



Kapok Fiber-Structure, Characteristics and Applications: (A Review)

REYGAN H. SANGALANG^{1,2}

¹Faculty, College of Arts and Sciences, Batangas State University, Philippines.

²Graduate Student, School of Science and Engineering, Ateneo de Manila University, Philippines.

*Corresponding author E-mail: reygan.sangalang@g.batstate-u.edu.ph

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ABSTRACT

Kapok fiber is a light, cottony, pale yellow to brown fiber obtained from Kapok fruit. The fiber is characterized by a large, hollow lumen and is generally hydrophobic due to its waxy surface. The fiber is difficult to spun into thread and it is commonly used as filling in mattresses, pillows, stuffed toys and upholstery. Compared to other natural fiber, kapok's use is limited in application. However, it is now gaining attention in the scientific community as an important material due to its outstanding properties. This review will provide a detailed overview on the structure, composition and morphology of kapok fiber. It will also discuss the recent researches conducted on kapok fiber including its application as adsorbent material, biocomposite, biotemplate, electrode material and others.

Keywords: Kapok fiber, Biocomposite, Biotemplate, Adsorbent, Electrode material.

INTRODUCTION

Kapok (*Ceiba pentandra*) is a tall, deciduous and emergent tree of the *Malvaceae* family which grows mainly in Southeast Asia and in other parts of East Asia and Africa¹. In the Philippines, it is known as *Buboi* or *Buboy*². Kapok is cultivated for its seed fiber, a cotton-like fluff obtained from its seed pods³. The fiber, the lightest fiber in the world⁴, is neutral, cottony, hypoallergenic, non-hazardous and resistant to deterioration². Locally, it is used as pillow, beddings and soft toy stuffing. It is also used in floating material such as life jackets due to its excellent buoyant properties and as insulation against sound and heat^{4,5}. Kapok fiber is underrated in comparison with cotton and other plant fibers; however, it is now gaining attention in the scientific community as an important material due to its outstanding properties⁶.

Chemical Composition, Structure and Surface Morphology

Kapok fiber is a natural seed fiber obtained from the fruits of Kapok tree. It is pale yellowish-brown in color, light-weight, fluffy and significantly hydrophobic^{6,7}. Its optimal fiber length ranges from 5-20 mm, and has wall thickness ranging from 0.5-2.00 μm ^{4,8-13}. Table 1 shows the chemical composition of kapok fiber as reported by different researchers.

The chemical composition of fibers, along with its structure, microfibrillar angle, cell dimensions and defects, are the most important factors that determine its overall properties¹⁷. As seen from the table, kapok fiber is highly acetylated and contains high quantity of cellulose. The amount of cellulose varies between location, maturity of the fruit used and the processing used^{1,18}. The reinforcing efficiency of



natural fiber is related to the nature of cellulose and its crystallinity¹⁷. Its considerable wax content^{4,9,14} is

thought to be responsible for its hydrophobicity and oil absorbency properties^{10,19}.

Table 1: Chemical Composition of Kapok Fiber

Chemical Composition	[7]						
	[4]	A*	B*	[9]	[14]	[15]	[16]
Cellulose, %	38.09+/-0.61	35.1	38.5	~64	53.40+/-0.23	59.6	64
Hemicellulose, %	-	-	-	~10	29.63+/-0.62	23.4	23
Lignin, %	14.10+/-0.84	21.5	19.2	13	20.73+/-0.21	15.2	19
Holocellulose, %	83.73+/-0.49	-	-	-	83.06+/-0.61	-	-
Ash, %	1.05+/-0.04	0.8	0.5	~1.60	0.54+/-0.09	-	-
Wax, %	2.34+/-0.06	-	-	0.8-1.2	5.31+/-0.29	-	-
Moisture, %	11.23+/-0.08	-	-	-	-	1.8	-
Xylan, %	-	21.9	22.8	-	-	-	-
Acetyl Group, %	-	13	12.5	-	-	-	-

*A-Philippine Kapok, B-Vietnam Kapok

Infrared absorption characteristics of the raw fiber show well defined broad peak at about 3200-3400 cm^{-1} which indicates the O-H stretching vibration of the intramolecular hydrogen bonds in cellulose^{9,15,20,21}. The peak about 2898-2917 cm^{-1} corresponds to the asymmetric and symmetric C-H stretching of aliphatic (CH_2 and $-\text{CH}_3$) groups^{12,15,20-22}. This denotes the presence of plant wax which is generally consists of n-alkanes with small fraction of alcohols, fatty acids, aldehydes, and esters. The peaks observed at about 1720-1737 cm^{-1} are associated with presence of carbonyl (CO) group stretching of ester, aliphatic aldehydes esters and ketones of plant wax and C-O stretching of ketones, carboxylic groups and esters in lignin and acetyl groups in xylan^{9,12,15,20,21}. The C-C stretching vibration in the aromatic structure of lignin is observed at 1504-1511 cm^{-1} ^{9,15,21} while the peak at 1425-1428 cm^{-1} denotes CH bending vibration in lignin and cellulose^{15,21}. The absorption bands at 1243-1250 cm^{-1} and 1155-1160 cm^{-1} is ascribed to the stretching of aryl-alkyl ether group in lignin and hemicellulose^{4,9,15} and to the asymmetric bridge stretching vibration of C-O-C group in the cellulose, respectively¹². Glucose ring stretching in hemicellulose and cellulose is indicated by absorption peak at 897-900 cm^{-1} ^{15,21}. Elemental analysis revealed that kapok fiber is composed mainly of C (75.3%) and O (24.2%). Abundance of C1 and C2 in the C1 spectra denotes that kapok fiber is consists mainly of cellulose and lignin²³.

Analysis of the fiber under scanning electron microscope (SEM), reveals its very smooth surface without any ripple and no coarse structure on its surface. The smoothness of the surface can

be attributed to the wax that is adhered on the fiber^{4,24,26}. A single kapok fiber can be viewed as a cylindrical microtube with a nano-scaled wrinkle on its surface. It exhibited hollow tubular structure with diameter ranging from 10-25 μm and large air-filled lumen^{4,11,12,23-30}.

The fiber has high degree of hollowness as indicated from the observed porosity of 77%^{11,12,13}. This characteristic makes the fiber as good material for insulation¹². Considering its large lumens, the fibers have a bulk density of 0.305 g/cm^3 ¹¹. X-ray diffraction pattern of the raw kapok fiber reveals characteristic peaks of cellulose to appear in the position of 2 θ close to around 15.5° and 22.6° corresponding to the (110), (101) and (200), (002) crystallographic planes. The former represents amorphous materials in cellulosic fibers while the latter represent the crystalline material in the cellulosic fibers^{20,23,26,31,32}. The index of crystallinity (CrI) of the raw kapok fiber is about 35%^{4,9,26} and is found to be 59% crystalline region and 41% amorphous region³³. The specific surface area of the fiber, calculated by the Brunauer-Emmett-Teller (BET) method, was 5.5 m^2/g ³¹. The fiber's conductivity ranges from 0.03 to 0.04 W/mK for density which varies between 5 and 40 kg/m^3 . Its average thermal diffusivity is 17.1 $\times 10^{-7}$ m^2/s which makes kapok as a good heat insulator³⁴. Kapok fiber exhibits low wettability as manifested by its high contact angle on water about 120°^{4,22,26} to as high as 155°-158°^{21,23,35} denoting that the surface is nonpolar and highly hydrophobic^{4,22}.

Mechanical Properties of Kapok Fiber

Table 2 shows the comparison of the

mechanical strength of kapok fiber with other natural plant fibers.

Table 2: Mechanical Properties of Kapok Fiber and other Plant Fibers

Fiber	Properties			
	Fiber Diameter (μm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Kapok ³⁶	22.65	45-64	1.725-2.485	2-4
Jute ³⁷	25-200	393-773	13-26.5	1.16-1.5
Flax ³⁷	10-40	600-2000	12-85	1-4
Sisal ³⁷	50-200	468-640	9.4-22.0	3-7
Coir ³⁷	100-450	131-175	4-6	15-40
Date Palm ³⁷	100-1000	58-203	2-7.5	5-10

From the table, it can be deduced that the mechanical property of kapok fiber is not outstanding in comparison with other plant fibers- low strength, low stiffness and high fragility³⁶. This is the reason why kapok is not suitable for spinning into yarn or textile applications due to its brittleness, slippery and smooth texture^{9,30}. The chemical composition of plant-based fibers has a great effect on its mechanical property. This is due to the presence of cellulose, hemicellulose and lignin which is responsible for the bond behavior and degradation of natural fibers in composite³⁸. The amount of cellulose and the orientation of its microfibrils also affects the strength and stiffness of the fiber²⁷. Due to high crystallinity orientation index (COI) of kapok (71.5 %), the fiber tends to exhibit poor flexibility which may cause problems during the spinning process⁹. It is also reported that the processing of fiber affects its mechanical properties. Mechanical forces exerted on kapok fibers may affect the weak locations present within the fiber. Traces of spiral lines present in the cell wall suggests that kapok fiber possesses axial weak links which yields uneven mechanical properties³⁰. Fibers produced by chemical extraction are stronger than those produced mechanically since it can soften the fibers and may also increase its surface area²⁶. When utilized in papermaking, NaOH-treated kapok fiber provided higher tensile strength due to increased fiber bonding as lignin was removed and fibers became more conformable¹.

Surface Modification Process of Kapok Fiber

The waxy surface and hollow structure of kapok fiber can be altered and the crystallinity of fiber wall matrix can be changed to improve its inherent properties. Different surface modification process, either chemical treatment and/or physical treatment, may improve the physical and chemical interactions at the fiber's interface⁴⁰.

Chemical Treatment of Kapok Fiber

The use of solvents to modify the surface structure of kapok is the most popular method being employed.

Superhydrophobic kapok fiber was developed in order to improve the hydrophobic and oleophilic characteristics of the fiber. In a study by Tigno *et al.*,³⁵ TiO₂ nanoparticles were immobilized onto the kapok fiber's surface via hydrothermal method. To tune the wettability of the TiO₂-based kapok nanocomposite, functionalization using 1H,1H,2H,2H-perfluorooctyltriethoxysilane (PTES) was then performed. Surface morphology analysis via SEM of the raw kapok fiber and TiO₂-based kapok nanocomposite before and after the PTES functionalization revealed changes from smooth fiber walls to rough and wrinkly surface as evident due to deposition of TiO₂ nanoparticles on the surface. FTIR spectra clearly depicted the presence of -OH groups which are attributed to the presence of cutin, cellulose and water molecules in the fiber and its disappearance after TiO₂ nanoparticles have been embedded. The prepared nanocomposite became superhydrophobic as shown from the high water contact angle of 151°.

By incorporating tetraethylorthosilicate (as source of silica nanoparticles) onto kapok fiber via sol-gel method, followed by hydrophobic modification using hydrolyzed dodecyltrimethoxysilane (DTMS), a superhydrophobic and oleophilic oil sorbent was successfully fabricated. Due to silica nanoparticles, existence of uniform nanoscale roughness with low surface energy was observed after surface modification as confirmed by FTIR spectroscopy, SEM and through wettability studies of water and oil on the fiber surface. Oil sorption studies on the prepared sorbent indicated that the coated fiber exhibited excellent oil sorption capacity owing to its superhydrophobic surface⁴¹.

In another study, kapok fiber was treated with five different solvents: water, NaOH solution, HCl solution, NaClO₂ solution and chloroform²⁶. After the treatment, the samples were filtered, washed several times with distilled water and dried at 70°C. The structures of untreated and treated kapok fibers were investigated and compared using Fourier transform infrared (FTIR) spectroscopy, scanning electron microscopy (SEM), X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS). Chemical treatment, particularly CHCl₃ treatment, successfully removed the waxy surface as implied by the increase of absorption bands at 3410 cm⁻¹ and an intensive band at 2914 cm⁻¹. It also denotes the increase of cellulose hydroxyl groups in fiber walls due to the breaking of hydrogen bond. Another notable observation is the deesterification of lignin as observed from the significant decrease in stretching vibration at 1730 cm⁻¹ which is ascribed to the C=O stretching vibration of ketones, carboxylic acid and esters in lignin⁴². NaOH-treated fiber showed reduction of band intensity at 1740 cm⁻¹ and 1245 cm⁻¹ which suggests that the strong alkali promotes deesterification of kapok fiber and complete removal of all the esters linked with aromatic ring of lignin. On the other hand, bleaching of kapok fiber leads to cleavage of the aromatic ring in lignin or delignification which is denoted by the disappearance of bands around 1602 cm⁻¹ and 1504 cm⁻¹, respectively. By delignification, the amorphous portion of the cellulose increases and a decrease in hydrophobicity as observed in the reduction of static water contact angle^{1,21,42}. The surface of kapok fiber, which is inherently smooth, is altered after chemical treatment. Treatment of strong alkali on the fiber resulted in the collapsed of the hollow tube of the fiber and coarseness of the surface which increased its surface area¹⁵. Changes in the surface structure enables better adherence of oil to the outer surface and better penetration at the inner lumen, thus increase oil absorbency for the solvent treated kapok than the untreated fiber. In terms of crystallinity, changes in crystallinity index (CrI) have been observed after the chemical treatment. Crystallinity index analysis revealed that the CrI is 35.34%, 33.93%, 22.17%, 32.00%, 26.97% and 27.17% for untreated, water-treated, HCl-treated, NaOH-treated, NaClO₂-treated, and chloroform-treated kapok fiber, respectively. Changes in the aggregate structure and expansion of amorphous portion present in kapok fiber is noted after treatment of fiber with HCl, NaClO₂

and chloroform however NaOH-treatment does not significantly alter the fiber's crystallinity. Subjecting the fiber to low-alkali concentration at a short time does not alter the crystalline region of lignocellulose significantly. XPS analysis of raw and treated kapok revealed that NaClO₂ treatment increased the O/C ratio which is attributed to the decomposition of lignin and increase in cellulose content of kapok fiber. Chemical treatment is indeed very effective in changing the inherent characteristic of the fiber^{8,26}.

Physical Treatment of Kapok Fiber

Cold plasma treatment on the surface of kapok fiber was done as a means to modify the surface composition of the fiber and improve wettability¹³. Changes in the FTIR spectra, thermal behavior and formation of irregular surface texture, as confirmed by SEM, was evident in plasma-treated fiber as opposed to untreated fiber. Improvement in wettability was also noted due to removal of hydrophobic groups such as oil and wax on the kapok surface and exposure of openings and pores which causes liquids to penetrate easily¹³. With these procedures, it can be concluded that plasma treatment is a good approach for the surface activation of kapok fiber and may be used for the enhancement of fiber-matrix adhesion.

High pressure treatment can also be used to modify the structure of the fiber⁴³. In a study conducted, kapok samples were heated in an oven at 45±2°C for 1 h and then treated under three different conditions: dry with 15% relative humidity (RH), wet with 99% RH and pressure of 100 kPa. SEM image of the treated fiber revealed that the once hollow and circular structure were crushed partially or totally to flat, thin ribbon-like thread after the application of 100 kPa pressure. Pressing the fibers devoid the cellulosic capsule of air space. The pressure treatment greatly changed the hollow structure of most kapok fibers.

Ultrasonic treatment is also used as an essential method of removing the impurities and breaking the weak sections in the fiber³⁰. Treatment of soaked kapok fiber (in distilled water) with ultrasonic power for 6 min and 80% power resulted in a degraded fiber at the spiral traces with some parts became a spiral belt. The consistency on the width of the belt varies among different fibers. It was suggested that the spiral belt is the weak link along the cell wall of the fiber and the location wherein breakage or deformation may originate.

Applications and Uses of Kapok Kapok Fiber-Based Composites

Reinforcement of kapok with other plant fibers or materials in composites is promising due to its ecological and environmental advantage and attractive mechanical properties.

Bionanocomposite films based on sodium alginate and kapok nanofibrils were prepared to enhance the potential of kapok fiber⁴⁴. Cellulose nanofibrils (CNF) were extracted from the fiber after subjecting it to alkaline treatment, bleaching and acid hydrolysis. The obtained CNFs were subjected to TEMPO (2,2,6,6-tetramethyl-piperidinyl-1-oxyl) mediated oxidation to yield surface-modified cellulose nanocrystals (TOCNC). Solution casting technique was used to prepare bionanocomposite films based on sodium alginate and nanocellulose (CNFs and TOCNCs). Analysis of the prepared bionanocomposite films revealed that ultrasonication of TOCNCs has significant effect in the reduction of surface roughness of the nanocomposite and contributed in the improvement of the mechanical strength of the polymer. Improved dispersion of TOCNCs particles in the alginate matrix was noted than those containing CNCs. It was demonstrated that nanocomposite films based on TOCNCs presents better reinforcement in alginate biopolymer and may have potential applications in tissue engineering, structural and packaging applications.

A phase change composite material utilizing kapok fiber-based aerogel to form a porous material as support framework was fabricated⁴⁵. A lightweight kapok fiber-based aerogel was made by oxidizing the fiber and combining it with sodium alginate and hydroxylated boron nitride which will be used to encapsulate polyethylene glycol (PEG) and prevent it from leaking. Phase change materials were then prepared by vacuum-assisted impregnation of PEG into the aerogels producing a highly thermally viable material with stable shape. The stability of the composite material's shape is noticeable and is reported without leakage even if it is heated to the PEG's melting point.

Surface activated kapok fiber using plasma

treatment was added with recycled polyethylene to produce a composite⁴⁶. Addition of plasma-treated fiber, as opposed to raw kapok fibers, were found to possess enhanced mechanical performance of the composite. Reduction in flow rate of the polymer was evident after the addition of the fiber as indicated by melt flow measurements. Furthermore, improvement in fiber/matrix adhesion was seen after the addition of plasma-treated fiber.

An iodine-doped polyaniline/kapok fiber (Pan/KF) composite is developed using the semidry method with iodine vapor as both dopant and oxidant²³. The prepared composite exhibited good hydrophilicity compared with raw kapok fiber. The contact angle of the Pan/KF composite was reduced from 107° to 86° and 4 h increase in the reaction time suggests that the surface has transformed from hydrophobic to hydrophilic. Surface morphology of the composite revealed a rough surface with wrinkles and groves. It was noted that the degree of wrinkles and grooves increased with increasing polymerization time of aniline. Also, the hollow structure of the fiber is preserved during the process of medication with polyaniline. The prepared composite demonstrated good adsorption performance towards Au (III) and methylene blue.

A reinforced thermoplastic cassava starch composite (TPCS) using jute fiber and kapok fiber was fabricated⁹. Different ratios of jute and kapok fiber was added into the TPCS matrix and shaped by compression molding machine. Results revealed that increasing the concentration of cellulose load increased the stress at maximum load and Young's modulus of the TPCS. It was noted that the stress at maximum and Young's modulus were higher in TPCS/kapok than TPCS/jute which may be attributed due to the former's lower density. Another reason cited is the evenness in the distribution of kapok fiber as compared with jute fibers. IR shift was detected in the composite which may be due to the formation of new hydrogen bond which is formed after the addition of the jute or kapok fibers. Water absorption of the TPCS matrix, particularly the TPCS/jute, was reduced after the incorporation of the fibers. Thermal stability of the composites was improved however the thermal degradation temperature of the TPCS

matrix were not changed by the addition of the jute fibers whereas it decreased after the addition of kapok fiber. Indeed, the overall property of the thermoplastic starch was improved after the addition of jute and kapok fiber.

Kapok Fiber as Oil Absorbing Material

Kapok fibers, which is naturally oleophilic¹³, have been extensively investigated for its ability to absorb oil in water systems^{2,41,47}. Table 3 lists the oil sorption studies conducted on kapok fiber.

Table 3: Oil Sorption Studies Utilizing Kapok Fiber

Materials	Process Used	Oil Sorption Capacity (g oil/g sorbent)	Findings	Reference
Kapok fiber filter (made from kapok fiber with polypropylene/polyethylene sheath-core, as binder)	No further treatment was carried out in the kapok fiber.	• Absorbed 795.6 g (32.31g/g) of oil 80-91% of oil recovery.	• The fabricated filter exhibits highly efficient oil absorption from wastewater and highly efficient recovery of oil from filter.	[11]
Polybutylmethacrylate (PBMA)/SiO ₂ -coated kapok fiber	Raw fiber was immersed in homogenized polybutylmethacrylate and nano-silica and dried afterwards.	• 99.7%, 65.0%, 41.1%, 23.1% and 26.8% for diesel, soybean oil, crude oil, 150SN, and 20cst, respectively.	• Coated fibers exhibit higher oil sorption capacity than raw kapok fiber. • Coated fiber has excellent reusability, fast oil uptake rate and high buoyancy in the removal of oil on artificial seawater surface.	[25]
Solvent-treated kapok fiber	Raw kapok fiber was reflux with NaOH, HCl, water, NaClO ₂ and chloroform.	• For NaClO ₂ -treated kapok fiber: for toluene, chloroform, n-hexane and xylene, respectively, 19.8%, 30.0%, 21.5%, and 24.1% • For HCl-treated kapok fiber: 35.5 g/g, 51.8 g/g, 34.8 g/g and 25.2 g/g for the above oils. • Maximum sorption capacities of 44.76, 39.48, 61.94 and 72.92 g/g were observed for diesel, gasoline, chloroform and vegetable oil, respectively.	• Variations in the fiber's chemical compositions, crystallinity and surface elemental composition after different treatments was found. • Fiber retained most of oil sorption capacity after squeezing. • TiO ₂ nanoparticles are anatase as shown using XRD.	[26]
1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane (PTES) modified	Immobilization of TiO ₂ nanoparticles, via hydrothermal method followed by functionalization		• The prepared TiO ₂ nanocomposite became superhydrophobic after kapok-TiO ₂ nanocomposite TiO ₂ nanocomposite was found to be a very promising oil sorbent material. • Low surface energy of fiber was reported (40.64 mN/m and high water contact angle was measured to 151° absorbing four oils. • The average adhesive energies of kapok to four oils were 3.78×10 ⁻¹¹ to 9.40×10 ⁻¹¹ J, with the highest for vegetable oil. • Surface coating of fiber with polymer is very effective for improving its oil sorption capability.	[35]
Raw kapok fiber	No pretreatment was done on the raw fiber.	• Not reported		[47]
Polybutylmethacrylate (PBMA) and polystyrene (PS)-coated kapok fiber	Facile solution-immersion step	• For PBMA-coated fiber, capacities are about 59.5, 64.9, 85.2 and 80.3 g/g for gasoline, diesel, soybean oil, and paraffin oil. • For PS-treated fiber, capacities are about 62.3, 67.8, 80.3, 83.3 g/g for gasoline, diesel, soybean oil, and paraffin oil, respectively		[48]
Kapok Fiber/Polypropylene (PP) blend	No further treatment was carried out in the kapok fiber. • Needle Punched nonwoven assembly	• Maximum oil sorption was found to be 40.80 g/g and 29.0 g/g for high density oil and diesel oil, respectively.	• The adsorption reaction is spontaneous and exothermic. • Small amount of PP was added to increase the strength of the structure. • The nonwoven sorbent was found to have a retention value of 0.88 to 1.00 which makes it a good synthetic sorbent alternative.	[49]
Raw kapok fiber	No further treatment was carried out in the kapok fiber.	• At 0.1 g/cm ² packing density, oil sorption taken at 20-90°C are as follows: 10.96 to 10.42 g/g, 10.73 to 10.18 g/g, and 10.25 to 9.89 g/g for engine oil, mineral oil and PAO4, respectively.	• Sorption coefficient is greatly influenced by temperature at the packing density of 0.1 g/cm ² . • The wettability of oil to the fiber's surface weakens as temperature increases. • Adhesion decreased as temperature is increased.	[51]
Kapok/microfibrillated cellulose aerogel (KCA)	Addition of chopped kapok fiber to microfibrillated cellulose followed by vacuum freeze drying and surface modification using vinyltrimethoxysilane (VTMO)	• Oil absorption of 104 g/g / to 190.2 g/g and 97.5% retention capacity.	• KCA exhibited high porosity, about 99.58% and ultralow density, 5.1 mg/cm ³ . • Hydrophobicity is about 140.1°	[51]

Due to its low surface energy (about 31-40 mN/m), adhesive forces between oil molecules and kapok fiber surface are higher, thus oil droplets are easily adhered on the fiber's surface^{10,11,47}. The surface energy of the fiber is close to the surface energy of the oils (20-30 mN/m)^{10,11,47} while lower than that of water (72 mN/m)⁴⁷. The kapok fiber is hydrophobic with water contact angle as high as 158^{21,23,35,47}. SEM and OM results revealed the presence of smooth surface due to wax content and hollow structure⁵². On the other hand, IR studies confirmed the waxy characteristic of the surface due to the presence of aliphatic, carbonyl stretching of ester and C-O stretch of acetyl group^{12,15,20-22}. As stated by the above-mentioned characteristics, kapok fiber is an excellent adsorbent for oil in water systems. However, observations on the low oil retention capacity of the fiber have been an issue as attributed to its smooth surface. To address this, modification of the surface morphology by polymer coating^{48,52} and solvent treatment²⁶ was ventured. The rough surface of the modified kapok fiber, together with its low surface energy, prevented more oil from escaping the surface of the fiber thus increasing its oil sorption

capacity. Sorption coefficient is greatly influenced by temperature at the packing density of 0.1 g/cm³. It was also reported that the wettability of oil to the fiber's surface and the adhesion work of kapok fiber to oil weakens as temperature increases⁵³.

Kapok Fiber as Adsorbent for Dyes and Heavy Metals

The use of kapok and other plant fibers as material for the development of inexpensive, high-capacity adsorbent has been pursued due to its renewability and broad spectrum of functional groups that can be involved in chemical modification. Modifications on the structure and/or composition of the fiber has been done in order to enhance its properties^{21,22,28,42}. Studies on the utilization of kapok fiber as adsorbent for heavy metals and dyes were explored to further expand the use of the fiber in water treatment technology. Due to the detrimental effects posed by heavy metals and dyes on the water systems, complete removal of it is deemed necessary^{22,54}. Table 4 shows the sorption studies on dyes and heavy metals being undertaken using kapok fibers.

Table 4: Studies on the Sorption of Heavy Metals and Dyes using Kapok Fiber

Material	Process Used	Adsorbed Component	Adsorption Capacities	Reference
Kapok-Polyaniline nanocomposite	In-situ polymerization of aniline monomer on the kapok surface using ammonium persulfate as the oxidizing agent	Methyl Orange (MO) and Pb (II)	136.75 mg/g for MO 63.60 mg/g for Pb (II)	[21]
Kapok-Polyacrylonitrile (KF-PAN) nanocomposite	In-situ polymerization of acrylonitrile monomer on the Kapok fiber surface	Pb (II)	22.05-26.81 mg/g (with higher acrylonitrile concentration and 78.34 mg/g upon alkali hydrolysis of the KF-PAN)	[22]
Polyacrylonitrile (PAN)-coated kapok hollow microtubules	Facile surfactant assisted method	Methyl Orange and Cu (II)	90.09 mg/g for Cu II ions 34.72 mg/g for MO	[54]
Raw kapok fiber	Treatment with NaClO ₂	Cationic dye methylene blue (MB)	110.13 mg/g	[55]
Activated hollow carbon fiber	High temperature carbonization	Methylene Blue	~320 mg/g (at pH 11) ~240 mg/g (at 60°C)	[56]
Magnetic Kapok biosorbent	Sonication of fine-sized kapok fiber with Fe ₂ O ₃	Pb(II), Cu(II), Zn(II), Mn(II) and Ni(II)	49.9 mg/g for Pb (99.4% removal efficiency)	[57]
Zeolitic imidazolate framework (ZIF-8) magnetic micromotor Kapok fiber	Kapok-Template method	Congo Red	394 mg/g	[58]
oriented-polyaniline nanofibers (KF/PAN)	<i>in situ</i> rapid polymerization of aniline (AN)	Cr (VI)	44.05 mg/g	[59]
Kapok fiber-oriented polyaniline (KF-O-PAN)	Facile polymerization of aniline on the surface of KF	Congo Red (CR), Orange II (OG-II), & Orange G (OG-G)	40.82 mg/g (CR), 188.7 mg/g (OG-II), 192.3 mg/g (OG-G)	[60]
Magnetic ZnFe ₂ O ₄ hollow fibers	Facile bio-template method	Acid Fuchsin	150.37 mg/g	[61]
Hydrophilic modified kapok fiber	Chemical modification by Fenton reaction	Pb (II)	94.41 ±7.56 mg/g (at pH6.0)	[62]
Dicarboxylic Kapok Fiber (DC- KF)	Surface in-situ oxidation	Natural Red (NR), Methylene Blue (MB), Rhodamine 6G(R6G)	816.4 mg/g (NR) 524.4 mg/g (MB) 613.4 mg/g (R6G)	[63]

Kapok Fiber as Biomass Material for Catalyst and Electrodes

The use of natural biomass material like kapok in the preparation of hollow ceramic material and hollow metal oxide fiber was being developed due to its diverse use as photocatalyst for dye degradation^{32,42,64,65}, electrocatalytic reduction and degradation of metals and other compounds such as Au (III), bisphenol A, paraquat, CO₂ and phenol^{28,66-69}, and for hydrogen gas generation^{32,70,71}. One of the methods employed for the utilization of kapok fiber as biomaterial is through template approach. Template approach is a simple process which involves the use of natural biomass material as template followed by impregnation of metal oxide and finally, heat decomposition to release the hollow metal oxide fiber. Due to its hollow structure and large number of surface functional groups such as –OH and C=O, metal cations are easily adsorbed into the template which are then converted to hollow ceramic structure upon heat decomposition^{72,73}. In other cases, pyrolysis of the chemically modified-fiber at high temperature is employed. Kapok fiber not only serves as carbon precursor but also transforms into activated carbon substrate during calcination^{65,67}.

Similarly, kapok fiber has been utilized as micro-tube biomaterial or biotemplate for electrodes in fuel cells or batteries⁷⁴⁻⁷⁷ and supercapacitor⁷⁸⁻⁸⁰. Synthesis using simple hydrothermal method followed by calcination at high temperature and inert atmosphere was the method employed to produce an electroactive hybrid composite. Other method involves the synthesis via micro-tube method to prepare kapok fiber as a micro-tube biotemplate and bio-carbon source to synthesize metal oxide/C composites⁷⁵. In another study, in-situ polymerization of pyrrole on oxidized kapok fiber followed by carbonization is done to produce an ultralight carbon aerogel⁷⁸. Due to the fiber's unique hollow tubular structure, faradaic reactive sites are more accessible and the transport length for ions and charges in real capacitive process is shortened⁷⁴. In addition, because of fibers large surface area, highly defective carbon matrix and the synergistic effect of the hybrid electroactive components, high specific capacitance was obtained in the electroactive hybrid composites⁷⁸.

Other Uses of Kapok Fiber

Kapok fiber has been explored for variety of uses apart from its conventional use. The potential use of kapok fiber as pulp source for paper making was explored¹. Sodium hydroxide treatment (10% optimum concentration) of the fiber reduced the amount of lignin and increased the yield of the pulp. Addition of kapok pulp to commercial softwood pulp, increased the tensile and burst strength of the blended sheets, however low tear resistance and elongation was observed due to the brittleness of the pulp. Kapok pulp can be used as additive to commercial softwood pulp for the manufacture of commercial packaging paper due to its light weightiness, high strength, and excellent water-resistant characteristics.

Kapok fibers also found use in biomedical applications. Hydroxyapatite (HAp) nanotubes were synthesized by hydrothermal process using kapok fiber as natural templates⁸¹. HAp nanotubes with average inner radius of 10 nm and length of several hundred nm were successfully developed and found to be biocompatible with HeLa cell lines. Hollow HAp nanotubes can be used as a nanocarrier for bone tissue engineering applications. On the other hand, zinc oxide-embedded paper with antimicrobial property was fabricated from kapok, in situ. The ZnO embedded paper exhibits superior antimicrobial index against *Gram-positive S. aureus* than *Gram-negative E. coli*⁸².

Kapok fiber was used as biotemplate for the green synthesis of cellulose-based copper oxide nanomaterial via simple sol-gel derived solvo-thermal method. The obtained nanocomposite exhibited effective antimicrobial activity against *Gram positive* and *Gram negative* bacteria, as well as good heterogeneous catalyst for the production of biodiesel from oleic acid and ethanol. Its outstanding specific capacitance performance can be utilized further in super capacitor applications⁸³.

Porous composite membrane (PCM) utilizing kapok fiber membrane as basement membrane was fabricated and studied⁸⁴. Facile synthesis of porous organic polymers (POPs) with macroporous structure were synthesized via click chemistry. The fabricated PCM exhibited porous structure, outstanding flexibility and excellent mechanical strength. The fabricated PCM was

used for particulate matter capture and exhibited outstanding capture efficiency for both PM 2.5 ($\geq 99.80 \pm 1.58\%$) and PM 10 ($\geq 99.89 \pm 0.89\%$) in 30 h period.

Kapok fiber was also used as bio-reinforcement material to virgin bitumen. The fiber surface, which is inherently smooth, underwent alkali-treatment to increase the surface' roughness which enhanced the interfacial bond strength between the fiber and matrix. In addition, treatment with silane coupling agents reinforces adhesion of the fiber and bitumen via surface grafting effect. Addition of kapok fiber increased the viscosity of bitumen and increased its permanent deformation resistance while decreasing its fatigue damage resistance. However, slight negative effect on the stress relaxation ability of bitumen was observed after the addition of kapok fiber⁶⁵.

Utilization of kapok fiber for the synthesis of a super insulating composite aerogel from polymethylsilsesquioxane-kapok fiber have been made as a promising candidate for uses wherein embedded mass is critical e.g., space application⁶⁶. Methyltrimethoxysilane (MTMS) was used as a silica precursor while kapok fibers were used as a reinforcing additive owing to its homogenous hollow structure and intrinsic low density. The synthesized aerogel can be made easily rollable like standard silica blanket and noted to possessed outstanding characteristic in comparison with commercially available aerogel composites. It has a density as low as 0.053 g/cm³,

thermal conductivity of 0.018 W/mK and a flexural strength (at maximum stress) of $108 \pm \text{kPa}^{21}$.

CONCLUSION

Kapok fiber transitioned from a simple stuffing material used for toys, pillow and lifejacket to a material of diverse uses in water treatment technology, packaging technology, papermaking and in the electronics industry. Due to its remarkable surface morphology and fiber structure, numerous applications were explored and investigated. However due to its poor mechanical properties and smooth surface, the use of fiber has been limited to some extent. To overcome this, reinforcement of kapok fiber with other polymer matrices was done to increase the strength of the material. Pretreatment of the fiber by physical or chemical process has been done to alter the surface characteristics and chemical composition of the fiber. By utilizing these approach, various research and applications on kapok fiber has expanded and ventured until today.

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Conflicts of Interest

The author declares no conflict of interest.

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