# MECHANICAL PROPERTIES OF BAMBOO PARTICLE REINFORCED POLYLACTIC ACID (PLA) COMPOSITE USING TAGUCHI METHOD

**NURNADIA BINTI MOHD JOHARY**

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**by**

**NURNADIA BINTI MOHD JOHARY**

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**I would like to dedicate this work for mamabah. This one is for both of you!**

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# LIST OF SYMBOLS

| | |
|---|---|
| % | percentage |
| ˚C | Degree Celcius |
| + | plus |
| × | multiply by |
| / | divided by |
| μm | micrometer |
| ± | plus minus |
| $T_m$ | Melting temperature |
| $T_g$ | Glass transition temperature |
| $T_{cc}$ | Cold crystallization temperature |
| $X_{cc}$ | Degree of cold crystallization |
| g | gram |
| cm | centimeter |
| $cm^3$ | centimeter cube |
| m | meter |
| rpm | revolution per meter |
| wt. % | weight fraction |
| MPa | megapascal |
| GPa | gigapascal |
| J/m | joule per meter |

## LIST OF ABBREVIATIONS

| | |
|---|---|
| PLA | Polylactic acid |
| BP | Bamboo particle |
| ASTM | The American Society of Testing and Material |
| ANOVA | Analysis of variance |
| DSC | Differential scanning calorimetry |
| DTG | Derivative thermogravimetric |
| SEM | Scanning electron microscopy |
| TGA | Thermogravimetric analysis |
| DoE | Design of experiment |
| OFAT | One-factor-at a time |
| DOF | Degree of freedom |

# SIFAT MEKANIKAL KOMPOSIT ASID POLILAKTIK DIPERKUAT PARTIKEL BULUH MENGGUNAKAN KAEDAH TAGUCHI

## ABSTRAK

Pelbagai kajian dalam bidang bahan biodegradasi telah dikaji terutamanya bahan daripada sumber alam disebabkan oleh isu alam sekitar yang semakin membimbangkan. Asid polilaktik (PLA) merupakan bahan termoplastik yang mudah terlerai dan mempunyai potensi yang tinggi untuk menggantikan polimer sintetik seperti polipropilena. PLA sering digunakan sebagai bahan asas untuk menghasilkan beg plastik mudah terlerai, bahan jahitan perubatan, automotif dan pelbagai jenis pembungkusan. Tetapi, penggunaannya masih kurang berbanding polimer sintetik. Sifat PLA yang rapuh dapat ditambahbaik dengan menggunakan gentian semulajadi sebagai penguat komposit supaya kegunaan komposit ini boleh dipelbagaikan. Buluh sesuai untuk dijadikan penguat PLA kerana buluh senang dijumpai, kadar pertumbuhannya yang tinggi dan sering tidak digunakan. Komposit yang diperbuat daripada PLA dan partikel buluh dihasilkan melalui dua proses iaitu penyemperitan dan mampatan kumai. Sifat fizikal, termal, mekanikal dan morfologi telah dikaji. Kajian ini menfokuskan penambahbaikkan sifat mekanikal dengan cara mengoptimumkan parameter yang mempengaruhi sifat mekanikal komposit tersebut dengan menggunakan kaedah Taguchi. Parameter yang dipilih dalam kajian ini adalah saiz partikel, kandungan partikel buluh, kelajuan skru dan suhu bahagian acuan di dalam penyemperit berskru kembar. Sampel disediakan dengan mencampur kedua-dua bahan asas menurut barisan sudut tegak L9 dan dicairkan dengan menggunakan penyemperit berskru kembar. Seterusnya, bahan yang telah dicair-campur dipotong kepada saiz pelet sebelum campuran tersebut dikenakan tekanan. Ketumpatan dan kadar penyerapan air telah diukur dan sifat termal dianalisa dengan menggunakan analisis termogravimetrik (TGA) dan kalorimetri pengimbasan pembezaan (DSC) manakala sifat mekanikal dapat dikenalpasti melalui ujian tegangan, lentur dan kekuatan impak. Analisis morfologi terhadap interaksi permukaan antara gentian and polimer dijalankan dengan menggunakan mikroskopi elektron penskanan (SEM). Kajian ini mendapati, kaedah Taguchi telah menyarankan penggunaan saiz partikel 150-250 µm, kandungan partikel buluh 10wt.%, 300 rpm kelajuan skru and 180°C suhu bahagian acuan dapat menghasilkan komposit dengan sifat mekanikal yang ideal. Parameter optimum disahkan dengan menjalani ujian pengesahan. Hasil kajian mendapati kandungan partikel buluh merupakan parameter yang mempengaruhi sifat mekanikal komposit. Analisis statistik ANOVA juga membuktikan bahawa terdapat perbezaan yang nyata pada penggunaan suhu di bahagian acuan terhadap sifat tegangan manakala kandungan partikel buluh terhadap semua respon. Hasil kajian menunjukkan kekuatan impak komposit ini adalah lebih baik jika dibandingkan dengan kekuatan impak bagi kandungan PLA sahaja sebanyak 55 %. Penambah-baikkan ini dapat diperoleh tanpa mengabaikan sifat mekanikal lain seperti sifat tegangan and lenturan.

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**MECHANICAL PROPERTIES OF BAMBOO PARTICLE REINFORCED POLYLACTIC ACID (PLA) COMPOSITE USING TAGUCHI METHOD**

## ABSTRACT

The field of biodegradable materials, especially those from biological sources has been extensively researched in response to environmental concerns. Poly (lactic) acid (PLA) is a well-known biodegradable thermoplastic whose potential is to replace synthetic polymers such as polypropylene. PLA is often used for the degradable plastic bag, medical sutures, automotive, and packaging, but the usage is still scarce compared with a synthetic polymer. Natural fibre can be added as reinforcement in the composite for more practical applications due to PLA polymer's brittleness. Bamboo is a possible choice for incorporated in PLA because it is abundant in nature, grows very quickly, and widely unused. This thesis discusses the manufacturing of composites made from PLA and bamboo particles using extrusion and compression moulding techniques. In order to explore the potential of the composites, a study of physical, thermal, mechanical and morphological properties was examined. This research focuses on improving the mechanical properties of PLA-bamboo of PLA-bamboo particle composite by optimising the parameters that influence the properties using Taguchi experimental design. The parameters such as particle size, particle load, screw speed and die temperature were chosen for evaluation by Taguchi Method. Samples were fabricated by mixing PLA pellets and bamboo particles according to L9 orthogonal array. The samples were melt-compounded by twin screw extruder. The extruded material was pelletised before moulding it into composite sheets by compression moulding. Thermal properties were investigated using thermogravimetric analysis

(TGA) and differential scanning calorimetry (DSC). The mechanical properties of the composites were analysed with a tensile test, flexural test as well as Izod impact test. The morphology analysis of the matrix-fibre interface was determined using scanning electron microscopy (SEM). Taguchi method suggested that 150-250 µm particle size, 10 wt. % particle loading, 300 rpm of screw speed and 180 $^{\circ}$C of die temperature gives the ideal mechanical properties of PLA/bamboo particle composite. The optimum parameters were validated by conducting a confirmation test. Taguchi method experimental results indicated that bamboo particle load is the most influential parameter among all studied parameters. ANOVA statistical analysis also showed a significant dependence on die temperature for tensile properties. Meanwhile, bamboo particle loading showed a significant difference for tensile, flexural and impact properties. The results showed a pronounced improvement of impact properties in comparison to neat PLA by 55 %, without compromising tensile as well as flexural properties.

# CHAPTER 1

# INTRODUCTION

## 1.1 Research background

In the past year, the biodegradable polymer has been the main subject of research and development with two main environmental concerns: the supply of the petroleum plummeting and the overload of plastic waste accumulation in landfills. If plastic production can stop depending on petroleum supplies, which will soon decrease, non-renewable resources can be preserved (Gamon *et al*., 2013). The excessive use of petroleum-based plastics will generate vast amounts of non-compostable solid wastes in landfills which can cause severe depletion of landfill capacities (Ho *et al*., 2015). The concern of plastic disposal increased as society became more concern with preserving the environment. Government environmental policies have been implemented to force the industries to find environmentally friendly material (biodegradable materials) to substitute the conventional non-biodegradable materials used in various applications such as automotive, packaging and construction.

Biodegradable polymers are the materials obtained from nature or by synthetic route, whose chemical bonds are cleaved at least in one step by enzymes from the biosphere, with appropriate pH and temperature conditions and total processing time for completion. A common technique to produce biodegradable materials is by compounding traditional petroleum-based thermosetting polymers (epoxy, unsaturated polyesters, phenol-formaldehyde resin) or thermoplastic polymers (polypropylene, polyethene) with natural fibres. However, many disadvantages arise by using thermoset polymer, includes brittleness, longer curing time and inability to repair/reuse. These advantages have led to the development of the thermoplastic matrix composite.

Polypropylene was among the first thermoplastic polymer to achieve industrial importance due to its low cost, easy processability and excellent mechanical properties (Dixit *et al.*, 2017). However, these composites are not considered as a biodegradable composite because the matrix is a non-biodegradable polymer. The recent development of green composites, most researches mixed natural fibres with biodegradable polymers including starch (Jumaidin *et al.,* 2017), soybean plastics (Boontima *et al.,* 2015), Polyhydroxyalkanoate (PHA) (Chan *et al.,* 2016), Polyhydroxybutyrate (PHB) (Torres-Tello *et al.,* 2017), Polycaprolactone (PCL) (Sarasini *et al.,* 2017) and Polylactic acid (PLA) (Siakeng *et al.,* 2018).

PLA has commercially attractive features such as its good optical, physical, mechanical and barrier properties, good appearance, low toxicity and good processability. PLA is now one of the most promising among biodegradable polymer due to its remarkable mechanical properties as an alternative to conventional synthetic polymer (Bax & Müssig, 2008). PLA also can be recycled or disposed of without harming the environment. PLA can be used for making plastic bags for household biowaste, barrier for sanitary products and diapers, planting cups, and disposable cups and plates. The drawbacks of PLA are, it is an expensive polymer to be used as commodities, low impact strength, low ability in resisting thermal deformation and brittle (Lu *et al*., 2014). In order to make it suitable for many technical applications, natural fibre is introduced into the PLA matrix-forming biocomposite. A biocomposite is a composite material formed by polymer matrix and natural fibres that acts as reinforcement. Thus, the production cost of PLA composites can be reduced because less PLA will be used (Shibata *et al*., 2003).

Natural fibres have been considered as potential reinforcement in biopolymer composites due to its excellent mechanical properties, biodegradable, renewable resources, abundantly available, low cost, low density, accessible, high specific modulus and strength (Yu *et al.,* 2014). Natural fibres as reinforcement to PLA matrix is an ideal alternative to increase the mechanical performance of the composites as well as making it environmental friendly. There are many natural fibres have been studied to reinforce polymers such as kenaf (Ochi, 2008), hemp (Masirek et al., 2007), jute (Gupta *et al.,* 2016), and flax (Duhovic *et al.,* 2009). Among natural fibres available, bamboo fibres are the most suitable candidate as reinforcement for PLA matrix. The critical interest of bamboo fibres, it has good mechanical properties; and low water absorption that makes it favour to blend with hydrophobic plastics such as PLA ( Yu *et al.*, 2014). In this research, a specific type of bamboo species known as *Gigantochloa Scortechinii* (Buluh Semantan) has been chosen as reinforcement. Semantan bamboo is an important commercial species that grows rapidly and vastly available in forests entire Malaysia (Rassiah *et al.,* 2018).

Enhancement of mechanical properties is often attributed due to the better distributive mixing that involves distributing fibres within the matrix. Distributive mixing can be achieved by extrusion. Extrusion can be operated continuously, which allows consistent product flow at relatively high throughput rates (Bhairav *et al.,* 2016). In order to increase the performance of mechanical properties of PLA-bamboo particles composite, material selection and processing parameters play a critical role because it will determine whether the fibre and matrix will be compatible well with each other or not (Gallos *et al.,* 2017). Material and processing parameters can be optimised to improve the quality of the PLA reinforced bamboo particle since it is directly related to porosity of the final product. The porosity of the composite can be determined by density result of the composite. The low mechanical performance of the composite may due to the high porosity (more void). Due to the low impact strength of the PLA, this research focuses on improving the impact properties PLA-bamboo particle composite without compromising the other mechanical properties such as the tensile and flexural properties. This can be achieved by optimising the parameters that influence the properties using Taguchi experimental design by using the design of the experiment.

Taguchi method is a robust and multiparameter optimisation statistical technique which employs a fewer number of experiments. This method is a systematic and straightforward way that acts as a tool to determine the effect of a factor on responses and optimum parameters to achieve the best mechanical properties (Ali *et al.*, 2004). Taguchi method uses a full fractional design called orthogonal arrays and Analysis of Variance (ANOVA) as a tool for Analysis. Orthogonal arrays are the minimum set of experiments which represent the various combinations of factors. The output of the orthogonal arrays is optimised with the mean value of the responses independently without interaction with other factors, thus reduces the process variability. This characteristic marks the difference between conventional statistical technique and the Taguchi Method. In this study, the Taguchi method was used in determining significant parameters and four main parameters were considered; bamboo particle load and size, as well as the screw speed and die temperature of twin screw extruder.

## 1.2 Problem statements

PLA has reasonably good optical, physical, mechanical, and barrier properties compared to the existing petroleum-based polymers. However, the main drawback of using PLA is it has low impact strength, and it is also not cost effective. The problem is solved through the use of composite materials based on natural fibres (Puglia *et al.*, 2003). Natural fibre reinforced polymer composites have been the focus of academic and industrial research interest due to several advantages, such as low cost, high strength-to-weight ratio and recyclability compared to the synthetic fibre composites. The reinforcement of PLA using natural fibres have been extensively reported, including bamboo fibre. Most researches on PLA reinforced bamboo fibres composites were mainly focusing on improving the mechanical properties by modifying the natural fibre without optimising the parameters regardless the process they are using (Lee & Wang, 2006; Yan Yu *et al*., 2014; Yu *et al*., 2015). Different studies experimented with different composites formulation and conditions of extrusion are also reported by these researches (Bourmaud & Baley, 2010; Gamon *et al.*, 2013; Ogbomo *et al.*, 2009; Sawpan *et al.*, 2011).

Bamboo fibre proved to be the most effective reinforcement among all studied reinforcements (Nuthong *et al.*, 2013). The study showed that the interfacial bonding between bamboo fibre and PLA matrix was better than vetiver grass fibre and coconut fibre. Tokoro *et al.*, (2008) also proved that the addition of bamboo fibre improves impact strength, thermal properties and heat resistance. Many studies have reported the remarkable mechanical properties of PLA composites reinforced by bamboo fibres. Iwatake *et al.*, (2008) showed the tensile modulus of PLA can be increased significantly with increasing fibre load but at the same time it leads to the problem such as losing properties such as yield strain, which resulting to the strength being decreased. Therefore, the recent research initiative is to use Taguchi approach to predict the parameter affecting the mechanical properties of the composite and obtaining an optimum set of parameters to produce a PLA composite with highest impact strength without compromising the other mechanical properties such as tensile and flexural properties. Navaneethakrishnan & Athijayamani, (2015) proved that mechanical performance characteristics of the plant based natural fibre and particle reinforced polymer composites can be effectively improved by Taguchi method. A study done by Rawi *et al.*, (2013) resulted in desirable tensile and flexural properties and acceptable impact performance of the bamboo fabric–PLA composite sheets by using Taguchi method.

Although there are some recent studies that investigated the mechanical behaviours of natural fibre reinforced polymer composites, not so much work has been done on the selection of parameters during the extrusion process to improve the mechanical properties of PLA reinforced bamboo particle composites, especially their impact properties without compromising the other properties such as tensile and flexural. Therefore, the material and processing parameters can be manipulated to improve the quality of the PLA reinforced bamboo particle.

## 1.3 Research objectives

The main objectives of this research are summarised as below:

1. To characterize the physical, thermal, mechanical and morphological properties of PLA reinforced bamboo particle composites.

2. To optimize the material and extrusion parameters on mechanical properties of PLA reinforced bamboo particle composites by Taguchi method.

## 1.4 Thesis outlines

The thesis begins with Chapter 1 which briefly introduces the research. The research background introduced the problems in our nature which are depletion of petroleum source and limited landfill caused by excessive plastic waste. The respective problems were solved by producing biodegradable products by reinforcing biopolymer with natural fibres. The problem statements and objectives of the research were also described in this chapter. The flow of this study continues by doing literature survey as presented in Chapter 2. This chapter presents the work done by other researchers related with the field of polymer reinforced natural fibre, manufacturing process and improvement part from the optimization process. Then, Chapter 3 describes the methodology used in this research, including the details of experimental procedures and the analysis performed. Chapter 4 analysed the results obtained and discussed according the methodology described in Chapter 3. Finally, Chapter 5 concludes the research work and suggests the appropriate future work for other researchers.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Over the past decades, research projects follow the concept of utilizing green material has become more popular. Natural fibres have been utilized to reinforced polymer matrix composites, replacing the conventional fibre. A considerable awareness of preserving the environment and effort across the globe has pushed many scientists to investigate the real potential of natural fibres as reinforcement materials for green bio-composites. Recently, with advantages of reasonable mechanical properties; low density, provides stiffness and strength, environmental benefits, renewability and economic feasibility. This chapter provides the background information on the issues to be considered in the present research work and to focus the relevance of the present study. The purpose is also to present a thorough understanding of various aspects of bamboo fibre particle reinforced PLA composites with a special attention to parameters affecting its mechanical strength.

## 2.2 Natural fibres: Classification and properties

Fibres are classified into two groups based on the origin of the fibres and production of fibres; natural fibres and man-made fibres. Natural fibres that occur in nature are categorized based on their origin, such as from animals, mineral, or plants sources. The plant fibres are provided by nature from various parts of plants, trees and geographies. Meanwhile, man-made fibres are manufactured spinning polymer prepared by human (synthetic fibre) or occurred naturally (chemical fibres). Synthetic fibre has remarkable mechanical properties and has been used in many applications. However, the toxicity fumes emitted from degraded synthetic fibres has led to serious environmental problem. Natural fibres can be the alternative to the synthetic fibres due to its biodegradability, renewability, low cost and toxicity. Plant-based natural fibres can be classified based on their natural form as shown in Figure 2.1

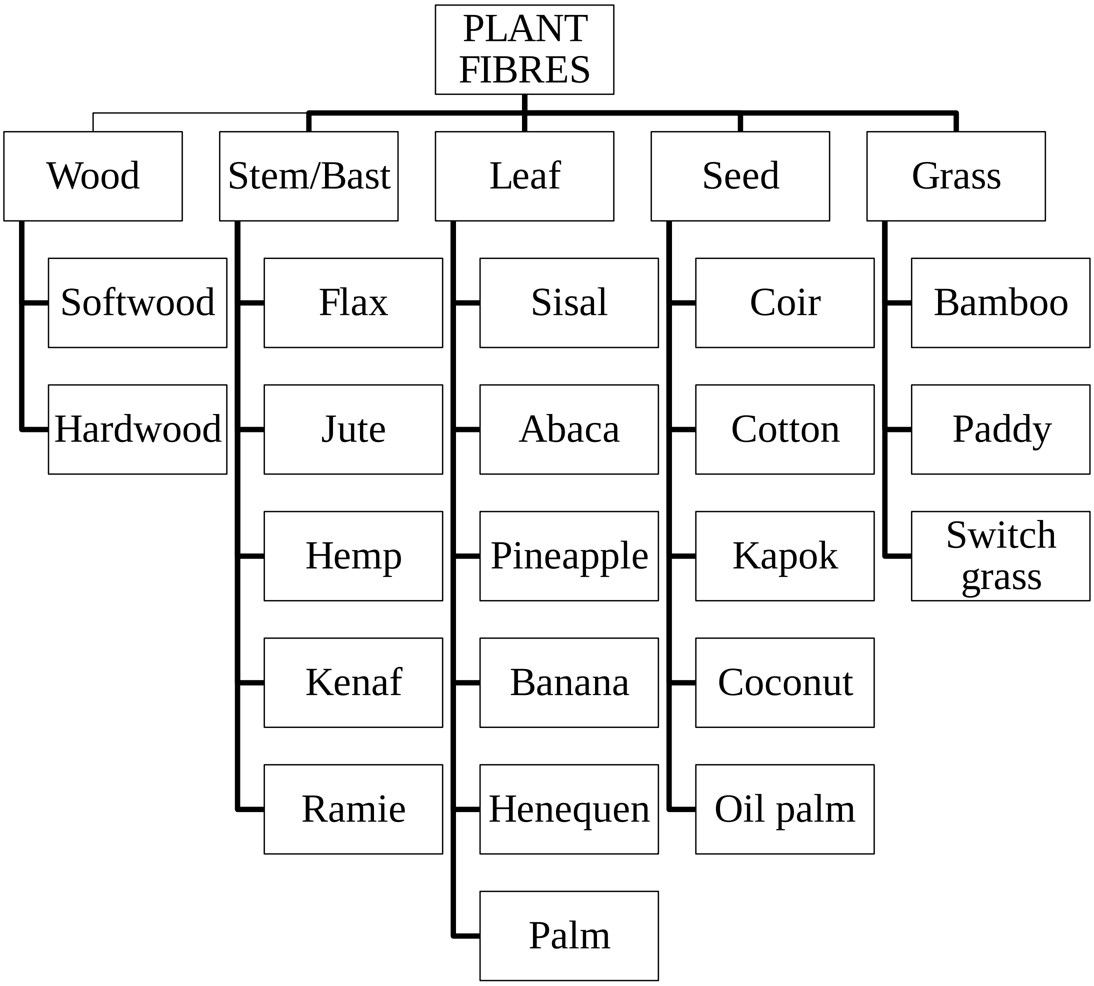


Figure 2.1 : Classification of plant-based natural fibres used as reinforcement in composites (Adekomaya *et al.*, 2016)

The main chemical components of plant-based natural fibres are cellulose, hemicellulose, lignin. The major component of all plant is cellulose. Cellulose exists in polymer form of its b D-glucopyranose monomers that make a strong, rigid chain structure through polymerization of 1, 4-b glycosidic linkages. The presence of hydroxyl group in each repeating monomer that are linked turn-over to each other gives it the ability to make strong intramolecular and intermolecular hydrogen bonding. Hemicellulose is relatively short chain length (low degree of polymerization) irregular cellulose structure that is very hydrophilic and dissolves in alkali and easily hydrolysed in acids, whereas lignin is a complex polymer made of three-dimensional copolymer of aliphatic and aromatic constituents with very high molecular weight. It acts as the structural materials and gives rigidity to the plant fibre. It is amorphous and hydrophobic in nature. Lignin cannot be hydrolysed by acid but soluble in hot alkali.

The source of lignocellulosic materials is widely spread throughout the world. Lignocellulosic materials exhibit diverse mechanical properties because the proportion of cellulosic contents in fibre are different to one another. Literature survey of lignocellulosic composite shows that the source material mostly was chosen in accordance with bioresource availability in a specific geographic location. For example, hemp fibres are  mainly used in composites made in France, China, New Zealand, United State of America, Canada, Morocco and Romania (Gallos *et al.,* 2017). In recent published paper wrote by Ali *et al.*, (2016), Mohamed & Appanah, (1998) highlighted that bamboo grew in abundance and widely scattered in about 5% of the total forest reserve area with more than 50 bamboo species in Malaysia. Almost 14 bamboo species are commercially exploited and *Gigantochloa* genus is one the most utilised bamboos in Malaysia. Its uniformity in size, thick culms wall and easy cultivation were the main reason bamboo genus is worth explored for industrial usage (Saurabh *et al.,* 2016). Besides that, natural fibres resources such as hemp, kenaf and flax are being commonly reinforced in the polymer system. Compared to different natural fibres available in Malaysia, bamboo received comparatively little research attention.

### 2.2.1 Bamboo

Bamboo is a perennial woody grass, which belongs to the family Gramineae and subfamily Bambuseae. It as an evergreen, monocotyledonous (non-woody) plant, which produces primary shoot without any later growth. Anokye *et al.*, (2014) stated that there are about 60-70 genera and over 1,200-1500 species of bamboo in the world that can be found in various climate from cold to hot tropical region. Liu *et al.*, (2018) mentioned that bamboo grow abundantly in most of the tropical and it is one of the fastest growing renewable resources in the world. It takes short period of time to mature and can be harvested within 3 to 4 years to be utilized. Bamboo has phenomenal growth rate potential, with some species growing at a rate of 15 to 18 cm daily, with maximum height in just four to six months.

Bamboo is a very well-known material for its versatility of uses since the ancient time. In China, people used bamboo chips to record ancient history. Bamboo is also important as it gives the traditional and cultural value to rural people. Traditionally in China, many products are made from bamboo for household utilities such as containers, chopsticks, toothpicks, woven mats, chairs and baskets. Among Malay folks, bamboo is used as a container in cooking *Lemang*, a famous rice cake. Besides being widely used as household products, bamboo also has been widely used traditionally for structural component in constructing house such as flooring as well as building material for bridges.

Bamboo fibres have begun receiving more attention by many researchers primarily due to their unique attribute, which is their regenerative characteristic. The fast-growing characteristic of the bamboo has made it the best alternative to timber in the future. The high potential and versatility of bamboo's characteristics has opened a wide area for study. Typically, bamboo fibre is a type of lignocellulosic fibre that has much lower density than glass or steel fibres. It possesses a high tensile modulus and low elongation at break (Shin *et al.,* 1989). Its low water absorption characteristic based on intrinsic fibrovascular bundle structure, making it desirable for blending it with hydrophobic polymers. These characteristics were the reasons bamboo fibre has attracted researchers as the potential reinforcement for polymer composites. Figure 2.2 showed the cross-sectional view of a bamboo. Bamboo is characterized by a jointed stem called culm. The bamboo culm grows as a hollow cylindrical pole. Each culm segment begins and ends with a solid joint called a node. The segments between the nodes are called internodes. The distance between each node varies depending on the bamboo species (Zakikhani *et al.,* 2014).

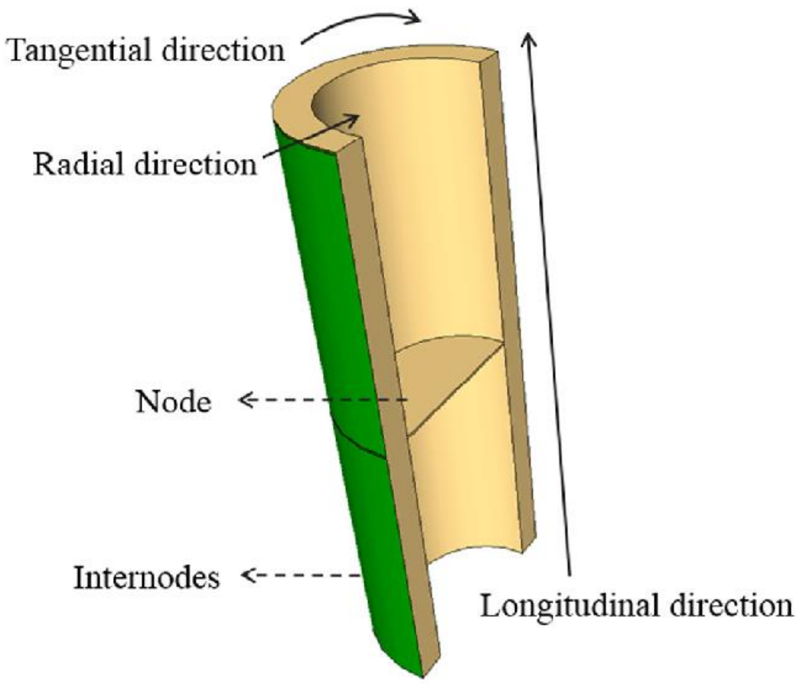


Figure 2.2: Cross sectional view of a bamboo (Huang *et al.* 2015)

From anatomical point of view, bamboo is composed of 40% of fibre bundles and 50% of parenchyma cells (phloem and parenchyma) and 10% of vessels as Figure 2.3. The structure of bamboo fibre distributed along the thickness. Bamboo fibre form bundles, which are components of vascular bundles dispersed within the diameter of the culm. The size of vascular bundles is smaller at the epidermis of the culm and bigger at the middle. The concentration of vascular bundles increases from the middle to the outer part of the culm. The culm diameter, thickness and internode length changes with the height position (Geroto, 2014). The age of bamboo does not affect the percentage of fibre significantly (Habibi & Lu, 2014; Londoño *et al.*, 2002).

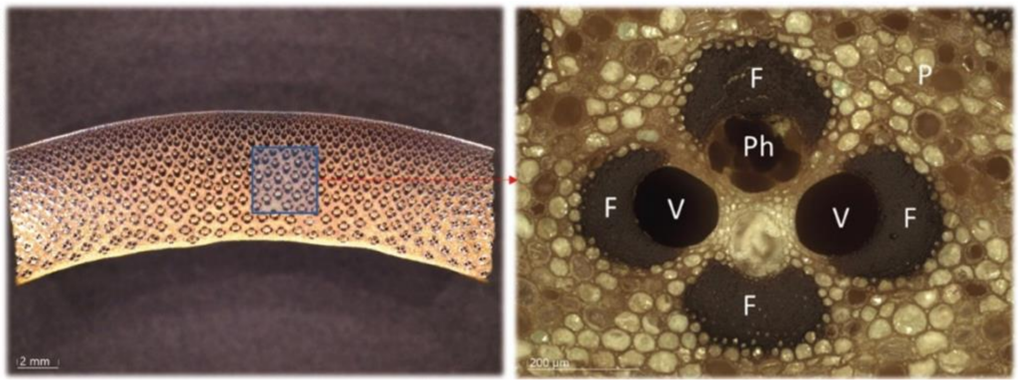


Figure 2.3: Anatomical overview of a bamboo culm. V: vessels; F: fiber bundles; Ph: phloem; P: parenchyma (Gauss *et al.*, 2019)

The strength of bamboo fibre is provided by multitudinal bamboo fibre bundles arranged longitudinally along its length; they are called "natural glass fibre". The mechanical properties mainly provided by the cellulose content. Among many natural fibres, bamboo fibres have drawn particular attention due to its low-density, high stiffness, high strength. The mechanical behaviour of natural fibre reinforced polymer composite are influenced by many parameters such as fibre loadings, fibre length, fibre-matrix adhesion, fibre orientation and stress transfer at the interface (Lokesh *et al.*, 2020).

In order to improve the overall mechanical behaviour, a lot of studies are done to improve the properties of the matrix and fibres first. Bamboo fibres cannot be obtained directly from the bamboo culm, it has to be extracted. There are three main types of procedures: mechanical, chemical and combined mechanical and chemical extraction. Mechanical extraction methods that have been used to extract fibre for the application of bamboo fibres are steam explosion of heat steaming, retting, crushing, grinding and rolling in the mill. The main advantage of mechanical fibre extraction over chemical procedures is its better environmental characteristic. After the fibres are obtained, different approaches can be selected for its use in the composite. It can be as an additive in biopolymers in form of powder/particle size, short fibre and long fibre reinforcement (Taborda-Ríos *et al.*, 2020). According to Jindal, (1986), tensile strength of bamboo fibre reinforced plastic composite is comparable to the mild steel, whereas their density is only 12%. Ochi (2012) studied a high strength biocomposites produced by an emulsion-type biodegradable resin as the matrix and bamboo fibre bundles as reinforcement. The study showed that the tensile strength of the composites increasing as the fibre increased up to 70%.

### 2.2.2 Bamboo particles

There has been rapid growth in the development of the engineered bamboo materials and diversity of bamboo products are available on the market. The fibres can be continuous or discontinuous with respect to the composite material that is reinforced. Continuous fibres refer to fibres that are as long as the size of the composites, whereas discontinuous fibres are comparatively small compared to the size of the composite material. Bamboo particle is also defined in relation to the composite material, which may be normal or irregular in shape but have overall aspect ratios which are closed to the unit (Verma *et al.*, 2020). According to the (Liu *et al.*, 2016), bamboo particles are produced after further process bamboo chips (1 to 20 mm in length) to the size of 1 to 5 mm in length. Just like the wood version, bamboo chips are important intermediate processing step that allows the tissue to be further processed into “particles” using the same wood machinery.

Agro-waste is becoming one of the main contributors to the environmental issue that has led to many studies were done to utilized natural fibres particulate found in various parts of crop. Natural fibre particulate like bamboo particle can be utilized for blending into polymer matrix and developing new material. However, the main problem of utilizing bamboo particle into polymer matrix is its hydrophilicity which results in low mechanical properties of the composite. Therefore, the focus on current work is primarily on modifying the properties of the polymer based composite material via chemical treatments, processing of the bamboo particulate reinforced thermoplastic composites and the mechanical properties of the composite materials. A study done by (Yeh and Yang, 2020) was focusing on the influence of the chemical composition and thermal decomposition behaviour of four bamboo particulate types; Makino bamboo, Moso bamboo, Ma bamboo, and Thorny bamboo. The study found that bamboo-PP composites Makino bamboo had high crystallinity and high lignin content, resulting better tensile properties.

## 2.3 Thermoplastic polymer

Thermoplastics are characterised by their melting and mould capability characteristics above a specific temperature and solidification under cooling conditions. Thermoplastics are very large linear molecules made of monomers (repeating units) bound together with covalent bonds along molecular chains without cross-linking

(Baley & Eco-design, 2012). Thermoplastics are either amorphous or semi-crystallic. Amorphous thermoplastics (i.e., polycarbonate (PC), polystyrene (PS), acrylics (PMMA), acrylonitrile-butadiene styrene (ABS), polyvinyl chloride (PVC) are characterised by transparency, high impact strength and high heat deflection temperature (HDT), but lack of flexibility and resistance to chemical attack or stress cracking compared to semi-crystalline thermoplastics (i.e., polyamides)

### 2.3.1 Biodegradable polymer

The production of petroleum-based synthetic polymers is estimated to reach 140 million tons per year, globally. They remain as a waste in the ecosystem after the usage due to their resistance against microbial attacks. Hence, biodegradable polymers have a vital role for sustainable replacement. Generally, biodegradable materials can be defined as materials that are able to be broken down into simple elements and compounds such as carbon dioxide and water by microorganisms under natural environment without generating any harmful substances (Farrington *et al.*, 2005).

Biodegradable polymer or biopolymers can be produced from renewable resources in certain ways; synthesised from petroleum based chemicals or microbial synthesised in the laboratory (Vink *et al.,* 2003). Biodegradable polymers can be divided into three main categories: natural polysaccharides and other biopolymers (e.g. cellulose, wool, silk and chitin); synthetic polymer, particularly aliphatic polyester (e.g. polylactic acid and polybutylene succinate); and polyester produced by microorganisms (e.g. poly (hydroxyl alkonate) (Okada, 2002) as shown in Figure 2.4.

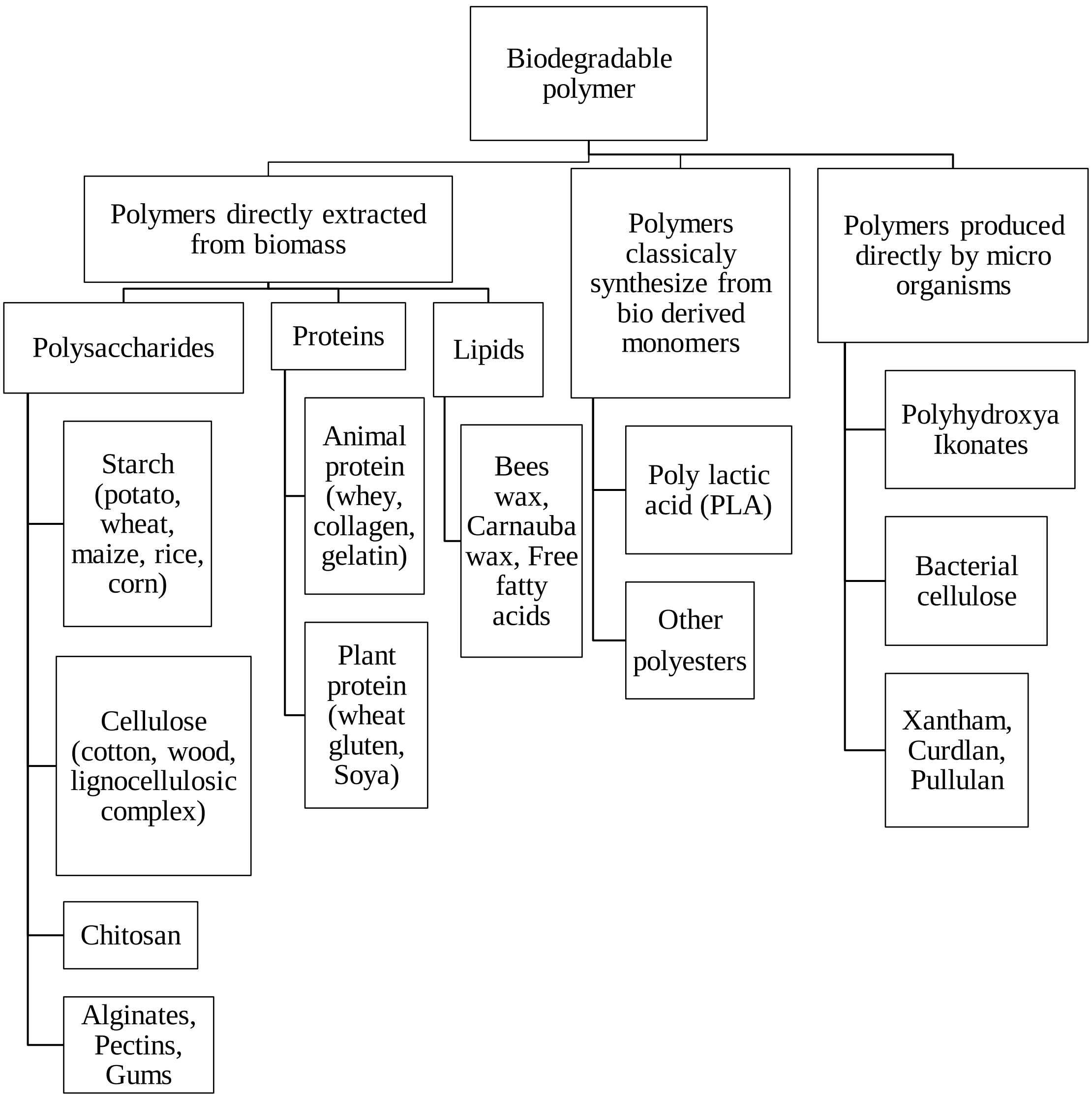


Figure 2.4: Classification of biodegradable polymers

#### 2.3.1(a) Polylactic acid (PLA)

Polylactic acid is not a new developed material. It was discovered by Wallace Carothers in 1932 (Balkcom *et al.,* 2003). Poly (lactic) acid polymers or also known as polylactides are polyesters of lactic acid. It is a sustainable alternative to petroleum-derived polymer because production of PLA produces less greenhouse gasses than the production of several synthetic polymer. The life cycle assessment studies are carried out by many researchers. Vink *et al.*, (2003) did a comparison study of energy conservation between Nature Works™ polylactide and petrochemical-based polymers such as Nylon 66 and PP.

PLA is renewable as it is made from agricultural raw materials such as potato, corn, and beat sugar, which are fermented into lactic acid. The presence of a hydroxyl and carboxyl group in lactic acid facilitate the ring-opening polymerisation to the wanted polylactic acid. Figure 2.5 showed the life cycle of PLA. When PLA is disposed under active composting conditions, it will  biodegrade over a period of several month to 2 years (Hermann *et al.,* 2011).

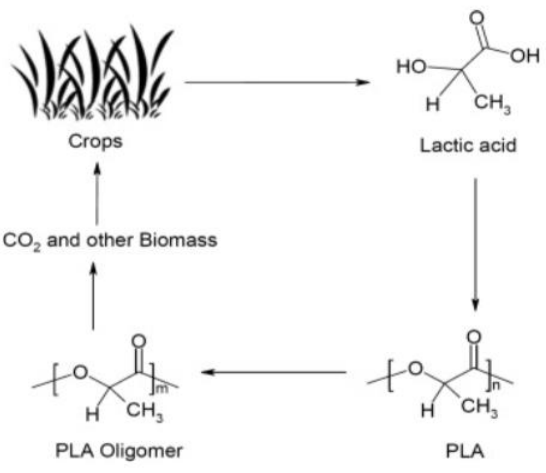


Figure 2.5: Life cycle of PLA (Colmenares and Kuna, 2017)

PLA has been commonly used in industrial application such as food packaging, degraded plastic bag, biomedical and consumer goods (Graupner *et al.,* 2009). One of the main concerns of PLA is its brittleness and stiffness that limits itself to be used in structural application. There have been several studies to overcome brittleness problem of PLA. These studies focused on the blending of PLA with elastomeric materials such as silicone rubber (Yıldız *et al.,* 2014), natural rubbers (Bitinis *et al.,* 2011; Jaratrotkamjorn *et al.*, 2012; Zhang *et al.*, 2013) as well as thermoplastic polyurethane elastomers (Feng and Ye, 2011; Han and Huang, 2011; Hong *et al.*, 2011). According to these studies, they highlighted that although there were significant improvements in ductility and toughness, the strength and modulus of these blends were sacrificed.

Another approach in the literature to improve mechanical properties of PLA is the "biocomposite" approach. Basically, natural fibres were used to reinforce PLA matrix. It was revealed that these PLA/natural fibre composites might have not only improved mechanical properties, but also improved thermal properties. Some of the studies will further discussed in the subsection 2.4.1.

## 2.4 Fibre reinforced polymer composites

In fibre reinforced polymer composites, the fibres can be either synthetic fibres or natural fibres. Most composites used in the industry are polymer matrix based which can be divided into thermosetting and thermoplastic. Thermosetting polymers are usually characterised by irreversible chemical change during solidification process whereas thermoplastic polymers can be reversibly re-melted by heating, and solidified by cooling without altering their mechanical properties (Hahladakis and Iacovidou, 2018) Thermosetting resins normally has a good penetration in fibre bundle, thus it has been used for fabrication of structural composites. The most common type of thermosetting resin is epoxy. Epoxy resins have distinct advantages compared with other traditional thermoplastic or thermoset resins such as minimum shrinkage during curing, cheaper and abundant, outstanding moisture and chemical resistance, free from volatile organic compound (VOCs), long shelf life, impact and corrosion resistant (Saba *et al.*, 2016). Carbon fibre reinforced epoxy resin has played an important role in many high-performance applications including construction, aerospace and automotive over the past two decades.

However, as the demand for high-performance composites increase, the recycling and biodegradation at the end of the lift cycle of these materials has become a serious issue. This has resulted in a series of new laws to control disposal and recycling new composites. Biodegradation and recycling process have become a great challenge because thermosetting polymer takes long period to degrade and the difficulty in separating the resin and fillers. Thus, in recent years thermoplastic composites are becoming more popular in many applications, especially in the automotive as alternatives to the traditional thermosetting composites.

### 2.4.1 Natural fibre reinforced PLA composites

Lignocellulosic natural fibres are the most common type of natural fibre reinforcement material in natural fibre polymer composites. Biopolymer composites have various advantages over polymer composite like biodegradability, lightweight, energy efficient and environmentally friendly (John and Thomas, 2008). Natural fibre polymer composites are composite material consisting a polymer matrix reinforced with natural fibres. There are many possible forms of natural fibres used to embedded with polymer such as loose fibre, non-woven mat, aligned yarns and woven fabrics. A great deal of works has been done to study the effect of various factors on mechanical properties on PLA based composites. Most of these studies showed the improvement of tensile and flexural strength with significant increase in modulus with their respective methods. These researches have been performed to examine the filler used to reinforce PLA which includes cotton linters maple hardwood fibre (Way *et al.,* 2013), sweet sorghum fibre (Zhong *et al.,* 2011), bamboo fibre (Okubo *et al.,* 2009) , ramie fibre (Yu *et al.,* 2014), and lyocell fibre (Shibata *et al.,* 2004).

However, there are a number of problems associated with incorporating such fibres into PLA matrices, most notably fibre-matrix incompatibility and thermal stability of the fibres where relatively high processing temperatures are required. There are many methods have been studied to promote interfacial adhesion for instance, Jandas *et al.,* (2013) studied the effect of fibre surface treatments on the mechanical properties of banana fibre /PLA composites. The effects of atmospheric pressure glow discharge plasma polymerization on basalt fibre to the properties of basalt fibre/PLA composite was evaluated (Kurniawan *et al.,* 2012). Song *et al.,* (2012) focuses on the physical behaviour of hemp/ PLA composites, particularly the thermal properties and viscoelastic behaviour. A biodegradable composite using jute fibre/PLA was developed by Goriparthi *et al.,* (2012). Their focus was to improve fibre-matrix adhesion by surface treatment. They concluded that surface treatments resulted in improvement of tensile and flexural properties and reduction in impact strength. This shows that interfacial compatibilization reduces the ability of stress transfer between the matrix and fibre. The use of surface treatments also has the disadvantages of increasing the cost of the final product (Tserki *et al.,* 2005).

Starch is a hydrophilic polymer used to blend with PLA to increase the biodegradability and reduce the cost. A research studies that the tensile strength and elongation decreases as the starch concentration increases. Starch concentration in PLA-starch blend is the main factor that affect the mechanical properties of blend. However, starch-PLA blend have major drawback in application due to its brittleness (Nampoothiri *et al.,* 2010). Besides blending PLA with other polymer to improve its properties, a large number of studies have been done on PLA reinforced by using various type of natural fibres to create fully biodegradable composites. A research study of flax and cordenka as reinforcement in PLA composites comes to conclusion that the flax reinforcement leads to a better improvement of Young's modulus than the pure PLA. Meanwhile, cordenka reinforcement has proven to a better improvement of the tensile strength (Bax and Müssig, 2008). A popular method of hybridisation whereby the composite is produced incorporation of two or more fibres in a matrix. This study showed the hybrid composites has higher strain energy (toughness) as compared to single plant fibre reinforcement. However, these hybrid green composites produced a diverse range of results. The hybrid combination compensated for the inherent disadvantages of the individual materials (Yusoff *et al.,* 2016).

### 2.4.2 Bamboo fibre reinforced polymer composites

Natural fibres as the alternative reinforce material for synthetic fibre in have been extensively reported, including bamboo fibres. Composite made by bamboo fibre has attracted researchers' attention due to its advantages that is lightweight, environmental friendly, and its mechanical strength is comparable to conventional composite strength (Khalil *et al.,* 2012). Bamboo fibre was proved to be the most effective reinforcement among all studied reinforcements (Nuthong *et al.,* 2013). Table 2.1 showed the reported work on the properties of bamboo fibre composites with different types of matrix and bamboo forms.

Table 2.1: Properties of typical thermoplastic polymers used in bamboo fibre composites fabrication

| Polymer | Bamboo form | Tensile strength (MPa) | Young's modulus (GPa) | Impact strength (J/m) | References |
|---|---|---|---|---|---|
| PLA | Fabric | 57.84-80.89 | 4.59-5.92 | 91.68-103.00 | Rawi *et al.,* (2013) |
| Epoxy resin | Fabric | 53.70 | 4.50 | - | Yan *et al.,* (2012) |
| Polypropylene | Fabric | - | - | 530.90 | Zuhudi *et al.,* (2016) |
| Epoxy resin | Fibre mat | 43.47 | 6.63 | - | Samanta *et al.,* (2015) |
| Unknown polymer | Scrimber | 1641.80 | 74.10 | - | Wei *et al.,* (2017) |
| Epoxy resin | Strips | 130-180 | - | - | Hebel *et al.,* (2014) |
| PLA | Fibre | 45-57 | 4.5-6.5 | - | Gamon *et al.,* (2013) |
| Polypropylene | Fibre | 30.3 | 3.66 | - | Okubo *et al.,* (2004) |
| Polypropylene | Short fibre | 12-15 | 2-3 | - | Thwe and Liao (2002) |

Bamboo composite fabrication is an important aspect to look at as it affects the properties of end-products. Bamboo composites properties were highly influenced by types of fibres, types of matrices and method of fabrication. These three factors are dependable to each other in order to produce good properties of bamboo composites. In general, many researchers studied different type of bamboo fibres such as bamboo fabric, bamboo scrimber, long and short bamboo fibres, bamboo powder and bamboo particles as reinforcements in composites.

Previous researchers have reported that the bamboo fabric is easy to handle, provides excellent tensile properties, easy to control fibre orientation and possess high flexibility. Rawi *et al.,* (2013) investigated the effect of compressing moulding parameters on mechanical properties of bamboo fabric-PLA composites. The influence of alkali treatment on tensile properties of flax, linen and bamboo single-strand yarns were studied by Yan *et al.,* (2012). Zuhudi *et al.,* (2016) studied the influence of hybridization on the flammability, thermal, dynamic mechanical and impact properties of bamboo-glass hybrid polypropylene composites. In another study, Samanta *et al.,* (2015), hybridized a plain woven E-glass with bamboo mat from *Bambusa tulda* bound with epoxy resin as matrix by hand lay-up method.

A bamboo scrimber is usually made from bamboo bundles treated with water-soluble phenol formaldehyde (PF) resin and compressed to the desired specific gravity and thickness. Wei *et al.,* (2017) investigated the influence of number fibre-reinforced polymer (FRP) layers and types of FRP on flexural performance of the bamboo scrimber beams. The relation between tensile strength, pressure, temperature and press/hold time of bamboo scrimber impregnated with epoxy matrix composite is being studied by Hebel *et al.,* (2014). However, the design of composites made by this type of fibre is limited due to its inability to deform or bend, which is an added value of a composite design.

Composite made from extracted single long or short fibre bundles exhibited high mechanical properties. Extracted fibre used in the composite were considered high quality because the most of lignin were detached during the process., resulting in better interfacial adhesion between fibre and polymer matrix. Okubo *et al.,* (2004) investigated the performance of bamboo fibre reinforcing polypropylene (PP) by using steam explosion technique. The performance showed to be equivalent to conventional glass fibres. Bamboo powder or bamboo particles can be obtained from several machining steps, followed by proper care of the powder during matrix addition to make sure the powders/particles are evenly distributed. In previous study, a composite made form bamboo powder was mixed with glass fibres size ranging 3mm  to 6 mm to improve the strength of the composites (Thwe and Liao, 2002).