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Ceiba pentandra (L.) Gaertn.: An overview of its botany, uses, reproductive biology, pharmacological properties, and industrial potentials

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ABSTRACT

In this review, the botany, uses, reproductive biology, pharmacological properties, and industrial potentials of *Ceiba pentandra* (kapok) are updated. Reproductive biology entailed phenology, floral and fruiting biology, pollination ecology, and breeding system. Among the pharmacological properties of extracts, anti-hyperglycemia or antidiabetes dominated, mostly from the stem bark of *C. pentandra*. Industrial potentials of *C. pentandra* were focused on biodiesel, bioethanol, absorbents, and adsorbents production from different plant parts. Sources of information were from Google Scholar, PubMed, Science Direct, and J-Stage. Selection of articles in the literature was based on topics rather than on the period of coverage, although higher priority was accorded to more recent references. Some areas for further research of *C. pentandra* were suggested.

1. INTRODUCTION

Ceiba species (family Malvaceae and subfamily Bombacoideae) are trees that are endemic to the seasonally dry tropical forests of the Neotropics comprising Central America, Caribbean, and South America [1,2]. A total of 18 species are naturally distributed in the Neotropics. Most of the trees are 5–20 m in height. Exceptions are *Ceiba pentandra* (30–50 m in height) which is the tallest and the most widespread while *Ceiba jasminodora* (1.5–2.0 m in height) is the shortest. Most *Ceiba* species produce digitate leaves and flowering occurs when trees are in the leafless condition [1]. Flowers open (anthesis) during sunset or at night. Flowers have five petals with corolla colors ranging from white, cream, pink, to red [3]. Pollinators of *Ceiba* species include bats, bees, butterflies, and moths.

The species *C. pentandra* spread from the Neotropics to West Africa, where populations grow wild along the coast from Senegal to Angola [4]. In Côte d'Ivoire, *C. pentandra* was planted along with cash crops such as cocoa and coffee. From Africa, the species was introduced to tropical Asia. Known as kapok, *C. pentandra* was first depicted in Java, Indonesia, and later in neighboring counties such as Thailand and Malaysia [5]. In Java, kapok was planted as a community-based forestry species together with other tree species such as sengon, teak, and mahogany [6].

Because of its myriad of uses, kapok has been frequently prescribed for agroforestry projects in rural communities in Gujarat, India [7]. The potential source of sustainable production of natural fibers of *Ceiba* species has been recently reviewed [3]. Fibers of *Ceiba* are light and hollow tubular structures of 1–2 cm in length. The fibers comprised microtubes with a mean diameter of 10 µm and a wall thickness of 0.1 µm. Compared to cotton fibers, which have a mean external diameter of 16.8 µm and a wall thickness of 3.9 µm, kapok fibers are short and light, and not as strong as cotton. *Ceiba* fibers are hydrophobic, porous, and buoyant, lack biodegradability, and contain a high content (69%) of cellulose. They are an excellent oil absorbent due to their hydrophobic nature.

In this review, the information on the botany, uses, reproductive biology, pharmacological properties, and industrial potentials of *Ceiba pentandra* (kapok) is updated. Previous reviews of *C. pentandra* are on the botany, uses, and pharmacological properties of the species [8,9]. The present review is unique in that it covers a wider scope, incorporating reproductive biology and industrial potentials of *C. pentandra*. Reproductive biology entailed phenology, floral and

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fruiting biology, pollination ecology, and breeding system. Among the pharmacological properties, anti-hyperglycemia or antidiabetes dominated, mostly from the stem bark. Industrial potentials were focused on the production of biodiesel, bioethanol, absorbents, and adsorbents.

2. BOTANY AND USES

Ceiba pentandra (L.) Gaertn. is commonly known as cotton silk tree or kapok tree [5,10]. Belonging to the family Malvaceae, the species is a deciduous tree that grows up to 15 m in height. The bark of the tree is grayish in color with or without large spines. The trunk produces buttress roots in older trees [8]. Branches are in horizontal tiers, mostly in threes, forming a crown with a pagoda shape. Leaves are palmately compound or digitate and have a long petiole, each bearing 5–8 leaflets that are lanceolate, acuminate, and having a slightly serrated margin [Figure 1]. Flowers are bisexual, creamy white, 5-merous, clustered on the branchlets, and have a milky fragrance [8,10]. Fruits are elongated capsules that are borne in clusters, pendulous, green when young [Figure 1], and brown when mature. Ripe capsules dehisce exposing numerous black seeds that are embedded in fibers consisting of fine, woolly hairs. The fibers aid in wind dispersal of the seeds.

In the Neotropics, *C. pentandra* trees are a keystone species of cultural and spiritual significance [11]. The Mayan and Aztec people in Central and South America regarded the kapok tree as sacred [5]. Nine trees of *C. pentandra* have been designated as heritage trees in Singapore [10]. In India, *C. pentandra* trees are planted in agro-forestry systems and as afforestation trials for rehabilitation of degraded coastal farmland [12]. The species is also a multipurpose tree that provides pollen for local beekeepers, as well as wood, fibers, oils, and fodder that sustain local livelihood.

The various parts of the kapok tree have medicinal and non-medicinal uses. In Southeast Asian countries, leaves are used to treat fever, cough, hoarseness, and venereal diseases. The bark is used for treatment of fever, asthma, gonorrhea, and diarrhea, and as aphrodisiac, while the root has diuretic and febrifuge properties [5,8,9]. Kapok fibers are used for stuffing pillows, cushions, mattresses, and life jackets. The light wood is used to make boats, canoes, wood carvings, musical instruments, and household utensils. It is also used as fuelwood and fence posts. The seed oil is used as fuel and lubricant, and for making soap. Leaves are used as fodder for livestock and as hair shampoo. Young leaves, flowers, and fruits are edible in Southeast Asian countries [5,8].

Figure 1: Line drawing (P. Verheij-Hayes) showing flowering branch, flower parts, and mature fruit (left), and photograph of young compound leaves and cluster of capsules (right) of *Ceiba pentandra*.

3. REPRODUCTIVE BIOLOGY

The phenology, floral biology, pollination ecology, and breeding system of *C. pentandra* were studied in the Brazilian Amazon [13]. Out of 21 trees studied, 17 trees flowered once or twice over a 6-year study period. In Singapore, flowers of *C. pentandra* open during dusk and fall off by noon the following day [10].

In the Brazilian Amazon, flowers of *C. pentandra* are visited by a wide range of nocturnal animals (bats and hawk moths) and diurnal animals (bees, wasps, and hummingbirds) [13]. Only these floral visitors, the nocturnal phyllostomid bats (*Phyllostomus hastatus* and *P. discolor*) are effective pollinators that promote cross-pollination. Pollination by diurnal floral visitors is ineffective as pollen tubes did not penetrate the style to reach the ovary. In Samoa, a remote island nation of the Pacific, *C. pentandra* is pollinated by one species of flying fox *Pteropus tonganus* [14]. In India, pteropodid bats *Cynopterus sphinx* and *Pteropus giganteus* have been reported to be pollinators of *C. pentandra* [15,16]. Pollen was dusted on the abdomen, wing, and head in 40% of *C. sphinx* caught in mist nets. Pollen loads on the abdomen were greater on males than on females. Bats were more efficient in pollinating flowers of *C. pentandra* than other pollinators such as insects.

In the Brazilian Central Amazon, controlled pollination carried out on one tree revealed no fruit set by selfing and 17% fruit set by outcrossing [13]. The fruit set of two neighboring trees was estimated to be 91% and 71%. Two isolated flowering trees did not set any fruits whereas another two isolated flowering trees set large quantities of seed, suggesting that variable degrees of self-incompatibility may occur in this species. Self-incompatibility was also reported in *C. pentandra* trees of Southeastern Costa Rica where self-pollination resulted in fruit set that is very low or absent whereas cross-pollination resulted in 25% fruit set [17].

A study was conducted on the nucleotides of 12 Neotropical and five West African populations of *C. pentandra* [18]. Results showed low levels of nucleotide divergence, falsifying vicariance biogeography for trans-Atlantic range disjunctions. The study suggests that long-distance dispersal might have created taxonomic similarities in *C. pentandra* plant communities in Africa and the Neotropics. The species originated from the Neotropics, and seeds probably dispersed to Africa by floating over the Atlantic Ocean [18]. A study on the genetic diversity of *C. pentandra* in the seasonally dry tropical forests of Colombia showed that most of the 12 locations studied had heterozygous scores [19]. Only two locations had positive inbreeding coefficients that require conservation measures.

4. PHARMACOLOGICAL PROPERTIES

Extracts of *C. pentandra* have been reported to possess pharmacological properties including hypoglycemic, anti-cancer, anti-inflammatory, analgesic, anti-ulcerogenic, anti-obesity, anti-angiogenic, hepatoprotective, anti-Alzheimer, renal protective, antivenom, and antipyretic activities [Table 1]. Plant parts included the stem bark, root bark, leaves, aerial parts, and roots of *C. pentandra*. Among the pharmacological properties, anti-hyperglycemia or antidiabetes dominated with nine studies, mostly from the stem bark. The antioxidant [20,21] and anti-inflammatory [22] properties of the seed oil of kapok have also been reported.

5. INDUSTRIAL POTENTIALS

5.1. Biodiesel and Bioethanol

Biodiesel can be produced from fat or oil by transesterification using an alcohol to form esters and glycerol [44]. Although methanol

Table 1: Pharmacological activities of *Ceiba pentandra.*

No.	Bioactivity	Plant part	Description	Reference
1	Hypoglycemic	Stem bark	Aqueous extract caused significant reduction in plasma glucose level in STZ-induced diabetic rats.	[23]
2		Root bark	CH_2Cl_2/MeOH extract had hypoglycemic effect on normal and STZ-induced diabetic rats by lowering blood and urine glucose.	[24,25]
3		Leaf	Feed containing 20% powder exerted hypoglycemic effect on alloxan-induced diabetic rats through significant decrease in LDL, VLDL, and TG.	[26]
4		Root bark	Methanol extract had hypoglycemic effect in normal and alloxan-induced diabetic rats by significantly reducing blood glucose level.	[27]
5		Stem bark	Ethanol extract improved glucose tolerance in normal and STZ-induced diabetic rats by significantly decreasing blood glucose level, total cholesterol, and TG level.	[28]
6		Stem bark	Methanol extract exerted antidiabetic effect by increasing glucose uptake and reducing glucose release in rats.	[29]
7		Stem bark	Methanol extract significantly reduced the blood glucose level of normal and alloxan-induced diabetic rats.	[30]
8		Stem bark	Aqueous extract pellets had insulin sensitive effects on DEX-induced insulin resistant rats by improving glucose tolerance, oxidative status, and plasma lipid profile.	[31]
9		Trunk bark	Twice daily administration of aqueous and methanol extracts significantly reduced glycemic and lipid profiles in diabetic rats.	[32]
10	Anti-cancer	Stem bark	The acetone extract showed the strongest cytotoxicity against B16F10 melanoma and MCF-7 breast cancer cells.	[33]
11		Stem bark	The *in vivo* antitumor effect of extracts in mice was stronger in the solid tumor model than in the liquid tumor model.	[33]
12	Anti-inflammatory	Stem bark	Aqueous extract inhibits inflammation of edema and granulation tissue in rats induced by carrageenan.	[34]
13	Analgesic	Stem bark	Aqueous extract reduced pain in rats caused by analgesimeter and hot plate.	[34]
14	Anti-ulcerogenic	Root	Methanol extract significantly decreased the index of gastric lesion in EtOH-induced ulcer and PL-induced ulcer in rats.	[35]
15		Leaf	Methanol extract exerted significant anti-ulcer effect on IND-induced and EtOH-induced gastric ulcers in alloxan-induced diabetic rats.	[36]
16	Anti-obesity	Leaf	Feeding of ethanol extract significantly decreased the body, liver, and fat pad weight of CD obese rats.	[37]
17	Hepatoprotective	Stem bark	Ethyl acetate fraction of the methanol extract possessed protected against PCM-induced hepatotoxicity in rats.	[38]
18	Anti-angiogenic	Stem	Methanol extract exhibited the strongest activity with inhibition of 87.5% at 100 µg/mL using the angiogenesis assay.	[39]
19	Anti-Alzheimer	Aerial part	Four new flavanolignans isolated from the ethyl acetate extract possessed potent inhibitory effects on amyloid β42 aggregation, comparable to or higher than curcumin.	[40]
20	Renal protective	Aerial part	EtOAc extract reduced MTX-induced renal damage in rats through antioxidant, anti-inflammation, and anti-apoptosis.	[41]
21	Antivenom	Leaf	Hemolysis in mice due to the venom of *Echis ocellatus* (carpet viper) was significantly reduced from 66 to 27% by methanol extract.	[42]
22	Antipyretic	Leaf	The antipyretic activity of the ethanol extract was 189 mg/kg, 6 times stronger than that of *Gossypium arboreum*.	[43]

CD: Cafeteria diet, CH_2Cl_2: Dichloromethane, CTC_{50}: Concentration at which 50% of the cancer cells die, DEX: Dexamethasone, EtOAc: Ethyl acetate, EtOH: Ethanol, IND: Indomethacin, LDL: Low-density lipoprotein, MeOH: Methanol, MTX: Methotrexate, PCM: Paracetamol, PL: Pylorus ligated, RBCs: Red blood cells, STZ: Streptozotocin, TG: Triglyceride, VLDL: Very low-density lipoprotein.

and ethanol are most frequently used, ethanol is preferred as it can be derived from agricultural products, and it is renewable and less objectionable to the environment. The transesterification reaction can also be catalyzed by alkali, acid, and enzyme. The search for more efficient feedstocks and catalysts for transesterification into biodiesel is an area of active research [45].

A group of scientists from the Faculty of Engineering in University of Malaya, Kuala Lumpur, Malaysia, conducted research on biodiesel production from *C. pentandra* seed oil [46,47]. The presence of cyclopropene fatty acids in kapok seed oil makes it less attractive as a cooking oil, and consequently, the oil is more suited as a resource for biodiesel. Transesterification of the seed oil was carried out using sulfuric acid as catalyst, applied at 1% v/v to a mixture of methanol and oil (10:1) for 3 h [47]. Transesterification of the seed oil yielded 98% of fatty acid methyl esters (FAME) that met the recommended biodiesel standards of ASTM D6751 and EN 14214 [47,48]. The performance of kapok biodiesel with 10%, 20%, 30%, and 50% of FAME which reduced CO_2 and CO emissions was studied [49,50]. The 10% biodiesel was found to have the best engine performance in terms of engine torque, engine power, fuel consumption, and brake thermal efficiency.

The performance of biodiesel from *C. pentandra* seed oil blended with other seed oils has been investigated. The biodiesel blend prepared from *C. pentandra* and *Nigella sativa* seed oils yielded better fuel properties than their individual biodiesel [51]. The fuel properties of *C. pentandra* biodiesel exhibited better calorific value, viscosity, and flash point, while that of *N. sativa* exhibited excellent cold flow properties and oxidation stability. When blended with *Jatropha curcas* seed oil, the optimum parameters for transesterification were 50:50 oil mixture at 60°C over a period of 2 h [52]. The physicochemical properties fulfill the ASTM D6751 and EN14214 standards. Biodiesel from *C. pentandra* seed oil and *Calophyllum inophyllum* seed oil was blended in a 60:40 ratio to improve its physicochemical properties [53]. The biodiesel blend had a lower kinematic viscosity and acid value, higher heating value, and superior cold flow properties than biodiesel from the unblended feedstock. The blend also had a higher cetane number than that of regular diesel. Cetane is a widely used standard used to benchmark ignition quality. Recently, that irradiation can be used to improve the efficiency of transesterification to reduce energy cost and improve the viability of *C. pentandra* as a biodiesel [54].

Elsewhere, the seed oil of *C. pentandra* in Benin, Nigeria, has been reported to be a suitable source of biodiesel based on its quality indices and fatty acid composition [55]. Several studies were conducted in India. The efficient production and optimization of biodiesel from kapok seed oil by lipase transesterification [56], and by two-step acid base transesterification [57] was developed. The performance of *C. pentandra* biodiesel blended with diesel in a single cylinder diesel engine [58] and blended with biogas fuels in a dual-fuel engine and the effect of injection timing [59] has been reported. In the diesel engine, the thermal efficiency for B25 blend was found to be superior than conventional diesel by 4% [58]. In the dual-fuel engine using B20 blend and injection timing, engine performance improved with emissions of smoke, CO, and NO reduced [59].

Another group of scientists from the School of Industrial Technology and the School of Chemical Engineering of the Science University of Malaysia in Penang assessed the feasibility of using *C. pentandra* fibers as feedstock for producing bioethanol. A study showed that the cellulose and glucose contents of kapok fibers were 51% and 60%, respectively [60,61]. The high glucose content indicated that kapok fibers may be a potential lignocellulosic resource for bioethanol production. However, the kapok fibers yielded only 0.8% of reducing sugar by enzymatic hydrolysis. Results showed that water, acid, and alkaline pre-treatments of the fibers before hydrolysis enhanced the yield of reducing sugar were increased to 39%, 85%, and >100%, respectively. The alkaline pre-treatment (120°C for 60 min in 2.0% NaOH) may serve as cue in producing bioethanol from kapok fibers by removing hemicellulose and lignin effectively.

5.2. Absorbents and Adsorbents

Briefly, sorption by sorbents is the process that involves absorption by absorbents or adsorption by adsorbents. Absorption is as endothermic process whereby one substance enters the volume or bulk of another substance. In this condition, substances such as atoms, ions, or molecules are taken up or absorbed by another substance usually a solid or liquid material. Adsorption is an exothermic process whereby substances such as gas, liquids, or dissolved solids loosely adhere or stick to the surface of another substrate which can be solid or liquid.

Kapok fibers are typical cellulosic fibers with thin cell walls, large lumens, low density, and hydrophobic-oleophilic properties, and are fluffy and resistant to rot, but have limited use as fabric due to their lack of elasticity to spinning [62,63]. These fibers have been considered as an absorbent material for oils, metal ions, dyes, and sound, with special attention to its oil-absorbing properties. An earlier study has reported that *C. pentandra* fibers are excellent oil absorbents [64]. They selectively absorbed significant amounts of oil (40 g/g of fibers) from an oil suspension in freshwater and seawater. It was suggested that these fibers could be used to remove oil from spilled in seawater.

In their unmodified state, kapok fibers have been shown to be a superior oil absorbent compared to polypropylene [62]. Kapok fibers can absorb diesel more than 40 times their weight compared to polypropylene that absorbs <10 times its weight. The superior absorption of kapok fibers can be explained by their high affinity to oil and low affinity to water. The affinity of materials towards liquids is generally measured based on their contact angle [62]. A high contact angle indicates that a round droplet is formed on contact and the liquid is being excluded by the material. A low contact angle indicates that the droplet is absorbed by the surface. Having a low contact angle of 13° when tested with diesel, kapok fibers have high water exclusion that allows more oil to be absorbed from a mixture of oil and water.

Kapok fibers can be modified by chemical or physical treatments to enhance their intrinsic properties or to alter their surface characteristics [63]. The former involves the use of alkali/acid, solvent, oxidation, and acetylation, while the latter involves the use of ultrasonic and radiation. Oxidation treatments with $NaClO_2$ and ultrasound have been shown to increase the porosity of kapok fibers and increase their sorption capacity [63]. Overall, pre-treatment of kapok fibers with polymers has led to an improvement in their adsorption capacity [65]. Kapok fibers modified with pentetic acid exhibited excellent adsorption capacity in the removal of Cu, Cd, and Pb [66], while fibers treated with Fenton reaction or NaOH showed a significant increase in Pb adsorption [67]. A study on the sorption characteristics of kapok fibers as a natural oil sorbent showed that the fibers are reusable for more than 15 cycles of sorption and desorption with sorption capacity reduction of only 30% using diesel [68]. When coated with polyaniline, kapok fibers were found to adsorb methyl orange dye and copper (II) ions from aqueous solution [69]. Isotherm studies showed that the adsorption followed the Langmuir isotherm model with maximum sorption at 76 and 81 mg/g, respectively.

Besides fibers, the kapok hull can also be converted to activated carbon at 200°C using a furnace [70]. When used to adsorb copper and cadmium ions from wastewater, the activated carbon follows a multilayer adsorption mechanism. Like the fibers, the activated carbon from kapok hull can be reused after desorption by immersion in HCl. The adsorption of dyes using other plant parts of *C. pentandra* has also been tested. Studies included the adsorption of methyl violet dye using kapok sawdust [71] or activated carbon prepared from kapok sawdust [72], and the adsorption of methylene blue dye using physically/chemically modified kapok seeds [73].

While kapok fibers are naturally hydrophobic, they can be modified to be a super-hydrophilic gel serving as a super-absorbent polymer (SAP) that can hold large quantities of water. This can be achieved by reacting kapok fibers with monochloroacetic acid which converts cellulose into carboxymethyl cellulose (CMC) [74]. CMC is a highly viscous, non-toxic, non-allergenic, and biodegradable anionic linear polysaccharide polymer that is derived from cellulose [75]. There are many ways; CMC can be converted into a hydrogel to serve as SAP including electron-beam irradiation and the use of chemical cross-linkers [76].

It was reported that kapok fibers cross-linked by grafting acrylic acid and butyl acrylate resulted in SAP with stronger gel strength than that produced from commercial CMC, probably due its higher grafting efficiency [74]. SAP from kapok exhibited maximum absorbency of 554 g/g in distilled water and 96 g/g in saline solution. Similar studies have also shown that kapok cellulose chemically cross-linked with citric acid and loaded with chlorhexidine diacetate is a feasible material for drug release applications [77,78]. Cross-linking cellulose with citric acid adds carboxyl groups which makes it chemically similar to CMC.

6. CONCLUSION

Endemic to the seasonally dry tropical forests of the Neotropics, *C. pentandra* (kapok) is a keystone species of cultural and spiritual significance, and a sacred and heritage tree. In most countries, the species is a multipurpose tree that is planted in agroforestry and afforestation projects. The species is non-invasive and naturalized in many areas around the globe. The tree provides pollen for local beekeepers, as well as wood, fibers, oils, and fodder that sustain local livelihood. There are prospects for developing useful products from *C. pentandra* that have commercial potential. They include biodiesel and absorbents from kapok fibers. The seed oil of *C. pentandra* has the potential to yield both medicinal and non-medicinal products. Research in this field should be accorded high priority. Other areas that warrant further research include identifying the mechanisms and molecular targets of bioactive compounds from the stem bark of *C. pentandra* that are responsible for the anti-hyperglycemic or antidiabetic properties; determining the feasibility of biodiesel production and absorption properties of other *Ceiba* species; enhancing the properties of biodiesel from *C. pentandra* by blending with other plant species; and developing super-absorbents from CMC modified from cellulose of *C. pentandra*.

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8. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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10. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

11. ETHICAL APPROVALS

This overview does not involve experiments on animals or human subjects.

12. DATA AVAILABILITY

In this overview of *C. pentandra*, information and data used are listed in the References, and are available for public access if so desired.

13. PUBLISHER'S NOTE

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