% protein, was more flexible compared to the gel with lower starch content [93]. According to Rodrigues et al. [93], the inflexibility of arrowroot

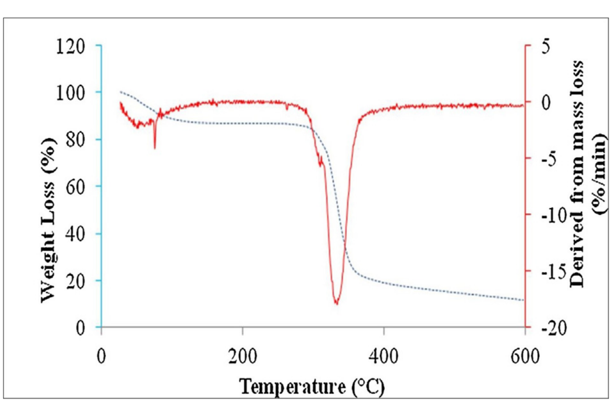

Fig. 8 – TGA curve of arrowroot starch Adapted from ref. [14], copyright 2018, Elsevier.

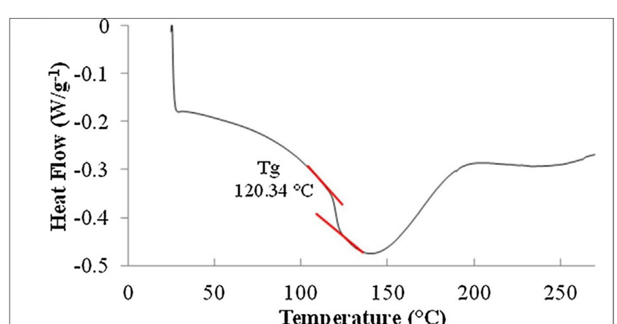

Fig. 9 – DSC curve of arrowroot starch Adapted from ref. [14], copyright 2018, Elsevier.

starch gels was found to be directly proportional to sucrose value and inversely proportional to protein. The Power Law model is a model that is commonly used to evaluate the flow behaviour index. The flow behaviour index of arrowroot starch suspensions was found to be at 0.66 ± 0.01. A value of less than 1 indicates pseudoplastic behaviour that corresponds to the breakdown of amylose and amylopectin chains as the first shear rate was applied [30].

3.9. *Modification of arrowroot starch*

Native starch has a high hydrophilicity and poor mechanical properties. Therefore, a wide range of modification methods are used to mitigate these two drawbacks and improve the properties of biopolymers in order to fulfil consumer expectations and reduce their cost, as they already more costly than commodity polymers [94,95]. One solution that has been used is chemical modification of starch. Derivatization of starch, such as etherification, esterification, cross-linking and grafting of starch, and decomposition, is the most common method of starch modification (acid or enzymatic hydrolysis and oxidation of starch). This modification has a significant impact on starch gelatinization, pasting, and retrogradation behaviour [96,97].

Astuti et al. [75] reported that, all physical changes applied to the starch in this sample did not substantially improve the resistant starch (RS). Meanwhile, Faridah et al. [98], reported increasing RS content during autoclaving-cooling (AC) and the combination of both AC and acid hydrolysis (AH), but similar results for RS content during AH treatment were reported. Besides, there was no change in the RS content than control due to AH similar to Faridah et al. [98] Similar studies were reported by Ozturk et al. [99] and, Nasrin et al. [100] that, there had been no notable change in RS content between native and modified corn starch and culled banana starches under the both of AH as well as AC treatment. Based on these findings, it is possible to conclude that AH and other physical changes such as AC and the combination of AH and AC do not always result in an improvement in resistant starch content.

Arrowroot starch was modified with the help of AH, which improves its solubility characteristic without disturbing its granule structure. In addition to this modification, the AC process can also enhance water-holding ability. However, this process influenced the granule as well as the arrowroot starch molecular structure. Modified starch from arrowroot has been used in numerous food items [75]. Kim and Ahn et al. [101] stated that, AH reduced the viscosity and increased the gel strength. Another similar study revealed that the breakdown of the starch polymeric chain leads to a reduction in thickness and increment of solubility as well as water holding capacity [102].

3.10. *Starch biopolymers*

The research is turning more and more towards the biopolymers regarding the characterization and development as its counterpart that is synthetic plastic materials are non-degradable [103,104]. In the list of biopolymers, starch comes at the top of the list because of its many advantages such as availability, lower cost, biodegradability, and renewability [105–107]. They can be found in plants like wheat, corn rice and potatoes in the form of stored carbohydrates [108]. The hydrophilic polymers are present in separate form and incomplete crystalline microscopic granules joined together by a micellar network of connected molecules [109]. Starch contains linear and branched polysaccharides which are also called amylose and amylopectin. The ratio varies with the botanical origin in native starch the ratio is 70–85% amylopectin followed by 15–30% amylose [110]. The process of crystallization in starch granules is due to amylopectin. There is a well-built intermolecular connection of hydrogen bonding in starch granules surface which are made up of hydroxyl groups [111]. The production of starch is influenced by the presence of multiple intermolecular hydrogen bonds, which have resulted in a higher temperature of starch than its temperature of decomposition. Plasticizers such as glycerol, water and sorbitol are used to promote the free volume rise and therefore decrease the softening temperature as well as the glass transition [112]. Thermoplastic starch (TPS) is created where there is a disturbance of the molecular structure of the starch where the heating of the starch granules induced swelling and non-irreversible transformation of the amorphous regions to the present plasticizer under a particular condition [113].

3.11. *Processing of biopolymer from arrowroot starch*

Starch has emerged as a possible future green resource to replace non-biodegradable plastic [114]. Arrowroot starch plays a significant role in the development of a biopolymer. In this context, the combination of arrowroot starch and natural rubber can enhance the elastic nature as well as decomposability [115,116]. It was also proven that the arrowroot starch with glycerol content could produce durable polymeric matrices in the membrane [29]. Besides, edible films with a biopolymer matrix were also successfully created by incorporating blackberry pulp into arrowroot starch. The use of fruit pulp has many advantages such as acting as natural antioxidants, antimicrobials, colourants, flavouring as well as improving the mechanical properties of bio-polymatrix [54]. Bio-based reinforcement materials can also be incorporated with the biopolymer to improve mechanical properties such as tensile and impact strength [117].

4. Arrowroot composite films

4.1. *Processing of edible composite films from arrowroot starch*

The active packaging is used to improve the life of consumable items as it contains active compounds such as antioxidants and antimicrobials [118,119]. An antioxidant is an essential component in an active film. It plays a key role in food packaging to reduce the possibility of food damage rate by preventing the oxidation process of oils or fats [118]. Due to its high amylose content (35.20%), it is suitable to produce films. The edible films were developed by mixing the glycerol and starch at a 1 to 1.4 ratio and compressed at 100 bar for 15 min at 130 °C [28]. To make compelling edible films, organic polymers such as PVA was added to arrowroot starch. PVA has many benefits such as transparent, non-toxic, thermally stable, and degrades easily [120–122].

According to Nogueira et al. [123], as the blackberry powder incorporated with plasticized arrowroot starch films with 0,20,30, and 40% (blackberry particles mass/biopolymer mass), it showed good results in terms of properties enhancement such as thickness, water permeability, water vapour penetrability, elongation at break and reduced the tensile strength of the films as compared to control films. Moreover, the films became less transparent and less luminous [123]. The thickness of the blackberry particle incorporated films significantly increased which varied from 0.065 to 0.153 mm with rising concentration (0%–40%). This phenomenon attributed to the increment in the content of blackberry powder in the same mass of film-forming solution in the same plate. The water vapour permeability and solubility of films also enhanced significantly with an increment of blackberry powder in films as compared to the control film. This tendency can be due to the extremely hygroscopic and hydrophilic nature of blackberry powder, which gives the film a higher tendency to bind to water molecules and thus better solubility and permeability. Similar attributions had also illustrated that moisture movement typically takes place through the hydrophilic part of the barrier and is closely connected to the hydrophilic-hyrophobic ratio of its elements [124,125]. The mechanical properties of films with blackberry powder significantly changed as lower tensile strength and higher elongation at break. These findings demonstrate the plasticizing effect of blackberry powder, which can be directly attributed to its sugar content. Blackberry is a fruit abundant in sugars such as fructose, glucose as well as sucrose [126]. Studies have documented the plasticizing effect of sugars found in fruit when introduced into polymer films [127–129].

In another study, Nogueira et al. [54], evaluated the effect of blackberry pulp on properties of arrowroot starch-based films. In this study, the results showed that increased concentration of blackberry pulp (from 0 to 40%, dry starch mass/mass), resulted in raised thickness (from 0.065 to 0.133 mm), increased elongation at break, water vapour permeability and solubility (from 3.18 to 13.59%), (3.62–4.60 g.mm/m^2.day.k.Pa) and (14.18–25.46%) respectively, while tensile strength reduced (from 22.71 to 3.97 MPa). Zhai et al. [130], also reported the same decreasing trend in tensile strength (from 48.97 MPa to 41.85 MPa) with the incorporation of roselle *(Hibiscus sabdariffa* L.) anthocyanins, rising from 30 to 120 mg/100 g of starch, whereas elongation at break enhanced (from 44.15% to 88.28%). These phenomena in film properties are caused by the structures extracted from blackberry pulp, such as proteins, fibres, lipids, sugars and which produce polymer matrix discontinuity.

Fakhouri et al. [37] studied the effect of the incorporation of cranberry powder (0, 5, 15, 25, 35, 45, and 55%) on the thermal properties of gelatin and arrowroot starch films produced by casting. The DSC results demonstrated that T_g of the films based on arrowroot starch and gelatin (%) began around 121.2 °C however, the glass transition temperature range decreased as the concentration of cranberry powder in films was increased by 5–55%, implying T_g around 118.8 and 101.2 °C. According to studies of Azeredo et al. [131] and Otoni et al. [128], when fruit pulps are added into the polymeric matrix of the film, the sugar present in the fruit may have a plasticizing effect. The plasticizer works in the film by changing the interface between the polymers, increasing the free volume of the structure and, as a result, an increase in chain motility and a decrease of the T_g of the system [132,133].

4.2. *Arrowroot starch/PVA blends/PHA blends*

According to Yulianti and Ginting [134], the film made of arrowroot starch had the best mechanical properties compared to cassava, sweet potato, and achira. Negim et al. [82] and Liu et al. [135] conducted similar research on starch (S) and polyvinyl alcohol (PVA) based polymer blends to improve the water barrier and thermal properties of films. PVA is preferred as an essential constituent of edible packets due to its high constancy on oil or fat, excellent tensile strength, high elastic nature, and ease to decompose [135]. From the result conducted by Negim et al. [82], DSC and SEM analysis of PVA/S blend showed a single glass transition temperature which indicates a single-phase and completely miscible blends due to the formation of hydrogen bonds between the hydroxyl groups of PVA and starch. Also, PVA/S blend film exhibited better mechanical properties, thermal stability as compared to pure PVA film. More interestingly, the results showed that the decomposition of PVA/S blends film happens within 10–14 days in dry soil depending upon the molecular weight of PVA. Blend films with PVA (31×10^3 g/mol) presented decomposition time 10 days whereas, films with PVA (205×10^3 g/mol) molecular weight decomposed within 13–14 days. On the other hand, with all PVA/S blends, the decomposition of the blend films in moist soil is accomplished within 3 days. This could be attributed to the presence of water in the soil, which is significantly reduced the decomposition time in moist soil by increasing the solubility of the PVA/S blend, contributing to short-term biodegradation. Therefore, an enhancement in biodegradability of PVA/S blend films and particularly in moist soil could be exploited for the manufacturing of biodegradable and environmentally friendly packaging materials at a low cost. Garcia et al. [136], reported that any alteration or changes in the physical and thermal conditions would affect the mechanical characteristics of the film. According to Sholichah et al. [137], the tensile strength of the film had improved by incorporating the PVA with starch by more than 1%. Besides, Negim et al. [82], described that the tensile strength could be further enhanced by the formation of hydrogen bonds in matrices. On top of that, the tensile strength of films can also be influenced by cross-linking of bonds between starch molecules, as the addition of citric acid in arrowroot starch-based film has reduced the tensile strength [138,139].

Recent developments in the field of arrowroot starch products have led to a renewed interest in the development of bio-based membranes. It can be done by enhancing the versatility and mechanical properties. Polyhydroxyalkanoate (PHA) is commonly used among all other biopolymers because it has desired features such as bio-adaptability, eco-friendly, non-toxic, and excellent mechanical properties [140,141]. Hence, PHA was blended with arrowroot starch powder (ASP) [142]. In some cases, additional treatment was required to improve the desired properties of these membranes such as grafting PHA with Acrylic acid (A.A.), i.e., PHA-G-AA, and treated ASP. After a review of several studies, it was proven that treated membranes had higher water resistivity and better mechanical properties [142].

4.3. *Fabrication processes and issues in development of biocomposites*

Various fabrication approaches have been utilized for bio-composites. These are devided in to two groups based on the form of reinforcing used: (1) particle or small fibres and (2) continuous fibres. Woven fabric preforms made from natural fibres have been used as reinforcements in continuous fibre reinforced biocomposites [143].

Besides, the efficiency and sustainability of natural fibre composites are dependent on the method of fabrication, which is dependent on the quality of the fibres and their volume proportion, as well as the processing conditions, namely temperature and pressure [144]. Table 5 includes a good overview of the various fabrication processes and advantages and limitations.

5. Natural fibres

Synthetic fibres are dominating the composite industries for several decades [151], but on the other hand, they are also the main cause of health and environmental issues [152,153]. The manmade fibre poses hazard and problems both for humans and nature as they are non-biodegradable, in contrast with the natural fibre (fibre from plants and animals) which poses no such problem as they are biodegradable [154]. Individual properties vary which depends majorly on geographical locations, processing techniques, application of reinforcement etc [155,156]. The extraction of natural fibres is done in various steps followed by trivial to high-end techniques and processes. In the initial stage of extraction, the fibre is in the form of a long-chain lignin matrix, also known as lignocelluloses fibres. Natural fibres are used in polymer composites as reinforcements. Various types of natural fibers had been used as reinforcement in polymer composites, including corn [157], water hyacinth [97], coir [158], ginger [121,159], cotton [160], kenaf [161–163], sugarcane [164], flax [165], ramie [166], hemp [167], kapok [168], sisal [169], wood [170], oil palm [171,172], banana [173] as well as sugar palm [6,174–179]. There is a subdivision of natural fibres as leaf, bast, fruit, stalk, seed and grass fibres [113]. Along with biodegradability natural fibres comes with many other advantages such as a substitute of timber for wood plastic composite, it is less costly, easily available and reduces deforestation [180]. Natural fibres have huge potential to be converted into useful products. The research of Ilyas et al. [155] reveals that natural fibre is the right material for the replacement of glass and carbon fibre.

5.1. *Classification of natural fibres*

The basis of dividing natural fibre depends on their origin like either it is from plants or animals or minerals [181]. The natural fibre application as reinforcement in bio-composites comes from plants. The division among the fibres is done based on from where and from which plant the fibre is extracted [182–184]. Different classes of plant fibre are depicted in Fig. 10, which include bast, leaf, seed, fruit, stalk, and grass fibres. The above-mentioned fibres fall under the category of non-wood fibres.

Today more and more researchers are interested in researching non-wood fibre. As gives great help in the preservation of nature and reduces deforestation. The consumption of wood in wood-plastic composites for construction and other applications will be reduced on a large scale. For example, the world's highest rate of forest loss was reported by Malaysia from 2000 to 2012 which was 14.4% of total forest equivalent to 47,278 km^2 [184]. Hence non-wood natural fibres are a great alternative for preventing ongoing deforestation. Malaysia contains a huge amount of natural fibre resources that can be used as an alternative for synthetic fibres, for examples natural fibres like kenaf, coconut fibre, sugar palm fibre, sugarcane, sago, pineapple leaf, cocoa pod husk to oil palm fruit bunches of oil palm fronds, oil palm trunks and many others come in this list. The majority of these natural fibres have a strong potential to turn them into valuable products.

6. Arrowroot fibre

Many natural fibres are dumped or burnt, which is inefficient for the fibre stock and can pollute the environment [185]. Arrowroot fibre is also abandoned among the many waste fibres; arrowroot rootstock includes a large volume of fibres, starch and carbohydrates; a large volume of waste arrowroot fibres are produced during the processing of arrowroot [186]. A review of the literature revealed that approximately 38.1% of bagasse residue fibre was found in arrowroot [34]. A massive amount of waste is produced during the processing of arrowroot starch [187]. According to a study conducted by Branco et al. [188], the arrowroot fibre is coarser and longer compared to cassava. Fig. 11 displays the residue that was obtained from the starch extraction mill. The fibre is short in length and small in diameter. Therefore, It can be summarised that the fibre can be used to make tear-resistant paper such as bags and wrapping paper [34].

According to Phil FIDA, Indonesian Fibre Utilization, and Technology Division, fibres with lower than 65% of holocellulose content are considered as low pulp producers [47]. In general, at least 65% of holocellulose content is required to produce pulp and paper.

Table 5 – Various fabrication processes of composites with advantages and disadvantages.

Fabrication process	Methods	Advantages	Disadvantages	References
Solution Casting	Polymer is dissolved or dispersed in solution, coated onto a carrier substrate, and then the water or solvent is removed by drying to create a solid layer on the carrier. The resulting cast layer can be stripped from the carrier substrate to produce a standalone film.	• Solution casting delivers high-quality thin-film products with improved optical and physical properties. • Uniformity of thickness and dimensional stability	• The polymer must be soluble in a volatile. • Not suitable for large scale production. • Takes a long time to dry	[145]
Injection moulding	For injecting molten pellets, the split chamber was used. After the split chamber, with the help of cooling system the temperature of natural composites fibre was decreased.	• The operating cost of this method is low. • The complex shapes can be produced.	• High tooling costs and long lead times.	[146]
Hand lay-up moulding	This is an easy technique to fabricate natural fibre composites. Resins are employed to fibres and layout is constructed layer by layer before the desire thickness has been achieved. Finally, refrigeration is carried out under normal conditions to obtain natural fibre composites	• It promises high accuracy and low tooling costs.	• Considerations of health and protection of resins. • In general, the lower molecular weights of hand lay-up resins make them dangerous than higher molecular weight composites. • The lower viscosity of the resins often leads to a stronger penetration of clothing etc.	[147]
Sheet moulding	A measured resin quantity with a supporting carrier foil is put between two sheets and is sent to storage via rolling. Later natural fibre composites can be achieved by heat, pressure and curation of the stored material.	• It requires less labour at production level.	• Sheet Moulding Compound parts have poor stiffness and strength, this is due to low fibre-volume fraction, a short fibre length and isotropic fibre distribution.	[148]
Extrusion moulding	This process begins with stored material (pellets form) in a hopper, then melts by heating. This molten product is used to obtain the needed shape and then cooling in last to obtain the required natural fibre composites.	• High strength and stiffness in NFCs obtained by this method. • The production costs are low. • Flexibility in manufacturing products with a uniform cross-section.	• At the time of process, expansion of plastic took place called die swell.	[149]
Resin transfer moulding (RTM)	Preheated resin would be poured into the holding chamber and injected into the preforming plastic. To prevent air bubbles, vacuum is preserved.	• Consistency of the product is better in this method in comparison to other methods. • This method is also suitable for very large components	• Reinforcement materials are limited due to the flow and resin saturation of the fibres.	[148]
Resin infusion moulding (RIM)	RIM is a twin moulding process, which starts with the moulding laying dry fibres in flexible metal face which is pressed down over composite. At last, to ensure product quality, it is exposed to vacuum.	• This approach will obtain NFC in a short time.	• Tooling cost is higher. • Surface is not finished.	[148]
Compression moulding (CM)	Preheated material in the mould cavity is compressed until NFC solidifies.	• It has very little wastage material and decent finish surface	• Slower process times, not suitable for complex moulds and Difficult to control flash.	[150]

Capiña et al. [47], reported that the extracted fibres and pulp had low bonding strength, small surface roughness, as shown in Table 6. The properties can be improved with the aid of high technology processes, chemicals, and different types of binding agents [47]. The performance of composites is affected by several aspects such as the orientation [189], strength [190], physical properties [191], and interfacial character of the fibre [192].

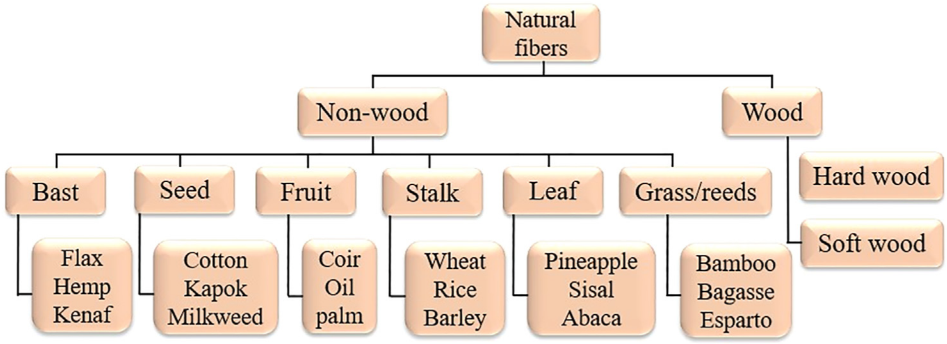

Fig. 10 – Classification of natural fibres, Reproduced from ref. [113], copyright 2016, Elsevier.

Fig. 11 – Arrowroot fibre obtained from arrowroot tubers, Adapted from ref. [188].

Table 6 – Physical testing of handmade paper from waste rhizomes "Sapal" [47].

Parameters	Handmade Paper
Density (bulk)	257 (kg/m^3)
Thickness	1410 (μm)
Air Permeability	0.420 (Gus)
Tensile Index	4.44 (Nm/g)
Elongation	3.41 (%)
Basis Weight	326.8 (g/m^2)
Tear Index	9.4 (mN.m^2/g)

6.1. *Downsides of arrowroot fibres as reinforcement for polymer composites*

6.1.1. *The hydrophilicity of natural fibres*

In industry, the outdoor applications of natural fibres had limited due to moisture content such as construction building parts and automotive parts. Besides, the swelling of starch and the attack of microbial will also be increased. These drawbacks of natural fibres would also impact long term accessibility, processing of composites and time spam of delivery. According to Burgueno et al. [193], the swelling of natural fibre does not only change the mechanical and physical properties, as well as decreases the strength of the dimension of the composite. The formation of the gel depends on the hydrophilic nature of starch.

6.1.2. *Poor fibre – matrix adhesion*

There are many limitations to the use of natural fibres in which poor fibre-matrix adhesion is also an important factor [194–196]. In general, the natural fibres have found hydrophilic properties whereas thermoplastic/thermoset polymer is hydrophobic. Due to this dissimilarity between natural fibres and polymers, poor adhesion properties are found. To transfer the load to the fibre through shear stress, the matrix is required strong bonding between natural fibre and polymer matrices. Therefore, the natural fibre reinforced polymer composites would show low mechanical properties because of poor adhesion between fibre and matrices. Using chemical "coupling" or "compatabilising" agents during fabrication may improve the affinity and adhesion of natural fibres and thermoplastic matrices. Hence, various surface modifications are conducted on arrowroot fibres to improve their adhesion with different matrices [26,142,197].

6.1.3. *Low thermal stability*

Low thermal stability is also a barrier to the usage of natural fibre as reinforced composites. Above 200 °C temperature, most of the natural fibres start to degrade while below this temperature they can endure degrading. When natural fibre would attend high temperature (>200 °C) it alters its chemical and physical properties due to the recrystallization process, depolymerization, oxidation, decarboxylation, and hydrolysis. It is essential to control the range of temperature, pressure and time to avoid these types of processing defects [198].

6.2. *Mitigating the downsides of arrowroot fibre and starch for better reinforcement*

It is essential to overcome the limitations of arrowroot fibres in order to maximise their optimum potential as a substitute for man-made synthetic fibre. This can improve the properties of AF reinforced polymer composites and, as a results, indirectly increase their area of application. Poor adhesion between the fibre and matrix, resulting in low mechanical properties, is a major problem for the most of the parts connected to AF reinforced polymer composites. As a result, it is important to improve the incompatibility of AF and polymer matrix. Several studies were caried out to enhance the AF surface by surface modification procedure in order to improve the mechanical properties of biocomposite as summarised in Table 7.

6.3. Treatment of arrowroot fibres

The surface treatment of natural fibre composites is required to enhance interfacial properties. The aspect ratio of arrowroot fibre that is suitable for fibre preparation varies from 40 to 80, whereas a higher ratio than 80 is ideal for synthetic reinforcement fibres. The procedure of surface treatment usually starts with washing and drying the untreated arrowroot fibres. Then, the fibre was treated with alkaline treatment using a 1% aqueous NaOH solution for about 3 h at 50 °C and cleaned utterly and dried afterwards. The treated fibre was crushed into 300–400 mesh size. The 10 g of crushed fibre and 1 g of silane was immersed in acetone for 12 h. Subsequently, the sample was cured in an oven for 24 h. By treating the arrowroot fibre with NaOH, the interfacial bonding between fibre and matrix can be improved. The enhancement will take place in a composite that contains up to 40% of fibre [197].

6.4. Nano-size fibre (preparation and characterization of nanowhiskers cellulose from fibre arrowroot)

Cellulose can be extracted in different sizes, depending on the intended application [199]. Micro and nanocellulose are the common sizes of cellulose used in industrial applications. Nanocellulose is divided into three types, (1) Bacterial Nanocellulose (BNC) also known as microbial cellulose, or biocellulose [200,201], (2) Nanofibrillated Cellulose (NFC), also known as nanofibrils or microfibrils or macrofibrillated cellulose or nanofibrillated cellulose [95,202,203], and (3) Nanocrystalline Cellulose (NCC), also known as crystallites, rodlike cellulose microcrystals, whiskers or nanowhiskerss [176,204]. The difference between microfibrillated cellulose and nanocrystalline cellulose is the fiber size distributions that are wide in microfibrillated cellulose and narrow or drastically shorter in nanocrystalline cellulose. Recently, arrowroot fibre had been used as a source of raw material to produce cellulose nanowhiskers by using acidic hydrolysis treatment. According to Ilyas et al. [202,205] and Renato Mariano de Sá [26], to prepare the nano whiskers, the lignin and hemicellulose were removed from treated arrowroot fibre using delignification and mercerization treatments. The chemicals that were used to remove lignin and hemicellulose were sodium hydroxide (NaOH) and sodium hypochlorite (NaOCl). After that, the fibre was treated with acid hydrolysis treatment at different concentrations of sulphuric acid (55% and 60%) and temperature (55 °C and 65 °C). The result manifests that the sample length and diameter vary depending on the treatment. For example, in the NA01 sample, nano whiskers that a treated with low acid concentration, and the higher temperature had higher aspect ratios displayed in Table 8. On the other hand, the NA03 sample was also treated with low acid concentration but at a lower temperature showed a longer length and larger diameter of the fibre. Renato Mariano de Sá [26], concluded that nanowhiskers obtained from arrowroot fibre had an optimum crystallinity index and decent thermal stability compared to the literature.

6.5. Properties of arrowroot fibre reinforced composites

6.5.1. Biodegradability of arrowroot fibre composites

The presence of arrowroot fibre in composites has a significant effect on the rate of degradation.

Wheat or cotton based composites have lower biodegradability than cellulose fibre-based composites [191]. For the investigation of arrowroot fibre composite biodegradation, two different compositions of the composite were tested; polylactic acid (PLA)/arrowroot fibre (AF) (PLA/AF) (20 wt%) composite and PLA-g-GMA (glycidyl methacrylate)/TAF (treated arrowroot fibre) (20 wt%) composite and soil incubation were conducted for 30 and 60 days as shown in Fig. 12 [197]. The PLA/AF composites (Fig. 12 E,F) had randomly distributed, wider and deeper holes compared to the PLA-g-GMA/TAF composites (Fig. 12H, I). Moreover, the biodegration of the AF phase in the PLA/AF increased over time. As a function of incubation time, this decomposition was demonstrated by increasing weight loss of the PLA matrix, which reached almost 14% after 60 days. Biodegradation was the most possible cause of this reduction of weight. The composite PLA-g-GMA/TAF (20 wt%) was decomposed rapidly compared to neat PLA and had larger and deeper pores. The weight loss rate of the PLA-g-GMA/TAF composite was also faster than that of PLA, exceeding 45% after 60 days. This behaviour was due to the comparatively slow degradation impact of soil water and microbes on PLA-g-GMA bonding with TAF. Wu et al. [197] reported the result that the degradability of the composite had increased by adding TAF with PLA-g-GMA.

6.5.2. Enhancement of properties of arrowroot fibre biopolymer composites

Recently, there has been renewed interest in the addition of (PLA) with agricultural residues of arrowroot fibre [197]. Because, PLA has strong mechanical properties, lightness and processing performance [206–208], and when buried in soil, it decomposes rapidly [209]. Franco et al. [194] reported that the incorporation of bio-fibres with polymers plays a vital role to control the destruction of the eco-environment as well as delivers high mechanical properties of composite materials. The arrowroot fibres are being investigated as a strengthening material in the production of nanocomposites with excellent thermal stability [26]. Recently, nanoparticles such as carbon nanotubes and cellulose nanowhiskers obtained from arrowroot fibres are being used as strengthening materials in nanocomposites [210].

The manufacturing and mechanical properties of arrowroot composites can be improved as the PLA content was changed and as the arrowroot fibres were treated with a coupling agent. And it also reduced the cost of composites because the individual cost of PLA is very high [4]. Coupling agents can be used to make the polymer matrix more compliant with fibre reinforcement [211,212]. It has been noted that when glycidyl methacrylate grafted polylactide (PLA-g-GMA) is mixed with treated arrowroot fibre (TAF), PLA-g-GMA/TAF composite is produced. According to Wu et al.

Table 7 – Summary of the published work on AF and AS for better reinforcement performance.

Author		Manufacturing Technique	Characterization	Description
Chin San Wu et al. [197]	PLA/AF PLA-g-GMA/TAF	Hot press	Structural, thermal, mechanical, and biodegradable properties	• The PLA-g-GMA/TAF composite showed better properties compared to the PLA/AF composite. • The water resistance of the PLA-g-GMA/TAF composite was greater than that of the PLA/AF composite. • The PLA-g-GMA/TAF composite showed better mechanical properties than PLA/AF. • The tensile strength of PLA/AF was decreased from 43.8 MPa to 19.8 MPa, which attributed to the poor adhesion of AF in PLA matrix. • The tensile strength of PLA-g-GMA/TAF composite was increased from 13 to 41 MPa, which ascribed to increased dispersion of TAF in the PLA-g-GMA matrix that developed from branched or cross-linked macromolecules. Also, this showed better compatibility between the grafted polymer and treated fiber. • The glass transition temperature of PLA was increased by addition of fiber, which may have increased the heat resistance of PLA. • PLA-g-GMA/TAF biodegraded at a slower rate than PLA/AF by around 6–10%, but it was still faster than PLA (100%). • Owing to innate biodegradability of TAF, this kind of reinforced PLA matrix will be more environmentally friendly compared to conventional ones.
Chin San Wu et al. [142]	PHA/ASP	Hot press	Structural, Mechanical, antioxidant, cytocompatibility properties	• The PHA-g-AA/TASP membranes had better mechanical properties than the PHA/ASP membrane. • This effect was attributed to greater compatibility between the grafted PHA and TASP. • The water resistance of the PHA-g-AA/TASP membranes was greater than that of the PHA/ASP membranes • Cytocompatibility evaluation with human foreskin fibroblasts (FBs) indicated that both materials were nontoxic. • PHA-g-AA/TASP and PHA/ASP membranes had better antioxidant activity than the control group.
Josemar et al. [127]	Arrowroot starch/ carnauba wax	Solution casting method	Physical, technological, optical	• The presence of carnauba wax reduced moisture content, water solubility and water vapour permeability. • This attributed to the hydrophobic nature of carnauba wax which can bind to the starch network, preventing hydrogen bonds from forming between starch and water molecules and lowering water absorption. Hence, the inclusion of carnauba wax was able to reduce the hygroscopic behaviour of the films. • Regardless of the wax concentration, the addition of carnauba wax reduced the tensile strength and improved the elongation of the films. • The reduced strength attributed to discontinuities in the polymeric matrix, promoted through the lipids, whereas increased elongation is ascribed to the plasticizer effect of the lipid phase wax.

Charles et al. [74]	Arrowroot starch/ Cassava composite Arrowroot starch/ Sweet potato composite	Solution casting method	Gelatinization, enthalpies, freeze–thaw properties	• The impact of arrowroot starches (AS) (10, 20, 30, and 40%) on sweet potato (SP) and cassava starches (CS) were investigated. • CS and SPS recorded lower gelatinization temperature compared to AS. • The inclusion of AS drastically changed the gelatinization enthalpy of SPS and CS, implying that the thermal energy involved during gelatinization to split the structural element in starch granular packaging was drastically changed in the presence of AS. • Freeze-thaw stability is essential in the food industry application. • The water separation from gelatinized arrowroot paste decreased from 38.85% to 2.04% after 1 to 3 freeze thaw cycles, respectively. • Therefore, high gel stability of AS under these conditions meant that it could be used food systems involving refrigeration or freezing processes.
Nogueira et al. [123]	Arrowroot starch/ Blackberry particles	Solution casting method	Physical properties	• The water solubility and water vapour permeability of films enhanced significantly with increasing content of blackberry particles concentration (20, 30, and 40%) in films as compared to control film. • This phenomenon may be ascribed to blackberry powder, that is highly hydrophilic and hygroscopic.
Carlos et al. [29]	Arrowroot starch/ Glycerol Membrane	Solution casting method	Thermal properties	• According to the study of Carlos et al. the thermal instability of films increases as glycerol incorporated. • This is due to an increase in weight loss at temperatures higher than 110 °C, which were related to the glycerol degradation.
Fakhouri et al. [37]	Arrowroot starch/ Cranberry powder	Solution casting method	Microstructure, Thermal properties	• Composite films with cranberry powder (5–55%) concentration resulted in glass transition temperature Tg decreased (118.8 °C and 101.2 °C). • The effect of plasticizer in the film as interaction between polymers, leading to an enhanced in the free volume of the system, and thus to an increase in chain motility as well as reduction of the Tg of the system, as a result less fragile and brittle film for handling. • The films with concentration of cranberry of 45 and 55% were difficult to peel out from casting plates.
Nogueira et al. [54]	Arrowroot starch/ blackberry pulp	Solution casting method	Physical, Mechanical, and barrier properties	• The increment of blackberry pulp concentration from (0–40% m/m dry starch) in the film caused in increased thickness (0.065–0.133 mm), enhanced elongation (3.18–13.59%), decreased tensile strength (from 22.71 to 3.97 MPa), increased water permeability (from 3.62 to 4.60 g.mm/m^2.day.kPa) as well as solubility increased (14.18–25.46%). • The addition of blackberry pulp in arrowroot starch films caused the transferring bioactive compounds, antioxidant capacity and colour. • After sterilization process the film with blackberry pulp showed darkness.

(*continued on next page*)

Table 7 – (*continued*)

Author		Manufacturing Technique	Characterization	Description
Solicha et al. [137]	Arrowroot starch/ PVA blend/citric acid	Solution casting method	Mechanical, Thermal, FTIR, Physical, XRD	• PVA was mixed at 0.25%, 0.50%, 0.75% and 1% and citric acid 0–0.75% with 2 g arrowroot starch. • There was no significant change in tensile strength when the concentration of PVA 0.25–0.75% was used. While the tensile strength of film increased significantly by the addition of 1% PVA. • This might be attributed that, every PVA monomer has –OH group resulting to form hydrogen bonds; therefore, it is possible to increase the tensile strength. • There were no significant changes in elongation at break of the films with the addition of PVA (0.25–1%). • The tensile strength of the film increased by adding citric acid less than 5%. • In summarised, the citric acid significantly affected the film properties.
Nogueira et al. [14]	Arrowroot starch/ Glycerol	Solution casting method	Mechanical, Solubility, Water vapor permeability	• Film with arrowroot starch/glycerol showed the increase in tensile strength (from 11.28 ± 1.46 to 25.79 ± 4.16 MPa higher than other starch-based films like rice, wheat, and sago where tensile strength ranged from 0.93 to 10 MPa. • WVP showed variation from 2.90 ± 0.04 to 8.71 ± 0.09 gmm/m^{2}daykPa similar like wheat, maize, and potato films. • The formulation (starch 4% and glycerol 17% was able to produce good films with lowest water vapor permeability rate as well as highest tensile strength.

[197], the mechanical properties and moisture absorption of this composite (PLA-g-GMA/TAF) are better than PLA/AF.

SEM micrographs were used to examine the morphology of the composites and to evaluate the tensile fracturing surfaces of PLA/AF (20 wt%) and PLA-g-GMA/TAF 20 wt%); the images are presented in Fig. 13. The weak adhesion was observed between the AF and the PLA matrix as shown in Fig. 13a, which was attributed to a large amount of AF being incompletely occupied by PLA. The uncovered AF on the outside showed weak wetting between the AF and the PLA, reducing interfacial adhesion. Besides that, the improved interfacial adhesion in the PLA-g-GMA/TAF was due to increased stability between TAF and the PLA-g-GMA matrix through covalent bond formation (Fig. 13b).

Moreover, the compatibility between the TAF and PLA-g-GMA enhanced by interfacial adhesion enhancement and was significant in the mechanical properties of composites. At failure, the composite (PLA-g-GMA/TAF) reports that the exclusive behaviour of the tensile strength enhanced with increased content of TAF. This study revealed that the original PLA had higher tensile strength than PLA-g-GMA. On top of that, it was demonstrated that PLA/AF had higher water absorption and biodegradation rate than PLA-g-GMA/TFA [197].

Table 8 – Length, diameter, and aspect ratio of the obtained cellulose nanowhiskers from arrowroot fibre [26].

Sample	NA01	NA02	NA03	NA04
Length (nm)	132 ± 33	121 ± 41	160 ± 77	129 ± 45
Diameter (nm)	3.1 ± 1.5	3.7 ± 1.2	4.1 ± 1.2	3.9 ± 1.8
Aspect ratio	46	33	37	35

7. Present applications of composite products from arrowroot

7.1. *Packaging*

There are numerous packaging materials such as paper, plastics, and glass. Petroleum-based plastic is extensively used among all other materials due to its excellent processing and physicochemical properties [213]. About 30 million tons of plastics are used annually for packaging-based applications such as organic mulch films, waste bags, ping bags or food packaging. This value is almost equal to 25% of the world's manufactured plastics, and their use is still on the rise [214]. It was expected that the global production of plastics surpasses 300 million tons by 2015 [213,215].

There are several advantages to using Petro-based products. Nevertheless, it causes severe pollution due to high resistance to degradation. Recently, researchers have shown an increased interest in the use of renewable resources to develop bio-degradable plastics. Over the past few decades, there has been a sharp increase in the application of bio-based packaging, which reduced the usage of plastics. The bio-based plastics industry is steadily leaving its development and

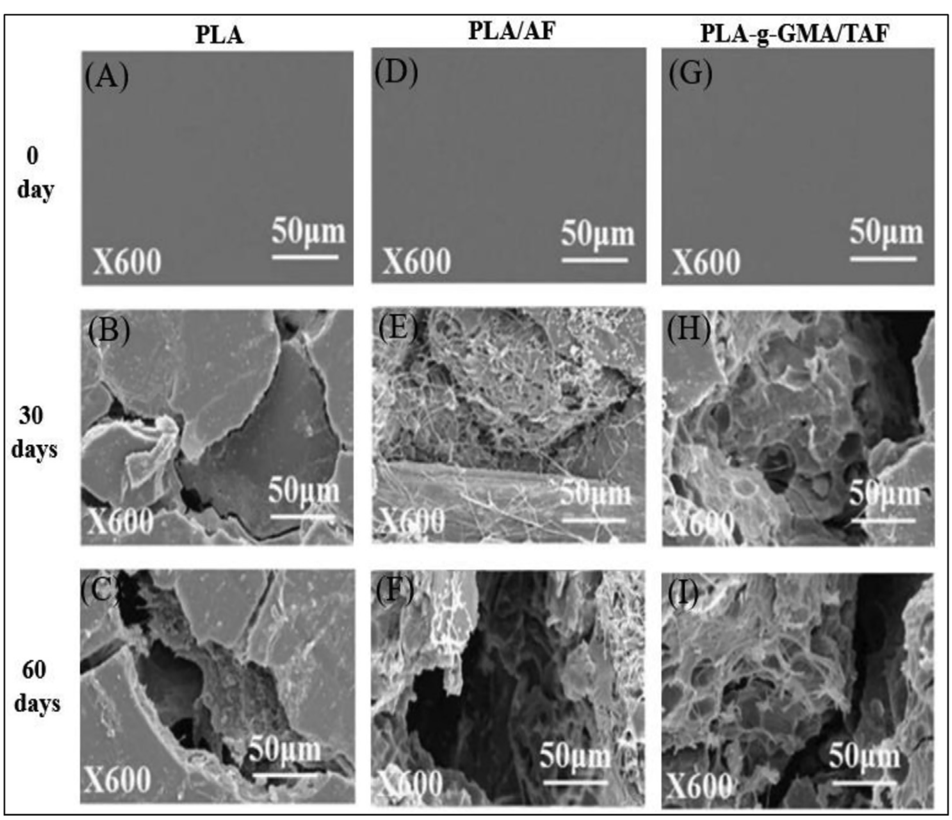

Fig. 12 – SEM analysis of the surface of PLA PLA/AF (20%) and PLA-g-GMA/TAF (20%) membranes in (A,B,C), (D,E,F), and (G,H,I) respectively [197].

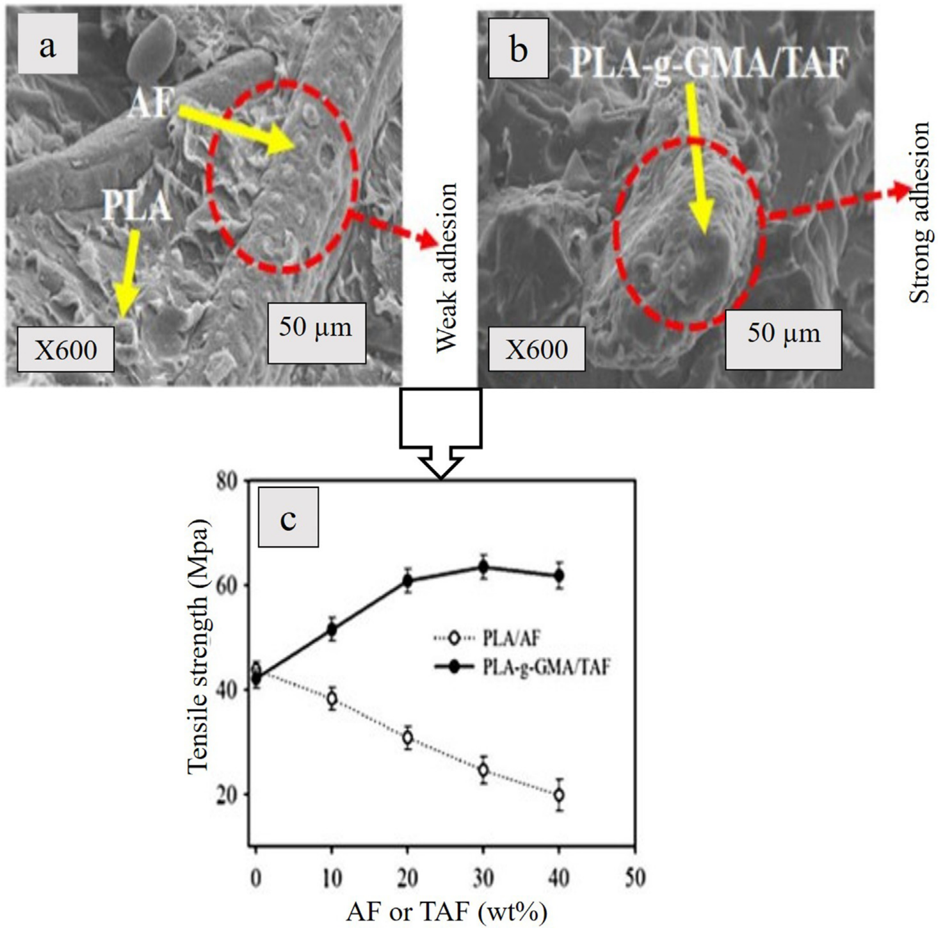

Fig. 13 – SEM micrograph showing the distribution and adhesion of arrowroot powder in (a) PLA/AF (20 wt%) and (b) PLA-g-TAF (20 wt%) composites. (c) The effect of fibre loading on the tensile strength at failure for PLA/AF and PLA-g-GMA/TFA reproduced from [197].

taking over the petroleum-based plastics market at an annual growth rate of 30% [214,216].

In many kinds of literature, the words “biobased” and “biodegradable” are defined reversibly but they are not the same. Not every biodegradable material needs to be biobased while biodegradability is a common property of biobased materials [217]. Biobased packaging materials are also packaging derived from recycled sources. Most of the bio-based plastics are obtained from marine and agriculture resources. Over the past few decades, starch has emerged as a vital bio-packaging material, and its usage is being anticipated to cross 30,000 tons per year in which about 20,000 tons are utilized for food preservation [217]. The exploration of biopolymer-based food packaging materials is also a possible mitigation step towards addressing environmental contamination from non-biodegradable food packaging materials. Numerous research programs are aimed at producing environmentally sustainable bio packaging products from renewable energy.

Food packaging preserves food from environmental impacts to maintain the standard of food and improve its self-existence. It also offers information on ingredients and diet to consumers [218]. Consequently, sufficient food packaging materials ensure the correct protection and consistency of food items from refining and production by handling and storage and eventually consumption [217].

Arrowroot starch and fibres have magnificent antioxidant and antibacterial properties, thus making it suitable for edible films and food packaging applications. Arrowroot starch-based films protect the food by preventing oxidation reaction with oil or fat. In the light of recent works, the authors [14,28] studied arrowroot starch (AS) based biofilms for food packaging application. In these studies, the effect of various plasticizer type PVA, polyethylene glycol (PEG), sorbitol (S) and glycerol(G) with (1:1) and (1:2) ratio of AS and plasticizers on the mechanical and thermal properties of AS films were evaluated. In all biofilms, starch-sorbitol (1:1) biofilm showed the best tensile strength (25.3 MPa), elongation at break (275%) and tear strength (72.5 kN/m). The results obtained revealed that starch-sorbitol (1:1) of the film showed better mechanical properties that could be useful for food packaging. A great deal of effort is currently being made to improve the functional properties of arrowroot starch as an important food packaging material.

7.2. Other applications of arrowroot fibre and starch

There are several other applications of both arrowroot fibres and starch. Both are used for edible film, food industries, medicine industries, nutraceutical applications, biomedical fields, cosmetic products, textiles, hygiene, biofuel, pulp, and paper-making [16,30]. The demand for biofuels is increasing day by day due to the excessive carbon dioxide (CO_2) emissions that are caused by conventional fossil fuel usage. The increasing carbon footprint is extremely harmful to public health. To reduce the emission of CO_2 to the environment, renewable energy resources are currently being developed to replace the existing fuel. 17.3 billion litres of bioethanol had been produced in 2000 and rose to 46 billion litres in 2007. In 2020, it is expected that the production of bio-ethanol exceeds 125 billion litres [25]. Two essential biofuels can be used to replace gasoline and other fossil fuels that are bio-ethanol and bio-diesel. In the study by Erdman et al. [34], the arrowroot biomass and residues can be used to develop fuel alcohol by fermentation. Arrowroot can be used as a raw material for biofuels to produce bioethanol. According to Sawarni et al. [65], bioethanol can be obtained from arrowroot starch by decomposition and fermentation processes. In the decomposition process, the starch decomposed into sugar because of *α-amylase* and *glucoamylase* enzymes. After decomposition, the sugar is fermented into bioethanol by using *Saccharomyces cerevisiae* yeast.

Due to the characteristics of arrowroot starch, it is also used to control various diseases such as diabetes, cardiovascular diseases, high blood pressure as well as cancer. In cancer, arrowroot starch is used for scavenging free radicals and eliminating the oxidant [142]. It is also used to make soup, candy, and ice cream. Arrowroot has been given priority by the Indonesian government because arrowroot can replace wheat flour, although it is grown and marketed in Indonesia [49]. To reduce the dependency on the main food source, arrowroot starch can play a significant role due to its quality and nutrient content. The rhizomes of arrowroot have high digestive starch that is good for human health [49]. The export of arrowroot starch is predicted to increase by approximately 3 million tons per annum.

8. Summary and future perspectives

The hope for the near future rests in green and biodegradable resources. With the combination of natural fibres and biopolymers in composite materials, the destructive environmental problems caused by petroleum-based materials can be avoided or at least reduced. The development of starch polymer composite will offer major environmental changes, resolving the recycling of plastic waste and reducing greenhouse gas emissions of petroleum-based products. Bio-resources are constantly being a viable alternative to non-biodegradable conventional products for a more sustainable nature. For the last few decades, the abundant amount and low cost of these green materials have brought them a lot of interest. Nevertheless, to address the serious drawbacks attributed to the use of natural fibres and biopolymers in composites, further research work is needed.

In this review, it can be concluded that the arrowroot starch or fibres obtained from arrowroot plants are useful for various applications. The arrowroot starch becomes more stable if it is blended by PLA, PVA and PHA. It contains about >80% of carbohydrates which is also good for food products. X-ray analysis proved that the arrowroot starch is categorized as a B-type crystal structure at the peaks of 17.10^0 accompanied by an interplanar distance' of 0.52, and 29.1% of crystallinity was recorded. The crystalline structure of the films increases as the intensity of citric acid is increased and substantially affected water vapour permeability, physical, chemical, and mechanical properties. TGA analysis showed that if the degradation temperature was between 280 °C and 330 °C then there was around 80% of dynamic weight degradation. DSC analysis manifested that the transition temperature of arrowroot starch film can be reduced to 118.8 °C by adding cranberry powder. Arrowroot fibre contains 65% holocellulose which is considered a suitable source for as low pulp products. In general, approximately 65% of holocellulose content is preferred for pulp and paper making. Interfacial bonding between fibre and matrix can be strengthened using the alkaline treatment. Some essential biological nutrients such as carbohydrates, fats, and proteins are found in the arrowroot starch which plays important roles in nourishing the human body as well as in life growth.

Nonetheless, a more advanced characterization of arrowroot fibres, biopolymers, and their biocomposites in terms of analysis and testing is needed. Aside from the basic mechanical (tensile and elongation at break), thermal (TGA), chemical (FTIR), and physical characterizations, there is a need for further characterizations using advanced techniques and equipment such as attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR), X-ray photoelectron microscopy (XPS), atomic force microscopy (AFM), field emission scanning electron microscopy (FE-SEM), and thermal analysis instruments (i.e., dynamic mechanical thermal analyser (DMTA). It is also essential to evaluate the barrier properties, sealability, and moisture absorption of arrowroot-based films and biocomposites for efficient packaging applications.

Thus far, extensive research has been conducted on arrowroot starch-based composites, but no research on arrowroot bagasse fibre and husk fibre as well as arrowroot-based nanocomposites have been published. Arrowroot fibre reinforced composites, hybrid composites and nanocomposites can strengthen the image of the arrowroot biocomposite industry even while opening new markets such as pharmaceutical and electronic packaging. This is a perspective area of study and engineering to overcome some of the issues that have been preventing future industrial uses of arrowroot fibres, biopolymers, and their composites. Overall, this paper provides a platform for the application of arrowroot fibre, starch, and biocomposites for food packaging, food products, medicines, and much more.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] Rangappa SM, Siengchin S, Dhakal HN. Green-composites: ecofriendly and sustainability. Appl Sci Eng Prog 2020;13. https://doi.org/10.14416/j.asep.2020.06.001.

[2] George A, Sanjay MR, Srisuk R, Parameswaranpillai J, Siengchin S. A comprehensive review on chemical properties and applications of biopolymers and their composites. Int J Biol Macromol 2020;154:329–38. https://doi.org/10.1016/j.ijbiomac.2020.03.120.

[3] Khan A, Vijay R, Lenin Singaravelu D, Arpitha GR, Sanjay MR, Siengchin S, et al. Extraction and characterization of vetiver grass (Chrysopogon zizanioides) and kenaf fiber (Hibiscus cannabinus) as reinforcement materials for epoxy based composite structures. J Mater Res Technol 2020;9:773–8. https://doi.org/10.1016/j.jmrt.2019.11.017.

[4] Gurunathan T, Mohanty S, Nayak SK. A review of the recent developments in biocomposites based on natural fibres and their application perspectives. Compos Part A Appl Sci Manuf 2015;77:1–25. https://doi.org/10.1016/j.compositesa.2015.06.007.

[5] Vinod A, Sanjay MR, Suchart S, Jyotishkumar P. Renewable and sustainable biobased materials: an assessment on biofibers, biofilms, biopolymers and biocomposites. J Clean Prod 2020;258:120978. https://doi.org/10.1016/j.jclepro.2020.120978.

[6] Ilyas RA, Sapuan SM, Ibrahim R, Abral H, Ishak MR, Zainudin ES, et al. Effect of sugar palm nanofibrillated cellulose concentrations on morphological, mechanical and physical properties of biodegradable films based on agro-waste sugar palm (Arenga pinnata(Wurmb.) Merr) starch. J Mater Res Technol 2019;8:4819–30. https://doi.org/10.1016/j.jmrt.2019.08.028.

[7] Acquavia MA, Pascale R, Martelli G, Bondoni M, Bianco G. Natural polymeric materials: a solution to plastic pollution from the agro-food sector. Polymers 2021;13:158. https://doi.org/10.3390/polym13010158.

[8] Medina Jaramillo C, Gutiérrez TJ, Goyanes S, Bernal C, Famá L. Biodegradability and plasticizing effect of yerba mate extract on cassava starch edible films. Carbohydr Polym 2016;151:150–9. https://doi.org/10.1016/j.carbpol.2016.05.025.

[9] Piñeros-Hernandez D, Medina-Jaramillo C, López-Córdoba A, Goyanes S. Edible cassava starch films carrying rosemary antioxidant extracts for potential use as active food packaging. Food Hydrocolloids 2017;63:488–95. https://doi.org/10.1016/j.foodhyd.2016.09.034.

[10] Chang-Bravo L, López-Córdoba A, Martino M. Biopolymeric matrices made of carrageenan and corn starch for the antioxidant extracts delivery of Cuban red propolis and yerba mate. React Funct Polym 2014;85:11–9. https://doi.org/10.1016/j.reactfunctpolym.2014.09.025.

[11] Fakhouri FM, Costa D, Yamashita F, Martelli SM, Jesus RC, Alganer K, et al. Comparative study of processing methods for starch/gelatin films. Carbohydr Polym 2013;95:681–9. https://doi.org/10.1016/j.carbpol.2013.03.027.

[12] Mohee R, Unmar GD, Mudhoo A, Khadoo P. Biodegradability of biodegradable/degradable plastic materials under aerobic and anaerobic conditions. Waste Manag 2008;28:1624–9. https://doi.org/10.1016/j.wasman.2007.07.003.

[13] Diyana ZN, Jumaidin R, Selamat MZ, Ghazali I, Julmohammad N, Huda N, et al. Physical properties of thermoplastic starch derived from natural resources and its blends: a review. Polymers 2021;13:1396. https://doi.org/10.3390/polym13091396.

[14] Nogueira GF, Fakhouri FM, de Oliveira RA. Extraction and characterization of arrowroot (Maranta arundinaceae L.) starch and its application in edible films. Carbohydr Polym 2018;186:64–72. https://doi.org/10.1016/j.carbpol.2018.01.024.

[15] Arsène MA, Bilba K, Junior HS, Ghavami K. Treatments of non-wood plant fibres used as reinforcement in composite materials. Mater Res 2013;16:903–23. https://doi.org/10.1590/S1516-14392013005000084.

[16] More Sanket J, Ravi V, Giri Namrata, Suresh Kumar Jabu AR. Arrowrrot - a multipurposr crop. Agric World 2017;3.

[17] Reddy PP. Plant protection in tropical root and tuber crops. Plant Prot Trop Root Tuber Crop 2015:1–336. https://doi.org/10.1007/978-81-322-2389-4.

[18] Kay DE. Tropical products institute crop and product digest tropical products Institute 245. London (UK): Trop Prod Inst; 1973. p. 266.

[19] Li M, Liu P, Zou W, Yu L, Xie F, Pu H, et al. Extrusion processing and characterization of edible starch films with different amylose contents. J Food Eng 2011;106:95–101. https://doi.org/10.1016/j.jfoodeng.2011.04.021.

[20] Romero-Bastida CA, Bello-Pérez LA, Velazquez G, Alvarez-Ramirez J. Effect of the addition order and amylose content on mechanical, barrier and structural properties of films made with starch and montmorillonite. Carbohydr Polym 2015;127:195–201. https://doi.org/10.1016/j.carbpol.2015.03.074.

[21] Tharanathan RN. Biodegradable films and composite coatings: past, present and future. Trends Food Sci Technol 2003;14:71–8. https://doi.org/10.1016/S0924-2244(02)00280-7.

[22] Fakhoury FM, Maria Martelli S, Canhadas Bertan L, Yamashita F, Innocentini Mei LH, Collares Queiroz FP. Edible films made from blends of manioc starch and gelatin - influence of different types of plasticizer and different levels of macromolecules on their properties. LWT - Food Sci Technol (Lebensmittel-Wissenschaft -Technol) 2012;49:149–54. https://doi.org/10.1016/j.lwt.2012.04.017.

[23] Silva Rafael, Haraguchi Shirani K, Muniz Edvani C, Rubira Adley F. Applications of lignocellulosic fibers in polymer chemistry and composites. SciELO Anal 2009;32(3).

[24] de Oliveira Guilherme D, Branco FP, Madeira NR, Brito VH, Oliveira CE de, Jadoski CJ, et al. Starch valorization from

corm, tuber, Rhizome, and Root crops. Elsevier Inc.; 2019. https://doi.org/10.1016/b978-0-12-809440-2.00005-8.
[25] Kralova I, Sjöblom J. Biofuels-renewable energy sources: a review. J Dispersion Sci Technol 2010;31:409–25. https://doi.org/10.1080/01932690903119674.
[26] De Sá RM, De Miranda CS, José NM. Preparation and characterization of nanowhiskers cellulose from fiber arrowroot (maranta arundinacea). Mater Res 2015;18:225–9. https://doi.org/10.1590/1516-1439.366214.
[27] Madineni MN, Faiza S, Surekha RS, Ravi R, Guha M. Morphological, structural, and functional properties of maranta (Maranta arundinacea L) starch. Food Sci Biotechnol 2012;21:747–52. https://doi.org/10.1007/s10068-012-0097-y.
[28] Nyo Aye Mon Thida, Win Arnt, Su Baby San Chit, Myint Mar Pi, Khaing Phyu Phyu. Study on characterization of various biofilms prepared by starch isolated from maranta arundinacea L. Int J Trend Sci Res Dev 2019;3:990–5. https://doi.org/10.31142/ijtsrd26588.
[29] Sandoval Gordillo CA, Ayala Valencia G, Vargas Zapata RA, Agudelo Henao AC. Physicochemical characterization of arrowroot starch (maranta arundinacea linn) and glycerol/arrowroot starch membranes. Int J Food Eng 2014;10:727–35. https://doi.org/10.1515/ijfe-2014-0122.
[30] Ayala Valencia G, Freitas Moraes IC, Vinicius Lourenço R, Barbosa Bittante AMQ, Do Amaral Sobral PJ. Physicochemical properties of maranta (maranta arundinacea L.) starch. Int J Food Prop 2015;18:1990–2001. https://doi.org/10.1080/10942912.2014.958162.
[31] Herawati ERN, Miftakhussolikhah M, Pusporini AR, Murdiati A. Sensorial and chemical characterization of snack bar with variation of gembolo flour (Dioscorea bulbifera) and arrowroot starch (marantha arundinaceae L.). Food Res 2019;3:564–9. https://doi.org/10.26656/fr.2017.3(5).099.
[32] Asha KI, KRN, VB, ADA, SMN, SJ. Diversity analysis of arrowroot germplasm using ISSR markers. 2015.
[33] Jayakumar A, Suganthi A. Biochemical and phytochemical analysis of maranta arundinacea (L.) Rhizome. Int J Res Pharm Pharm Sci 2017;2:2455–698.
[34] Erdman MD, Erdman BA. Arrowroot (Maranta arundinacea), food, feed, fuel, and fiber resource. Econ Bot 1984;38:332–41. https://doi.org/10.1007/BF02859011.
[35] Tabasum S, Younas M, Zaeem MA, Majeed I, Majeed M, Noreen A, et al. A review on blending of corn starch with natural and synthetic polymers, and inorganic nanoparticles with mathematical modeling. Int J Biol Macromol 2019;122:969–96. https://doi.org/10.1016/j.ijbiomac.2018.10.092.
[36] Winarti C, Widaningrum, Surono IS, Uswah M. Effect of acid and hydrolysis duration on the characteristics of arrowroot and taro starch nanoparticles. IOP Conf Ser Earth Environ Sci 2019;309. https://doi.org/10.1088/1755-1315/309/1/012039.
[37] Fakhouri FM, Nogueira GF, de Oliveira RA, Velasco JI. Bioactive edible films based on arrowroot starch incorporated with cranberry powder: microstructure, thermal properties, ascorbic acid content and sensory analysis. Polymers 2019;11. https://doi.org/10.3390/polym11101650.
[38] Leonel M, Cereda MP, Ferrari TB. USE OF GINGER (Zingiber officinale) OF INFERIOR QUALITY AS RAW MATERIAL MILÁCEA. Trop Roots Starches Mag 2005;1:9–18.
[39] Ferrari TB, Leonel M, Sarmento SBS. Características dos rizomas e do amido de araruta (Maranta arundinacea) em diferentes estádios de desenvolvimento da planta. Braz J Food Technol 2005;2:93–8.
[40] Leonel M, Cereda MP, Sarmento SBS. Processamento da araruta (Maranta arundinacea): extração e caracterização da fração amilá- cea. Rev Bras Tecnol Agroindustrial 2002:151–5.
[41] Malinis AP, Pacardo CO. Adaptation of arrowroot (Maranta Arundinacea) processing technologies in Typhoon prone marginal areas in Bicol. Ontario Int Dev Agency 2012;4(3):51–62.
[42] Sajeev MS, Nanda SKSJ. An efficient blade type rasper for cassava starch extraction. J Root Crops 2012;38(2):151–6.
[43] Saengchan K, Nopharatana M, Lerdlattaporn R, Songkasiri W. Enhancement of starch-pulp separation in centrifugal-filtration process: effects of particle size and variety of cassava root on free starch granule separation. Food Bioprod Process 2015;95:208–17. https://doi.org/10.1016/j.fbp.2015.05.008.
[44] Sheriff JTBC. Evaluation of multi-purpose starch extraction plant. Trop Sci 1999;39:147–52.
[45] Barth M, Sidegum Renner J, Fagundes Nunes M, Roese Sanfelice G. Características do trabalho na agricultura familiar e sua influência na emigração dos jovens. ILUMINURAS 2016;17:256–76. https://doi.org/10.22456/1984-1191.64569.
[46] Tan DLS, Gayanilo VG. Technical evaluation of different systems in level processing of arrowroot starch. Baybay, Leyte, Philippines: Philippine Root Crop Research and Training Center. Visayas State College of Agriculture; 1993. Retrieved from, http://agris.fao.org/agris-search/search. Http//AgrisFaoOrg/Agris-Search/SearchDo?RecordID=PH19970084322. Philipp Root Crop Res Train Center Visayas State Coll Agric Baybay, Leyte, Philipp Retrieved from.
[47] Capiña MV, Capiña VLL. Arrowroot (maranta arundinacea): starch extraction, processing, and by-products utilization. 2017. p. 240–4. https://doi.org/10.17758/uruae.ae0117711.
[48] Pascua AM. Development and testing of arrowroot (marantha arundinacea L .). Grind Mach 2018;5:17–30. https://doi.org/10.5281/zenodo.1336093.
[49] Deswina P, Priadi D. Development of arrowroot (maranta arundinacea L.) as functional food based of local resource. In: IOP conf ser earth environ sci. vol. 439; 2020. https://doi.org/10.1088/1755-1315/439/1/012041.
[50] Rahman M, Chowdhury M, Uddin A, Islam MT, UM. Advances in pharmacological sciences1; 2015. p. 1–6.
[51] Olayemi O, Oyi A, Allagh T. Comparative evaluation of maize, rice and wheat starch powders as pharmaceutical excipients. Niger J Pharm Sci 2008;7:131–8.
[52] Wang W, Wang K, Xiao J, Liu Y, Zhao Y, Liu A. Performance of high amylose starch-composited gelatin films influenced by gelatinization and concentration. Int J Biol Macromol 2017;94:258–65. https://doi.org/10.1016/j.ijbiomac.2016.10.014.
[53] Zhang Z, Chen P, Du X, Xue Z, Chen S, Yang B. Effects of amylose content on property and microstructure of starch-graft-sodium acrylate copolymers. Carbohydr Polym 2014;102:453–9. https://doi.org/10.1016/j.carbpol.2013.11.027.
[54] Nogueira GF, Soares CT, Cavasini R, Fakhouri FM, de Oliveira RA. Bioactive films of arrowroot starch and blackberry pulp: physical, mechanical and barrier properties and stability to pH and sterilization. Food Chem 2019;275:417–25. https://doi.org/10.1016/j.foodchem.2018.09.054.
[55] Axelsson L, Franzén M, Ostwald M, Berndes G, Lakshmi G, Ravindranath NH. Perspective: Jatropha cultivation in southern India: assessing farmers' experiences. Biofuel Bioprod Bioref 2012;6:246–56. https://doi.org/10.1002/bbb.

[56] Swinkels JJM. Composition and properties of commercial native starches. Starch - Stärke 1985;37:1–5. https://doi.org/10.1002/star.19850370102.
[57] Sahari J, Sapuan SM, Zainudin ES, Maleque MA. Physico-chemical and thermal properties of starch derived from sugar palm tree (Arenga pinnata). Asian J Chem 2014;26:955–9. https://doi.org/10.14233/ajchem.2014.15652.
[58] Tie APL, Karim AA, Manan DMA. Physicochemical properties of starch in sago palms (Metroxylon sagu) at different growth stages. Starch Staerke 2008;60:408–16. https://doi.org/10.1002/star.200700707.
[59] Ahmad FB, Williams PA, Doublier J-L, Durand S, Buleon A. Physico-chemical characterisation of sago starch. Carbohydr Polym 1999;38:361–70. https://doi.org/10.1016/S0144-8617(98)00123-4.
[60] Alebiowu G, Osinoiki KA. Assessment of Tapioca starches obtained after different steeping periods as binders in a paracetamol tablet formulation. FARMACIA 2010;58:341–52.
[61] Pérez E, Lares M, González Z. Some characteristics of sagu (canna edulis Kerr) and Zulu (maranta sp.) rhizomes. J Agric Food Chem 1997;45:2546–9. https://doi.org/10.1021/jf960680i.
[62] Wahjuningsih SB, Susanti S. Chemical, physical, and sensory characteristics of analog rice developed from the mocaf, arrowroof, and red bean flour. IOP Conf Ser Earth Environ Sci 2018;102. https://doi.org/10.1088/1755-1315/102/1/012015.
[63] Raja MKC, Sindhu P. Properties of steam-treated arrowroot (maranta arundinacea) starch. Starch - Stärke 2000;52:471–6. https://doi.org/10.1002/1521-379X(200012)52:12<471::AID-STAR471>3.0.CO;2-U.
[64] Erdman MD. Starch from arrowroot (Maranta arundinacea) grown at Tifton, Georgia. Am Assoc Cereal Chem Inc 1986;63(3):277–9.
[65] Hasibuan S, Zain ER, Novita ITA. Optimization of liquid sugar production for bioethanol processing from arrowrot using Aspergillus Niger and amiloglucosidase. 2012. p. 4–6.
[66] Yousf N, Nazir F, Salim R, Ahsan H, Sirwal A. Water solubility index and water absorption index of extruded product from rice and carrot blend. J Pharmacogn Phytochem JPP 2017;6:2165–8.
[67] Seena S, Sridhar KR. Physicochemical, functional and cooking properties of under explored legumes, Canavalia of the southwest coast of India. Food Res Int 2005;38:803–14. https://doi.org/10.1016/j.foodres.2005.02.007.
[68] Jyothi AN, Sheriff JT, Sajeev MS. Physical and functional properties of arrowroot starch extrudates. J Food Sci 2009;74. https://doi.org/10.1111/j.1750-3841.2008.01038.x.
[69] PATON D, SPRATT WA. Component interactions in the extrusion cooking process: influence of process conditions on the functional viscosity of the wheat flour system. J Food Sci 1984;49:1380–5. https://doi.org/10.1111/j.1365-2621.1984.tb14995.x.
[70] Badrie N, Mellowes WA. Effect of extrusion variables on cassava extrudates. J Food Sci 1991;56:1334–7. https://doi.org/10.1111/j.1365-2621.1991.tb04766.x.
[71] Granados CC, Guzman CE, Acevedo CD, Díaz MM, Herrera AA. Propiedades funcionales del almidon de sagu (Maranta arundinacea). Colomb Biotecnol En El Sect Agropecu y Agroindustrial, Cauca 2014;12(2):90–6.
[72] Hoover R. Composition, molecular structure, and physicochemical properties of tuber and root starches: a review. Carbohydr Polym 2001;45:253–67. https://doi.org/10.1016/S0144-8617(00)00260-5.
[73] Pérez E, Lares M. Chemical composition, mineral profile, and functional properties of Canna (Canna edulis) and Arrowroot (Maranta spp.) starches. Plant Foods Hum Nutr 2005;60:113–6. https://doi.org/10.1007/s11130-005-6838-9.
[74] Charles AL, Cato K, Huang TC, Chang YH, Ciou JY, Chang JS, et al. Functional properties of arrowroot starch in cassava and sweet potato composite starches. Food Hydrocolloids 2016;53:187–91. https://doi.org/10.1016/j.foodhyd.2015.01.024.
[75] Astuti RM, Widaningrum Asiah N, Setyowati A, Fitriawati R. Effect of physical modification on granule morphology, pasting behavior, and functional properties of arrowroot (Marantha arundinacea L) starch. Food Hydrocolloids 2018;81:23–30. https://doi.org/10.1016/j.foodhyd.2018.02.029.
[76] Peroni FHG, Rocha TS, Franco CML. Some structural and physicochemical characteristics of tuber and root starches. Food Sci Technol Int 2006;12:505–13. https://doi.org/10.1177/1082013206073045.
[77] Wang X, Reddy CK, Xu B. A systematic comparative study on morphological, crystallinity, pasting, thermal and functional characteristics of starches resources utilized in China. Food Chem 2018;259:81–8. https://doi.org/10.1016/j.foodchem.2018.03.121.
[78] Villas-Boas F, Franco CML. Effect of bacterial β-amylase and fungal α-amylase on the digestibility and structural characteristics of potato and arrowroot starches. Food Hydrocolloids 2016;52:795–803. https://doi.org/10.1016/j.foodhyd.2015.08.024.
[79] Moorthy SN. Physicochemical and functional properties of tropical tuber starches: a review. Starch - Stärke 2002;54:559–92. https://doi.org/10.1002/1521-379X(200212)54:12<559::AID-STAR2222559>3.0.CO;2-F.
[80] Thitipraphunkul K, Uttapap D, Piyachomkwan K, Takeda Y. A comparative study of edible canna (Canna edulis) starch from different cultivars. Part I: chemical composition and physicochemical properties. Carbohydr Polym 2003;53:317–24. https://doi.org/10.1016/S0144-8617(03)00081-X.
[81] Franklin MEE, Pushpadass HA, Kumar B, Kulkarni S, Muthurayappa M, Kandasamy R, et al. Physicochemical, thermal, pasting and microstructural characterization of commercial Curcuma angustifolia starch. Food Hydrocolloids 2017;67:27–36. https://doi.org/10.1016/j.foodhyd.2016.12.025.
[82] Negim E, Rakhmetullayeva R, Yeligbayeva G, Urkimbaeva P, Primzharova S, Kaldybekov D, et al. Improving biodegradability of polyvinyl alcohol/starch blend films for packaging applications. Int J Basic Appl Sci 2014;3:263–73. https://doi.org/10.14419/ijbas.v3i3.2842.
[83] Atwell WA. The terminology and methodology associated with basic starch phenomena. Cereal Foods World 1988;33:306–11.
[84] Waterschoot J, Gomand SV, Fierens E, Delcour JA. Production, structure, physicochemical and functional properties of maize, cassava, wheat, potato and rice starches. Starch Staerke 2015;67:14–29. https://doi.org/10.1002/star.201300238.
[85] Zobel HF. Starch crystal transformations and their industrial importance. Starch - Stärke 1988;40:1–7. https://doi.org/10.1002/star.19880400102.
[86] Srichuwong S, Sunarti TC, Mishima T, Isono N, Hisamatsu M. Starches from different botanical sources I: Contribution of amylopectin fine structure to thermal properties and enzyme digestibility. Carbohydr Polym 2005;60(4):529–38. https://doi.org/10.1016/j.carbpol.2005.03.004.
[87] Pal J, Singhal RS, Kulkarni PR. Physicochemical properties of hydroxypropyl derivative from corn and amaranth starch.

Carbohydr Polym 2002;48:49–53. https://doi.org/10.1016/S0144-8617(01)00209-0.
[88] Cooke D, Gidley MJ. Loss of crystalline and molecular order during starch gelatinisation: origin of the enthalpic transition. Carbohydr Res 1992;227:103–12. https://doi.org/10.1016/0008-6215(92)85063-6.
[89] Barroso AG, Mastro NL. Physicochemical characterization of irradiated arrowroot starch. Radiat Phys Chem 2019;158:194–8. https://doi.org/10.1016/j.radphyschem.2019.02.020.
[90] Chuang L, Panyoyai N, Katopo L, Shanks R, Kasapis S. Calcium chloride effects on the glass transition of condensed systems of potato starch. Food Chem 2016;199:791–8. https://doi.org/10.1016/j.foodchem.2015.12.076.
[91] Chuang L, Panyoyai N, Shanks RA, Kasapis S. Effect of salt on the glass transition of condensed tapioca starch systems. Food Chem 2017;229:120–6. https://doi.org/10.1016/j.foodchem.2017.02.063.
[92] Perdomo J, Cova A, Sandoval AJ, García L, Laredo E, Müller AJ. Glass transition temperatures and water sorption isotherms of cassava starch. Carbohydr Polym 2009;76:305–13. https://doi.org/10.1016/j.carbpol.2008.10.023.
[93] Rodrigues LBO, Veloso CM, Bonomo RCF, Rodrigues LB, Minim LA, Costa RAS. Rheological and textural studies of arrowroot (Maranta arundinacea) starch–sucrose–whey protein concentrate gels. J Food Sci Technol 2018;55:2974–84. https://doi.org/10.1007/s13197-018-3215-x.
[94] Imre B, Pukánszky B. Compatibilization in bio-based and biodegradable polymer blends. Eur Polym J 2013;49:1215–33. https://doi.org/10.1016/j.eurpolymj.2013.01.019.
[95] Ilyas RA, Sapuan SM, Ishak MR, Zainudin ES. Sugar palm nanofibrillated cellulose (Arenga pinnata (Wurmb.) Merr): effect of cycles on their yield, physic-chemical, morphological and thermal behavior. Int J Biol Macromol 2019;123:379–88. https://doi.org/10.1016/j.ijbiomac.2018.11.124.
[96] Singh J, Kaur L, McCarthy OJ. Factors influencing the physico-chemical, morphological, thermal and rheological properties of some chemically modified starches for food applications-A review. Food Hydrocolloids 2007;21:1–22. https://doi.org/10.1016/j.foodhyd.2006.02.006.
[97] Syafri E, Sudirman, Mashadi, Yulianti E, Deswita, Asrofi M, et al. Effect of sonication time on the thermal stability, moisture absorption, and biodegradation of water hyacinth (Eichhornia crassipes) nanocellulose-filled bengkuang (Pachyrhizus erosus) starch biocomposites. J Mater Res Technol 2019;8:6223–31. https://doi.org/10.1016/j.jmrt.2019.10.016.
[98] Faridah DN, Rahayu WP, Apriyadi MS. Modification of arrowroot (Marantha arundinacea L) through acid hydrolysis and autoclaving-cooling cycling treatment to produce resistant starch type. J Food Ind Technol Teknol Ind Pangan 2013;23:61–9.
[99] Ozturk S, Koksel H, Ng PKW. Production of resistant starch from acid-modified amylotype starches with enhanced functional properties. J Food Eng 2011;103:156–64. https://doi.org/10.1016/j.jfoodeng.2010.10.011.
[100] Nasrin TAA, Anal AK. Resistant starch III from culled banana and its functional properties infish oil emulsion. Food Hydrocolloids 2014;35:403–9. https://doi.org/10.1016/j.foodhyd.2013.06.019.
[101] Kim RE, Ahn SY. Gelling properties of acid-modified red bean starch gel. Agric Chem Biotechnol 1996;39(1):49–53. 2468-0834 (pISSN).
[102] Polesi F, Bruder S, Sarmento S. Structural and physicochemical characterization of RS prepared using hydrolysis and heat treatments of chickpea starch. 2011. p. 226–35. https://doi.org/10.1002/star.201000114.
[103] Abdul Khalil HPSPS, Yusra AFIFI, Bhat AHH, Jawaid M. Cell wall ultrastructure, anatomy, lignin distribution, and chemical composition of Malaysian cultivated kenaf fiber. Ind Crop Prod 2010;31:113–21. https://doi.org/10.1016/j.indcrop.2009.09.008.
[104] Idicula M, Joseph K, Thomas S. Mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites. J Reinforc Plast Compos 2010;29:12–29. https://doi.org/10.1177/0731684408095033.
[105] Asrofi M, Sujito Syafri E, Sapuan SM, Ilyas RA. Improvement of biocomposite properties based tapioca starch and sugarcane bagasse cellulose nanofibers. Key Eng Mater 2020;849:96–101. https://doi.org/10.4028/www.scientific.net/KEM.849.96.
[106] Ilyas RA, Sapuan SM, Ishak MR, Zainudin ES. Sugar palm nanocrystalline cellulose reinforced sugar palm starch composite: degradation and water-barrier properties. In: IOP conf ser mater sci eng, vol. 368; 2018, 012006. https://doi.org/10.1088/1757-899X/368/1/012006.
[107] Ilyas RA, Sapuan SM, Ishak MR, Zainudin ES. Water transport properties of bio-nanocomposites reinforced by sugar palm (Arenga Pinnata) nanofibrillated cellulose. J Adv Res Fluid Mech Therm Sci J 2018;51:234–46.
[108] Abral H, Basri A, Muhammad F, Fernando Y, Hafizulhaq F, Mahardika M, et al. A simple method for improving the properties of the sago starch films prepared by using ultrasonication treatment. Food Hydrocolloids 2019;93:276–83. https://doi.org/10.1016/j.foodhyd.2019.02.012.
[109] Satyanarayana KG, Arizaga GGC, Wypych F. Biodegradable composites based on lignocellulosic fibers-An overview. Prog Polym Sci 2009;34:982–1021. https://doi.org/10.1016/j.progpolymsci.2008.12.002.
[110] Reddy MM, Vivekanandhan S, Misra M, Bhatia SK, Mohanty AK. Biobased plastics and bionanocomposites: current status and future opportunities. Prog Polym Sci 2013;38:1653–89. https://doi.org/10.1016/j.progpolymsci.2013.05.006.
[111] Lu DR, Xiao CM, Xu SJ. Starch-based completely biodegradable polymer materials. Express Polym Lett 2009;3:366–75. https://doi.org/10.3144/expresspolymlett.2009.46.
[112] Fishman M, Coffin D, Konstance R, Onwulata C. Extrusion of pectin/starch blends plasticized with glycerol. Carbohydr Polym 2000;41:317–25. https://doi.org/10.1016/S0144-8617(99)00117-4.
[113] Sanyang ML, Sapuan SM, Jawaid M, Ishak MR, Sahari J. Recent developments in sugar palm (Arenga pinnata) based biocomposites and their potential industrial applications: a review. Renew Sustain Energy Rev 2016;54:533–49. https://doi.org/10.1016/j.rser.2015.10.037.
[114] Ilyas RA, Sapuan SM, Ishak MR, Zainudin ES. Development and characterization of sugar palm nanocrystalline cellulose reinforced sugar palm starch bionanocomposites. Carbohydr Polym 2018;202:186–202. https://doi.org/10.1016/j.carbpol.2018.09.002.
[115] Shuhada N, Makhtar M, Fadzrel M, Muhd MN. Tacca leontopetaloides starch: new sources starch for biodegradable plastic. Procedia Eng 2013;68:385–91. https://doi.org/10.1016/j.proeng.2013.12.196.
[116] Norul Izani MA, Paridah MT, Anwar UMK, Mohd Nor MY, H'Ng PS. Effects of fiber treatment on morphology, tensile and thermogravimetric analysis of oil palm empty fruit bunches fibers. Compos B Eng 2013;45:1251–7. https://doi.org/10.1016/j.compositesb.2012.07.027.

[117] Sadasivuni KK, Saha P, Adhikari J, Deshmukh K, Ahamed MB, Cabibihan JJ. Recent advances in mechanical properties of biopolymer composites: a review. Polym Compos 2020;41:32–59. https://doi.org/10.1002/pc.25356.

[118] Realini CE, Marcos B. Active and intelligent packaging systems for a modern society. Meat Science 2014;98(3):404–19. https://doi.org/10.1016/j.meatsci.2014.06.031.

[119] Ghaani M, Cozzolino CA, Castelli G, Farris S. An overview of the intelligent packaging technologies in the food sector. Trends Food Sci Technol 2016;51:1–11. https://doi.org/10.1016/j.tifs.2016.02.008.

[120] Sholichah E, Nugroho P, Purwono B. Preparation and characterization of active film made from arrowroot starch/PVA film and isolated quercetin from shallot (Allium cepa L. var, aggregatum). AIP Conf Proc 2018;2024. https://doi.org/10.1063/1.5064299.

[121] Abral H, Ariksa J, Mahardika M, Handayani D, Aminah I, Sandrawati N, et al. Highly transparent and antimicrobial PVA based bionanocomposites reinforced by ginger nanofiber. Polym Test 2019:106186. https://doi.org/10.1016/j.polymertesting.2019.106186.

[122] Abral H, Atmajaya A, Mahardika M, Hafizulhaq F, Kadriadi, Handayani D, et al. Effect of ultrasonication duration of polyvinyl alcohol (PVA) gel on characterizations of PVA film. J Mater Res Technol 2020;9. https://doi.org/10.1016/j.jmrt.2019.12.078.

[123] Nogueira GF, Fakhouri FM, de Oliveira RA. Effect of incorporation of blackberry particles on the physicochemical properties of edible films of arrowroot starch. Dry Technol 2019;37:448–57. https://doi.org/10.1080/07373937.2018.1441153.

[124] Sartori T, Menegalli FC. Development and characterization of unripe banana starch films incorporated with solid lipid microparticles containing ascorbic acid. Food Hydrocolloids 2016;55:210–9. https://doi.org/10.1016/j.foodhyd.2015.11.018.

[125] Rojas-Graü MA, Avena-Bustillos RJ, Friedman M, Henika PR, Martín-Belloso O, McHugh TH. Mechanical, barrier, and antimicrobial properties of apple puree edible films containing plant essential oils. J Agric Food Chem 2006;54:9262–7. https://doi.org/10.1021/jf061717u.

[126] Kafkas E, Koşar M, Türemiş N, Başer KHC. Analysis of sugars, organic acids and vitamin C contents of blackberry genotypes from Turkey. Food Chem 2006;97:732–6. https://doi.org/10.1016/j.foodchem.2005.09.023.

[127] Gonçalves J, Filho DO, Cris C, Nobre DO, Regina B, Campos F, et al. New approach in the development of edible films : the use of carnauba wax micro- or nanoemulsions in arrowroot starch-based films. Food Packag Shelf Life 2020;26:100589. https://doi.org/10.1016/j.fpsl.2020.100589.

[128] Otoni CG, Moura MR de, Aouada FA, Camilloto GP, Cruz RS, Lorevice MV, et al. Antimicrobial and physical-mechanical properties of pectin/papaya puree/cinnamaldehyde nanoemulsion edible composite films. Food Hydrocolloids 2014;41:188–94. https://doi.org/10.1016/j.foodhyd.2014.04.013.

[129] Espitia PJP, Avena-Bustillos RJ, Du W-X, Teófilo RF, Soares NFF, McHugh TH. Optimal antimicrobial formulation and physical–mechanical properties of edible films based on açaí and pectin for food preservation. Food Packag Shelf Life 2014;2:38–49. https://doi.org/10.1016/j.fpsl.2014.06.002.

[130] Zhai X, Shi J, Zou X, Wang S, Jiang C, Zhang J, et al. Novel colorimetric films based on starch/polyvinyl alcohol incorporated with roselle anthocyanins for fish freshness monitoring. Food Hydrocolloids 2017;69:308–17. https://doi.org/10.1016/j.foodhyd.2017.02.014.

[131] Azeredo HMC, Morrugares-Carmona R, Wellner N, Cross K, Bajka B, Waldron KW. Development of pectin films with pomegranate juice and citric acid. Food Chem 2016;198:101–6. https://doi.org/10.1016/j.foodchem.2015.10.117.

[132] Bergo PVA, Carvalho RA, Sobral PJA, dos Santos RMC, da Silva FBR, Prison JM, et al. Physical properties of edible films based on cassava starch as affected by the plasticizer concentration. Packag Technol Sci 2008;21:85–9. https://doi.org/10.1002/pts.781.

[133] Ivanič F, Jochec-Mošková D, Janigová I, Chodák I. Physical properties of starch plasticized by a mixture of plasticizers. Eur Polym J 2017;93:843–9.

[134] Yulianti R, Ginting E. Perbedaan Karakteristik fisik edible film Dari umbi-umbian yang. Dibuat dengan Penambahan Plasticizer 2015;31:131–6. https://doi.org/10.21082/jpptp.v31n2.2012.p%p.

[135] Liu B, Xu H, Zhao H, Liu W, Zhao L, Li Y. Preparation and characterization of intelligent starch/PVA films for simultaneous colorimetric indication and antimicrobial activity for food packaging applications. Carbohydr Polym 2017;157:842–9. https://doi.org/10.1016/j.carbpol.2016.10.067.

[136] García MA, Pinotti A, Martino MN, Zaritzky NE. Characterization of starch and composite edible films and coatings. In: Embuscado Milda E, Huber Kerry C, editors. Edible film. Coatings food appl. New York: Springer New York; 2009. p. 169–209. https://doi.org/10.1007/978-0-387-92824-1_6.

[137] Sholichah E, Purwono B, Nugroho P. Improving properties of arrowroot starch (maranta arundinacea)/PVA blend films by using citric acid as cross-linking agent. In: IOP conf ser earth environ sci, vol. 101; 2017, 012018. https://doi.org/10.1088/1755-1315/101/1/012018.

[138] Jiugao Y, Ning W, Xiaofei M. The effects of citric acid on the properties of thermoplastic starch plasticized by glycerol. Starch - Stärke 2005;57:494–504. https://doi.org/10.1002/star.200500423.

[139] Yun Y-H, Na Y-H, Yoon S-D. Mechanical properties with the functional group of additives for starch/PVA blend film. J Polym Environ 2006;14:71–8. https://doi.org/10.1007/s10924-005-8709-8.

[140] Anjum A, Zuber M, Zia KM, Noreen A, Anjum MN, Tabasum S. International Journal of Biological Macromolecules Microbial production of polyhydroxyalkanoates (PHAs) and its copolymers: a review of recent advancements. Int J Biol Macromol 2016;89:161–74. https://doi.org/10.1016/j.ijbiomac.2016.04.069.

[141] Leong YK, Show PL, Ooi CW, Ling TC, Lan JC. Current trends in polyhydroxyalkanoates (PHAs) biosynthesis: Insights from the recombinant Escherichia coli. J Biotechnol 2014;180:52–65. https://doi.org/10.1016/j.jbiotec.2014.03.020.

[142] Wu CS, Liao HT. Interface design and reinforced features of arrowroot (Maranta arundinacea) starch/polyester-based membranes: preparation, antioxidant activity, and cytocompatibility. Mater Sci Eng C 2017;70:54–61. https://doi.org/10.1016/j.msec.2016.08.067.

[143] Zampaloni M, Pourboghrat F, Yankovich SA, Rodgers BN, Moore J, Drzal LT, et al. Kenaf natural fiber reinforced polypropylene composites: a discussion on manufacturing problems and solutions. Compos Part A Appl Sci Manuf 2007;38:1569–80. https://doi.org/10.1016/j.compositesa.2007.01.001.

[144] Suriani MJ, Rapi HZ, Ilyas RA, Petrů M, Sapuan SM. Delamination and manufacturing defects in natural fiber-

reinforced hybrid composite: a review. Polymers 2021;13:1323. https://doi.org/10.3390/polym13081323.

[145] Ilyas RA, Sapuan SM, Ibrahim R, Abral H, Ishak MR, Zainudin ES, et al. Thermal, biodegradability and water barrier properties of bio-nanocomposites based on plasticised sugar palm starch and nanofibrillated celluloses from sugar palm fibres. J Biobased Mater Bioenergy 2020;14:234–48. https://doi.org/10.1166/jbmb.2020.1951.

[146] Singh I, Chaitanya S. Injection molding of natural fiber reinforced composites. Green Biorenew Biocomp 2015:293–308. https://doi.org/10.1201/b18092-14.

[147] Raji M, Abdellaoui H, Essabir H, Kakou CA, Bouhfid R, El Kacem Qaiss A. Prediction of the cyclic durability of woven-hybrid composites. 2018. https://doi.org/10.1016/B978-0-08-102290-0.00003-9.

[148] Dasore A, Rajak U, Balijepalli R, Verma TN, Ramakrishna K. An overview of refinements, processing methods and properties of natural fiber composites. Mater Today Proc 2021. https://doi.org/10.1016/j.matpr.2021.02.103. ISSN: 22147853, In press.

[149] Toghyani A, Matthews S, Varis J. Forming challenges of extruded wood plastic composite products in a post-production process. Procedia CIRP 2020;93:502–7. https://doi.org/10.1016/j.procir.2020.04.156.

[150] Park CH, Lee WI. Compression molding in polymer matrix composites. Woodhead Publishing Limited; 2012. https://doi.org/10.1533/9780857096258.1.47.

[151] Mohd Nurazzi N, Asyraf MRM, Khalina A, Abdullah N, Sabaruddin FA, Kamarudin SH, et al. Fabrication, functionalization, and application of carbon nanotube-reinforced polymer composite: an overview. Polymers 2021;13:1047. https://doi.org/10.3390/polym13071047.

[152] Omran AAB, Mohammed AABA, Sapuan SM, Ilyas RA, Asyraf MRM, Koloor SSR, et al. Micro- and nanocellulose in polymer composite materials: a review. Polymers 2021;13:231. https://doi.org/10.3390/polym13020231.

[153] Ilyas RA, Sapuan SM, Harussani MM, Hakimi MYAY, Haziq MZM, Atikah MSN, et al. Polylactic acid (PLA) biocomposite: processing, additive manufacturing and advanced applications. Polymers 2021;13:1326. https://doi.org/10.3390/polym13081326.

[154] Alsubari S, Zuhri MYM, Sapuan SM, Ishak MR, Ilyas RA, Asyraf MRM. Potential of natural fiber reinforced polymer composites in sandwich structures: a review on its mechanical properties. Polymers 2021;13:423. https://doi.org/10.3390/polym13030423.

[155] Ilyas RA, Sapuan SM, Sanyang ML, Ishak MR, Zainudin ES. Nanocrystalline cellulose as reinforcement for polymeric matrix nanocomposites and its potential applications: a Review. Curr Anal Chem 2018;14:203–25. https://doi.org/10.2174/1573411013666171003155624.

[156] Aisyah HA, Paridah MT, Sapuan SM, Ilyas RA, Khalina A, Nurazzi NM, et al. A comprehensive review on advanced sustainable woven natural fibre polymer composites. Polymers 2021;13:471. https://doi.org/10.3390/polym13030471.

[157] Sari NH, Pruncu CI, Sapuan SM, Ilyas RA, Catur AD, Suteja S, et al. The effect of water immersion and fibre content on properties of corn husk fibres reinforced thermoset polyester composite. Polym Test 2020;91:106751. https://doi.org/10.1016/j.polymertesting.2020.106751.

[158] Siakeng R, Jawaid M, Asim M, Saba N, Sanjay MR, Siengchin S, et al. Alkali treated coir/pineapple leaf fibres reinforced PLA hybrid composites: evaluation of mechanical , morphological , thermal and physical properties14; 2020. p. 717–30.

[159] Abral H, Ariksa J, Mahardika M, Handayani D, Aminah I, Sandrawati N, et al. Transparent and antimicrobial cellulose film from ginger nanofiber. Food Hydrocolloids 2020;98:105266. https://doi.org/10.1016/j.foodhyd.2019.105266.

[160] Prachayawarakorn J, Limsiriwong N, Kongjindamunee R, Surakit S. Effect of agar and cotton fiber on properties of thermoplastic waxy rice starch composites. J Polym Environ 2012;20:88–95. https://doi.org/10.1007/s10924-011-0371-8.

[161] Aisyah HA, Paridah MT, Sapuan SM, Khalina A, Berkalp OB, Lee SH, et al. Thermal properties of woven kenaf/carbon fibre-reinforced epoxy hybrid composite panels. Int J Polym Sci 2019;2019:1–8. https://doi.org/10.1155/2019/5258621.

[162] Mazani N, Sapuan SM, Sanyang ML, Atiqah A, Ilyas RA. Design and fabrication of a shoe shelf from kenaf fiber reinforced unsaturated polyester composites. In: Ariffin H, Sapuan SM, Hassan MA, editors. Lignocellul. Futur. Bioeconomy. 1st ed. Amsterdam, Netherlands: Elsevier; 2019. p. 315–32. https://doi.org/10.1016/B978-0-12-816354-2.00017-7.

[163] Aiza Jaafar CN, Zainol I, Ishak NS, Ilyas RA, Sapuan SM. Effects of the liquid natural rubber (LNR) on mechanical properties and microstructure of epoxy/silica/kenaf hybrid composite for potential automotive applications. J Mater Res Technol 2021;12:1026–38. https://doi.org/10.1016/j.jmrt.2021.03.020.

[164] Jumaidin R, Ilyas RA, Saiful M, Hussin F, Mastura MT. Water transport and physical properties of sugarcane bagasse fibre reinforced thermoplastic potato starch biocomposite. J Adv Res Fluid Mech Therm Sci 2019;61:273–81.

[165] Nassiopoulos E, Njuguna J. Thermo-mechanical performance of poly(lactic acid)/flax fibre-reinforced biocomposites. Mater Des 2015;66:473–85. https://doi.org/10.1016/j.matdes.2014.07.051.

[166] Syafri E, Kasim A, Abral H, Asben A. Cellulose nanofibers isolation and characterization from ramie using a chemical-ultrasonic treatment. J Nat Fibers 2018:1–11. https://doi.org/10.1080/15440478.2018.1455073. 00.

[167] Battegazzore D, Noori A, Frache A. Hemp hurd and alfalfa as particle filler to improve the thermo-mechanical and fire retardant properties of poly (3-hydroxybutyrate-co-3-hydroxyhexanoate). Polym Compos 2019;40(9):3429–37. https://doi.org/10.1002/pc.25204.

[168] Prachayawarakorn J, Chaiwatyothin S, Mueangta S, Hanchana A. Effect of jute and kapok fibers on properties of thermoplastic cassava starch composites. Mater Des 2013;47:309–15. https://doi.org/10.1016/j.matdes.2012.12.012.

[169] Gupta M, Singh R. PLA-coated sisal fibre-reinforced polyester composite: water absorption, static and dynamic mechanical properties. J Compos Mater 2019;53:65–72. https://doi.org/10.1177/0021998318780227.

[170] Asyraf MRM, Ishak MR, Sapuan SM, Yidris N, Ilyas RA. Woods and composites cantilever beam: a comprehensive review of experimental and numerical creep methodologies. J Mater Res Technol 2020;9:6759–76. https://doi.org/10.1016/j.jmrt.2020.01.013.

[171] Ayu RS, Khalina A, Harmaen AS, Zaman K, Isma T, Liu Q, et al. Characterization study of empty fruit bunch (EFB) fibers reinforcement in poly(butylene) succinate (PBS)/Starch/Glycerol composite sheet. Polymers 2020;12:1571. https://doi.org/10.3390/polym12071571.

[172] Suriani MJ, Radzi FSM, Ilyas RA, Petrů M, Sapuan SM, Ruzaidi CM. Flammability, tensile, and morphological properties of oil palm empty fruit bunches fiber/pet yarn-reinforced epoxy fire retardant hybrid polymer composites. Polymers 2021;13:1282. https://doi.org/10.3390/polym13081282.

[173] Jumaidin R, Diah NA, Ilyas RA, Alamjuri RH, Yusof FAM. Processing and characterisation of banana leaf fibre reinforced thermoplastic cassava starch composites. Polymers 2021;13:1420. https://doi.org/10.3390/polym13091420.
[174] Ilyas RA, Sapuan SM, Atiqah A, Ibrahim R, Abral H, Ishak MR, et al. Sugar palm (Arenga pinnata [Wurmb .] Merr) starch films containing sugar palm nanofibrillated cellulose as reinforcement: water barrier properties. Polym Compos 2020;41:459–67. https://doi.org/10.1002/pc.25379.
[175] Atiqah A, Jawaid M, Sapuan SM, Ishak MR, Ansari MNM, Ilyas RA. Physical and thermal properties of treated sugar palm/glass fibre reinforced thermoplastic polyurethane hybrid composites. J Mater Res Technol 2019;8:3726–32. https://doi.org/10.1016/j.jmrt.2019.06.032.
[176] Ilyas RA, Sapuan SM, Ishak MR. Isolation and characterization of nanocrystalline cellulose from sugar palm fibres (Arenga Pinnata). Carbohydr Polym 2018;181:1038–51. https://doi.org/10.1016/j.carbpol.2017.11.045.
[177] Atikah MSN, Ilyas RA, Sapuan SM, Ishak MR, Zainudin ES, Ibrahim R, et al. Degradation and physical properties of sugar palm starch/sugar palm nanofibrillated cellulose bionanocomposite. Polimery 2019;64:680–9. https://doi.org/10.14314/polimery.2019.10.5.
[178] Hazrol MD, Sapuan SM, Ilyas RA, Othman ML, Sherwani SFK. Electrical properties of sugar palm nanocrystalline cellulose reinforced sugar palm starch nanocomposites. Polimery 2020;65:363–70. https://doi.org/10.14314/polimery.2020.5.4.
[179] Suriani MJ, Sapuan SM, Ruzaidi CM, Nair DS, Ilyas RA. Flammability, morphological and mechanical properties of sugar palm fiber/polyester yarn-reinforced epoxy hybrid biocomposites with magnesium hydroxide flame retardant filler. Textil Res J 2021:1–12. https://doi.org/10.1177/00405175211008615.
[180] Nurazzi NM, Asyraf MRM, Khalina A, Abdullah N, Aisyah HA, Rafiqah SA, et al. A review on natural fiber reinforced polymer composite for bullet proof and ballistic applications. Polymers 2021;13:646. https://doi.org/10.3390/polym13040646.
[181] Siregar JP. Tensile and flexural properties of arenga pinnata filament (Ijuk Filament) reinforced epoxy composites [MScthesis]. Malaysia: UniversitiPutra; 2005.
[182] Wielage B, Lampke T, Marx G, Nestler K, Starke D. Thermogravimetric and differential scanning calorimetric analysis of natural fibres and polypropylene. Thermochim Acta 1999;337:169–77. https://doi.org/10.1016/S0040-6031(99)00161-6.
[183] Lilholt H, Lawther JM. Natural organic fibers. Compr. Compos. Mater.. Elsevier; 2000. p. 303–25. https://doi.org/10.1016/B0-08-042993-9/00048-6.
[184] ButlerRA. Malaysia has the world's highest deforestation rate, reveals Google forest map [accessed 15.02.2014.]. [n.d], http://news.mongabay.com/2013/1115-worlds-highest-deforestationrate.html#kSLrdoEdX5RhOw2a.99.
[185] Korjenic A, Zach J, Hroudová J. The use of insulating materials based on natural fibers in combination with plant facades in building constructions. Energy Build 2016;116:45–58. https://doi.org/10.1016/j.enbuild.2015.12.037.
[186] Väisänen T, Haapala A, Lappalainen R, Tomppo L. Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: a review. Waste Manag 2016;54:62–73. https://doi.org/10.1016/j.wasman.2016.04.037.
[187] Abesinghe N, Vidanarachchi J, Silva S. The effect of arrowroot (maranta arundinacea) extract on the survival of probiotic bacteria in set yoghurt. Int J Sci Res Publ 2012;2:2–5.
[188] Branco FP, Naka MH, Cereda MP. Granulometry and energy consumption as indicators of disintegration efficiency in a hammer mill adapted to extracting arrowroot starch (Maranta arundinacea) in comparison to starch extraction from cassava Appropriate these starches are commodities4430; 2019. p. 341–9.
[189] Shalwan A, Yousif B. In state of art: mechanical and tribological behaviour of polymeric composites based on natural fibres. Mater Des 2013;48:14–24.
[190] Shinoj S, Visvanathan R, Panigrahi S, Kochubabu M. Oil palm fiber (OPF) and its composites: a review. Ind Crop Prod 2011;33:7–22. https://doi.org/10.1016/j.indcrop.2010.09.009.
[191] Bénézet JC, Stanojlovic-Davidovic A, Bergeret A, Ferry L, Crespy A. Mechanical and physical properties of expanded starch, reinforced by natural fibres. Ind Crop Prod 2012;37:435–40. https://doi.org/10.1016/j.indcrop.2011.07.001.
[192] Kakroodi AR, Cheng S, Sain M, Asiri A. Mechanical, thermal, and morphological properties of nanocomposites based on polyvinyl alcohol and cellulose nanofiber from Aloe vera rind. J Nanomater 2014;2014:12–8. https://doi.org/10.1155/2014/903498.
[193] Burgueño R, Quagliata MJ, Mohanty AK, Mehta G, Drzal LT, Misra M. Hybrid biofiber-based composites for structural cellular plates. Compos Part A Appl Sci Manuf 2005;36:581–93. https://doi.org/10.1016/j.compositesa.2004.08.004.
[194] Herrera-Franco PJ, Valadez-González A. A study of the mechanical properties of short natural-fiber reinforced composites. Compos B Eng 2005;36:597–608. https://doi.org/10.1016/j.compositesb.2005.04.001.
[195] Saba N, Jawaid M, Hakeem KR, Paridah MT, Khalina A, Alothman OY. Potential of bioenergy production from industrial kenaf (Hibiscus cannabinus L.) based on Malaysian perspective. Renew Sustain Energy Rev 2015;42:446–59. https://doi.org/10.1016/j.rser.2014.10.029.
[196] Li X, Tabil LG, Panigrahi S. Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. J Polym Environ 2007;15:25–33. https://doi.org/10.1007/s10924-006-0042-3.
[197] Wu CS. Enhanced interfacial adhesion and characterisation of recycled natural fibre-filled biodegradable green composites. J Polym Environ 2018;26:2676–85. https://doi.org/10.1007/s10924-017-1160-9.
[198] Koronis G, Silva A, Fontul M. Green composites: a review of adequate materials for automotive applications. Compos B Eng 2013;44:120–7. https://doi.org/10.1016/j.compositesb.2012.07.004.
[199] Norrrahim MNF, Norizan MN, Jenol MA, Ahmad Farid MA, Janudin N, Aziz Ujang F, et al. Emerging development on nanocellulose as antimicrobial material: an overview. Mater Adv 2021. https://doi.org/10.1039/D1MA00116G.
[200] Abral H, Chairani MK, Rizki MD, Mahardika M, Handayani D, Sugiarti E, et al. Characterization of compressed bacterial cellulose nanopaper film after exposure to dry and humid conditions. J Mater Res Technol 2021;11:896–904. https://doi.org/10.1016/j.jmrt.2021.01.057.

[201] Abral H, Pratama AB, Handayani D, Mahardika M, Aminah I, Sandrawati N, et al. Antimicrobial edible film prepared from bacterial cellulose nanofibers/starch/chitosan for a food packaging alternative. Int J Polym Sci 2021;2021:1–11. https://doi.org/10.1155/2021/6641284.
[202] Ilyas RA, Sapuan SM, Ibrahim R, Abral H, Ishak MR, Zainudin ES, et al. Sugar palm (Arenga pinnata (Wurmb.) Merr) cellulosic fibre hierarchy: a comprehensive approach from macro to nano scale. J Mater Res Technol 2019;8:2753–66. https://doi.org/10.1016/j.jmrt.2019.04.011.
[203] Sabaruddin FA, Paridah MT, Sapuan SM, Ilyas RA, Lee SH, Abdan K, et al. The effects of unbleached and bleached nanocellulose on the thermal and flammability of polypropylene-reinforced kenaf core hybrid polymer bionanocomposites. Polymers 2020;13:116. https://doi.org/10.3390/polym13010116.
[204] Ilyas RA, Sapuan SM, Atikah MSN, Asyraf MRM, Rafiqah SA, Aisyah HA, et al. Effect of hydrolysis time on the morphological, physical, chemical, and thermal behavior of sugar palm nanocrystalline cellulose (Arenga pinnata (Wurmb.) Merr). Textil Res J 2021;91:152–67. https://doi.org/10.1177/0040517520932393.
[205] Ilyas RA, Sapuan SM, Ishak MR, Zainudin ES. Effect of delignification on the physical, thermal, chemical, and structural properties of sugar palm fibre. BioResources 2017;12:8734–54. https://doi.org/10.15376/biores.12.4.8734-8754.
[206] Zuo Y feng, Gu J, Qiao Z, Tan H, Cao J, Zhang Y. Effects of dry method esterification of starch on the degradation characteristics of starch/polylactic acid composites. Int J Biol Macromol 2015;72:391–402. https://doi.org/10.1016/j.ijbiomac.2014.08.038.
[207] Södergård A, Stolt M. Properties of lactic acid based polymers and their correlation with composition. Prog Polym Sci 2002;27:1123–63. https://doi.org/10.1016/S0079-6700(02)00012-6.
[208] Mukaffa H, Asrofi M, Sujito Asnawi, Hermawan Y, Sumarji, et al. Effect of alkali treatment of piper betle fiber on tensile properties as biocomposite based polylactic acid: solvent cast-film method. Mater Today Proc 2021. https://doi.org/10.1016/j.matpr.2021.02.218.
[209] Pivsa-art S, Kord-sa-ard J, Sijong W, Pivsa-art W, Ohara H, Yamane H. Biodegradation in landfilled of biodegradable micro-braided yarn. Energy Procedia 2016;89:282–90. https://doi.org/10.1016/j.egypro.2016.05.036.
[210] Silva R, Haraguchi SK, Muniz EC, Rubira AF. Applications of lignocellulosic fibers in polymer chemistry and in composites. Quim Nova 2009;32:661–71. https://doi.org/10.1590/S0100-40422009000300010.
[211] George J, Sreekala MS, Thomas S. A review on interface modification and characterization of natural fiber reinforced plastic composites. Polym Eng Sci 2001;41(9):1471–85. https://doi.org/10.1002/pen.10846.
[212] Lu JZ, Wu Q, McNabb HS. Chemical coupling in wood fiber and polymer composites: a review of coupling agents and treatments. Wood Fiber Sci 2000;32:88–104.
[213] Rhim JW, Park HM, Ha CS. Bio-nanocomposites for food packaging applications. Prog Polym Sci 2013;38:1629–52. https://doi.org/10.1016/j.progpolymsci.2013.05.008.
[214] Fang J, Fowler P. The use of starch and its derivatives as biopolymer sources of packaging materials. Food Agric Environ 2003;1:82–4.
[215] Arvanitoyannis I. Totally-and-partially biodegradable polymer blends based on natural and synthetic macromolecules: preparation and physical properties and potential as food packaging materials. J Macromol Sci 1999.
[216] Arvanitoyannis IS. Totally and partially biodegradable polymer blends based on natural and synthetic macromolecules: preparation, physical properties, and potential as food packaging materials. Mater Chem Phys 1999;C39:205–71.
[217] Weber CJ, Haugaard V, Festersen R, Bertelsen G. Production and applications of biobased packaging materials for the food industry: food Additives & Contaminants: vol 19, No sup 1. Food Addit Contam 2010;19:37–41. https://doi.org/10.1080/0265203011008748.
[218] Tang XZ, Kumar P, Alavi S, Sandeep KP. Recent advances in biopolymers and biopolymer-based nanocomposites for food packaging materials. Crit Rev Food Sci Nutr 2012;52(5):426–42. https://doi.org/10.1080/10408398.2010.500508.