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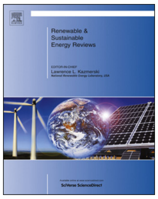

Recent developments in sugar palm (*Arenga pinnata*) based biocomposites and their potential industrial applications: A review

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ABSTRACT

Rapid exhaustion of petroleum resources coupled with increasing awareness of global environmental problems related to the use of conventional plastics are the main driving forces for the widespread acceptance of natural fibers and biopolymers as green materials. Natural fibers and biopolymers have attracted considerable attention of scientist and industries due to their environmentally friendly and sustainable nature. Sugar palm is a multipurpose tree grown in tropical countries and it is regarded as a potential source for natural fibers and biopolymer. Sugar palm fibers (SPF) are mainly composed of cellulose (~66.49%) which leads to their outstanding mechanical properties. The starch extracted from sugar palm tree can be plasticized, blend with other polymers or reinforced with fibers to enhance their properties. From literature review, it is clear that no comprehensive review paper published on sugar palm fibers, starch, and its biocomposites. Present review focuses on recent works related to properties of sugar palm fibers and starch, and their fabrication as green composites. The review also unveils the potential of sugar palm fibers and biopolymer for industrial applications such as automotive, packaging, bioenergy and others.

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1. Introduction: natural fibers

Synthetic fibers are dominantly used in the composite industry for the past several decades. However, the negative environmental and health effects associated with these fibers fueled the increasing usage of natural fibers as promising alternative. Several material scientists and engineers were enticed by the numerous merits of natural fibers over man-made fibers. Table 1 [1,2] shows the comparison between natural and synthetic fibers. The escalating usage of natural fibers can be ascribed to their availability, affordability, processability, renewability, recyclability, and biodegradability [3–5]. Moreover, natural fibers demonstrated several other advantages such as comparable specific tensile properties, less health hazards, acceptable insulating properties, low density and less energy consumption during processing over synthetic fibers [5].

Generally, the properties of natural fibers vary depending on their species, growing conditions, geographical location, method of fiber preparations and many other factors [4,6]. Natural fibers extracted from plants are mainly referred to as lignocellulosic fibers because they are mostly of cellulose fibrils embedded in lignin matrix. The characteristic value for the structural parameter varies from one plant to another [7]. The structure of natural fibers normally entails complex layered structures which consist of a primary cell wall and three different secondary cell walls. Each cell wall is built of three vital components which are cellulose, hemicellulose and lignin [8].

Cellulose is a polysaccharides $(C_6H_{12}O_5)_n$ and solely composed of carbon, hydrogen and oxygen; which when degraded gives only glucose $(C_6H_{12}O_6)$. Cellulose exist in the form of slender rod like crystalline microfibrils which are disorderly and helically arranged along the length of the primary cell wall and the thick middle layer of the secondary cell walls of the fiber, respectively. There are normally 30–100 cellulose molecules in extended chain conformation in each rod like crystalline microfibrils and these provide mechanical strength and stability to the fiber [9]. Cellulose is considered the most crucial structural component of cell walls as compared to the other chemical constituents of any natural fiber. Mechanical properties, cost of production and various potential applications of fibers are greatly influence by the amount of cellulose in their cell walls.

Table 1
Advantages of natural fibers compared to synthetic fibers [1,2].

	Natural fibers	Synthetic fibers
Density	Light	Twice that of natural fibers
Cost	Low-cost	Higher than natural fibers
Renewability	Yes	No
Recyclability	Yes	No
Energy consumption	Low	High
Distribution	Wide	High
CO_2 neutral	Yes	No
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Yes, not biodegradable

2. Classification of natural fibers

Natural fibers are classified depending on their origin either from plants, animals or minerals [17]. However, natural fibers from plants are the most widely used reinforcement material in biocomposites. Plant fibers are subdivided based on the type of plants or parts of the plant the fibers were extracted [10–12]. Fig. 1 shows the various classes of plant fibers which include bast, leaf, seed, fruit, stalk, and grass fibers. All these mentioned plant fibers are term as non-wood fibers. Of late, many researches focus on the usage of non-wood fibers. The utilization of such natural fibers assists in the preservation of the natural forest because deforestation is an increasing environmental threat worth tackling. Heavy consumption of wood (i.e. timber) in wood-plastic composites for construction and other applications results in deforestation which in turn cause loss of biodiversity. For instance, Malaysia is reported to have the world's highest forest loss rate [14] from 2000 to 2012. About 14.4% of Malaysia's forest cover for year 2000 has been loss by 2012. The loss is equivalent to 47,278 km^2 [14]. Hence, resorting to non-wood natural fibers can address the ongoing forest devastation. Malaysia has rich and vast untapped natural fiber resources available as potential alternative to synthetic fibers. These indigenous existing natural fibers range from kenaf, coconut trunk fibers, sugar palm fibers, sugarcane, sago, pineapple leaf, cocoa pod husk to oil palm fruit bunches oil palm fronds, oil palm trunks and many others. Most of these natural fibers are suitable and potential to be fabricated into composite products as well as other value-added products.

3. Sugar palm (*Arenga pinnata*)

Sugar palm is a tall and large palm with a single unbranched stem which can grow up to 20 m high and 65 cm in diameter. The trunk is covered with long black fibers and the bases of broken leaves. The trunk also acts as storage for starch. The starch is usually converted into sugars at the commencement of flowering, for the production of seeds or palm juice that is tapped [15]. However, the starch can be extracted and utilized for other purposes when the tree is unproductive in terms of sugar and fruits [16].

Sugar palm tree is a member of the *Palmae* family and naturally a forest species [17]. It belongs to the subfamily *Arecoideae* and tribe *Caryoteae* [18,19]. Sugar palm tree can be found in altitudes ranging from sea level up to 1400 m [20]. It grows at 1200–1500 m from sea level and in areas with rain fall of 500–1200 cm^3. Sugar

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