CHARACTERIZATION, THERMAL AND MECHANICAL PROPERTIES OF TROPICAL PLANT FIBRES

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CHARACTERIZATION, THERMAL AND MECHANICAL PROPERTIES OF TROPICAL PLANT FIBRES

By

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LIST OF ABBREVIATIONS

BPS	Banana pseudo-stem
CC	Cell corner
CML	Compound middle lamella
COIR	Coconut
cr	Crystal
DTG	Differential
ep	Epidermis
f	Fibre
FAO	Food Agricultural Organization
FT-IR	Fourier Transform Infrared
FWHM	Full width half maximum
gc	Guard cell
GPa	Giga pasca
Ha	Hactare
LM	Light microscopy
mf	microfibril
ML	Middle lamella
MOA	Ministry of Agricultural
Mpa	Mega pascal
MT	Metric ton
mx	Metaxylem
PALF	Pineapple leaf

pc	Parenchyma
ph	Phloem
pth	Pith
S1	Secondary wall 1
S2	Secondary wall 2
S3	Secondary wall 3
SCB	Sugarcane bagasse
SEM	Scanning Electron Microscope
SEM-EX	Scanning Electron Microscopy coupled with energy dispersive X-ray analysis
st	Stoma
SW	Secondary wall
TEM	Transmission Electron Microscopy
TG	Thermogravimetry Analysis
Uf	Ultimate fibre
v	Vessel
vb	Vascular bundle
XRD	X-ray Diffraction

LIST OF SYMBOLS

α	Conversion rate
°C	Degree celsius
μm	Micrometer
A	pre-exponential factor
A	Cross-sectional area
a.u	Arbitary unit
d	diameter
E	Young' modulus
E_a	Activation energy
F	Force
K	Kelvin
L	Original Length
L_o	Final length
m	mass
nm	Nanometer
P_{max}	Maximum load
R	Gas constant
T_m	Peak temperature
T_o	Onset temperature
TS	Tensile strength
ε	Elongation
σ	Stress

LIST OF PUBLICATIONS AND CONFERENCE PROCEEDINGS

SIFAT-SIFAT PENCIRIAN, TERMA DAN MEKANIKAL GENTIAN TUMBUHAN TROPIKA

ABSTRAK

Kajian ini berkaitan dengan kajian yang sistematik tentang sifat-sifat kimia, morfologi, anatomi, sifat terma dan mekanikal gentian tumbuhan tropika. Standard ujian Tappi dan spektroskopi Fourier inframerah (FT-IR) telah digunakan untuk mengkaji komposisi kimia dan sifat-sifat spektroskopi gentian tumbuhan. Penghabluran yang telah ditentukan menggunakan pembelauan sinar-X (XRD).Mikroskop cahaya (LM) dan penghantaran elektron mikroskop (TEM) telah digunakan untuk melihat morfologi dan struktur dinding sel gentian. Penyebaran lignin seluruh lapisan dinding sel dianalisis menggunakan mikroskop imbasan elektron ditambah dengan x-ray serakan tenaga (SEM-EDX) dan spektroskopi Raman. Di samping itu, analisis termogravimetri (TGA) telah digunakan untuk menyiasat kestabilan haba gentian. Sementara itu, penguji tegangan kecil juga digunakan untuk mengukur sifat-sifat mekanik gentian. Dalam kajian ini empat jenis gentian tumbuhan telah dipilih termasuk sabut kelapa (COIR), pseudo-batang pisang (BPS), daun nanas (PALF) dan hampas tebu (SCB) gentian. Kandungan kelembapan dalam semua jenis gentian tumbuhan yang dikaji adalah dalam julat di antara 6-9%. Kandungan selulosa adalah paling tinggi dalam PALF (70%) manakala lignin adalah paling tinggi dalam COIR (28%). Sementara itu, SCB terdiri daripada hemiselulose kandungan yang tertinggi (10%) berbanding dengan gentian lain dan kandungan abu adalah yang tertinggi dalam SCB (2.2%). Penghabluran dalam gentian tumbuhan dikira mengikut ketinggian puncak dan kaedah puncak *deconvulated*. Ia adalah diperhatikan bahawa kedua-dua kaedah menunjukkan keputusan yang berbeza.

COIR menunjukkan penghabluran tertinggi (52.0%) dengan ketinggian kaedah puncak sementara penghabluran dikira dengan puncak "*deconvulated*" adalah tertinggi dalam PALF (68.3%). Semua tumbuhan yang dikaji menunjukkan ketidakseragaman dalam bentuk, saiz dan pembahagian sel-sel. Permukaan luar semua tumbuhan telah ditutup dengan lilin dan bahan-bahan lain yang terdiri daripada hemicelulose, lignin dan selulosa.The mikrograf elektron yang diperoleh juga mengesahkan bahawa struktur dinding sel semua gentian terdiri daripada satu lapisan primer (P) dan lapisan sekunder (S1, S2, dan S3). Penentuan taburan lignin dalam dinding sel tumbuhan oleh LM menunjukkan bahawa kebanyakan gentian, salur dan epidermis mempamerkan bukti lignifikasi yang tinggi kecuali floem dan sel parenkima yang menunjukkan reaksi positif yang lemah dengan toluidine biru. Hasil dari Raman spektroskopi dan SEM-EDX juga menunjukkan bahawa penyebaran relatif lignin dalam dinding sel adalah yang tertinggi di kawasan CC berbanding SW dan kawasan CML. Pemerhatian oleh TGA juga menunjukkan bahawa COIR adalah yang paling haba stabil berbanding dengan gentian lain dengan tenaga pengaktifan yang tertinggi dalam julat 100-200 kJ/mol dikira dengan menggunakan tiga kaedah yang berbeza (Kissinger, FWO dan kaedah Friedman). Ujian mekanikal ikatan gentian tunggal menggunakan mini penguji tegangan menunjukkan bahawa PALF menunjukkan nilai tertinggi kekuatan tegangan (309.7 MPa) dan modulus Young (7.4 GPa) manakala pemanjangan pada adalah yang tertinggi di COIR dengan nilai 32.7%. Kajian ini diharapkan dapat memberikan data dan pengetahuan mengenai sifat-sifat asas tropika sisa serat tumbuh-tumbuhan untuk digunakan dalam penyelidikan lanjut untuk aplikasi yang lebih luas pada masa hadapan.

CHARACTERIZATION, THERMAL AND MECHANICAL PROPERTIES OF TROPICAL PLANT FIBRES

ABSTRACT

The work deals with systematic evaluation of chemical, morphological, anatomical, thermal and mechanical properties of tropical plant fibres. The TAPPI test standard and Fourier transform infrared (FT-IR) spectroscopy were used to study the chemical composition and spectroscopic properties of plant fibre. The crystallinity was determined using X-ray diffraction (XRD). Light microscopy (LM) and transmission electron microscopy (TEM) were used to observe the morphology and cell wall structure of the fibre. Lignin distribution across cell wall layers was analyzed using scanning electron microscopy coupled with x-ray energy dispersive (SEM-EDX) and Raman spectroscopy. In addition, thermogravimetry analysis (TGA) was used to investigate thermal stability of the fibres. Meanwhile, miniature tensile tester also was used to measure the mechanical properties of fibres. Four different types of plant fibre were chosen which include coconut (COIR), banana pseudo-stem (BPS), pineapple leaf (PALF) and sugarcane bagasse (SCB) fibres for the study. Moisture content in all types of plant fibre studied was in the range between 6-9%. Cellulose content was highest in PALF (70%) while lignin was highest in COIR (28%). Meanwhile, SCB consists of the highest hemicelluloses content (10%) compared to other fibres and ash content was the highest in BPS (2.2%). Crystallinity was calculated by to peak height and deconvulated peak method. However, the results were completely different for these two methods. COIR showed the highest crystallinity (52.0%) by peak height method, whereas it was the highest in PALF (68.3%) when calculated by peak deconvulated method. The studied plants showed non-homogeneity in size, shape and cell distribution. The outer surface of the studied materials was covered with waxes and other encrusting substances consist of hemiceluloses, lignin and cellulose. The electron micrographs confirmed that the cell wall structure of all fibres consists of a primary layer (P) and secondary layers (S1, S2, and S3). Most of the fibres, vessels and epidermis had an evidence of lignification except for phloem and parenchyma cell which showed weak positive reaction with toluidine blue when studied for lignin distribution by LM. Results from Raman spectroscopy and SEM-EDX also indicated that relative lignin distribution was the highest in CC region compared to SW and CML region. An observation by TGA indicated that COIR was the most thermally stable compared to other fibres with the highest activation energy of 100-200 kJ/mol calculated using by three different model free methods (Kissinger, FWO and Friedman method). The mechanical testing of single fibre bundle using mini tensile tester revealed that PALF fibre had the highest tensile strength value (309.7 MPa) and Young's modulus (7.4 GPa), while elongation at break was the highest for COIR with value of 32.7%. This study is hoped to provide an extend data and knowledge regarding the fundamental properties of tropical plant waste fibres to use in further research for wider application in the future.

CHAPTER 1: INTRODUCTION

1.1 Background of the Study

The growing concern over increasing fossil fuel prices, global warming issues and green house effects have stimulated a tremendous interest in the use of renewable materials that compatible with the environment. In this respect, plant fibres or lignocellulosic biomass is the most suitable candidate that represents an abundant, inexpensive and readily available source for new interests in renewable and sustainable technology.

Plant fibres, including wood, agricultural residues, grasses and other plant substances is a resource comprises primarily of cellulose, hemicelluloses and lignin (Rowell et al., 2000). Global production of these renewable resources is estimated to be more than 220 billion tons annually while the primary production of fibrous raw materials from agricultural waste was estimated at 2.5 billion tons every year. It is worth noting that only 3% of these raw materials have been used by human (Foust et al., 2009, Satyanarayana et al., 2011).

In Malaysia, the total land area under natural forest is 20.1 million ha and agricultural area is accounted about 4.89 million ha which is only 14.9% of the total land area in Malaysia (Ong et al., 2011).The major agricultural grown in Malaysia are coconut (105,000 ha.), banana (31,000 ha.), pineapple (15,000 ha.) and sugarcane (2,000 ha.) (MOA, 2012). Large quantities of lignocellulosic biomass are generated during harvesting of these crops. Among these enormous wastes, only a minor amount of this residue is reserved as an animal feed or household fuel and a major of this inexpensive waste is burned in the field creating a problem in replanting operations and tremendous environmental concerns. The reuse of this by-product can represent a sustainable alternative for creating new environmental friendly materials (Thomas et al., 2011).

Plant waste fibres have the composition, properties and structure that make them suitable for uses in various applications such as composites, textile, pulp and paper, fuel, chemicals and food. These organic plant wastes are annually renewable, abundant, biodegradable, low cost, low density and non-toxic. They could be a principal source for fibres, chemicals and other industrial products. All these advantages make plant fibres as a potential replacement for glass fibres in composite materials that can be applied in various applications such as plastics, automobiles and packaging industries to reduce cost. Currently, the diverse ranges of products based on natural materials are now being produced and developed all over the world and giving a new insight and avenue to the development of renewable and sustainable technology and materials.

During the last few years, a series of works have been done to replace the conventional synthetic fibre with natural fibre composites. Reports shows that sisal, jute, oil palm empty fruit bunch (OPEFB), pineapple leaf, banana, oil palm, bamboo, coir, kenaf fibres have all proved to be good reinforcement materials as composites in thermoplastic and thermosetting matrices (El-Tayeb, 2008; Aji et al., 2011).Using these fibres in the production of composites polymer improves properties of polymers like the modulus, impact strength and toughness (Vikalati et al., 2010). Composites made of natural fibres offer the opportunity for extensive applications in fields such as consumer goods, low-cost housing and civil structures, and for many other common applications where the prohibitive cost of reinforcements at present restricts the use of conventional lightweight reinforced plastics (Harish et al., 2009). Nevertheless, certain aspects of natural fibre reinforced composite behavior still poorly understood such as their visco-elastic, thermal stability and interfacial adhesion that need further research to produce composites with optimum performances.

One of the most promising ways to utilize the lignocellulosic biomass is to convert the biomass to biofuel and biogas. It is estimated that about 150-200 billion tons of dry biomass are produced through photosynthesis each year, but less than 1% of the biomass has been utilized for production of bio-energy (Zhao et al., 2011). Tye et al. (2011) reported that biomass including plant fibres are considered as one of the most important renewable energy source because they contribute to world energy supply security, reduce dependence on fossil fuel resources, and provide opportunities for mitigating greenhouse emissions. Thermo-chemical conversion processes, including gasification, pyrolysis and combustion were proven the best available technology to convert these renewable materials into valuables biofuel and fine chemical feedstock (Wan Abdul Karim Ghani et al., 2009). Hence, continuous efforts and researches are focused to improve technologies which produce biofuel and biopower. Future use of biomass is totally dependent on the cost of producing energy from biomass compared to fossil fuels and realization of environmental impacts caused by fossil fuels (Mekhilef et al., 2011).

The use of plant fibre biomass not only limited to production of composite and biofuel but progressing to unlimited applications including paper, pharmaceutical, food, cosmetics and many other products. These expanding applications of plant fibres will need a systematic and continuous research on its properties in every aspect to provide imperative information in developing renewable and sustainable materials in the future. These not only help in preventing the environmental pollution, but also generating employment and contributing to the improvement of people's livelihood.

1.2 Problem Statement

Although natural fibres possess many advantages compared to synthetic materials, they are not totally free of problems. In addition to cellulose, plant fibres also contain different natural substances including hemicelluloses and lignin that influence its structure, properties, and morphology (Venkateshwaran and Elayaperumal, 2010). John and Anandiwala, (2008) mentioned that the overall properties of plant fibres are determined by large variables including structure, chemical composition, cell dimension, defects and microfibril angle. Furthermore, these properties are also varying considerably between different plant species and even in the same individual plant.

Plant fibre has certain drawbacks when considering its corporation in composite application. They have poor compatibility with polymer matrix and high moisture absorption which responsible for the poor mechanical and thermal properties that hinders the effective utilization of these fibres (Vikalati et al., 2010). Previous author (Mishra et al., 2001) used chemical modifications to activate the hydroxyl groups that can effectively interlock with the matrix. Efforts of modifying the filler or matrix are still currently put into consideration to produce polymer composites with better performance.

Plant fibre is also highly biodegradable and has low thermal stability because of their rich organic matter and high moisture content. High moisture content might cause instability of the material because it biodegrades easily with the action of microbes. This can cause problems with dry matter loss and hygiene due to the release of the pungent odor and fungi production (Yan Tock et al., 2010). Therefore, is important that its thermal properties be fully studied. This analysis can help to study the properties of the raw materials used in the fabrication of their composite as well as understanding the behavior of the final product (Aji et al., 2011).

Lignin is one of the major constituents in plant cell wall that imparts mechanical strength and stiffness of the plant. However, lignin inhibits scarification process in order to convert biomass to biofuels. Lignin also describe as undesirable in pulp and paper industry because high lignin content in biomass will need higher energy and reagent consumption for chemical and bleaching process (Reddy et al., 2007). Consequently, study of lignin including its distribution in the cell wall is crucial for its important in plant fibre processing industries.

Extensive studies have been done to characterize the plant fibre properties either individually or as part of their composite development such as pineapple (Costa et al., 2013, Kengkhetkit and Amornsakchai, 2012, Cherian et al., 2011), bamboo (Wang et al., 2012), banana (Sathasivam and Haris, 2012, Jayaprabha et al., 2011), sugarcane (Zhao et al., 2011, Mandal and Chakrabarty, 2011, Hemmasi et al., 2011), coconut (Prieto et al., 2011, Al-Adhroey et al., 2011), cotton (Sadegh et al., 2011), sisal (Noorunnisa Khanam et al., 2011), hemp (Fan and Yang, 2011). They mentioned that these plant fibres have the potentials to use as raw materials for different applications. However, there are very limited research has been carried out so far to evaluate the morphology, anatomy, lignin distribution, cell wall ultrastructure, thermal and mechanical properties of Malaysian tropical plant waste fibres. On the other hand, most of the works related to plant fibre characterization has done as part of the composites development (Maleque et al., 2007; Ibrahim et al., 2010). Moreover, a significant amount of research has been carried out to optimize the industrial use of the readily available organic raw materials. The complete and successful exploitation of this vast resource is still in its early days. Defeating barriers that prevent commercial exploitation of lignocellulose will be the key to its successful application in biotechnological field (Malherbe and Cloete, 2002).

In order to evaluate the full potential of these fibres for new applications, a detailed and compressive study on fundamental properties is necessary. Systematic evaluation of fundamental data will help to understand the relation between structure and properties of the fibre, and also open up new avenues for their efficient utilization. Studies on the use of these fibres as replacement to man-made fibre in fibre-reinforced composites will increase and open up further industrial possibilities. It is required to reduce the knowledge and information gap before the full commercialization of these materials and its sustainable uses. This research will help to understand better about the chemical compositions, cell wall structure and mechanical properties of agro-wastes, which necessary to a material scientist, polymer and food technologist for its further applications.

1.3 Objectives of the Study

This study deals with four different types of tropical plant fibres (coconut, banana pseudo-stem, pineapple leaf and sugarcane bagasse) for their fundamental properties. These four different types of fibre were chose as they are among the major agricultural plant in Malaysia. The purpose of this research is to provide a new database and extend the knowledge regarding the properties of tropical plant waste fibres. The database can be used for further research and for the development of diverse application of this material in food and non-food industries (biocomposites, pulp and paper, substituted carcinogenic polymeric materials in furnishing, food additives, natural pharmaceutical and cosmetics products, etc.). The information is also very important to reduce the environmental and health hazards associated with the disposal of these agricultural wastes. Within this scope, the specific objectives of this study are:

a) To determine the chemical composition and spectroscopic characterization of plant fibres

b) To characterize plant fibre morphology, anatomy and cell walls structure.

c) To investigate the lignin distribution in plant waste fibres using three different method; light microscopy (LM), scanning electron microscopy coupled with energy dispersive X-ray analysis (SEM-EDX) and Raman spectroscopy.

d) To analyze the thermal properties and kinetic study of plant waste fibres using Thermogravimetric analysis (TGA)

e) To determine the mechanical properties of plant fibres

1.4 Organization of Thesis

This thesis consists of eight chapters including this introductory chapter.

Chapter 1: It includes the background, justification and objectives of the study

Chapter 2: This chapter addresses the review of literature on various aspect of tropical plant fibres including its composition and properties which is relevant to the scope and objectives of this study.

Chapter 3: This chapter includes the chemical characterization of plant fibres using Fourier Transform Infrared (FT-IR) analytical and X-ray Diffraction (XRD) techniques.

Chapter 4: It focuses on the morphology, anatomical and cell wall ultrastructure of plant fibres using light and electron microscopy.

Chapter 5: This chapter explains the non-homogeneity of lignin distribution in plant cell wall layers by means of three different method; light microscopy (LM), scanning electron microscopy coupled with energy dispersive X-ray analysis (SEM-EDX) and Raman spectroscopy.

Chapter 6: This chapter discusses the thermal properties of plant fibres using Thermogravimetric analysis (TGA)

Chapter 7: This chapter determines the mechanical properties of plant fibres including tensile strength, Young's modulus and elongation at break.

Chapter 8: this chapter mentions the finding of the study and gives recommendation for further researches.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to Plant Cell

Plants provide the earth and its inhabitants with a large and varied set of exceptional biologic resources and economic importance. Plants account for 90% of the biomass on Earth and contribute to the world's rich diversity with an estimated 350,000 species (Roessner and Pettolino, 2007).

The plant cell (Figure 2.1) is the elementary and the smallest unit of plant life. They will continue cell division to develop the whole new plants. The cell normally consists of a protoplast and is enclosed by a fibrous wall that grows as the cell expands to its mature size, which become cross-linked and eventually limits the growth of the cell (McAdam, 2009). They are surrounded by a plasma membrane which consists of a nucleus containing the cell's genetic information. There is also a nucleolus for processing and assembly of ribonucleoprotein subunits, an endoplasmic reticulum and Golgi apparatus, mitochondria, ribosomes, peroxisomes and vacuoles. The plant cell wall is then can be defined as is a rigid semi-permeable structure surrounding all plant cells that govern the shape, size and growth rate of the cell, the texture and growth of the tissue, and the plant's resistance to microbial digestion (Fry, 2003).

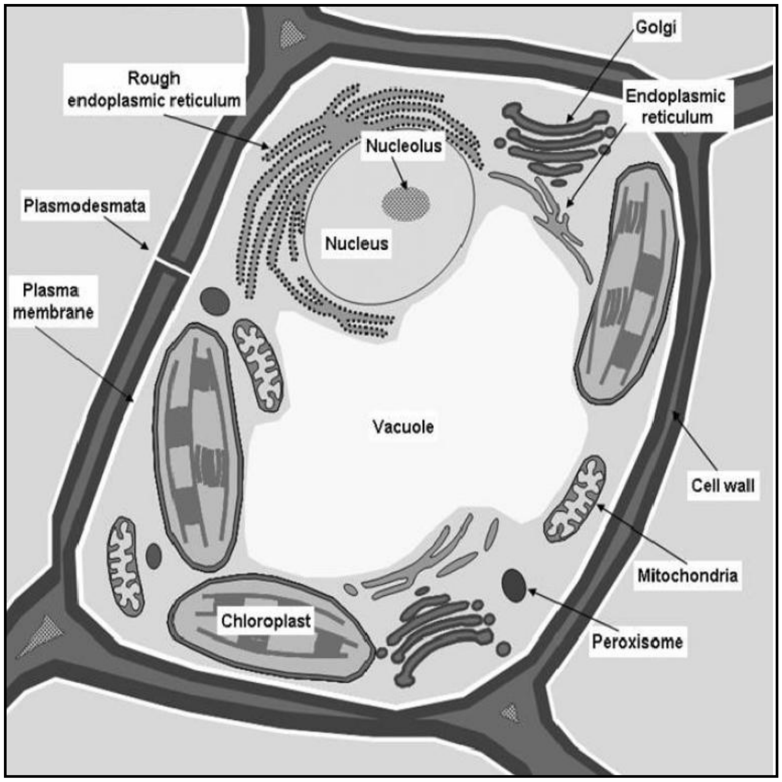

Figure 2.1: A typical plant cell. (Source: Roessner and Pettolino, 2007)

Higher plants are constructed different tissues classed as dermal, ground or vascular tissues. These are organized to form three vegetative organs: roots,- which function mainly to provide anchorage, water, and nutrients; stem,- which provides support; and leaves-, which produce food for growth (Barclay, 2002).

Vascular tissues play essential roles that range from physiological in transporting process of water and nutrients to transferring of signaling molecules. They also contribute to physical support of the plant. A typical system contains two basic units, xylem and phloem. Xylem moves and stores water and nutrients, transports diverse plant hormones, and lends major mechanical support. On the other hand, phloem provides passageways for the distribution of photosynthetic products, such as sucrose, and for translocating the proteins involved in growth and development. Both xylem and phloem usually comprise a number of specialized vascular cell types, including conducting elements, parenchyma, and sclerenchyma cells (Jung and Park, 2007). Different types of plant have been subject to research by many researchers since the last few decades. For the various applications, it is important to gain control over plant characteristics, which in turn are determined by cell wall composition and interaction of cell wall components.

2.2 Plant Fibres Classification

In this research, the term of plant fibre is used to assign numerous kinds of fibres that are naturally derived from plants of its various parts including roots, stem and leaves. Plant fibres are basically constituted mainly of cellulose, lignin, hemicelluloses and pectin. For this reason, plant fibres are also referred to as “cellulose fibres” and “lignocellulosic fibres” (Snegireva et al., 2010). Agricultural crop residues such as coconut, bagasse, pineapple leaf and oil palm are produced in billions of tones around the world every year. These fibres often contribute greatly to the structural performance of the plant and, when used in plastic composites, can provide significant reinforcement. There are wide varieties of plant fibres worldwide. The classifications, depending on the part of the plant from which they are taken as shown in Figure 2.2.

Plant fibres have been historically used for primitive tools, construction materials, clothes and as a source of energy (Zimniewska et al., 2011). However, there has been a dramatic increase in the use of plant fibre recently for the development of environmental renewable materials especially as a reinforcing agent in polymeric composites materials in substitution of synthetic fibres like glass fibres. This situation is largely spurred by environmental awareness, ecological consideration and technological advances. The favorable properties of plant fibres in comparison to glass fibre are shown in Table 2.1.

Plant fibres represent as an abundant, inexpensive and readily available source of lignocellulosic biomass. They are also renewable, biodegradable, low density and high strength to weight ratio compared to native materials. These interesting features make them applicable to be used as raw materials for various purposes. Recent advances in plant fibre development, genetic engineering and composite science offer significant opportunities for an exploration and development of improved materials from renewable resources which can be used in various applications such as biocomposites, pulp and paper, automotive, medical, packaging, construction, aerospace, marine, electronics, pharmaceutical and biomass energy production (Lau et al., 2010).

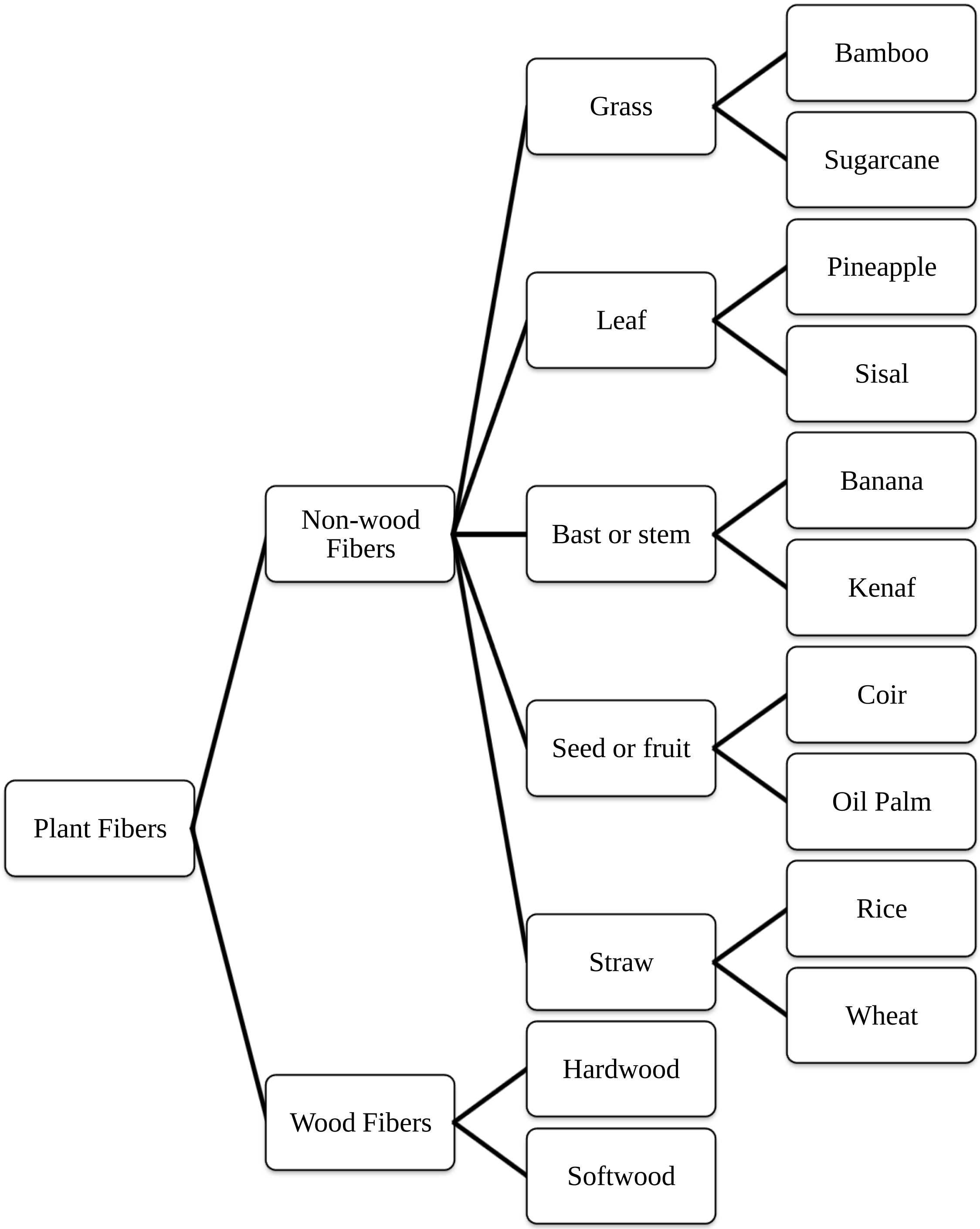

Figure 2.2: Classification of plant fibres (Source: Bagiotti et al., 2004)

Table 2.1: Comparison between plant fibres and glass fibres (Source: Marsh, 2008).

	Plant fibres	Glass fibres
Density	Low	Twice than that of plant fibres
Cost	Low	Low but higher than plant fibres
Renewable	Yes	No
Recyclable	Yes	No
Energy consumption	Low	High
CO_2 neutral	Yes	No
Abrasion to machines	No	Yes
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Not biodegradable

2.3 Types of Plant Fibres

Plant fibres are the largest source of cellulose in the world. Justiz-Smith et al. (2008) reported that in 2006, the annual global production of lignocellulosic plant fibres was about 4 billion tons of which 60% came from agriculture and 40% from the forest. In comparison, the annual world production of steel was around 0.7 billion tons and plastic was about 0.1 billion tons.

Malaysia is a country located in Southeast Asia which has a tropical and humid climate and blessed with a wide variety of agricultural resources. Agricultural industry has significantly contributed to the economy over the past four decade. Consequently, Malaysia produced more than 2 million tons of lignocellulosic plant wastes annually (Wan Abdul Karim Ghani et al., 2010). These wastes comprise of biomass in the form of cellulose and lignocellulosic that can be used to produce variety of value added products. Table 2.2 represents the land area for crops plantation and average crop production in Malaysia in the year of 2010. This research will focus on plant fibre that comes from major types of crops in Malaysia which is coconut, banana, sugarcane and pineapple.

Table 2.2: Land area for crops plantation and annual crop production in Malaysia in 2010 (Source: MOA, 2012)

Types	Area of planting (ha)	Production (MT)
Oil palm	4,202,381	64,282,738
Rubber	999,327	939,241
Paddy	677,884	2,464,000
Coconut	105,659	550,140
Banana	31,144	332,659
Sugarcane	2,216	44,780
Pineapple	15,456	331,081

2.3.1 Coconut

Coconut palms (*Cocos nucifera* L.) (Figure 2.3) is a monocotyledons plant species belonging to the members of family Arecaceae and order of Arecales, and are abundantly growing in coastal areas of all tropical countries. The trees are typical single-trunked and growing up to 30 m in height. Its pinnate leaves are 60–90 cm long, and borne in a spiral arrangement at the apex of the trunk (Foo and Hameed, 2012).

Coconut fibres are found between the husk and the outer shell of a coconut. About 55 billion of coconuts are harvested annually in the world, but only 15% of the husk fibres are actually recovered for use. Every year, coconut agricultural industry generates a significant amount of waste where most husks are left in the field that can cause environmental problem (Muensri et al. 2011). The coconut fibre is a short fibre as well as a little flexible and hard when compared to the others fibres. Their hardness is associated mainly to the presence of lignin, which is also responsible for the yellowish color and for the brown color to the mature coconut.

The economic importance of coconut fibres depends on their structure, physical properties, and chemical composition. The utility of coconut fibre is principally determined by its physical properties such as breaking load, elongation, and tensile strength (Nanayakkara et al., 2005). According to previous research (Martinschitz et al., 2008), coconut fibres exhibit valuable physical properties like high fracture strain and toughness, which make the coconut fibre an interesting material to be used for various domestic and commercial applications including ropes, brushes, carpets and mats. Nowadays, as a potential biodegradable and renewable fibre, coconut fibres have been increasingly used as raw materials in biocomposites, automobiles, construction, packaging and insulation applications (Da Costa Castro et al., 2012). Recent study (Vaithanomsat et al., 2011) also discussed the use of coconut as a promising substrate for bioethanol production. On the other hand, Foo and Hameed (2012) highlighted the potential of coconut husk as an efficient raw precursor for the preparation of activated carbon with noticeable decolorazation capacity by microwave heating.

Figure 2.3: Coconut palm

2.3.2 Banana

Bananas (*Musa* spp.) are perennial monocotyledonous herbs (Figure 2.4). They are native to regions of Southeast Asia and cultivated throughout the tropics. As the world's leading fruit crop, it has been estimated that world production of bananas in 2008 was more than 90 million tons (FAO, 2012). In Malaysia, banana is grown in most of the states. It remains the second most important fruit crop after durian. There are 25-80 species in the genus *Musa*. Most of the produced bananas are consumed locally and about 10% are exported to other countries (Salman and Hameed, 2010).

A banana plant consists of a true stem called corm with roots and a false stem called pseudostem that consist of overlapping leaf sheaths (Yan Tock et al., 2010). Since each banana plant cannot be used for next harvest, pseudostem bears fruit only once before it dies down and replaced by new sprouts. This bulky portion therefore generates the largest amount of banana plant residue. After harvesting the fruit, the pseudostem is normally discarded and left on plantation floor as organic fertilizer or mixed with the rejected fruits to make animal feed (Zuluaga et al., 2009). This process creates several environmental problems including the production of fungi which causes diseases to bananas and the launching of methane in the atmosphere, one of the gases, responsible for the greenhouse effects (Barreto et al., 2010).

This residual resource is rich in cellulose, a feature that has attracted much interest due to the potential use as raw materials for high performance composite materials, pulp and paper and bioethanol productions. It has been reported (Justiz-Smith et al., 2008) that the fibre of banana pseudostem has a high Young's modulus and water absorption capacity. The application of banana pseudo-stem has been proved promising in various technical field including composites, pulp and paper, activated carbon and absorbent. Alkali treated banana fibre-reinforced soy protein composite was developed by Kumar et al. (2008). They concluded that the composite was 100% biodegradable and its mechanical properties of the fibre reinforced composites were strongly dependent on the volume fraction of the banana fibres and the amount of plasticizer used. In addition, Majhi et al. (2011) had studied the effect of variable fibre composition, mercerization of fibre as well as incorporation of maleic anhydride as compatibilizer and glycerol triacetate ester on the properties of polylactic acid/banana fibre composites. Some other valuable products can also be obtained from banana pseudostem. Study on the synthesis of sodium carboxymethylcellulose from Cavendish banana pseudostem was reported by Adinugraha et al. (2005). Anirudhan (2006) studied new absorbent system containing banana pseudostem which could remove phosphate from wastewater, exhibit high absorption potential and satisfactory recyclability.

Figure 2.4: Banana plantation

2.3.3 Pineapple

Pineapple (*Ananas comosus*) (Figure 2.5) is one of most produced fruits worldwide which is cultivated throughout the tropical and subtropical regions. Pineapple is a perennial monocot belonging to the order Bromeliales, family Bromeliaceae, subfamily

Bromelioideae. Native to Central and South America, pineapple is now grown extensively in Hawaii, Philippines, Caribbean, Malaysia, Thailand, Australia, Mexico, Kenya, South Africa and China (Aquije et al., 2010). Pineapple leaf fibres at present are a waste product of pineapple cultivation. They are extracted from the leaves of the plant. The fibres have a ribbon-like structure and consist of a vascular bundle system present in the form of bunches of fibrous cells, which are obtained after mechanical removal of all the epidermal tissues. Hence, pineapple fibres can be obtained for industrial purposes without any additional cost input

The fibre is very hygroscopic, relatively inexpensive and abundantly available. Among various natural fibres, pineapple fibre exhibit excellent mechanical properties that are associated with their high cellulose content and low microfibrillar angle that exhibits high specific strength and stiffness. Its specific modulus and strength are close to or even higher than that of glass fibre (Kengkhetkit and Amonrnsakchai, 2012; Arib et al., 2006).

The use of pineapple fibre in plastic or polymer reinforcement has been demonstrated by many researchers. Aji et al. (2011) studied the thermal degradation behavior of hybridized kenaf/pineapple leaf fibre reinforced high density polyethylene (HDPE) composites by thermogravimetric and derivative thermogravimetric analyses (TG/DTG) regarding the proportions of fibre in the composite, variation in fibre loading and fibre length. George et al. (1996) studied stress relaxation behavior of pineapple fibre reinforced polyethylene composites. They found that stress relaxation to be decreased with the increase of fibre content due to better reinforcing effect.

Figure 2.5: Pineapple plantation

2.3.4 Sugarcane

Sugarcane (*Saccharum* spp) (Figure 2.6) is a widely cultivated monocotyledonous in many countries and regions of the world. It belongs to the tribe Andropogoneae of the family Gramineae and the genus *Saccharum*. Around 20 million ha of sugarcanes are grown annually worldwide. Bagasse is the residue left after crushing the sugarcane for juice and about 28% bagasse is produced from every tone of sugarcane. The sugar product from this plant represents only thirteen percent of the total biomass of sugarcane (Said et al., 2008). The wastes are mostly burnt to generate energy for the mills but a considerable amount of it is still wasted.

The cane stalk consists of inner pith that contains mostly sucrose where the external part is composed with lignocellulosic fibres. The sucrose is extracted by crushing the entire stalk (de Barros Filho et al., 2011). Compared with others fibres, sugarcane fibre has a lower tensile strength, lower Young's' modulus, higher moisture content and better biodegradability due to its higher contents of hemicellulose and lignin (Bertoti et al., 2008).

In recent years, there has been an increasing trend towards more efficient utilization of sugarcane bagasse. Several processes and products have been reported that utilize sugarcane bagasse as a raw material. These include composites, pulp and paper product, products based on fermentation, fuel and electricity generation (Sindhu et al., 2010; Zhao et al., 2011). Bagasse has also been used for the production of microcrystalline cellulose and nanocellulose (Mandal and Chakrabarty, 2011). Said et al. (2009) studied the usefulness of raw bagasse for oil absorption after modification using acetylation grafting with fatty acid. They concluded that the grafted bagasse would be more suitable for applications where oil is to be removed from aqueous environment. The various products, which have been obtained during the processing of bagasse also include chemicals and metabolites such as alcohol and alkaloids, mushrooms, protein enriched animal feed (single cell protein), and enzymes (Parameswara, 2009).

Figure 2.6: Sugarcane plant

2.4 Chemistry of Plant Fibre

Natural plant fibres consist of cell wall is mainly composed of three major polymers: cellulose, hemicelluloses and lignin. Table 2.3 shows the variability in cell wall composition in plant fibre. The table shows that content of the polymers are highly variable in plant fibres not only in different plant species but also in different parts of the same plants. There are many factors that will influence the composition, structure and distribution of these polymers in various layers of plant cell walls such as age, soil condition and other environmental factor including stress, humidity and temperature. The polymer chemistry of these fibres will affect their characteristics, functionalities and processing efficiency in different applications (Gorshkova et al. 2010).

Table 2.3: Chemical composition of major types of plant fibres

Fibre	Extractive	Cellulose	Hemicellulose	Lignin	Pectin	Ash	References
Coconut husk	6.4	44.2	12.1	32.8	4.0	2.2	1,2
Banana pseudo-stem	10.6	63.9	1.3	18.6	3.0-5.0	1.5	1,2
Coconut shell	3.2	43.0	13.3	45.0	-	2.2	3
Banana leaf	9.8	25.6	17.0	24.8	-	7.0	4
Pineapple leaf	5.5	73.4	7.1	10.5	2.0-2.5	2.0	1,2
Sugarcane Bagasse	4.3	39.4	26.9	22.5	10.0	1.0-4.0	2,4,5
Oil palm (empty fruit bunch)	3.2	50.4	29.6	17.8	-	3.4	1
Oil palm (trunk)	5.3	41.0	32.0	24.5	-	2.2	1
Oil plam (frond)	4.5	49.8	33.7	20.5	-	2.4	1
Kenaf	-	57.0	21.5	8.0-13.0	3.0-5.0	-	6
Ramie	-	76.2	13.0-16.0	0.6-0.7	1.9	-	6
Bamboo	5.7	46.3	23.4	22.2	-	1.5	3
Flax	-	60-81	14.0-18.0	2-3	1.8-2.3	-	2
Coniferous	-	40-45	7.0-14.0	26.0-34.0	-	<1.0	7
Deciduous	-	38-49	19.0-26.0	23.0-30.0	-	<1.0	7

1- Abdul Khalil et al., 2006; 2- Biagiotti et al., 2004; 3- Abdul Khalil et al., 2010; 4- Arsène et al., 2007; 5- Guimarães et al., 2009; 6- Akil et al., 2011; 7- Kozlowski and Wladyka-Przybylak, 2008