Contributions to Sustainable Textile Design with Natural Raffia Palm Fibers

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Abstract Sustainability is to maintain the ability to be permanent while ensuring productivity and continuity of diversity. Sustainability is one of the biggest problems in the textile industry. Indeed, sustainable design is an indispensable element of today's production world from the ecology point of view. The solution is to take into account the ecological criteria in the process from the raw material selection of the textile product to the finished product. In other words, textile designs to be realized and the raw materials of these designs should be sustainable. Therefore, the use of sustainable natural fibers in the textile industry is increasing day by day. One of these is raffia palm fibers. Raffia fibers stand out because of their important performance characteristics and natural, renewable, sustainable, biodegradable, and environmental identity, and raffia fibers can be found in many different kinds of applications. Frankly, raffia palm plant is considered as a multifunctional plant due to its different usage areas. Generally, it is a plant used in food, cosmetics, medicine, and agricultural fields. It also has been traditionally used in the textile industry for many years. Since it is sustainable and renewable, it is becoming an alternative raw material in textile and different industries. Indeed, many different designed products can be generated from raffia palm fibers. For instance, many different designed products such as clothing (garment, dresses, shirts, ceremonial skirts, costumes, velvet tribute cloths, headdresses, cloaks, etc.), upholstery fabrics, blankets, carpets, mats, ropes, belts, hats, decoration products, baskets and basketry products, bags, shoes, women's accessories and jewelry, masks, knitted furniture, ornamental materials, art objects, rods, support beams and concrete reinforcement in the construction sector, ceiling panels and roofing sheets, geotextiles, and composites for different aims can be produced from raffia palm fibers. In this chapter, the structure, properties, production methods, and end use applications and designs of the raffia palm fibers are examined in detail.

Keywords Raffia palm fiber · Raffia · Sustainable · Design · Biodegradable · Renewable · Environment friendly · Natural fiber · Textile

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S. S. Muthu, M. A. Gardetti (eds.), *Sustainability in the Textile and Apparel Industries*, Sustainable Textiles: Production, Processing, Manufacturing & Chemistry, https://doi.org/10.1007/978-3-030-37929-2_4

Introduction

The problems created by our habits of settlement and consumption are one of the common problems of the whole world. Global warming, environmental pollution, tabescent living spaces, and unhealthy societies are the most important problems of our time. The solution to all these problems is sustainability. Sustainability is not to harm people and the environment while ensuring social and economic development. Sustainability is to establish the balance between man and nature. Sustainability is to program the life and development of the future. In other words, sustainability aims to transfer natural resources to future generations. There is an increase in production and consumption with the increasing world population in the textile sector. Therefore, the use of recyclable natural raw materials is important for sustainability. With the help of developing technology and increasing environmental awareness, the use of natural, environmentally friendly, and recyclable plant-derived fibers is important not only for the textile industry but also for many different industries (Elenga et al. 2009; Chukwudi et al. 2015; Kocak et al. 2015; Fadele et al. 2017). Increased environmental pollution through the use of synthetic fibers increases awareness and increases interest in natural fibers, which are renewable, biodegradable resources (Elenga et al. 2009; Chukwudi et al. 2015; Dhas and Pradeep 2017; Kocak et al. 2015; Fadele et al. 2017). Particularly with the preference of natural fibers in composite structures, it is common to use flax, hemp, jute, kenaf, sisal, pineapple leaf, banana, abaca, raffia palm fibers, and many other plant fibers in fiber-reinforced composite structures (Elenga et al. 2009, 2013; Chukwudi et al. 2015; Anike et al. 2014; Johnson 2011; Obasi 2013; Dhas and Pradeep 2017; Rodrigue et al. 2017). Besides being environmentally friendly and renewable, being available in abundance and cheap and low density is another reason that increases the interest in the preference of plant fibers as reinforcing materials in composite structures (Chukwudi et al. 2015; Anike et al. 2014; Obasi 2013; Dhas and Pradeep 2017; Rodrigue et al. 2017; Kocak et al. 2015; Fadele et al. 2017).

Raffia fibers stand out because of their important performance characteristics and natural, renewable, sustainable, biodegradable, and environmental identity, and plant-derived raffia palm fibers can be found in many different kinds of applications. Therefore, in this chapter, it is aimed to draw attention to raffia palm fiber which is plant-derived sustainable and natural leaf fiber. Raffia palm is a species of plant belonging to the Palmae or Arecaceae family (Sikame Tagne et al. 2014). Therefore, it is similar to palm plant. The raffia palm which is used in textile is also used as a traditional beverage and edible oil in food sector. Also, it can be utilized for different usage types such as medication, cosmetic oil, building material, and broom and paper production. Therefore, raffia palm plant is in the category of multifunctional plants (Elenga et al. 2009, 2013; Johnson 2011; Akpabio et al. 2012; Abu et al. 2016). Raffia palm, which is mostly grown in Africa, has about 28 different species (Abu et al. 2016; Mert 2011). Raffia palm species used for textile purposes are known as *Raphia farinifera*, *Raphia hookeri*, *Raphia vinifera*, *Raphia textilis*, and *Raphia taedigera* (Mert 2011; Rodrigue et al. 2017; Fadele et al. 2017; Yazıcıoğlu

1999). These raffia palm species, which are cultivated in the same regions, are mostly grown in Central and West Africa, India, Singapore, Cameroon, Gabon, Congo, Cambodia, Nigeria, and Madagascar (Akpabio et al. 2012; Mert 2011; Wake 2006; Wiriadinata and Sari 2010; Odera et al. 2015; Musset 1933). Generally two types of fiber, piassava and raffia, are obtained from these raffia palm types used in the textile industry (Mert 2011; Raffia fibre 2019; Sikame Tagne et al. 2014). Raffia palm fibers are obtained from different parts of the raffia palm plant. Therefore, fibers obtained from the raffia palm species are named with different names (Mert 2011; Raffia fibre 2019; Sikame Tagne et al. 2014). Raffia fibers are obtained from the leaves of raffia palm species, while piassava fibers are obtained from the stems of the *Raphia hookeri* species, in particular, and thus the piassava fibers obtained are known to be coarser than raffia fibers (Akpabio et al. 2012; Mert 2011; Raffia fibre 2019; Sikame Tagne et al. 2014). Raffia palm fibers also attract attention with their elastic structure, break resistance, and easy dyeability (Mert 2011). Many different designed products can be generated from raffia palm fibers. In this chapter, the structure, properties, production methods, and end use applications and designs of the raffia palm fibers are examined in detail.

In this chapter, firstly, brief preliminary information about raffia palm plants and their cultivation is given. Then, the methods of obtaining fiber from raffia palm plant were classified. The physical and chemical structure and physical, chemical, and mechanical properties of the obtained fibers are reviewed in detail. Finally, different applications areas and designs of biodegradable, sustainable, and natural raffia palm fibers are examined in detail in order to raise awareness of this valuable fiber.

Raffia Palm Plant and Cultivation

Raffia is a type of palm with long leaves and large stems (Akpabio et al. 2012; Mert 2011; Raffia Palm 2017). Palm is the common name of the plants that grow in tropical regions that make up the palm tree family and have more than 200 genera whose leaves are mostly collected at the top of the stem. Its scientific name is known as Arecaceae (Sikame Tagne et al. 2014). The raffia palm plant is called monocarpic because it yields fruit only once (Figs. 1 and 2) (Mert 2011; Wiriadinata and Sari 2010; Odera et al. 2015; Raffia Palm 2017). Raffia palm, grown in the tropical regions of West and East Africa in Central and South America, is mostly produced in Madagascar. Also, it is produced in Congo, Central Africa Gabon, Cameroon, Nigeria, Guinea Bay, and Liberia (Akpabio et al. 2012; Mert 2011; Wake 2006; Odera et al. 2015; Musset 1933; Sikame Tagne et al. 2014; Sandy and Bacon 2001; Rodrigue et al. 2017; Fadele et al. 2017; Yazıcıoğlu 1999). Although the length of the raffia palm plant varies depending on the type of the raffia palm, it is generally in the range of approximately 10–25 m (Odera et al. 2015; Musset 1933). For example, plant lengths for some raffia palm species are as follows: *Raphia farinifera*, *Raphia hookeri*, and *Raphia vinifera* species can be around 25, 10, and 13 m, respectively (Mert 2011; Wiriadinata and Sari 2010). The leaves of the raffia palm

Fig. 1 View of raffia palm plant and its leaves (Wikimedia Commons 2018a, b)

Fig. 2 Raffia palm fibers

plant are quite large and consist of a large number of leaflets in the form of a feather about 150–200 pieces linearly arranged individually and in a regular manner (Mert 2011; Wiriadinata and Sari 2010; Raffia 2002). Leaf length of the raffia palm can be up to 15–25 m. Therefore, among the flowering plants, raffia palm is known as the broadest-leaved plant (Mert 2011; Odera et al. 2015; Musset 1933; Raffia 2002). Leaflets forming the leaves can be 1.5–1.8 m long and 4–5 cm wide (Fig. 1) (Mert 2011; Wiriadinata and Sari 2010; Musset 1933; Raffia 2002). The seeds of the raffia palm plant, which only bloom once, die after ripening (Odera et al. 2015; Musset 1933). Plant stalks die after the fruits are finished, but plant roots remain alive and produce new stems (Odera et al. 2015; Musset 1933).

The blooms of the raffia palm can be droop between the leaves or dense and clustered on the leaves (Mert 2011; Wake 2006). The type and cultivation conditions of the raffia plant affect the time from planting to flowering and fruiting (Mert 2011; Wiriadinata and Sari 2010). *Raphia vinifera* species need 8 years after planting for blooms. This period ranges from 3 to 7 years for *Raphia hookeri* (Mert 2011; Wiriadinata and Sari 2010; Tuan et al. 1985). *Raphia farinifera*, which is grown in Madagascar, blooms in 20–25 years and its fruits ripening takes 3–6 years (Mert 2011; Wiriadinata and Sari 2010; Tuan et al. 1985). Fruits of raffia palms are cylindrical-ellipsoid in shape, brown in color, covered with scales, single seed, and have a hard core structure (Mert 2011; Wake 2006; Wiriadinata and Sari 2010). The fruits of some raffia palm species can be edible (Johnson 2011; Wake 2006). Reproduction of raffia palm is usually provided by seed. Mostly grown in tropical rainforests, Savannah riverbanks, freshwater swamps, and wetlands, the raffia palm is very sensitive to salty soil conditions (Johnson 2011; Mert 2011; Wake 2006). According to research made by Otedoh, 18 raffia palm species living in the swamp were found (Johnson 2011; Wake 2006; Musset 1933; Otedoh 1982). Today, it is known that there are about 20 species of raffia palm, especially in Madagascar (Johnson 2011; Mert 2011; Wake 2006; Odera et al. 2015; Sikame Tagne et al. 2014; Raffia Palm 2017; Raffia 2002; Dransfield et al. 2008). According to paleoecological studies, it was suggested that a type of raffia palm was found in 2800 BC, and it is known that it was the first seen in Nigeria in the eleventh century AD (Mert 2011; Wake 2006). The international trade of the raffia palm is mainly carried out by Madagascar (Eicher 2001). In the 1950s, Madagascar exported 5000 tons of raffia fibers every year. In the 1980s and 1990s, the average annual export figure of raffia fibers was 2000 tons. Today, it is known that between 8000 and 10,000 tons are exported every year (Eicher 2001).

Raffia Palm Fiber Production Methods

Raffia palm fibers, commonly known as leaf fibers, are of two types, raffia and piassava (Johnson 2011). Raffia fibers are known as soft and durable fibers obtained from the leaves of *Raphia farinifera*, *Raphia hookeri*, and *Raphia vinifera* species. *Piassava* fibers are known as coarser fibers obtained from the leaf sheath and stems of the *Raphia hookeri* species (Mert 2011). The leaves of the raffia palm are mainly composed of thin-walled cells, vascular tissue strands, and longitudinally extending fibers (Mert 2011; Sandy and Bacon 2001). Its surfaces consist of epidermis and there is hypodermis underneath (Mert 2011; Sandy and Bacon 2001; Tomlinson 1961; Picton and Mack 1980). The hypodermis is composed of a plurality of fibers placed on the long axis of the parallel leaflets, and the upper hypodermis has more fibers. The upper surfaces of raffia leaves are generally used to obtain fibers (Mert 2011; Sandy and Bacon 2001; Tomlinson 1961; Picton and Mack 1980). Mechanical fiber extraction methods or retting methods are generally preferred in order to separate the raffia palm leaves from the woody structure or epidermis layer, to obtain usable and dyeable textile fibers (Abu et al. 2016; Mert 2011).

Production of Raffia Palm Fibers with Mechanical Methods

In this method, machines are generally used to extract the fibers. Moreover, different kinds of knives and manual stripping also can be utilized to extract the fibers as a kind of primitive method. The upper parts of the young leaves of the raffia palm plant are cut, and the raffia fibers are manually removed from the cut opening manually or with the aid of a knife (Elenga et al. 2013; Mert 2011). The extracted fibers have a strip-shaped appearance of 1–2 m long and 2–3 cm wide (Elenga et al. 2013; Mert 2011). The ribbon-shaped raffia fibers are tied at one end for drying at room temperature (25 °C). The fibers obtained are 15 μm thick and exhibit mostly creamy and yellowish color tones (Elenga et al. 2013; Mert 2011).

Leaf shells of *Raphia hookeri*-type raffia palm, where coarser fibers are obtained, are broken into pieces, and fibers are extracted quickly and efficiently with the help of these machines which can provide high pressure with crushing cylinders and blunt blades called decorticators or raspadors (Mert 2009). Although the energy consumption is high, the process time is short and the obtained fiber quality is high. Therefore, preferableness of raffia palm fiber production method with these kinds of machinery is increasing. However, in the most African countries, the fine fiber obtained from the leaflets of the raffia palm plant can still be produced by manual stripping (Mert 2009).

Production of Raffia Palm Fibers with Retting Method

Piassava fibers obtained from the leaf sheaths and stems of the *Raphia hookeri* plant, a type of raffia palm, can be obtained with the machines as well as with the conventional method of retting (Mert 2011). The leaf stalks of the *Raphia hookeri*-type raffia palm are divided into 3–4 pieces for the retting process, and it is ensured that the retting process is carried out in bunches in dew and pond or with chemicals. This process can take from a few weeks to 2–3 months. The fibers obtained in reddish and brownish tones are dried under the sun for a few days (Abu et al. 2016; Mert 2011). In dew retting method, plant leaves and sheaths are laid on the soil, fields. The laid leaves are kept in dew for fermentation. Thus, it is provided that the cellulosic structure on the fiber is removed from the fiber by soil fungi. The processing time in this method ranges from 4 to 6 weeks (Mert 2009). In the method of water retting, leaves prepared in bunches are kept for 14–28 days at the sides of the water, pools or rivers. Cellulosic substances on the leaves are removed by anaerobic and pectinolytic bacteria (Mert 2009). *Raphia hookeri*-type raffia palm leaf bundles are kept for 2–3 weeks in a still swamp pond on the shore of Homonica, and at the end of the process, reddish fibers are obtained (Chukwudi et al. 2015; Abu et al. 2016; Dhas and Pradeep 2017). The resulting fibers should not be exposed to direct sunlight. It is therefore dried in semi-shaded areas or at room temperature. The length of the fibers obtained varies between 400 and 1200 mm and the fiber diameter is 0.70 mm (Abu et al. 2016; Dhas and Pradeep 2017). In the chemical retting method, raffia palm leaves are softened with boiling acid or alkali in high pressure. The most commonly used alkali in this process is sodium hydroxide (NaOH) (Chukwudi et al. 2015; Mert 2009). In addition, the processing time is quite short in this method, which is an expensive method (Mert 2009). The quality, color, and physical and mechanical properties of raffia palm fibers may vary depending on production differences, growth conditions, harvesting time, and processing type for the fiber (Fig. 2) (Elenga et al. 2009; Mert 2011).

Gum Removal in Raffia Palm Fibers

The degumming method is a process which is applied after the raffia palm fibers are obtained by retting or mechanical methods. The degumming process is applied to the fibers in order to remove the gum substances remaining on the fiber bundles obtained. The fibers are treated with hot soap or alkali solution for this process. The nonremovable impurities on the fiber surface make the subsequent use of the fibers difficult, especially preventing the interfacial adhesion in the composite structures (Ganan and Mondragon 2004; Hetal et al. 2012; Alvarez et al. 2003; Nekkaa et al. 2008; Beg and Pickering 2004; Jähn et al. 2002). Although the presence of wax, oil, and impurities on the raffia palm fibers forms a protective layer on the fiber surface, it causes poor bonding with the polymer when not removed for composite applications. On the other hand, the alkali-treated fibers display a much cleaner surface although they are more rough when touched (Hetal et al. 2012; Alvarez et al. 2003; Fadele et al. 2017).

Thus, the morphological and chemical structure of the raffia palm fibers is changed, and impurities that block interface adhesion with the polymer are removed from the fiber. It also forms less hydroxyl groups (Beg and Pickering 2004; Jähn et al. 2002; Fadele et al. 2017).

Gum removal by treating the raffia fibers with NaOH is mentioned above (Xiao et al. 2011). But nowadays, ecological methods have gained importance with the increasing environmental concerns. Therefore, the use of enzymes in the degumming process is also increasing. Enzymes can be used also in the degumming process of raffia fibers. The use of enzymes in the degumming process is ecological. Thanks to this process, the natural properties of raffia fibers are preserved and more valuable fibers are obtained. Recently, new enzymes have also been produced for new applications. Biodegradable enzymes have replaced chemical substances in the degumming process. Pectinase enzymes are the most commonly used enzymes for degumming from raffia fibers. This process is carried out at 45–60 °C. The pectins in the structure of treated (for 1 h) raffia fibers are broken down and removed. Enzymes are powerful biocatalysts that accelerate reactions. Thus, degumming with enzymes is carried out under more mild conditions. Thus, thanks to the degumming process with enzymes for raffia palm fibers, significant energy savings and easier reaction controls can be acquired leading to more economical, sustainable, environmentally friendly, and better quality production (Xiao et al. 2011).

Physical and Chemical Structure of Raffia Palm Fibers

Raffia palm fibers generally consist of overlapping flat sheets, as opposed to other plant fibers with luminal cylindrical and cut shapes (Elenga et al. 2009; Baley 2002). The structure of the upper surface of the raffia fibers is formed by the parallel fibrils adhering to each other in the longitudinal direction (Elenga et al. 2009; Sandy and Bacon 2001). It was reported that the average width of these fibrils is 10 μm and the average thickness is approximately 5 μm. These fibers, which have a smooth structure, consist of a structure similar to pula or tile unlike other vegetable fibers (Elenga et al. 2009, 2013). This tile-like structure which is 6–20 μm long covers the entire width of the fibril. This morphological structure of raffia palm fibers makes it possible to use these fibers as relatively waterproof construction materials and as roofing materials (Elenga et al. 2009). The lower surface of the fiber, i.e., the surface in contact with the body of the leaflets, has a honeycomb-like structure (Elenga et al. 2009, 2013). It was reported in the literature that the diameter of the alveoli in the honeycomb network is between 6 and 13 μm. It is separated by a wall approximately 0.5 μm thick (Elenga et al. 2009; d'Almeida et al. 2006). These alveoli are uneven in shape and size and show a random distribution in the volume of material. These alveoli and tile-like scaly structures can act as mechanical bonding in composite matrices. It also increases the willingness of the fibers to bond with the matrix (Elenga et al. 2009).

Raffia palm fibers, which have a layered structure, displayed a tile-like layer separated by a vertical thin interface aligned with the longitudinal axis of the fiber when examined under SEM microscope (Elenga et al. 2009). The longitudinal axis of the raffia palm fiber is almost vertical (Elenga et al. 2009, 2013).

It was observed that the fibers were not round but longitudinal as a result of SEM analysis of raffia palm fibers (Odera et al. 2015). At the same time, the surface morphology of the fibers is very important for their use in composite materials (Odera et al. 2015). The raffia palm fiber is a lignocellulosic fiber and is composed of cellulose, hemicellulose, lignin, and pectin (Table 1). The cuticula contains mineral substances, gum, and resinous, oily, and waxy substances. Cellulose, hemicellulose, and pectins in the structure of raffia palm fibers add elasticity and bendability to the fibers, while lignin in the fiber makes the fibers hard and brittle. The lignin in the structure of the raffia palm is among the micelles of the cellulose structure in the fiber (Mert 2009). The proportions of the chemical components of raffia palm fibers are indicated in different amounts in different sources.

Table 1 Comparison of chemical components of raffia palm fibers with other cellulosic fibers (Elenga et al. 2009; Schuchardt et al. 1995; Fadele et al. 2017; Lewin 1998; Taj et al. 2007; Kalia and Avérous 2011)

Fiber type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Ash (%)	Moisture content (%)	Crystallinity index (%)	References
Raffia palm	53.36–54.4	12.32	23.78–28.6	–	0.8	14	51–64	Elenga et al. (2009), Schuchardt et al. (1995), Fadele et al. (2017)
Abaca	63.2–70.1	19.6–21.8	5.1–5.7	0.5–0.6	4.80	14	–	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Banana	60–67.6	6–19	5–10	3–5	–	10–11	60	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Cotton	82–96	2–6	0.5–1.5	5–7	1–1.8	6–8.5	–	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Bamboo	26–43	30	21–31	–	–	–	–	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Flax	71–82	18.6–20.6	2.2–4	2.3	3.4	7.7	80	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Hemp	70.2–88	17.9–22.4	3.7–6.8	0.9	3.9	1.8	88	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Jute	51–84	13.6–20.4	12–13	0.2	1.0	1.5	71	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Ramie	68.6–80	13.1–16.7	0.6–0.7	1.9	–	–	58	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Sisal	60–78	10–18.1	5.9–11	10	1.0	4.0	71	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Kenaf	31–57	21.5	15–19	2	–	–	–	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Pineapple	70–82	16–22.2	5–13	1–3	–	–	–	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)
Coconut	36–46	0.15–0.3	41–45	3–4	–	–	–	Lewin (1998), Taj et al. (2007), Kalia and Avérous (2011)

The chemical components of raffia palm fibers are given as a 53.36% cellulose, 12.32% hemicellulose, and 23.78% as lignin in a performed study by Fadele, Opeoluwa et al. (Fadele et al. 2017). Raffia palm fibers contain 54.4% cellulose, 14% moisture, 0.8% ash, and 28.6% lignin which were reported in another study (Schuchardt et al. 1995). Accordingly, the excess lignin content in the structure of raffia fibers supports the leaf and makes the fiber harder (Schuchardt et al. 1995). Raffia palm fibers have elements, which confirm its organic nature, such as carbon (C), hydrogen (H), and oxygen (O) (Odera et al. 2015). Raffia palm has carbon (C) content greater than the amount of carbon present in a normal plant material (Schuchardt et al. 1995). Total hydroxyl groups are about 14% of a normal plant material (Schuchardt et al. 1995). The chemical components of raffia palm fibers were compared with different cellulosic fibers and are shown in Table 1 (Elenga et al. 2009; Schuchardt et al. 1995; Fadele et al. 2017). The chemical components of raffia palm fibers were compared with other cellulosic fibers, and it was observed that the crystalline index (51–64%) was higher than ramie (58%), close to cotton (60%), but lower than sisal (71%), jute (71%), flax (80%), and hemp (88%) fibers (Elenga et al. 2009).

Physical, Chemical, and Mechanical Properties of Raffia Palm Fibers

The raffia palm fibers (51–64%), which have a high crystalline index, have very good mechanical properties, strength, and hardness when compared to many other natural fibers (Elenga et al. 2013). When the various physical and chemical properties of raffia palm fibers are examined, the raffia fibers exhibit around 500–660 MPa tensile strength, 12.3–30 GPa starting modulus, and 2–4% elongation at break (Table 2) (Elenga et al. 2009, 2013; Sandy and Bacon 2001). In the literature, the crystalline size of raffia fibers is 9.6 nm and the cell wall density is 1.52 g/cm^3 (Elenga et al. 2013; Sandy and Bacon 2001). The angle of its microfibril varies

Table 2 Properties of raffia palm fibers (Elenga et al. 2009, 2013; Sandy and Bacon 2001)

Density (g/m^3)	Tensile strength (MPa)	Initial module (GPa)	Elongation at break (%)	Crystallinity index (%)	References
–	527–660	26	–	51	Elenga et al. (2013)
0.75	500 ± 97	30	2–4	64	Elenga et al. (2009)
	500	12.3	–	–	Sandy and Bacon (2001)
0.128–0.236	–	0.88–7.92	–	–	Rodrigue et al. (2017)

Table 3 Comparison of properties of raffia palm fibers with other fibers (Elenga et al. 2009, 2013; Aizi and Harche 2015; Rodrigue et al. 2017)

Fiber type	Density (g/m³)	Tensile strength (MPa)	Initial module (GPa)	Elongation at break (%)	Hygroscopic (%)
Raffia palm	0.75	500–660	26–36	2–4	–
Raffia farinifera	–	500	12.3	4	–
Raffia textilis	0.75	148–660	28–36	2	–
Abaca	1.50	12–980	31.1–41	2.9–3.4	14
Banana	1.35	540–550	20	5–6	10–11
Cotton	1.60	300–590	5.5–12.6	3–10	8
Bamboo	0.8	220–1000	22.8	1.3	–
Flax	1.50	345–1035	27–39	2.7–3.2	8
Hemp	1.48	550–900	70	1.6	8–10
Sisal	1.41	511–635	9.4–22.0	2.0–2.5	11
Jute	1.3–1.46	393–800	13–26.5	1.5–1.8	12
Ramie	1.5	220–938	44–128	2–3.8	12–17
Pineapple	1.07–1.52	170–1627	6.21–82.5	1.6	11.8
Fiberglass	2.50–2.55	2000–3500	70.0–73	2.5–3	–
Aramid	1.38–1.47	3000–3150	63.0–67.0	3.3–3.7	–
Carbon	1.7–2.1	4000	230–240	1.4–1.8	–

between 29,81° and 48,65° (Rodrigue et al. 2017). *Raphia farinifera* and *Raphia textilis* fibers, which are raffia palm species, were compared, and it was found that both raffia palm fibers had the same breaking strength, but *Raphia textilis*-type raffia palm fibers were stiffer and exhibit less flexibility. Changes in the mechanical properties of raffia palm fibers depend on the raffia palm species as well as on the production methods (Elenga et al. 2009; Sandy and Bacon 2001).

When the mechanical properties of different fibers and raffia palm fibers are compared, it is shown in Table 3 that the initial module of raffia palm fibers (26–36 GPa) is three times higher than that of cotton fiber (5,5–12,6 GPa) and slightly lower than that of the flax fiber (27–39 GPa) (Elenga et al. 2009, 2013; Aizi and Harche 2015). This suggests that raffia textile fibers appear to be more flexible than flax fibers but stiffer than cotton fibers (Elenga et al. 2009). In general, elongation at break of raffia palm fibers is known to be around 2–4% (Elenga et al. 2009). Raffia fibers are similar to hemp, sisal, and ramie fibers in terms of elongation at break (Elenga et al. 2009). Fiber density of raffia palm is generally known as 0.75 g/m³. This value was lower than all other plant fibers in the literature (Elenga et al. 2009, 2013; Aizi and Harche 2015; Rodrigue et al. 2017). It is known that the density of raffia fibers is approximately half the density of abaca (1,50 g/m³), flax (1,50 g/m³), and sisal (1,41 g/m³) fibers (Elenga et al. 2009, 2013; Aizi and Harche 2015; Rodrigue et al. 2017). This difference shows that the structure of raffia fibers is different from that of other plant fibers and the mechanical properties of raffia palm fibers are generally superior to other plant fibers (Elenga et al. 2009, 2013; Aizi and Harche 2015; Rodrigue et al. 2017). Raffia textile fiber is a potential reinforcing element for composites with its unusual structure and high mechanical properties (Elenga et al. 2009).

Applications Areas of Raffia Palm Fibers

The contribution of sustainable raffia palm fibers to textile design is promising. Since, first of all, raffia fibers are completely environmentally friendly due to the fact that they are natural and can be re-evaluated in the production line by disassembling the produced products and moreover waste raffia palm fiber materials that cannot be used anywhere are biodegradable in nature (Yıldırım and İşmal 2011). Raffia fibers are therefore important fibers for sustainable development. The ecological aspect of the design, which has an integral connection with technology and adds value to the textile product, should also be evaluated. At this point, the most important task falls to fashion designers. Today, shopping preferences are influenced by fashion trends. If fashion shifts towards sustainable natural raw materials, interest in natural products and environmental awareness can spread beyond a small segment. Thus, more raffia-like fibers can be used in the design. While environmental sensitivity of products in other sectors is the subject of advertisiment, unfortunately this sensitivity is not yet fully available for the textile sector. However, with the widespread use of raffia fibers and various natural raw materials, our world will be less polluted, people can buy more ecofriendly products and natural products with high added value will provide also economic development (Yıldırım and İşmal 2011). Natural raffia fibers are flexible, strong and extremely durable and can be dyed easily. Therefore, raffia fiber is a very popular material in crafts and high fashion (Abury 2018). For instance, Madonna Kendona-Sowah uses raffia fibers to create beautiful and stylish designs (Africa Fashion and Style 2014). Even, Madonna Kendona-Sowah has made Raffia fibers as a main raw material used in her designs. In 2013, she established the Raffia brand. It has proven that beautiful things can be designed from raffia fibers that are rough and dry in the raw state (Africa Fashion and Style 2014). Furthermore, Alexander McQueen, who gained fame in design, made products from raffia fibers such as clothes, bags, shoes and hats (Cohan 2011). McQueen uses elegance and an uncomfortable asymmetry in products designed from raffia fibers. What is more, Gucci also designed an elegant blouse made of raffia fiber (Cohan 2011). Different applications areas and designs of raffia palm fibers are examined below in more detail.

Raffia palm is one of the plants used in many tropical regions for the daily needs of the population (Bussmann et al. 2015). Besides being economical, it is used in different sectors due to its soft, flexible, and strong structure (Elenga et al. 2009, 2013; Johnson 2011; Odera et al. 2015; Fadele et al. 2017). Raffia palm fibers are used in different fields such as food construction, cosmetics, and paper making besides textile sector. So it is said to be among the multipurpose plant fibers (Elenga et al. 2009, 2013; Johnson 2011; Odera et al. 2015). Especially in America, *Raffia*

Fig. 3 Woven fabrics made from raffia fibers

Fig. 4 Rug made from greige raffia fibers (on the left); Bag made from raffia fibers and colored with natural dyes (on the right)

taedigera species are used in food sector and even consumed as food. In addition, the raffia palm produced for oil and the fruit juices obtained by fermenting from the raffia palm are of great importance (Elenga et al. 2009; Johnson 2011; Akpabio et al. 2012; Wake 2006; Musset 1933; Balick 1989; Beck and Balick 1990; Haynes and McLaughlin 2000). Raffia fibers are used in ropes, belts, baskets, bags, hats, shoes, women's accessories, knitted furniture, decorative products, ornamental materials, and rods and support beams in the construction sector (Figs. 3 and 4) (Elenga et al. 2009, 2013; Johnson 2011; Akpabio et al. 2012; Wake 2006; Fadele et al. 2017).

Fig. 5 Bell silhouette skirt made from greige raffia fibers (Gündoğan et al. 2018)

Although the use of synthetic fabrics affects the use of different textile fibers such as raffia, many designers in the fashion world today use straw-like natural raffia fibers in many designs, such as dresses, shirts, shoes, hats, and bags (Fig. 5) (Fadele et al. 2017). A dress made of raffia fibers was designed for Alexander McQueen in Paris, and raffia fiber was used for a stylish upper garment design for Gucci in Milan. Interior designer Michael Smith also used raffia fibers in decoration products, carpets, and upholstery fabrics (Cohan 2011). Raffia palm fibers have traditionally been used in African countries since the nineteenth and twentieth centuries. The use of raffia fibers is frequently encountered, especially in complex garments, carpets (Kasai Velvet), blankets, and art objects (Elenga et al. 2009). Today, the textile museum of George Washington University exhibits the textile products of the Kuba kingdom, which is one of the most outstanding and impressive work of African art. There are ceremonial skirts, velvet tribute cloths, headdresses, and basketry products, many of which are made from raffia palm fibers, in the museum. There are also more than 140 objects of the nineteenth and twentieth centuries, including many private collections (Weaving Abstraction: Kuba Textiles and the Woven Art of Central Africa 2011). In addition, the Horniman Museum, founded by Frederick Horniman, contains many African artifacts collected over the last 100 years. Many of the African objects in the collection are known to contain raffia fibers produced from the leaves of the raffia palm trees (Sandy and Bacon 2001).

Raffia palm fibers, which are very popular on the shores of the Gulf of Guinea and among some ethnic groups in Central Africa, are also used to make special ceremonial garments (Fadele et al. 2017). At the same time, the Pende people, an ethnic group in the South-West Democratic Republic of Congo, use masks, costumes, and dance clothing for traditional African folk festivals and Bapende ceremony with different animal figures made of raffia palm fibers (Fig. 6) (Haveaux

Fig. 6 Mask made from raffia fibers (Wikimedia Commons 2019)

1954; Van De Ginste 1946; Pende People 2019; Tribal African Art, Pende (Bapende, Phenbe, Pindi, Pinji) Democratic Republic of the Congo 2019; Fadele et al. 2017). In addition, raffia fibers are also used to bind tree vaccines, especially in Europe. Raffia fibers, which are widely used in textile and construction sectors, are also used today in the production of bags, hats, and shoes and are also used in composites such as other plant fibers, reinforcing concrete, panels, and geotextiles (Elenga et al. 2009; Odera et al. 2015; Musset 1933). Raffia palm fibers are used as reinforcing materials in composite structures due to its low cost and low weight. Thanks to raffia fiber, which is also used as a reinforcing material in cement mortar, composites used in roofing sheets are produced economically, sustainable, safe, and long-lasting environment-friendly building materials (Odera et al. 2015, 2011). Concrete, which is frequently used as construction material, is a material which is strong in compression but weak in tensile strength. These weaknesses of concrete are improved by using steel bars. However, due to their high cost, fibers, especially raffia palm fibers, are used instead of steel bars (Abu et al. 2016; Salau and Sharu 2004). Concrete becomes a homogeneous and isotropic material with the addition of raffia fibers to concrete. Fibers used as reinforcements stop crack formation and crack propagation and thus improve strength and ductility of materials (Abu et al. 2016; Wafa 1990).

In the literature, studies have been conducted to test the suitability of the use of raffia palm fibers in composite structures in the construction sector, and the thermal degradation behavior of raffia fibers has also been investigated. As a result of these studies, it has been suggested that raffia palm fibers are a potential composite reinforcing material and their thermal stability is improved by different methods (Odera et al. 2015). In another study, the use of raffia palm fibers as concrete reinforcement was investigated, and it was concluded that raffia palm fibers increased the tensile strength and toughness modulus of concrete (Abu et al. 2016). In Nigeria, the suitability of using raffia palm fibers as a ceiling panel in building design for the tropical region was investigated in terms of the current economic situation, alternative structural and thermally suitable building materials, and thermal properties. They concluded that the thermal properties of the raffia palm fibers were positively compared with those of other good insulators and that, if used appropriately, raffia palm fibers could be used as efficient ceiling panels for passive cooling building design (Abu et al. 2016).

Conclusion

The life of all people depends on natural resources and these natural resources are not infinite. At this stage, sustainability comes into play. Sustainability means creating a balance between nature and human. The creation of this balance is carried out, thanks to people again. Textile sector is one of the most polluting sectors in the world. Therefore, it is very important to use sustainable raw materials and production methods in textile. Raffia palm fibers are environmentally friendly, biodegradable, renewable, natural, and sustainable. Raffia palm fibers can be potentially used in many industrial fields due to their high strength properties. Raffia palm fibers, which date back to ancient centuries, are notable for being a preferred raw material in the food and construction sectors besides textile industry. Although raffia fibers are material that is used for almost all needs in these regions, which are better known and cultivated in African countries where it is grown, it is becoming a preferred raw material today especially in composite structures due to its superior performance properties.

Indeed, raffia fibers stand out because of their important performance characteristics and natural, renewable, sustainable, biodegradable, and environmental identity, and raffia fibers can be found in many different kinds of applications. Truthfully, raffia palm plant is considered as a multifunctional plant due to its different usage areas. Besides being economical, it is used in different sectors due to its soft, flexible, and strong structure**.** Raffia palm fibers can be used in different fields such as food, construction, cosmetics, medicine, agricultural fields, and paper making apart from textile sector. However, it has been traditionally used in the textile industry for many years. Since it is sustainable and renewable, it is becoming an alternative raw material in textile and different industries. Indeed, many different designed products can be generated from raffia palm fibers. For instance, many different designed products such as clothing (garment, dresses, shirts, ceremonial skirts, costumes, velvet tribute cloths, headdresses, cloaks, etc.), upholstery fabrics, blankets, carpets, mats, ropes, belts, hats, decoration products, baskets and basketry products, bags, shoes, women's accessories and jewelry, masks, knitted furniture, ornamental materials, art objects, rods, support beams and concrete reinforcement in the construction sector, ceiling panels and roofing sheets, geotextiles, and composites for different aims can be produced from raffia palm fibers. The use of plant fibers as reinforcing materials for renewable composite materials is increasing with sustainable production becoming increasingly important. Indeed, raffia textile fiber is a potential reinforcing element for composites with its unusual structure and high mechanical properties.

Today, it is necessary to use recyclable, sustainable raw materials and production techniques in order to reduce the damage caused by the textile sector to the world. Therefore, it is very important to increase the awareness of the raffia palm fibers which can be used in many different textile products and composites as well as in other sectors such as food, construction, cosmetics, medicine, agricultural fields, paper making, etc. and their different designed products in order to increase the utilization and preference of this valuable fiber.

Raffia fibers are environmentally friendly and high-quality fibers that can be used in all areas of textile. The choice of enzymatic methods for obtaining raffia fibers provides high energy savings. In addition to being a natural fiber, this fiber has a clean production technique. For this reason, it is in the form of a fiber sought by large companies. Famous brands and designers such as Alexander McQueen and Gucci used raffia fibers in their products. They proved with their aesthetic designs that raffia fibers are not coarse fibers. Studies conducted in this sense show that raffia fibers will be recognized by more designers and brands in the coming years and their usage in different designs will become widespread. Raffia and raffia-like fibers, natural fibers used in textile design applications, are predicted as a promising solution for increased environmental problems. Raffia-like fibers can be expected to replace nonbiodegradable synthetic fibers over the next few years.

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