Chapter

Banana Pseudo-Stem Fiber: Preparation, Characteristics, and Applications

Asmanto Subagyo and Achmad Chafidz

Abstract

Banana is one of the most well-known and useful plants in the world. Almost all the parts of this plant, that are, fruit, leaves, flower bud, trunk, and pseudo-stem, can be utilized. This chapter deals with the fiber extracted from the pseudo-stem of the banana plant. It discusses the production of banana pseudo-stem fiber, which includes plantation and harvesting; extraction of banana pseudo-stem fiber; retting; and degumming of the fiber. It also deals with the characteristics of the banana pseudo-stem fiber, such as morphological, physical and mechanical, durability, degradability, thermal, chemical, and antibacterial properties. Several potential applications of this fiber are also mentioned, such as the use of this fiber to fabricate rope, place mats, paper cardboard, string thread, tea bags, high-quality textile materials, absorbent, polymer/fiber composites, etc.

Keywords: banana, pseudo-stem, fiber, production, extraction, characteristics, applications

1. Introduction

In recent years, people have focused on forest preservation and finding a rational way to use agricultural and forest residues. This trend is caused by the rapid increase in consumption of wood fiber-based products, which may result in an illegal logging activity due to decreasing permitted wood resources. Additionally, the use of cellulose fiber from the forest and agricultural residues has many advantages, such as environmental friendliness, recyclability, and low cost or even free raw material. Statistically, the annual production of lignocellulose fiber from crops in the world was about 4 billion tons (i.e., 60% agricultural produce and 40% forest produce). Compared to other major commodities, the global annual production of steel was only 0.7 billon tons, while that of plastic was only 0.1 billion tons [1]. These data show us the high opportunity for the utilization of cellulose fiber.

Banana plants, which belong to the family of Musaceae, are native to the Malaysia-Indonesian region of South-East Asia. Bananas are widely produced and abundant natural resources in tropical and subtropical countries in the world [1–3]. The banana plants are considered as one of the world's most useful plants. Almost all the parts of this plant, for example, fruit, peel, leaf, pseudo-stem, stalk, and inflorescence (flower), can be utilized [3, 4]. They are used in several food and non-food-related applications, for example, as thickener, colorant and flavoring, macro- and micro-nutrient source, livestock feed, fibers, bioactive compound source, and organic fertilizers [4]. The banana leaf is frequently used in food processing (in some countries, e.g., Indonesia), food esthetic, food packaging, etc. The banana fruit itself is one of the most popular fruits and important diet due to its high nutritional content [5], thus it becomes a valuable commodity all around the world. The banana pseudo-stem has also been considered for use as pulp and paper raw material, fiber for textiles, and filler or structural reinforcement in composites materials [6–10]. Additionally, all parts of the banana plant have some medical added values, such as the flower can be cooked and consumed by diabetics, bronchitis, dysentery, and ulcer patients. The banana pseudo-stem sap can be orally taken or externally applied for stings and bites. The young leaf can be used for skin irritations (as a poultice). The roots, ashes of leaves, peels, and seeds also can be used for medicinal purposes in some countries [11]. In recent years, banana fruits have been the fourth most important fruit crop produced in the world. Approximately, 72.5 million tons of banana fruit are produced yearly in the world [2]. The fruit can be consumed directly (after ripe) or processed into other products, for example, dried fruit, smoothie, flour, ice-cream bread, etc. [5]. The flower bud can also be processed into a dish.

The most widely known banana plant species for its fiber is Abaca (*Musa textiles*). Its fiber is highly important among the leaf fiber group, whereas the most common banana that is consumed by humans is a member of *Musa acuminata* species [12]. Figure 1 shows the photograph of banana tree and its several parts. The pseudo-stem of banana plant is the stem of banana plant that provides and transports nutrients from the soil to the fruits. This pseudo-stem will be cut and become waste biomass after the banana fruit is ripe and harvested, because the banana plant is unusable for the next harvest [1, 12, 13]. For every ton of banana fruit harvested, about 100 kg of the fruit is rejected (i.e., rotten fruit) and approximately 4 tons of biomass wastes (e.g., leaf, pseudo-stem, rotten fruit, peel, fruit-bunch-stem, rhizome, etc.) are produced. This means, for every cycle of banana fruit production, four times of biomass wastes are also produced [13]. Based on another literature, it can be estimated that one hectare of banana farm could produce approximately 220 tons of biomass wastes [12] (**Figure 1**). These wastes are usually disposed of by the farmer into lakes and rivers or simply burned. The banana tree wastes if not properly managed can cause problem to the environment, because if they are dumped in wet conditions or burned can produce greenhouse gas, which can cause a problem to the environment [12]. It is believed that this crop waste can be used in a more rational way, namely, as a source of cellulose fiber for further applications [9].

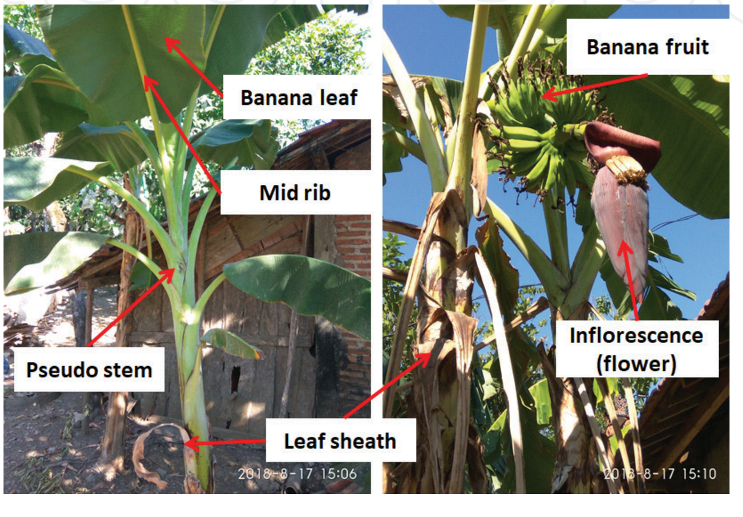

Figure 1.
Several parts of banana tree (photos were taken on August 17, 2018).

The pseudo-stem is a part of the banana plant that looks like a trunk, which consists of a soft central core and tightly wrapped up to 25 leaf sheaths. These leaf sheaths unwrap from the stem and transform to recognizable banana leaves when they have matured. The height of banana plant can reach approximately 7.5 m and since the leaf sheaths grow from the base of the plant, some of the leaves, on the inner side, have approximately the same length of the tree. Whereas the outer side leaves, which grow later, are shorter. The width of the banana leaves can reach approximately 30 cm [14].

2. Production of banana pseudo-stem fiber

The pseudo-stem fiber of banana plant is like the pineapple leaf, sisal, and other hard fibers, though the pseudo-steam fiber is a little more elastic. The major uses of banana pseudo-stem fiber are in making specialized and high-quality sanitary products such as baby pampers, textiles, and papers such as banknotes. The banana pseudo-stem fiber can also be used for ropes such as marine rope since this fiber has good resistance to sea water and has buoyancy properties. Other uses of this fiber are for making coffee and tea bags, filter cloths, as reinforcement fibers for plaster, disposable fabrics, and light-density woven fabrics. According to the literature, the production of Abaca (*Musa textiles*) fiber in the world has reached around 100,000 ton/year. The production in the year 1960 was also near this amount (i.e., 97,000 ton/year), whereas in the year 2002, the production of Abaca was about 99,320 ton/year. **Figure 2** shows the data percentage of banana production across the world in 2010.

2.1 Plantation and harvesting

The banana plant has a shallow rooting system in which the pseudo-stems sprout vertically. As it develops, a single plant may produce about 25 of these pseudo-stems, which mature at different times. When the plants are 18–24 months old, the outer pseudo-stems are already mature and ready to be harvested. Then, about three or four pseudo-stems are stripped at a period of 6–12 months based on the rate of growth of the pseudo-stem. When the flower is out, the pseudo-stems are completely ready for harvesting. Furthermore, the shaft is cut off below the inflorescence with a knife or sickle attached to a long pole and then the pseudo-stems are cut at their base. Based on the extraction methods, the pseudo-stems can be either

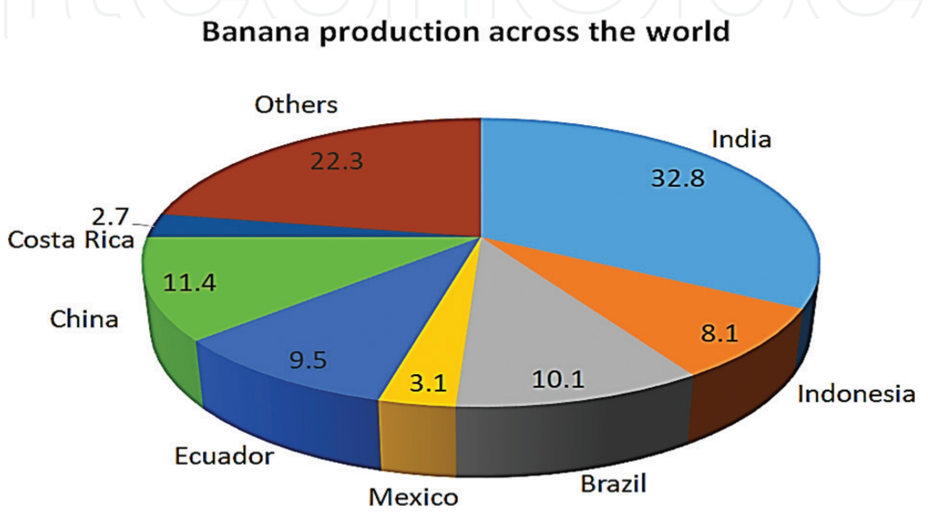

Figure 2.
Percentage data of banana production across the world in 2010 [15].

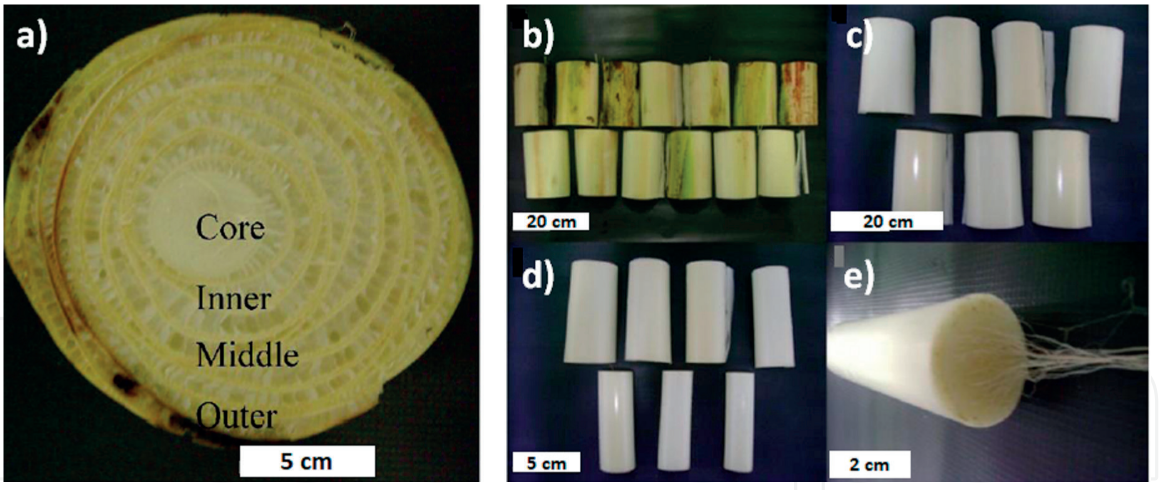

Figure 3.
(a) Banana pseudo-stem trunk cross section and its parts: (b) outer parts; (c) middle parts; (d) inner parts; and (e) core parts [16].

stripped/extracted of their fibers in situ or by using a decorticating machine [14]. The leaves are variable in length, the outer side leaves are shorter than the inner side. **Figure 3** shows the cross section of banana pseudo-stem and its parts.

2.2 Extraction of fiber

Fibers from the banana pseudo-stem leaves can be extracted by a decorticator machine. It is a machine used to strip bark, skin, wood, stalk, and grain. The extraction process is conducted as soon as the pseudo-stem's leaves are cut. The common method in practice is a combination of water retting and scraping. The first step, called tuxing, is separating the fiber bundles from the remaining parts. Tuxing can be done either manually or mechanically using machine [17]. The leaves are stripped from the cut pseudo-stems. Afterward, a knife is put at the butt end between the outer and middle layers of the leaf shaft, and then the outer part is held firmly and pulled out. The width of fiber bundles that resulted from this tuxing process is approximately 5–8 cm and is the same as the length of the leaf. The second step is to remove the gum or non-fibrous and any residual components contained in the fibers after the tuxing process [14]. Furthermore, the fibers are then thoroughly washed and dried. These processes demand considerable skill and patience. In general, only 11 exterior leaf sheaths in the banana pseudo-stem that can be extracted for its fibers. The fibers inside the interior sheaths have poor strength, and peeling of these fibers is found to be difficult due to their brittleness and poor strength [18].

One of the authors (A. Subagyo) has developed a decorticator machine, which could be used effectively by an average village artisan or an agriculturist for the extraction of fiber from banana pseudo-stem. The schematic diagram of the decorticator machine developed by Subagyo is shown in **Figure 4**. The decorticator machine consists of a rotating drum mounted on a shaft. On the circumference of the drum are mounted several blades which create a beating action as the drum is rotated by an electrical drive. As the drum rotates, the pseudo-stem is fed between the drum and backing plate or feeding roller. Owing to the crushing, beating, and pulling action, the pulpy material is removed when it is half way through. The pseudo-stems are slowly pushed from the drum and fall out to the conveyer belt, and eventually, the fibers are collected on the bucket. The next step is the degumming process of the fibers to remove foreign matter that are then washed and dried at room temperature of approximately 27–32°C. This machine can handle approximately two tons of dry fiber/day.

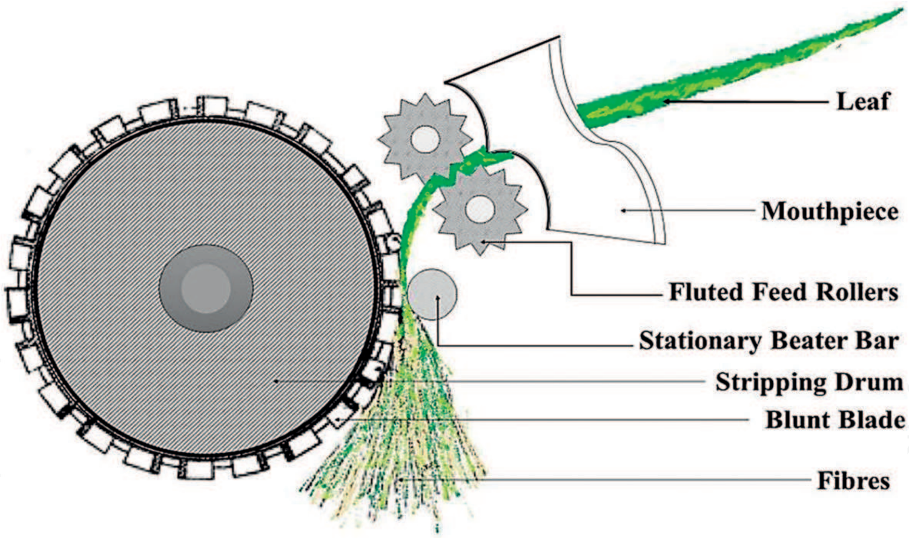

Figure 4.
Pseudo-stem fiber extraction machine.

2.3 Retting of banana pseudo-stem fiber

Retting of banana fiber is defined as the separation of the fiber bundles from the cortex or wood, which effects on partial digestion of the cementing material (such as lignin and hemicellulose) between the fibers in the bundles. This loosening of the fiber bundles is also due to the removal of various cementing tissue components. The retting of banana fiber is analogous to the general retting process, where two stages occur. The first stage is the physical stage in which the water is absorbed; then swelling happens, and some of the soluble substances are extracted. The second stage is the microbial stage, either aerobic or anaerobic by the action of fungi or bacteria, respectively.

Since retting process is basically a microorganism process, several factors such as: microbiological agents (bacteria or fungi), nature of retting water, aeration, and macro-nutrients. Microbial growth on plant fibers usually results in tenacity loss, odor release, and various types of strains on the fiber substrates. Sometimes, a specific microorganism can grow on a living plant stem and produce brownish stains on the fiber, which are usually known as rust. According to Subagyo [19], the factors like temperature, length of retting time, type of chemical additives (e.g., magnesium oxide), and pure culture of microorganisms such as pectin-decomposing bacteria in the retting liquor can reduce the retting time by approximately 78%. The pseudo-stem retting time of 28 h was found to be quite sufficient, and the process was effective at a controlled pH between 6.8 and 7.4 with sodium carbonate, and at room temperature.

Retting is carried out to increase the mechanical properties of natural fiber, such as banana pseudo-stem fiber [20]. Fiber tenacity tests indicated that the extractive removal of pectin from pseudo-stem fiber through retting did not cause any significant change in the tenacity of the fiber except when over-retting had begun. Furthermore, analysis of decorticated and retted pseudo-steam fibers indicated that retting can significantly reduce hemicellulose and lignin that are present in the pseudo-stem fiber. It has been reported that the pulping process of retted natural fibers gave pulps with better strength and chemical properties compared to those of the unretted fibers [21].

2.4 Degumming of banana pseudo-stem fiber

Banana pseudo-stem fiber produced by decorticator machine contains a quite large percentage of gum and non-fibrous cell or parenchyma (approx. 30–35%).

These gums and cells are mostly not soluble in water and must be extracted before the fiber is mechanically spun into fine yarn count. It is a numerical expression which indicates whether the yarn is fine or coarse, and thick or thin. The unit of count is mass per unit length or length per unit mass of the yarn. These gums basically consist of arabans and xylans, which are soluble in the alkaline solutions. The basic degumming process steps are as follows: boiling the fibers couple of times in aqueous alkaline solution with/without agitation and pressure, and with/without reducing agents; second, washing the fibers with water for neutralizing; third, fiber bleaching with dilute hydrogen peroxide or hypochlorite; and fourth, fiber washing with water for neutralizing and oiling with a sulfonated hydrocarbon. Most of the processes involve caustic soda to treat the residual pectin, lignin, and gum. Although pseudo-stem fibers are commonly degummed by chemicals, there are also promising alternatives in retting (microbial degumming). Additionally, several literature studies have reported that the use of ultrasonic vibrations could speed up the degumming process [22].

3. Banana pseudo-stem fiber properties

3.1 Morphological properties

Optical microscopy examination of pseudo-stem fiber of banana plant revealed that it is a multicellular fiber, like other vegetable fibers. The cells in this fiber have a diameter of approximately 10 μm and an average length of 4.5 μm with L/D ratio of 450. The cell wall thickness of banana fiber was found to be 8.3 μm, which lies between that of sisal (about 12.8 μm) and ramie (about 11.5 μm). The structural and fracture morphology of raw and chemically treated banana pseudo-stem fiber has been investigated using scanning electron microscopy after coating with a thin layer of gold or iridium [19]. Banana pseudo-stem fiber has a scaly and cellular structure with vegetable matter intact, as shown in **Figure 5a** and **b**. The horizontal marks on the fiber surface are attributed to the bundle structure of the fibers, in which each bundle consists of several fibrils. The transverse section of the pseudo-stem fiber is shown in **Figure 5c** and **d**, which confirms the multi-cellular structure, whereas the structure of the raw fiber is shown in **Figure 5e** and **f**. As seen in the figure, the lumen is clearly seen in the cross section (indicated by arrow no. 2), as well as the fiber-cell walls (indicated by arrow no. 1).

The hollow structure of the banana pseudo-stem suggests that the fiber will have good insulation and absorbance properties. Treating the fiber with either alkali or acid may result in good quality of fibers. For example, the treatment of pseudo-stem fiber with different concentrations of NaOH has indicated that the surface morphology of the 5% NaOH-treated fibers was not much different from that of the raw fibers. The surface looked clearer due to the removal of some impurities and debris, though the fiber is not clearly visible. The fibers and their fibrils are clearly visible when the pseudo-stem fiber is treated with 10% NaOH.

3.2 Physical and mechanical properties

Banana pseudo-stem fibers have physical and chemical characteristics and other properties that make them good quality fiber. In terms of physical properties, it has been reported in the literature that the banana pseudo-stem fiber has good modulus of elasticity, tensile strength, and stiffness, which makes it a promising fiber material [1]. The appearance of banana pseudo-stem fiber is quite like ramie and bamboo fiber, but its spin ability and fineness are much better than that of ramie and bamboo. It

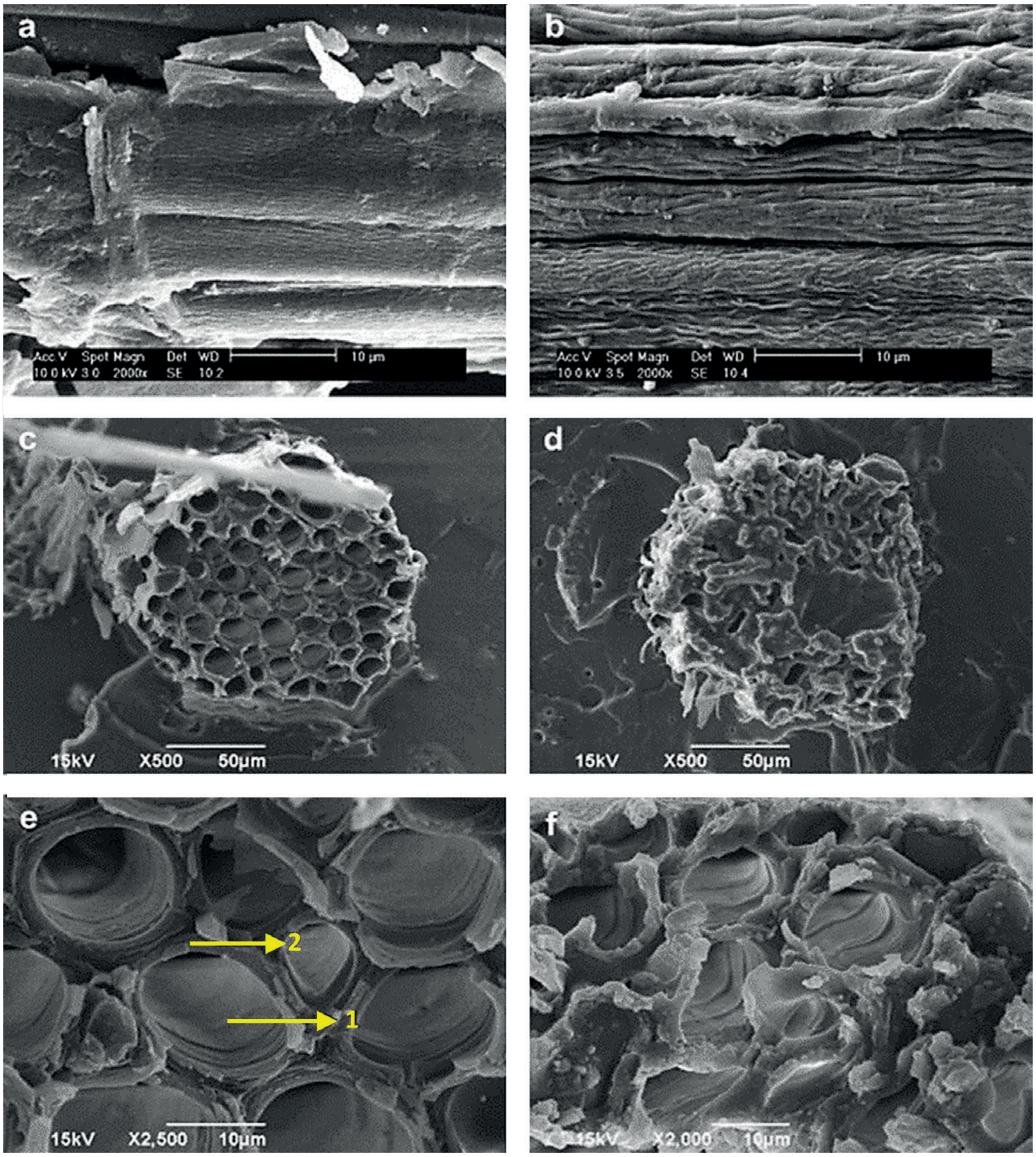

Figure 5.
SEM images of banana pseudo-stem fiber.

has average fineness of 2400 Nm. It is a strong fiber and has lower strain at break. Its appearance is quite shiny, which depends on the extraction and spinning processes. It has low density and strong moisture absorption quality. Its absorbance and release of moisture are quite fast. **Table 1** shows the physical and mechanical properties of banana pseudo-stem fiber in comparison with other types of plant/natural fibers. Additionally, studies of X-ray indicate that banana pseudo-stem fiber has a high degree of crystallinity with a spiral angle of about 15°. In the crystalline region, the molecules are packed more tightly. The acid and alkali-treated banana pseudo-stem fibers showed greater amorphous region than the untreated fiber.

3.3 Durability and biodegradability

Studies on the durability of banana pseudo-stem fiber have been carried out at the Center of Study for Natural Fiber and Natural Dyes (CSNFD) at the Department of Chemical Engineering, Concentration Textile Engineering, Universitas Islam Indonesia (UII). The studies showed that the durability of banana pseudo-stem fiber can stay up to 3 months of storage. However, if the storage period of the fiber is longer than 3 months, the strength of the fiber is considerably decreased.

Fibers	Width or diameter (μm)	Density (kg/m^3)	Cell L/D ratio	Microfibrillar angle (degree)	Initial modulus (GPa)	Tensile strength (MPa)	Elongation (%)
Banana pseudo-stem	80–250	1350	150	10 ± 1	7.7–20.0	54–754	10.35
Coir	100–450	1150	35	30–40	4–6	106–175	17–47
Pineapple leaf	20–80	1440	450	8–14	34.5–82.5	413–1627	0.8–1
Sisal	50–200	1450	100	10–22	9.4–15.8	568–640	3–7
Palmyra	70–1300	1090	43	29–32	4.4–6.1	180–215	7–15

Table 1.
Physical and mechanical properties of some plant fibers [23, 24].

Furthermore, banana pseudo-stem fibers are biodegradable, and thus can be categorized as environmentally friendly. Banana pseudo-stem fiber can be spun using almost any method of spinning, such as open-end spinning, ring-spinning, bast fiber spinning, and semi-worsted spinning.

The study of biodegradability of the banana pseudo-stem fiber can be done by burying the fiber in the ground. While buried in the ground, the growth of microorganisms plays a major role during the degradation process of fiber cellulose by secretion of enzyme cellulose, which results in the loss of tenacity. Based on the soil burial test, it was found that the banana pseudo-stem fiber loses strength rapidly when buried in the ground. The decrease of tensile strength after soil burial for 3 days is only approximately 21.8%, compared to that of sisal and jute, which is approximately 65.8 and 78%, respectively. Banana pseudo-stem fibers also lose strength and elongation conditions, the loss of fiber strength could be ascribed to the penetration of water molecules in the multicellular lignocellulose fibers. Swelling up of the fibers and, to some extent, loosening of the binding of the ultimate cells result in cell slippage when load is applied. Under wetting conditions, extension of untreated and degummed fibers is reduced by 6 and 11%, respectively.

3.4 Thermal properties

Thermogravimetric analysis (TGA) is carried out to analyze the heat stability or thermal degradation of banana pseudo-stem fiber. The TGA analyzer records the weight loss as a function of temperature with a resolution of 0.1 mg. The fiber samples (about 3–6 mg) were accurately weighed and randomly distributed in the sample pan. A small amount of sample was used to ensure the uniformity or reproducibility of the TGA result. The following is an example of TGA of banana pseudo-stem. The thermal degradation of the fiber started at a temperature of 25–700°C in N_2 environment at a constant heating rate of 10°C/min. Thermal degradation of the banana pseudo-stem fiber occurred in three stages.

The first stage of degradation was evaporation of moisture at a temperature range of 30–144°C [26]. As the fiber was continuously heated, the weight of the fiber decreased by releasing moisture and some volatile extractives. This is a common phenomenon that occurs in plant fibers, which makes the fibers become more flexible and collapse easily, and increases heat transfer [27]. Nevertheless, the moisture contained in the fiber cannot be completely removed due to structural resistance from the fiber and the hydrophilic nature of the fiber. In this first stage, the weight loss of the fiber was in the range of 5–10 wt%. The second stage was the degradation of hemicellulose. For banana pseudo-stem fiber, the hemicellulose

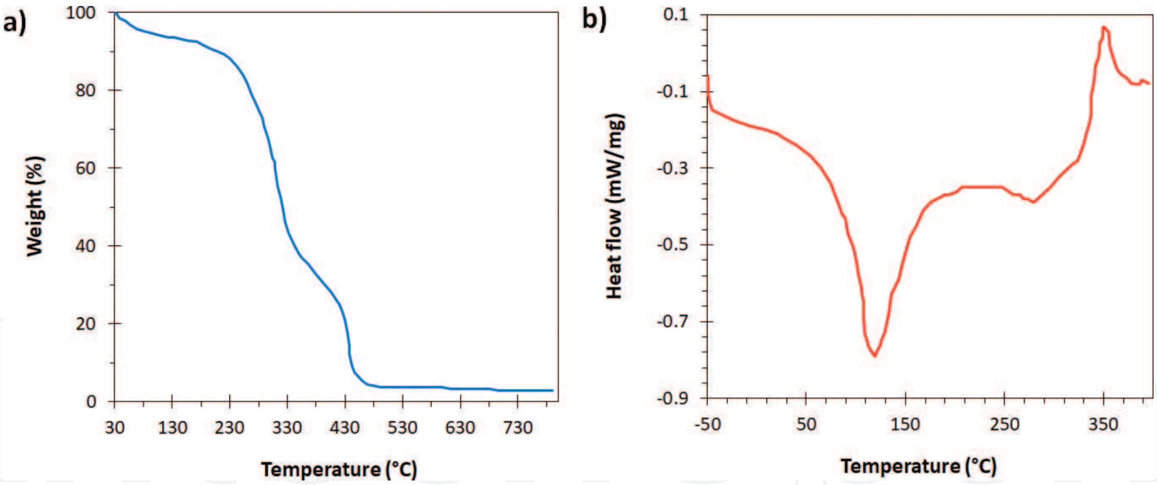

Figure 6.
(a) TGA curve and (b) DSC thermogram of banana pseudo-stem fiber [29, 30].

started to decompose at a temperature of approximately 178°C [26]. The lower stability of the hemicellulose is likely due to the presence of acetyl groups, which make the hemicellulose degrade much more quickly than the other components, for example, lignin and cellulose. The third stage was the degradation of cellulose, which occurred at a temperature of approximately 296°C. The last stage (that is, fourth stage) is the decomposition of lignin. Lignin is more difficult to decompose compared to other components. Generally, for any plant fiber, the decomposition of lignin occurred slowly in all ranges of temperature up to 700°C.

Nevertheless, for banana pseudo-stem fiber, there was a considerable lignin degradation peak that reached maximum degradation temperature of 501°C [20]. This was a result of broken protolignin bonds present in the fibers. This confirmed that the degradation of lignin happened in a wider range of temperature as compared to other components (e.g., hemicellulose, cellulose, and moisture) [28]. **Figure 6a** shows the TGA curve of banana pseudo-stem fiber. Moreover, **Figure 6b** shows the differential scanning calorimetry (DSC) thermogram of banana pseudo-stem fiber. According to the literature, the trend of DSC thermogram of the banana pseudo-stem is quite similar to that of other lignocellulosic fibers. The peak shown in the DSC (approximately 50–150°C) can be attributed to the heat required by the fiber to evaporate the moisture contained in the fiber. The range of temperature is in agreement with the TGA results, in which the first stage of degradation was evaporation of moisture at a temperature range of 30–144°C. Additionally, thermal conductivity of banana pseudo-stem fiber is found to be quite low at 0.0253 W/m^2 K, which suggests that these fibers could be used as good thermal insulations.

3.5 Chemical properties

In the past, many researchers were interested in the chemical constituents of plant fibers. It was found that plant fibers contain some of the following components [31]:

a. Fat and waxes, which are mostly found on the surface of the plants and can be extracted using benzene.

b. Pectin, which exists in water-soluble form as calcium and magnesium from galacturonic acid. These substances are converted into butyric and acetic acids during biological retting.

c. Hemicelluloses, which are amorphous short-chain polysaccharides and polyuronides. The polysaccharide hemicelluloses are chemically partly linked or intermingled with cellulose molecules.

d. Cellulose, which is the major constituent of the fiber.

e. Lignin, which is a short-chain isotropic and non-crystalline polymer made up of units derived from phenyl propane.

f. Ash content.

g. Aqueous extract, which is extracted by boiling the dewaxed fibers in water.

Table 2 shows the composition of constituents of banana pseudo-stem based on different literatures [17]. As shown in both of the tables, the banana pseudo-stem mostly consists of cellulose. Cellulose fiber can be considered as the most available natural, biodegradable, and renewable polymer that can be used in many applications (reinforcing materials, textiles, polymer matrix, and raw materials for paper) [32].

Additionally, there was a method reported in the literature [3] that showed the steps to deconstruct the banana pseudo-stem fiber to know the chemical composition of the fiber. The detailed steps of this method are exhibited in **Figure** 7. Step 1 is the determination of lipo-soluble extractive (LSE) content. Step 2 is determination of water-soluble extract (WSE) content. Step 3 is determination of pectin content. Step 4 is the determination of lignin content. Step 5 is the separation of cellulose-hemicellulose. The details about the determination procedure of these components have been explained in the literature [3].

Several methods can be used to extract cellulose fibers from their biomass sources, which are steam explosion treatment, alkali treatment, enzyme treatment, and liquefaction [24]. The focus of this chapter is the alkali treatment method. The properties of alkali-treated banana pseudo-stem fiber have been studied. The treatment of the fiber with 18% NaOH has enhanced the breaking elongation of fiber. This caustic treatment also resulted in length shrinkage, with the maximum shrinkage found to occur within 20 min of the alkali-treatment, after which there was only very little shrinkage. The length shrinkage has been found to be proportional to the weight loss. The weight loss is mainly due to the removal by caustic treatment of hemicellulose component and other substances. However, with an alkali-treatment, the banana pseudo-stem fiber also experienced a decrease in dynamic modulus. This decrease can be related to structural change caused by alkali treatment. The diameter of the fiber increased by the caustic treatment by 15–100%, which resulted in bundle fiber bulk improvement.

Sample	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractives (%)	Ash content (%)	Moisture content (%)	Ref.
1	63.20	18.60	5.10	1.40	1.02	10.00	[31]
2	31.27	14.98	15.07	4.46	8.65	9.74	[33]
3	63.9	1.3	18.6	10.6	1.5	—	[34]
4	31.26	14.98	15.07	4.45	8.64	9.74	[7]
5	57	10.33	15.55	—	—	20.23	[35]
Average	49.33	12.04	13.88	5.23	4.95	12.43	

Table 2.
Components' composition of banana pseudo-stem (based on different literatures).

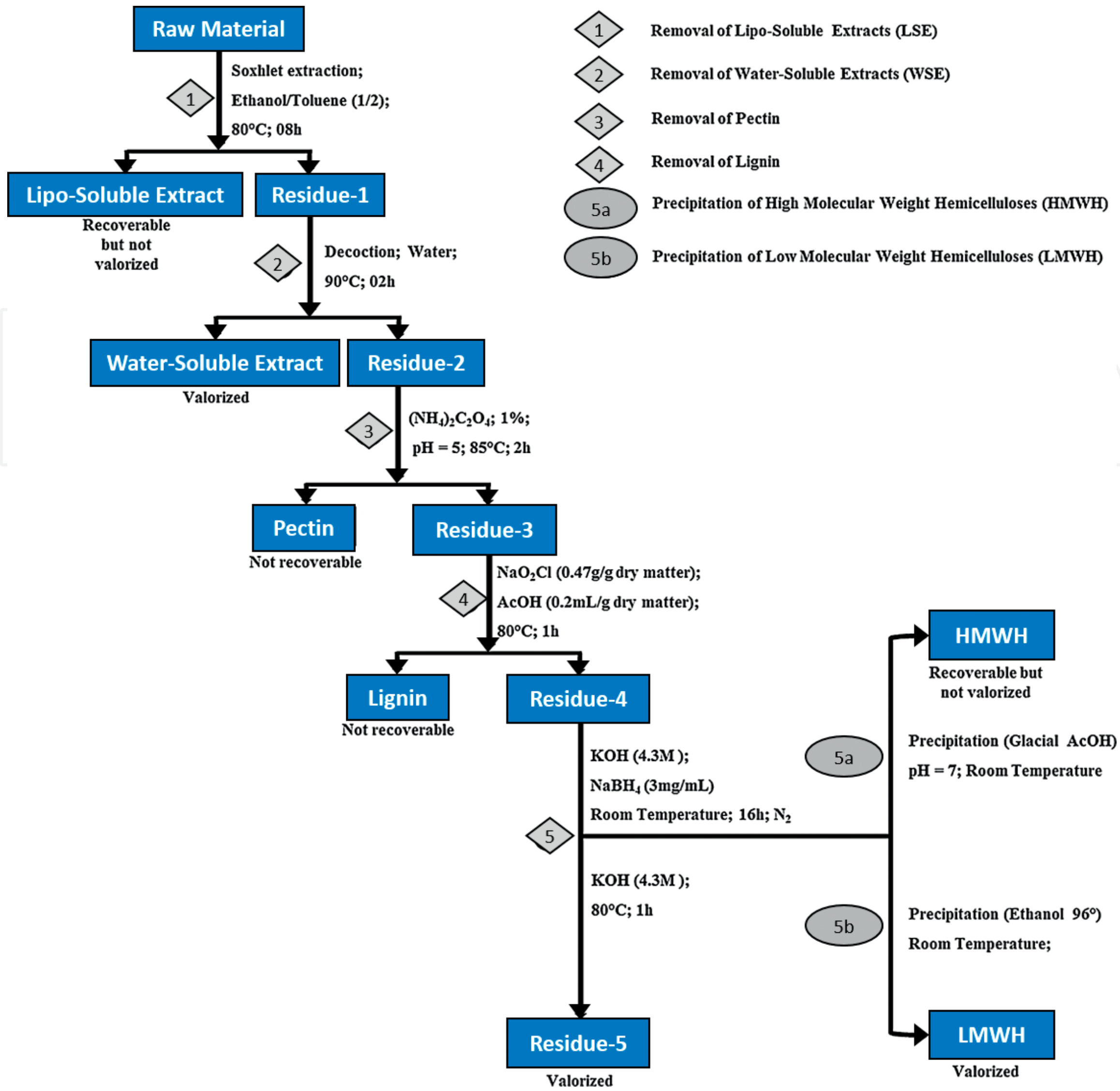

Figure 7.
Several steps of chemical deconstruction of banana pseudo-stem fiber [3].

The main problem to be encountered during wet processing of banana pseudo-stem fiber is the removal of lignin, residual gum, and other cementing materials, which interferes with the absorption property and thus leads to poor scouring, bleaching, and dyeing of the fiber. The exact structure of lignin is not clearly revealed, although it is generally regarded as a three-dimensional polycondensate of dehydrogeneration products of hydroxy and methoxy cinnamyl alcohols. Lignin is mainly composed of methoxyl, hydroxyl, and carbonyl groups.

Additionally, the physico-chemical properties of the banana pseudo-stem fiber were also studied. Infrared (IR) spectroscopy is probably one of the most widely used instrumental methods for investigating physico-chemical properties of textile materials. When a sample of organic compound is passed by infrared, certain frequencies are absorbed while others are transmitted through the sample. The IR spectrum is obtained by plotting the percentage of absorbance or percentage transmittance values against the frequencies. Fourier transform infrared spectroscopy (FTIR) was used to study the absorption peaks of banana pseudo-stem fiber. **Figure 8a–c** shows the FTIR spectrum of untreated, acid-treated, and alkali-treated pseudo-stem banana fiber, respectively. The appearance of absorption peaks was due to the presence of some functional groups.

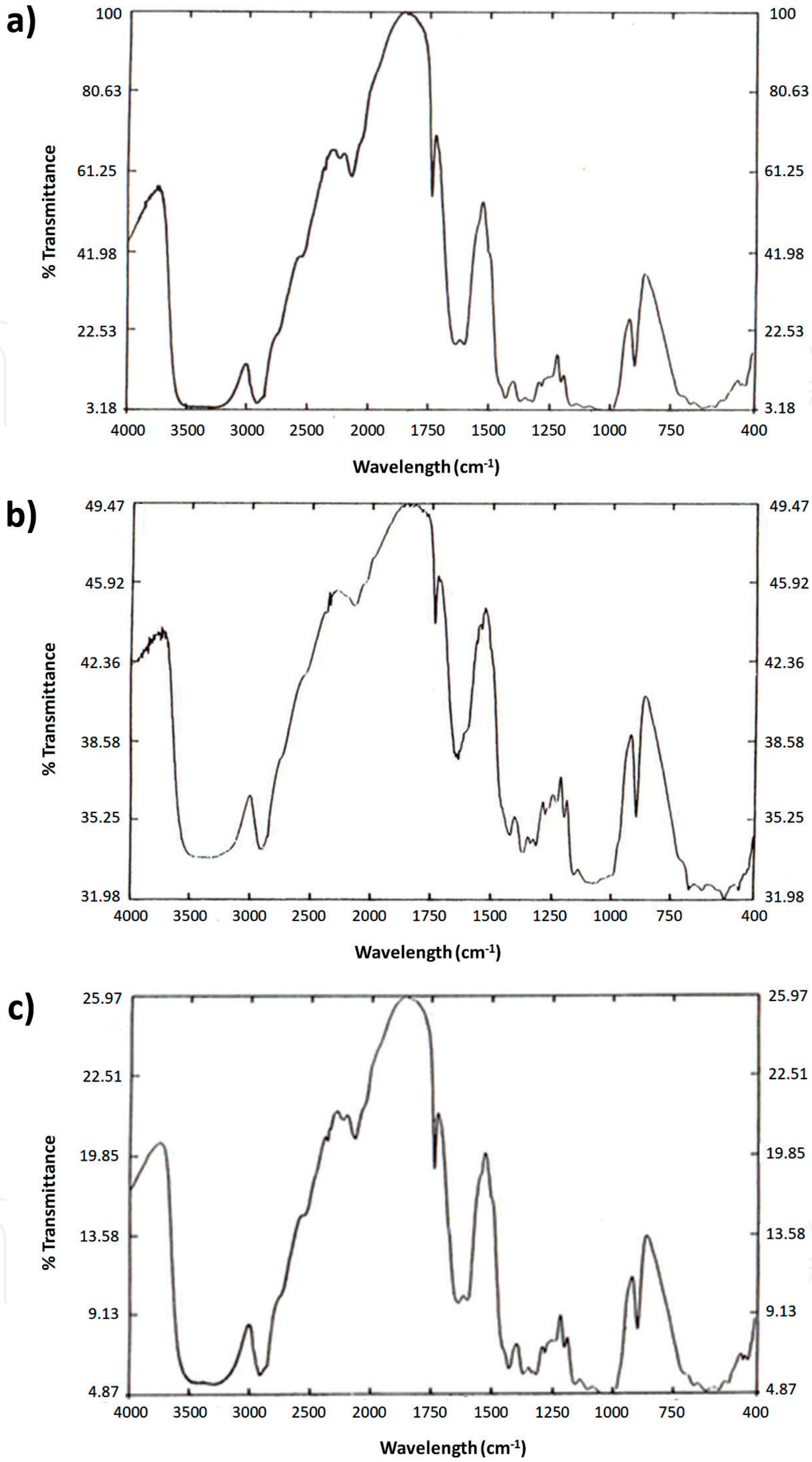

Figure 8.
FTIR spectrum of banana pseudo-stem fiber: (a) untreated banana; (b) acid-treated; and (c) alkali-treated.

3.6 Antibacterial test

Banana and banana pseudo-stem contain pathogenesis proteins, which possess antimicrobial properties [39]. The antibacterial activity of the banana pseudo-stem fiber can be analyzed using a shake flask test, according to Standard of Textiles Evaluation for antibacterial activity Part 3: Shake flask method, GB/T 20944.3-2008. Analysis of the effect of banana pseudo-stem fiber physical state on its

Plant fibers	Moisture regain (%)
Banana pseudo-stem fiber	9.8–12
Cotton fiber	7.75–9.50
Flax fiber	9.24–10.50
Ramie fiber	6.81–9.80

Table 3.
Moisture regain of textile fiber.

antibacterial properties can be done as follows. Untreated/raw cotton was used as the control sample, and the antibacterial/treated cotton was used as the test sample. The antimicrobial properties were determined by calculating the bacteriostatic rate using Eq. (1).

$$Y = \frac{W_t - Q_t}{W_t} \times 100\% \tag{1}$$

where Y is the bacteriostatic rate (%), W_t is the average colony-forming unit (CFU) per mm for the flask that contains the control sample after 18 h of contact, and Q_t is the average CFU/mm for the flask which contains the test sample after 18 h of contact. The extractives' effect on the microbial resistance properties of the banana pseudo-stem fiber can also be investigated. The growth condition of the bacteria in the flasks, which contains the unextrvacted and extracted fiber, is compared. The extractives' effect on the microbial resistance properties is evaluated by calculating the antimicrobial efficiency using Eq. (2). A negative number in the calculation result is represented as 0.

$$E = \left(1 - \frac{D_t}{D_0}\right) \times 100\% \tag{2}$$

where E is the antimicrobial efficiency (%), D_t is the average CFU/mm for the flask that contains extracted fiber after 18 h of contact, and D_0 is the average CFU/mm for the flask containing the untreated banana pseudo-stem fiber after 18 h of contact [37].

The microorganisms that can be used for the antibacterial test are *Staphylococcus aureus* (gram positive bacteria), *Escherichia coli* (gram negative bacteria), and *Candida albicans* (fungi). Nutrient broth and culture medium (agar) are used for the bacterial growth, whereas for the fungal growth, Sabouraud's culture medium (agar) is used. Additionally, there is a correlation between bacteriostatic rate and moisture regain of the natural fiber. The higher the moisture regain of a natural fiber, the lower the bacteriostatic rate. **Table 3** shows moisture regains (hygroscopicity) of different plant fibers. As seen in the table, the hygroscopicity of the banana pseudo-stem fiber is the highest among the others, whereas the ramie fiber has the lowest moisture regain.

4. Applications of banana pseudo-stem

As previously explained in the beginning, banana pseudo-stem usually becomes biomass waste once the harvest time of banana fruit is finished. Its disposal has become a major problem due to the amount of the waste. Therefore, researchers have started to extract the fibers and other components from the stem and used them to produce various value-added products. One of the most common banana pseudo-stem fiber products produced today is rope and cordage. The seawater resistance of the pseudo-stem fiber and its natural buoyancy characteristic have made a market for this fiber in the shipping cable manufacture. This fiber is also used to produce fishing nets, other types of cordage, mats, packaging, sheets, etc. **Figure 9** shows some value-added products made of banana pseudo-stem fiber. Additionally, in the Edo period of Japan (1600–1868), banana pseudo-stem fiber was used to make traditional dresses such as kimono and kamishimo. This fiber is usually used due to its light weight and comfort. Furthermore, banana pseudo-stem fiber is also utilized to produce cushion cover, bag, table cloth, curtain, and others [38]. Additionally, there are some potential uses of banana fibers, such as: to be used as natural absorbent, for production of mushroom, arts/handicrafts, string thread, paper cardboard, tea bag and high-quality textiles/fabric materials, currency note paper, and many other products. The use of banana fiber as natural absorbent also has promising potential to absorb oil spilling in oil refinery. It also can be used as absorbent in colored wastewater from the dyes of textile industry [39, 40]. Banana and banana pseudo-stem contain pathogenesis proteins, which possess antimicrobial properties [39]. The pseudo-stem can also be converted into bio-fertilizer [41]. It also contains high amount of cellulose and starch, and thus it can be utilized as feed for cattle [15]. Moreover, there have been numerous research studies that reported the use of banana pseudo-stem fiber in fabrication of polymer/fiber composites [17, 42].

Cellulosic cotton textile very easily catches flame, and it is very difficult to be extinguished. This problem of course poses a dangerous risk to life of human beings and textile products. Therefore, major efforts have been made in the past years to improve the flame retardancy of the cotton textile material by using many synthetic chemicals, which are available commercially. Phosphorous-based flame retardancy agents together with nitrogen-based compounds are the most effective combination that have been reported so far. However, there are some drawbacks such as high cost

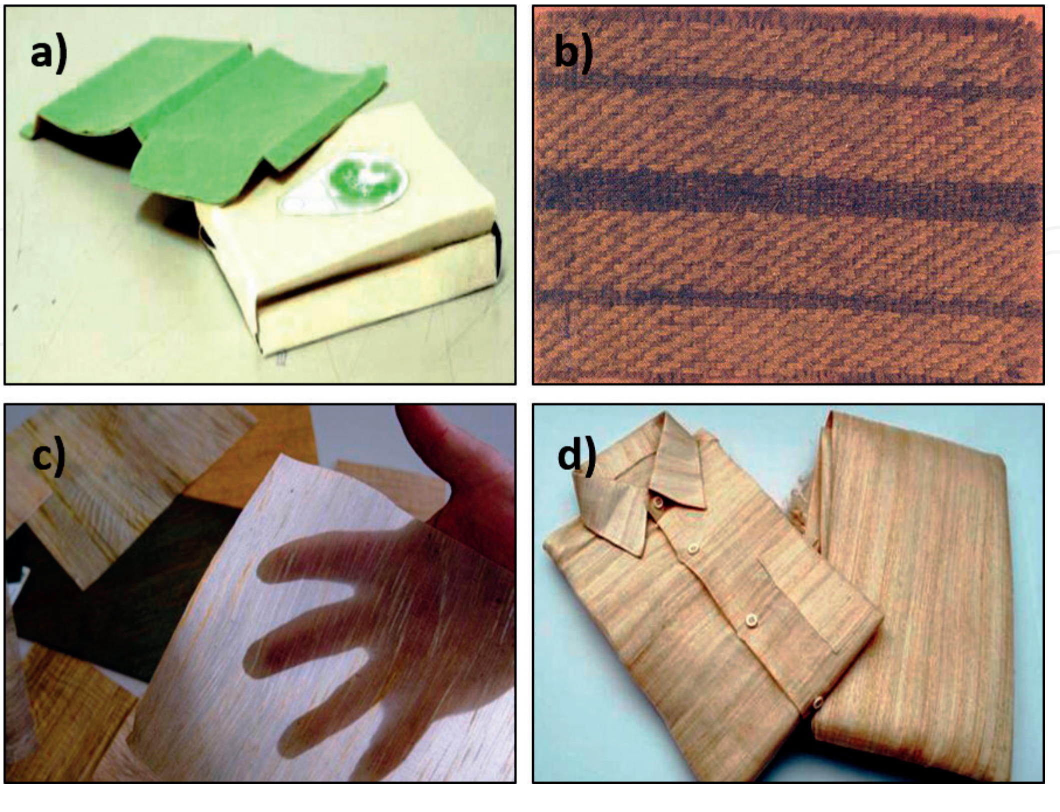

Figure 9.
Value-added products made from banana pseudo-stem fiber: (a) banana fiber package; (b) banana fiber mat; (c) banana sheets; and (d) banana fiber textile/shirt.

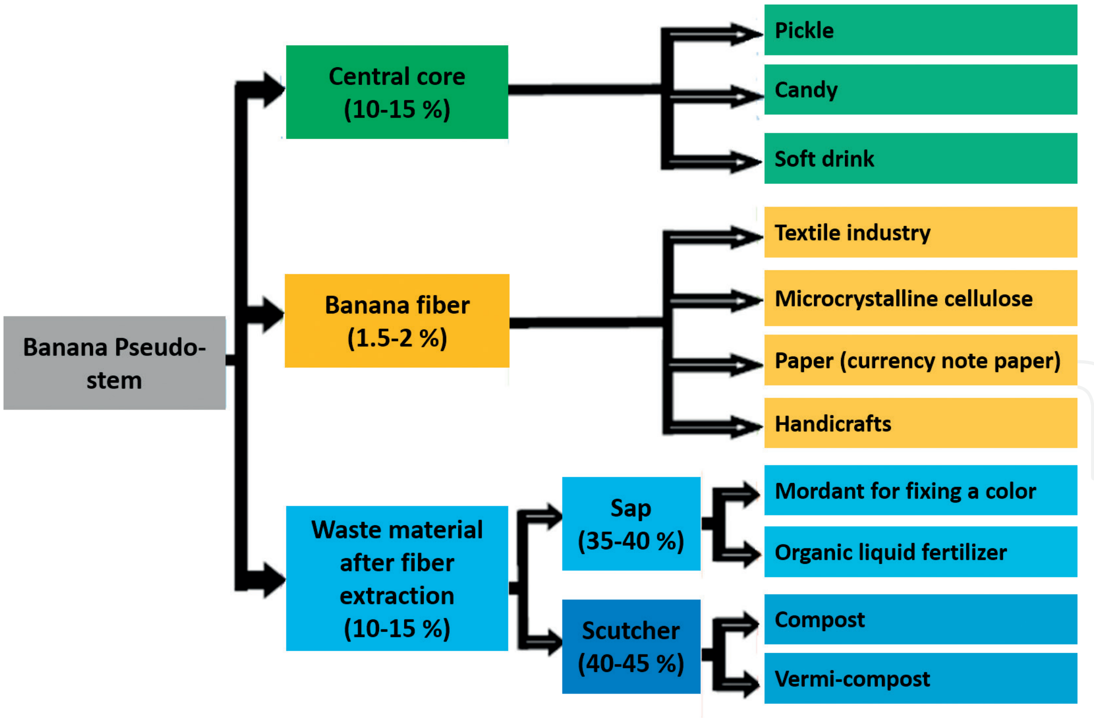

Figure 10.
Potential applications of components from the banana pseudo-stem.

and not environmentally friendly [43]. Hence, there is a growing trend that focuses on more cost-effective, environmentally friendly methods, and sustainable fire-retardant products. Several literature studies have been reported on providing fire retardancy to the cotton textile material by using natural products. One of them is using the waste banana pseudo-stem sap (BPS) [36]. Banana pseudo-stem sap (BPS) is a liquid that is extracted from the banana pseudo-stem. Additionally, there are many more potential applications of banana pseudo-stem components. **Figure 10** shows several value-added products made of components, which are derived from the banana pseudo-stem.

5. Conclusion

Banana plants are considered as one of the world's most useful plants. Almost all of the parts of this plant, for example, fruit, peel, leaf, pseudo-stem, stalk, and inflorescence, can be utilized. The banana fruit itself is one of the most popular fruits that is a valuable commodity all around the world. Nevertheless, banana pseudo-stem usually becomes biomass waste once the harvest time of banana fruit is finished. Therefore, researchers have started to extract the fibers and other components from the stem and used them to produce various value-added products. The fibers from the banana pseudo-stem can be extracted by a decorticator machine. The next processes are retting and degumming of the fibers. The fibers derived from the banana pseudo-stem can be made into several value-added products, such as rope, cordage, fishing net, mat, packaging material, paper sheets, textile fabrics, bag, table cloth, handicrafts, absorbent, polymer/fiber composites, etc. Additionally, other components derived from the banana pseudo-stem can also be used. The central core can be used for making pickle, candy, and soft drink, whereas banana pseudo-stem sap (BPS) can be used for mordant for fixing a color and organic liquid fertilizer, while the scutcher can be used for making compost and vermi-compost.

Author details

Asmanto Subagyo and Achmad Chafidz*
Chemical Engineering Department, Universitas Islam Indonesia, Yogyakarta, Indonesia

*Address all correspondence to: achmad.chafidz@uii.ac.id

References

[1] Li K, Fu S, Zhan H, Zhan Y, Lucia L. Analysis of the chemical composition and morphological structure of banana pseudo-stem. BioResources. 2010;**5**:576-585

[2] Aziz NAA, Ho L-H, Azahari B, Bhat R, Cheng L-H, Ibrahim MNM. Chemical and functional properties of the native banana (*Musaacuminata×balbisiana Colla cv. Awak*) pseudo-stem and pseudo-stem tender core flours. Food Chemistry. 2011;**128**:748-753

[3] Sango T, Cheumani Yona AM, Duchatel L, Marin A, Kor Ndikontar M, Joly N, et al. Step-wise multi-scale deconstruction of banana pseudo-stem (*Musa acuminata*) biomass and morpho–mechanical characterization of extracted long fibres for sustainable applications. Industrial Crops and Products. 2018;**122**:657-668

[4] Padam BS, Tin HS, Chye FY, Abdullah MI. Banana by-products: An under-utilized renewable food biomass with great potential. Journal of Food Science and Technology. 2014;**51**:3527-3545

[5] Vu HT, Scarlett CJ, Vuong QV. Phenolic compounds within banana peel and their potential uses: A review. Journal of Functional Foods. 2018;**40**:238-248

[6] Annie Paul S, Boudenne A, Ibos L, Candau Y, Joseph K, Thomas S. Effect of fiber loading and chemical treatments on thermophysical properties of banana fiber/polypropylene commingled composite materials. Composites Part A: Applied Science and Manufacturing. 2008;**39**:1582-1588

[7] Bilba K, Arsene M-A, Ouensanga A. Study of banana and coconut fibers: Botanical composition, thermal degradation and textural observations. Bioresource Technology. 2007;**98**:58-68

[8] Cherian BM, Pothan LA, Nguyen-Chung T, Mennig Gn, Kottaisamy M, Thomas S. A novel method for the synthesis of cellulose nanofibril whiskers from banana fibers and characterization. Journal of Agricultural and Food Chemistry. 2008;**56**:5617-5627

[9] Cordeiro N, Belgacem MN, Torres IC, Moura JCVP. Chemical composition and pulping of banana pseudo-stems. Industrial Crops and Products. 2004;**19**:147-154

[10] Tock JY, Lai CL, Lee KT, Tan KT, Bhatia S. Banana biomass as potential renewable energy resource: A Malaysian case study. Renewable and Sustainable Energy Reviews. 2010;**14**:798-805

[11] Kumar KS, Bhowmik D, Duraivel S, Umadevi M. Traditional and medicinal uses of banana. Journal of Pharmacognosy and Phytochemistry. 2012;**1**:51-63

[12] Ahmad T, Danish M. Prospects of banana waste utilization in wastewater treatment: A review. Journal of Environmental Management. 2018;**206**:330-348

[13] Abdullah N, Sulaiman F, Miskam MA, Taib RM. Characterization of banana (*Musa spp.*) pseudo-stem and fruit-bunch-stem as a potential renewable energy resource. International Journal of Biological, Veterinary, Agricultural and Food Engineering. 2014;**8**:712-716

[14] Franck RR. 8—Abaca. In: Franck RE, editor. Bast and Other Plant Fibres. United Kingdom: Woodhead Publishing; 2005. pp. 315-321

[15] Ray D, Nayak L, Ammayappan L, Shambhu V, Nag D. Energy conservation drives for efficient extraction and utilization of banana fibre. International Journal of Emerging Technology and Advanced Engineering. 2013;**3**:296-310

[16] Pereira ALS, Nascimento DM, Men de Sá Filho MS, Cassales AR, Morais JP, Paula RC, et al. Banana (*Musa sp. cv. Pacovan*) pseudostem fibers are composed of varying lignocellulosic composition throughout the diameter. BioResources. 2014;**9**:7749-7763

[17] Pappu A, Patil V, Jain S, Mahindrakar A, Haque R, Thakur VK. Advances in industrial prospective of cellulosic macromolecules enriched banana biofibre resources: A review. International Journal of Biological Macromolecules. 2015;**79**:449-458

[18] Jayaprabha JS, Brahmakumar M, Manilal VB. Banana pseudostem characterization and its fiber property evaluation on physical and bioextraction. Journal of Natural Fibers. 2011;**8**:149-160

[19] Subagyo A. Degumming agave cantala fiber using microbial (green degumming) and economic review. In: 88th Textile Institute World Conference. Malaysia; 2012. p. 733

[20] Srinivasan VS, Rajendra Boopathy S, Sangeetha D, Vijaya Ramnath B. Evaluation of mechanical and thermal properties of banana–flax based natural fibre composite. Materials & Design. 2014;**60**:620-627

[21] Khan MZH, Sarkar MAR, Al Imam FI, Khan MZH, Malinen RO. Paper making from banana pseudo-stem: Characterization and comparison. Journal of Natural Fibers. 2014;**11**(3):199-211

[22] Kozlowski R, Rawluk M, Barriga-Bedoya J. 5—Ramie. In: Franck RE, editor. Bast and Other Plant Fibres. United Kingdom: Woodhead Publishing; 2005. pp. 207-227

[23] Venkateshwaran N, Elayaperumal A. Banana fiber reinforced polymer composites—A review. Journal Reinforced Plastics and Composites. 2010;**29**:2387-2396

[24] Satyanarayana KG, Sukumaran K, Mukherjee PS, Pavithran C, Pillai SGK. Natural fibre-polymer composites. Cement and Concrete Composites. 1990;**12**:117-136

[25] Alwani MS, Khalil HA, Sulaiman O, Islam MN, Dungani R. An approach to using agricultural waste fibres in biocomposites application: Thermogravimetric analysis and activation energy study. BioResources. 2013;**9**:218-230

[26] Ndazi B, Tesha J, Bisanda ET. Some opportunities and challenges of producing bio-composites from non-wood residues. Journal of Materials Science. 2006;**41**:6984-6990

[27] Faulstich de Paiva JM, Frollini E. Unmodified and modified surface sisal fibers as reinforcement of phenolic and lignophenolic matrices composites: Thermal analyses of fibers and composites. Macromolecular Materials & Engineering. 2006;**291**:405-417

[28] Subramanya R, Satyanarayana KG, Shetty Pilar B. Evaluation of structural, tensile and thermal properties of banana fibers. Journal of Natural Fibers. 2017;**14**:485-497

[29] Guimarães J, Frollini E, Da Silva C, Wypych F, Satyanarayana K. Characterization of banana, sugarcane bagasse and sponge gourd fibers of Brazil. Industrial Crops and Products. 2009;**30**:407-415

[30] Batra S. Other long vegetable fibers: Abaca, banana, sisal, henequen, flax, ramie, hemp, sun, and coir. In: Handbook of Fiber Science and Technology. New York: Marcel Dekker; 1985. pp. 728-791

[31] Li W, Zhang Y, Li J, Zhou Y, Li R, Zhou W. Characterization of cellulose from banana pseudo-stem by heterogeneous liquefaction. Carbohydate Polymers. 2015;**132**:513-519

[32] Mukhopadhyay S, Fangueiro R, Arpac Y, Şentürk Ü. Banana fibers—Variability and fracture behaviour. Journal of Engineered Fabrics & Fibers. 2008;**3**(2)

[33] Khalil HSA, Alwani MS, Omar AKM. Chemical composition, anatomy, lignin distribution, and cell wall structure of Malaysian plant waste fibers. BioResources. 2007;**1**(2):220-232

[34] Patil VVV. Banana fibre epoxy composites and its potential for engineeringapplication [M.Tech thesis]. Vellore, India: VIT University; 2012

[35] Basak S, Samanta KK, Saxena S, Chattopadhyay S, Narkar R, Mahangade R, et al. Flame resistant cellulosic substrate using banana pseudostem sap. Polish Journal of Chemical Technology. 2015;**17**:123-133

[36] Xi L, Qin D, An X, Wang G. Resistance of natural bamboo fiber to microorganisms and factors that may affect such resistance. BioResources. 2013;**8**:6501-6509

[37] Vigneswaran C, Pavithra V, Gayathri V, Mythili K. Banana fiber: Scope and value added product development. Journal of Textile and Apparel, Technology and Management. 2015;**9**:1-7

[38] Mohapatra D, Mishra S, Sutar N. Banana and its by-product utilisation: An overview. Journal of Scientific & Industrial Research. 2010;**69**:323-329

[39] Bello K, Sarojini BK, Narayana B, Rao A. A study on adsorption behavior of newly synthesized banana pseudo-stem derived superabsorbent hydrogels for cationic and anionic dye removal from effluents. Carbohydrate Polymers. 2018;**181**:605-615

[40] Phirke NV, Patil RP, Chincholkar SB, Kothari RM. Recycling of banana pseudostem waste for economical production of quality banana. Resources, Conservation and Recycling. 2001;**31**:347-353

[41] Jordan W, Chester P. Improving the properties of banana fiber reinforced polymeric composites by treating the fibers. Procedia Engineering. 2017;**200**:283-289

[42] Basak S, Saxena S, Chattopadhyay S, Narkar R, Mahangade R. Banana pseudostem sap: A waste plant resource for making thermally stable cellulosic substrate. Journal of Industrial Textiles. 2016;**46**:1003-1023