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Effect of interfacial bonding capacity on the tribological performances of plant fiber reinforced polymer composite

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ABSTRACT

Plant fibers are increasingly used in fabricating polymer components useful in the automotive, construction and aerospace industries. It allows for the implementation of a more advanced application, targeting highly reliable tribology material for bearing application with efficiency improvement by minimizing the wear and friction. However, optimization of the interfacial bonding between the reinforcing plant fiber and polymer, which is often least understood is required. The literature identifies 1) the physical and chemical incompatibility between the plant fiber and polymer, causing poor interfacial bonding and ultimately poorer composite properties, can be improved by simple and cost-effective sodium hydroxide (NaOH) treatment with strategical treatment parameters, 2) in depth knowledge of the interfacial bonding of the composite can be obtained by running practical characterization methods including morphology, wettability, spectroscopic and micromechanical measurements and 3) the physical, mechanical and tribological properties of the NaOH treated plant fiber reinforced polymer composite are highly dependent on their fiber-matrix interfacial bonding capacity. More attention should be paid to the characterization methods of the interfacial bonding to identify the stress transfer and fiber-matrix interaction in providing better understanding for scholars dealing with the formulation of plant fiber reinforcement in polymer-based composites to further enhance their surface characteristics.

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1.0 INTRODUCTION

Tribology is the study of interdisciplinary science and technology of interacting surfaces in motion that involve wear, friction and lubrication (Bhushan, 1999). From a broader perspective, it deals with a study of the interface between two or more bodies in relative motion. The interaction of these bodies leads to the transmission of forces and dissipation of (1) mass which refers to wear and (2) energy which refers to friction (Bhushan, 2013). Evaluation of tribological performances in machine components and systems is significantly critical today due to its significant amount of energy loss to friction and wear related failures. Approximately 23% of the world's total energy consumption originated from tribological contacts where 20% of it is to reduce friction and 3% is used to replace worn components caused by wear and wear-related failures (Holmberg & Erdemir, 2017). By taking advantage of the new advanced technologies in materials, surface and lubrication to reduce the friction and wear of machinery, vehicles or other equipment, energy losses may be reduced. Hence, the need for energy efficiency and cost-effectiveness has initiated growth in tribology, creating a more sustainable and greener world.

Currently, researchers are focused on developing tribo-materials that are more economical and sustainable, that fulfil the required properties of synthetic materials and achieve appropriate tribological properties. The primary importance here is to create tribo-materials with efficiency improvement by minimizing the wear and friction in the tribological system, aiming for environmental protection and saving energy and resources, which subsequently improve the quality of human life.

In this regard, friction is one of the most significant issues when dealing with dynamic machines. When friction increases, it will slow down the process and make it inefficient. It is also possible that frequent contact between surfaces will cause damage to the machine. Hence, it takes careful consideration when designing tribology materials for bearing application. Ideally, most equipment involving moving parts uses one or more bearings which are usually sourced from polymer materials.

Despite the unique characteristics of the polymer offered as tribo-materials, there are certain drawbacks such as a lower temperature range, load limitation, and dimensional stability in comparison to metallic bearings. As the demand for structural purposes requiring excellent mechanical and tribological performances rises, using single unmodified polymer is insufficient (Huang et al., 2007). This is because polymer bearings may suffer failures such as wear, surface fatigue and plastic flow (Marshek, 1979).

In this regard, polymer composite now emerges as an excellent alternative for advanced technology applications. Jena (2019) reported that polymer composites are attractive materials for automotive and construction applications because they offer a high strength-to-weight ratio, high resistance to wear, corrosion and thermal expansion, improved fatigue resistance and self-lubrication properties. Another unique feature of the polymer composite described by Arumugaprabu et al. (2021) is its tailor-made characteristics that fulfil the requirements of advanced materials. Friedrich (2018) has presented different types of polymer composite that are successfully used in obtaining many excellent tribological performances.

To make an attractively economical composite, innovative manufacturing techniques and advanced materials are now being used in the composite industry. Hence, there is rapid research interest in strengthening polymer material by incorporating fillers, as their properties may change considerably. The most commonly used reinforcement in polymer composite is synthetic fiber such as glass and carbon (Deng et al., 2017). In 2019, Mao et al. (2019) demonstrated that

polyoxymethylene (POM) gears have higher mechanical and tribological performances when reinforced with glass fiber compared to the neat POM. Here, the elastic modulus of tensile and flexural for the glass fiber reinforced POM composite gears is approximately three times that of neat POM. In addition, glass fiber reinforced POM composite gear showed about 50 % enhanced load capacity as to the neat POM. On another note, neat POM may experience a much higher tooth deformation which can cause much higher friction, given in the same loading condition such as at 7.5 Nm.

But the current challenge is producing a composite with cost-effective and environmentally friendly. Though, there is no doubt that synthetic fiber has excellent mechanical properties, its production has a few drawbacks, such as non-recyclable, high cost, high level of energy consumption and poses a threat to the environment and human health. As the industrial demand for more sustainable materials used for manufacturing, researchers and engineers are now shifting their interest from synthetic fiber to plant based natural fiber as reinforcing materials in polymer composite (Begum et al., 2020; Kumar et al., 2019; Yashas Gowda et al., 2018). Hence, there is potential development of green tribo-materials that are made from the eco-friendly nature of plant fiber, while tackling their agricultural disposal problem that has arisen due to the positive growth of the plant to date. The required specifications for these composite materials to be used as key-bearing components include long-lasting performance, small to moderate load capacity, lightweight, high thermal resistance, high wear resistance and low frictional properties. This material may provide a significant contribution to the bearing performances, efficiency, durability and reliability while maintaining the cost of operation.

In this regard, several attempts have been made to determine the effectiveness of using plant fiber as reinforcement in polymer composite for tribological applications since the early years (Chegdani et al., 2017; Nirmal et al., 2015; Parikh & Gohil, 2019). The first tribological application in aircraft bearing using cotton fiber reinforced phenolic composite was held in 1986 (Lancaster, 1986). This is followed by another study on the enhancement in wear properties of coccinea indica fiber reinforced epoxy composite (Mylsamy et al., 2020). These plant fibers have caught the researcher's interest due to their advantages over man-made synthetic fiber, such as biodegradable, renewable, abundant and lower health risk due to their plant resources. In the following years, rapid research has been done on the usage of different types of plant fiber such as flax (Chegdani et al., 2020; Chegdani et al., 2018), oil palm (Shuhimi et al., 2016), abaca (Cai et al., 2016), hemp (Roumeli et al., 2015), jute (Russo et al., 2015) and sugar palm (Oumer & Bachtiar, 2014) as reinforcement in polymer-based composite.

On the other hand, the selection of polymer matrix is limited to low processing temperatures, generally ranging from 200 to 220 ℃ only, which is below the degradation temperature of plant fiber (Irawan & Sukania, 2015). Over the years, considerable research has been done to determine the appropriate processing technique to manufacture high performance polymer composite that is subjected to four main procedures; (1) incorporation of the fiber with polymer, (2) forming of the structure, (3) curing or thermal processing and (4) finishing (Divya et al., 2016). Some of the frequently used processing techniques for the polymer composites are injection moulding, resin transfer moulding, compression moulding, pultrusion, extrusion and hand lay-up (Bai, 2013; Bajpai & Singh, 2019; Chohan et al., 2020; Jawaid et al., 2015).

However, as much as the effort has been put into embedding plant fiber in polymer composite, replacing the existing synthetic fiber is still a great challenge. Begum and Islam (Begum & Islam, 2013) reported that the mechanical strength of plant fiber composite does not compete with synthetic fiber composite and could not be used in all applications. For example, the tensile

strength of jute and ramie fiber was reported at 393 - 773 MPa (Avérous & Le Digabel, 2006; Chand & Fahim, 2020; Wambua et al., 2003) and 400 – 938 MPa (Avérous & Le Digabel, 2006; Chand & Fahim, 2020; Holbery & Houston, 2006), respectively. Meanwhile, the tensile strength of glass and carbon fiber was reported at 3400 MPa and 3400 – 4800 MPa, respectively (Avérous & Le Digabel, 2006; Chand & Fahim, 2020). In an effort to use a partially degradable composite, these results represent the significant difference in strength between plant and synthetic fiber, raising concerns about the feasibility of the plant fiber as an alternative reinforcing material in polymer composite. Nevertheless, the mechanical and tribological properties of plant fiber reinforced polymer composite is subject to other important factors such as type of fiber, fiber orientation and fiber loading (Ahmed et al., 2021; Amiandamhen et al., 2020; Thomason & Rudeiros-Fernández, 2021). Fiber-matrix interfacial adhesion, however, is the most important factor to be considered. This is because a highly reliable interfacial bonding is needed along with the plant fiber and polymer matrix interfaces to ensure effective stress transferability, resulting in improvement in final composite properties.

The current review effort is to address an overview of the previous works on the influence of interfacial bonding of composite by mixing the polymer and modifying plant fiber in final composite properties such as physical, mechanical and tribological. This can be done by understanding the compatibility between plant fiber and polymer matrix, along with their appropriate selection of composite processing techniques. The interfacial bonding capacity can be measured through different types of characterization such as morphology, wettability, spectroscopic and micromechanical measurements. The significance of having good interfacial bonding from modifying the plant fiber surface and selection of other material and operating parameters will be observed in the final composite properties including physical, mechanical and tribological. This review may also contribute to providing a research pathway in plant fiber for tribological application in terms of academic and commercial use.

2.0 OVERVIEW OF PLANT FIBER REINFORCED POLYMER COMPOSITE

The potential of using plant fiber as reinforcement in polymer composite was observed through past research. Plant fiber can be used as reinforcement from various types of groups such as wood, stalk, seed, fruit, leaf and bast fiber. Meanwhile, polymer matrix materials are mainly derived from petrochemicals. The compression moulding technique is commonly used to fabricate plant fiber reinforced polymer composite. This type of processing technique employs similar steps with the fabrication of the conventional polymer composite. Different kinds of material and methods used will result in diverse final composite properties. Thus, the properties of plant fiber reinforced polymer composite can be tailored according to the needs by selecting a proper fiber, matrix and processing technique.

2.1 Plant Fiber

Plant fibers are considered natural fibers because they exist naturally and are not man-made. This review will focus on applying plant fiber as a reinforcing material in the polymer-based composite. In Malaysia, being hot and humid throughout the year provides an advantage when using plant fiber because the tropical climate is ideal for planting crop plants such as oil palm, kenaf, sugarcane, betelnut and coconut trees. The importance of this plant is not only from its original product, but also its waste. It has great potential as a renewable source of materials for

reinforcement in industrial products and applications. Besides, the biodegradability and abundant source of these plant fiber waste justify the reason for maximum utilization.

There is no doubt that synthetic fibers which are man-made processes such as carbon, glass, aramid and ultra-high molecular weight polyethylene (UHMWPE) have opted for their significant performances because they possess high strength-to-weight ratio, high moisture resistance properties, non-corrosive, longer lifespan, stable coefficient of friction and durability for many applications such as aircraft, building construction, ship, automobiles and sports equipment. However, the production of these types of fibers has several drawbacks specifically to the environment as they are hazardous, non-biodegradable, have large carbon dioxide emissions and increase landfilled. That is why plant fiber is suitable as an alternative to synthetic fiber as reinforcement in polymer-based composite. Besides their traditional applications in the textile or fabrics industry, plant fibers can also be found in wider applications including structural (e.g. automotive parts, building materials and furniture) and non-structural (e.g. food packaging and paper). Both plant fibers and synthetic fibers provide a practical way of producing lightweight and superior performance when reinforced in polymer-based composite materials. However, the remarkable mechanical strength provided by the synthetic fibers is highly competitive with the plant fibers as seen in Table 1. The tensile strength of synthetic fibers is comparatively higher than plant fibers. Thus, it makes the synthetic fiber remain relevant and required in the polymer-based composite for structural and non-structural applications. Despite this, plant fibers may find their unique application as an alternative to synthetic fibers. In this way, one can reduce the dependency on fossil fuel usage and the negative environmental impact when producing synthetic fibers. Nevertheless, there is some potential in developing the plant fibers as reinforcement in polymer composite with the appropriate methods.

Different types of plant fiber groups have been used for the preparation of the composite. These plant fibers are classified into six different fiber groups as listed in Table 2. The wide variation offered by the fiber's physical properties has been the real challenge when selecting materials. This is because the method and process are unique for each fiber and must correspond to their natural properties such as the type of fibers, weather conditions, moisture content, fiber's process and age of fibers to get optimum mechanical and tribological performances. However, these plant fibers are commonly extracted from the retting process. It is a process to separate the fiber bundles from the central stem of its plant mechanically or by soaking it in water (Sapuan et al., 2018).

Table 1: Density and mechanical properties of natural fibers (flax, sisal, jute, oil palm and basalt) and synthetic fibers (carbon, glass, aramid and UHMWPE) .

Fiber	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Ref.
Natural					
Flax	1.50	345-1035	27-51	1.5-3.2	(Fragassa et al., 2018)
Sisal	1.45	510-700	9-38	2.2-2.9	(Sathishkumar et al., 2018)
Jute	1.45	450-550	10-32	1.1-1.5	(Pandita et al., 2014)
Oil Palm	1.55	50-400	1-9	8-18	(Jawaid, Khalil, Hassan, et al., 2013)
Synthetic					
Basalt	2.80	3100-4840	85-95	3.15	(Kim et al., 2011)
Carbon	1.80	3500-5000	260	1.4-1.8	(Pandita et al., 2014)
Glass	2.60	1800-2700	73	2.5	
Aramid	1.45	2700-4500	130	3.3-3.7	(Qing et al., 2017)
UHMWPE	0.97	2950-3000	100-110	2.8	(Zhang et al., 2020)

Table 2: Types of plant fiber groups (Azwa et al., 2013; Holbery & Houston, 2006; Nirmal, Hashim, et al., 2012).

Wood fiber	Stalk fiber	Seed fiber	Fruit fiber	Leaf fiber	Bast fiber
Hardwood	Bamboo	Kapok	Oil palm	Sisal	Hemp
Softwood	Wheat	Alfalfa	Coconut	Pineapple	Jute
Sawdust	Rice	Cotton	Betelnut	Banana	Flax
	Grass			Date palm	Ramie
	Corn			Abaca	Kenaf

Plant fiber is a lignocellulosic material consisting of five main constituents: cellulose, hemicellulose, lignin, pectin, and wax (Komuraiah et al., 2014). Details of the constituents and its properties are presented in Table 3.

Table 3: Structural composition of plant fiber and its properties (Gowthaman et al., 2018; Kabir et al., 2012 ; Mohanty et al., 2001; Mwaikambo & Ansell, 2002; Saheb & Jog, 1999).

Structural constituents	Properties
Cellulose	• Made of chained-cellulose molecules • Major component in the fiber structure • Provide stiffness, strength and stability of the fiber • Aligned along the fiber length
Hemicellulose	• Random and amorphous structure with low strength • Exist on primary cell wall • Has branched polymers consist of carbon sugar of varied chemical structure
Lignin	• Amorphous and contain aromatic structure • Acts as a barrier to prevent degradation of the fiber
Pectin	• Consist of complex polysaccharides • Provide flexibility of the fiber • Side chains are cross-linked with the calcium ions and arabinose sugars
Wax	• The last part of the fiber • Alcoholic compound

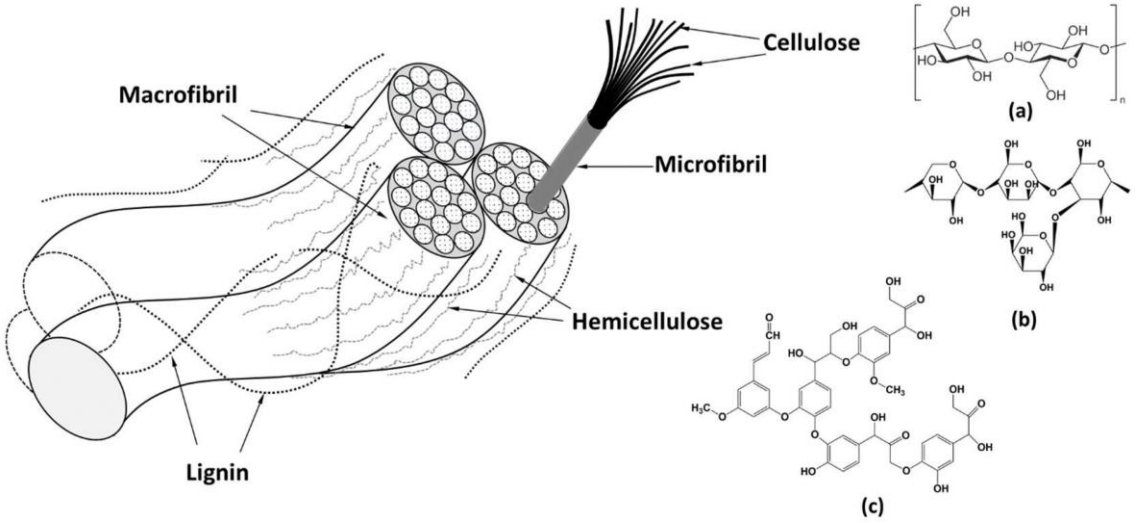

Figure 1: Plant fiber structure and its three primary compositions; (a) cellulose, (b) hemicellulose and (c) lignin (Gowthaman et al., 2018).

Figure 1 shows the schematic image of fiber structure where cellulose is aligned on the fiber length and embedded in a matrix of hemicellulose and lignin. The properties of plant fiber are influenced by the nature of cellulose microfibrils as it has its own cell geometry which is linked with its crystallinity (Bordoloi et al., 2016). The composition of these fibers depends on the weather conditions and geographic location where the plants grew up, as plant fibers contain

similar constituents, but with different compositions, causing them to function differently (Komuraiah et al., 2014).

Plant fiber, specifically fiber extracted from the bast and leaf fiber groups, often has higher tensile strength than others and is used in several commercial applications such as textile and automotive (Ramesh, 2018). Meanwhile, other types of fiber groups such as fruit fiber are being studied at the research level, mostly for non-structural applications. Therefore, many researchers are now attempting to maximize the usage of all types of plant fiber groups for a wider purpose including mechanical and tribological applications. Thus far, some of the reported studies on the tensile strength for bast, leaf, fruit and stalk fiber groups from different types of plants are listed in Table 4. The studies unveil the potential of plant fiber as a reinforcing material.

Table 4: Tensile strength of different fiber groups composite for mechanical application.

Fiber	**Matrix**	**Fiber loading, wt.%**	**Tensile Strength, MPa**	**Young's Modulus, GPa**	**Elongation at Break, %**	**Ref.**
Bast						
Hemp	Polypropylene	30	40-52	2-3	-	(Panaitescu et al., 2020; Ribeiro et al., 2021)
Jute	Polyester	30	29	-	-	(Sajin et al., 2021)
Jute	Polypropylene	10	18	-	-	(Chatterjee et al., 2020)
Flax	Epoxy	30	36	-	-	(Karthi et al., 2021)
Ramie	Polyamide	4	76	4	-	(Matsunaga et al., 2018)
Kenaf	Epoxy	30	40	-	-	(Khan et al., 2020)
Leaf						
Sisal	Epoxy	30	84	1.5	-	(Gupta & Srivastava, 2016)
Pineapple	Polyester	30	89	2.5	3-6	(Rajesh et al., 2018)
Banana	Epoxy	30	66	-		(Gairola et al., 2020)
Date Palm	Phenolic	50	20	4.3		(Asim et al., 2020)
Fruit						
Oil Palm	Polypropylene	10	29	-	-	(Ramli et al., 2013)

Oil Palm	Phenolic	50	5	-	8-18	(Ramlee et al., 2019)
Oil Palm	Epoxy	10	33	2.6	-	(Valášek et al., 2017)
Coconut	Epoxy	30	29	3.2	-	(da Luz et al., 2018)
Betelnut	HDPE	22	21	-	-	(Kuan et al., 2019)
Betelnut	Epoxy	5	16	-	-	(Borah & Dutta, 2018)
Stalk						
Bamboo	Polypropylene	50	60	4.2	-	(Nahar et al., 2012)
Rice	Polypropylene	20	37.4	1.7-2.2	-	(Yiga et al., 2020)

2.2 Polymer Matrix

Polymer matrix plays an important role in binding fiber reinforcement, transfers load between fibers, gives the composite component its net shape and determines its surface quality. Plant fiber reinforcement has been used largely with both polymer matrices; thermoplastics (e.g., polyethylene, polycarbonate, polypropylene and polyamide) and thermosets (e.g., epoxy, polyester and phenolic) (Sanjay et al., 2018). Thermoset and thermoplastic are two different types of polymers. They are categorized based on their heat reaction behaviour. Thermoset is a polymer that is permanently formed when heated from a soft solid or viscous liquid. Meanwhile, thermoplastic is a polymer that is reversibly softened by heat. They can be cooled and heated as required while maintaining their chemical and physical properties. These properties justify the low melting point of thermoplastic and thermoset can withstand high temperatures without changing their structural properties (Chawla, 2012). However, thermoplastic polymers are widely used for their recyclability and versatility. Though the current research needs to develop green tribo-materials using plant fiber as the reinforcement, using a polymer does not guarantee its fully biodegradable composite. At this stage, the best it can be is to develop a partially biodegradable composite using thermoplastic polymer. For it is known, that thermoplastic polymer can be reformed and recycled without having a negative effect on its material properties. Besides, they were also found in many tribological applications such as bearings and gears. Therefore, a study on the tribological application of polymer materials reinforced by plant fiber will be very beneficial.

To date, most plant fibers were commonly reinforced with thermosets such as epoxy and polyester and thermoplastic such as polypropylene and polyurethane. Among these matrix materials, epoxy was highly used in the literature (Jeyapragash et al., 2020; Kumar & Anand, 2019; Mittal et al., 2016; Parbin et al., 2019). This is owing to its excellent properties, including easy processing, good bonding properties, high strength, low toxicity, low shrinkage and economic (Kumar & Anand, 2019). Despite this, some of the most commonly used polymers for bearing materials are phenolic, polyester, polytetrafluorethylene (PTFE), polyoxymethylene (POM), ultra-high molecular weight polyethylene (UHMWPE) and nylon (Khonsari & Booser, 2017). But limited

research was found on the usage of POM in plant fiber composite as it gives the lowest number of articles published as shown in Figure 2.

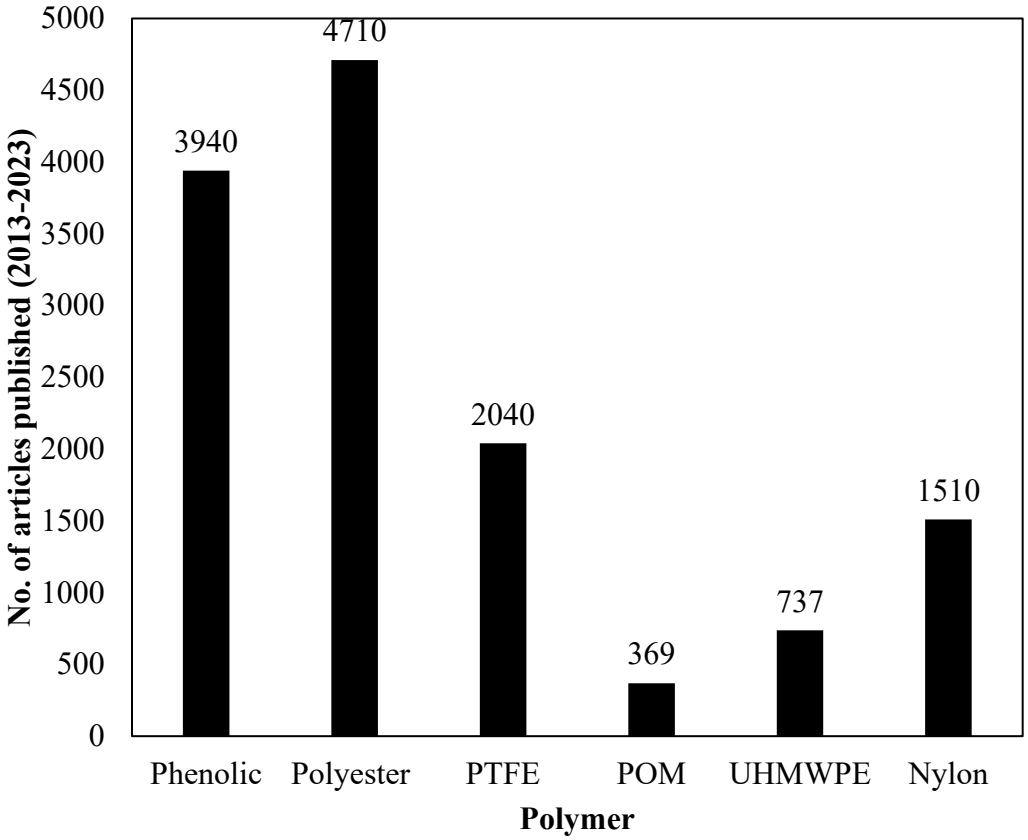

Figure 2: A number of articles published (2013-2023) based on types of polymers used as reinforcement in plant fiber for tribological approach. *Source*: https://scholar.google.com/. Keywords used: 'types of polymers', plant fiber, alkaline treatment, tribology.

Therefore, more research can be done in developing POM material in plant fiber composite. It may find its usage in a more comprehensive tribological application. Besides, POM is a suitable candidate as a matrix in plant fiber composite due to its excellent properties such as low coefficient of friction and wear, low moisture absorption, dimensional stability, high stiffness, high strength and wear resistance (Lüftl et al., 2014). In addition, POM has a relatively low melting and processing temperature of 175 ℃ compared to other polymers (Czarnecka-Komorowska & Sterzynski, 2018). This is a very important factor to consider when dealing with plant fiber as they only operate under a low processing temperature of 200 ℃. Hence, the fabrication of plant fiber reinforced POM composite will be more effective than other polymer materials requiring higher melting temperatures. The following paragraph is the insight detail on the potential of combining POM with plant fiber. Details of the physical and mechanical properties of the POM as provided by the supplier are listed in Table 5.

Table 5: Physical and mechanical properties of polyoxymethylene.

Properties	Unit
Density	1.41 g/cm^3
Water absorption (23°C,24hrs,1mmt)	0.5 %
Tensile strength	62 MPa
Tensile Modulus	2700 MPa
Elongation at break	15 – 35 %
Mold shrinkage	2 %
Rockwell hardness	80 M (scale)

(Source: Acetal copolymer (POM), Grade M90-44, Polyplastics Co., Ltd., Japan)

Several studies that use plant fiber as reinforcement in POM based composite has been reported (Bledzki et al., 2012; Dan-Mallam et al., 2016; Dan-Mallam et al., 2013; Dan-Mallam et al., 2015; Dan-Mallam et al., 2014; Espinach et al., 2017). Bledzki et al. (2012) studied the effect of abaca and man-made cellulose fibers when reinforced with POM composite. They found significant improvement in their mechanical, dynamic mechanical and thermal properties for both fibers. In another study, a variation of investigation were conducted on the short and long fiber (Dan-Mallam et al., 2013), woven fabrics (Dan-Mallam et al., 2014) and short and continuous (Dan-Mallam et al., 2015) kenaf/polyethylene terephthalate (PET) fiber reinforced POM hybrid composite. They found that most of the composites showed enhancement in their mechanical properties compared to neat POM. Espinach et al. (2017) revealed the tensile strength of eucalyptus bleached fiber reinforced POM composite at 30 % fiber loading was higher than its neat POM and achieved comparable tensile strength values to that of glass fiber reinforced polypropylene composite. Finally, there was a study on the influence of weave structure on the mechanical and tribological performance of woven flax fabric reinforced POM composite by Xiong et al. (2018). This study focused on finding the relationship between the mechanical properties and abrasive wear resistance of the composite. The results showed that the composite has possible application in abrasive wear as it gains good mechanical properties and abrasive wear resistance.

Hence, these studies suggest that the POM exhibits the potential to enhance composite properties when reinforced with plant fiber. However, it is noted that these studies were not using fiber treatment as one of the improvement methods in obtaining excellent mechanical and tribological properties. This leads to a pathway in adapting fiber treatment methods to improve tribological properties. The adaptation of fiber treatment in plant fiber reinforced polymer composite is significant in ensuring stronger compatibility and fiber-matrix interfacial bonding.

2.3 Processing Technique of Plant Fiber Reinforced Polymer Composite

Two basic processing techniques are available for composite making, each with its benefit. They are open moulding and closed moulding. In open moulding, the fiber and matrix material are prepared uncovered during curing or hardening. This type of moulding has different processes: casting, filament winding, spray-up and hand lay-up (Kar, 2016). It has been one of the most selected methods for composite fabrication due to its easy processing with little equipment. The process starts with the placement of fiber material in the mold. Subsequently, the matrix material is added with a brush or roller. They can make both small and large items. Meanwhile, the closed moulding process involves the curing of fiber and matrix material inside a two-sided mold or vacuum bag. This process normally uses special automated equipment. Some of the

processes that use this technique are resin transfer moulding, vacuum bagging, vacuum infusion, injection moulding, compression moulding and pultrusion (Kar, 2016).

For the manufacturing of plant fiber reinforced polymer composite, the most used method is compression moulding (Pramendra Kumar Bajpai et al., 2013; Rashid et al., 2017; Yallew et al., 2014). The mixed material of fiber and matrix is placed in between two matched metal dies that are mounted in a hydraulic press. Then, the metal dies will be closed with a certain amount of pressure, temperature and time (Salit et al., 2015). In addition, this process also can use loose chopped fiber or short or long fiber mats either aligned or random orientation. These fibers are then placed alternately with thermoplastic or thermoset polymer matrix before applying pressure, time and temperature. To ensure the matrix is fully dispersed between fibers, the viscosity of the matrix plays a vital role. Also, high quality composites can be made by controlling pressure, holding time and temperature (Ho et al., 2012).

The physico-mechanical properties of the coir fiber reinforced polypropylene composite was investigated by Mir et al. (2013). In a succession of their research, they have used the compression moulding technique for the composite preparation. After the coir fiber was uniformly mixed with the polypropylene, it was placed in the hot press machine at 170 ℃ with 30 kN pressure for 20 minutes. Subsequently, the compressed composite sample was cooled slowly before being taken out

To develop a promising plant fiber reinforced polymer composite, a suitable manufacturing process is needed. Apart from the matrix material selection, the physical, mechanical, chemical and thermal properties of the matrix and plant fiber are the most essential factors in selecting a processing technique (Ketabchi et al., 2015). One of the critical parameters to control is the temperature because there is usually a difference between the temperature when plant fiber degradation occurs and the matrix processing temperature (Rahman et al., 2015). Evidence shows that the fiber strength was reduced by 10 % in ten minutes during processing at temperatures as low as 150 °C and 200 °C (Herrmann et al., 1998). Therefore, selecting matrix materials with low processing temperatures in the range of processing temperature of fiber is useful. Generally, there is a compromise between getting good interfacial bonding and preventing fiber degradation, leading to an optimum temperature for plant fiber composite.

3.0 COMPATIBILITY BETWEEN PLANT FIBER AND POLYMER

Fiber-matrix interface acts as a reaction or diffusion area in a composite material. It justifies the importance of strong interfacial bonding between fiber and matrix in determining the composite's excellent mechanical and tribological properties. Unfortunately, plant fiber is hydrophilic in nature, which can absorb large amounts of water. Subsequently, it will result in poor bonding with the polymer, which generally possesses a hydrophobic characteristic. Hence, the difference in the surface nature of these fiber and matrix causes ineffective stress transfer throughout the interface of the composites, which then lead to weak interfacial bonding, weak compatibility and cause poor mechanical and tribological properties. In line with this, several studies have shown that composite interfacial bonding and stress transfer can be improved by modifying fiber through effective chemical and physical treatment (Subramanya et al., 2020; Subramanya et al., 2022). The current review only focused on the chemical approach as it is more represented within the literature than physical with better improvements obtained to date. Fiber surface characterization such as surface morphology, dimensional, energy, wetting and porosity can be enhanced through chemical treatment (John & Anandjiwala, 2008). This section has

attempted to provide a summary of the previously published work relating to the effectiveness of chemical treatment mainly based on alkaline treatment using NaOH solution on the fiber-matrix interfaces that lead to the improvement of the overall composite properties.

3.1 Plant Fiber Modification

Plant fibers are chemically treated before being fabricated into composites. It will be immersed in a commonly used chemical solution such as alkali, acetyl, silane, benzyl, permanganate, peroxide, isocyanate and maleated anhydride grafted coupling agent for a certain time, concentration and temperature (Faruk, 2014 ; Singh et al., 1996). This method attempts to change the fiber surface characteristics by exposing more reactive groups on the surface and allowing effective matrix coupling (Karthi et al., 2020). Though many types of chemical solutions are available for plant fiber treatment, alkali treatment is one of the most common and effective methods to modify the fiber surface structure. Despite its simple and low-cost method, this treatment has shown its best way of improving fiber properties. Among many types of alkaline treatment such as potassium hydroxide (KOH) and lithium hydroxide (LiOH), sodium hydroxide (NaOH) treatment has been widely used until today. Ighalo et al. (Ighalo et al., 2021) summarized in their review article about 70 % of their research studies on fiber treatment for polymer composite used NaOH solution. Mostly, the treatment involved at room temperature with a concentration below 20 wt.%. This treatment effectively removed impurities and thus, improved fiber-matrix bonding in plant fiber reinforced polymer composite (Kabir et al., 2012). Findings on the influence of using NaOH treatment on various plant fibers and its effect on polymer composite properties are reported here.

Gunge et al. (Gunge et al., 2019) stated that immersing woven banana fabric (WBF) in 6 % of NaOH solution for 4 hours before reinforcement in polyvinyl alcohol (PVA) composite, gives a higher tensile, flexural and impact properties than the untreated and other treated WBF/PVA composites (2, 4, 8 and 10 %). Here, the tensile test was increased by about 79.4 % compared to the untreated WBF/PVA composite. The significant increment was due to the effect of alkali treatment, which increases the surface roughness of the fiber and thus, provides better mechanical interlocking between fiber and matrix. Surface roughness was increased due to the removal of hemicellulose, lignin, pectin and waxy substances which expose the fibrils and hence, give rough surface topography on the fiber (Jayabal et al., 2012). In addition, NaOH treatment transforms the orientation of highly packed crystalline cellulose form into an amorphous region, giving accessibility for chemical penetration. This is because the cellulose macromolecules in the amorphous region are separated at a large distance and filled with water molecules. Equation 1 refers to the chemical reaction of the fiber–cell and NaOH (Kabir et al., 2012), where the existence of alkali hydroxyl group (OH) in the molecules is broken down and thus, react with water molecules and subsequently, moves out from the fiber structure along with the impurities such as fats, pectin and waxes. Therefore, the rest of the reactive molecules form fiber-cell-O-Na groups between the cellulose molecular chains (John & Anandjiwala, 2008).

$$\text{Fiber-cell-OH} + \text{NaOH} \rightarrow \text{Fiber cell-O}^{-}\text{Na}^{+} + \text{H}_2\text{O} + \text{impurities} \qquad (1)$$

Another study (Rizal et al., 2018) reported that NaOH treatment had removed some of the constituents of Typha fiber and converted its region from amorphous to crystalline form. This removal is observed through Fourier-transform infrared spectroscopy (FTIR) analysis as depicted in Figure 3. In the FTIR spectrum of Typha fiber and untreated Typha fiber composite,

the peaks at 1247 and 1249 cm-1 due to the stretching of the C-O functional group representing lignin were observed, respectively. But this peak was not found on the spectrum of alkali treated Typha fiber composite. Similarly, the peak at 1735 cm-1 which is denoted as C=O referring to the carboxylic acid and ester group of hemicellulose was present, but not on the alkali treated Typha fiber composite. The absence of these peaks on the FTIR spectrum signifies hemicellulose and lignin have been successfully removed during the alkali treatment of the fiber.

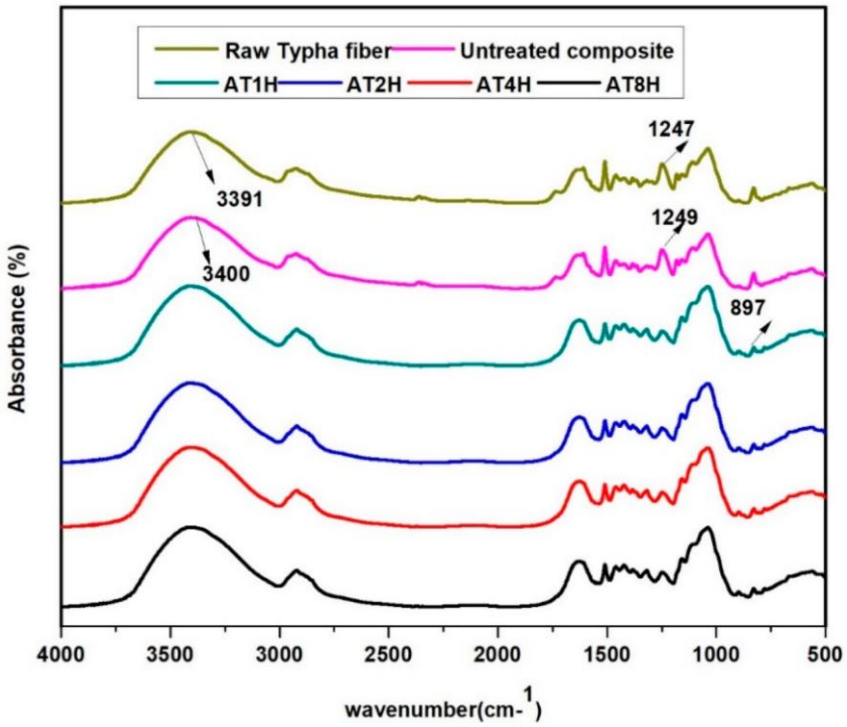

Figure 3: FTIR spectra of raw single Typha fiber, untreated and treated Typha fiber reinforced epoxy composites (Rizal et al., 2018).

A simple alkali treatment with NaOH solution on banana fiber reinforced polyester composite done by Pothan et al. (Pothan et al., 2002) was found to be more effective compared to silane and untreated fiber. They reported that 1.0 % concentration of NaOH solution has improved fiber-matrix interaction as proven by the enhanced tensile and flexural properties of the composite. The reason is due to the cementing material which is lignin dissolved during the NaOH treatment. The interfibrillar region became less dense and rigid, therefore the fibrils were more able to rearrange themselves along the tensile deformation. Also, the removal of lignin has increased the percentage of crystallinity index, resulting in better packing of the cellulose chain.

Thus far, the effect of NaOH treatment on fiber structure and properties has been studied by many researchers (Liu & Dai, 2007; Sawpan et al., 2011b). It was evident in the micrograph study of betel nut fiber where the impurities were removed after NaOH treatment (Haque & Hasan, 2018). Also, the treatment caused more fibrillation on the fiber which provides better mechanical interlocking with the matrix and thus, increases the contact area between them as supported by other studies (Fu et al., 2024). Consequently, tensile strength increases due to increase adhesion

between fiber and matrix. Hence, most of the studies reported were focusing on the improvement of fiber strength and stiffness that are associated with the improvement in their mechanical properties. However, these results originated from a wide selection of NaOH concentration and treatment time, ranging from 0.03 to 40 wt.% and 30 minutes to 48 hours, respectively (Gassan & Bledzki, 1999; Liu & Dai, 2007; Mwaikambo & Ansell, 2006; Sawpan et al., 2011b; Van de Weyenberg et al., 2006). It shows that the fiber composition changes due to the NaOH treatment parameter. Also, the amorphous parts of the fiber were dissolved, meaning the hemicellulose, lignin and other impurities content decreased. This is proven in a study on sugarcane bagasse fiber where NaOH treatment had effectively modified its fiber structure, composition and properties (Bartos et al., 2020). As the cellulose content increased after treatment, the crystallinity was reported to be a small change and the microfibril angle remained the same with increasing NaOH concentration, which is different from many other published works. The author justified that the fiber structural effects and microfibril angle are not the main factors for the changes in properties.

The application of NaOH treatment in plant fiber was extended to OPEFB fiber by many researchers over the past decades. In 1997, Sreekala et al. (Sreekala et al., 1997) reported the potential of using OPEFB as reinforcement in phenol-formaldehyde resin due to significant improvement in mechanical properties by incorporating the OPEFB fiber through NaOH treatment. Though, the properties of the OPEFB fiber will depend greatly on the nature of the plant, time of harvest, weather conditions, location and extraction method. After being treated with a 5 % concentration of NaOH for 48 hours, they found that the OPEFB fiber weight was decreased by 22 % due to the removal of surface plant and artificial impurities, resulting in a diameter reduction. Also, it caused rough surface topography that benefited polymer attachment as supported by Norul and Paridah (Norul & Paridah, 2012). The development of rough surface topography and increased fiber aspect ratio will benefit adhesion between fiber and matrix, resulting in the enhancement of mechanical properties. However, excessive time and concentration of the treatment may lead to further fiber degradation and thus reduce its strength.

Hence, many previous researchers have agreed on the significant impact of using NaOH treatment on plant fiber and its composite behavior. The treatment directly affects the cellulosic fibrils, the extraction of lignin and hemicellulose compounds and the level of polymerization (Jähn et al., 2002). Also, NaOH treatment reduced the plant fiber diameter and density which increased its fiber crystallinity and thus, a stronger plant fiber reinforced polymer composite is produced. Based on the previous works mentioned above, they suggested a simple and cost-effective method of treating plant fiber by immersing it in a selected concentration and soaking time of NaOH solution. It is noted that different levels of concentration and soaking time for NaOH treatment give different results in the final composite properties. Therefore, the appropriate parameter selection for NaOH treatment is carefully chosen to meet the specific requirements.

While most of the researchers have focused on the effect of NaOH treatment on the mechanical properties, some studies investigated the tribological properties which have risen significantly over the year as referred to in Figure 4. Therefore, it can provide confidence for the researcher to use NaOH solution as the main fiber treatment and focus on expanding another area of development in plant fiber reinforced polymer composite. The effectiveness of using NaOH fiber treatment on different plant fibers and their properties has been further summarized in Table 6.

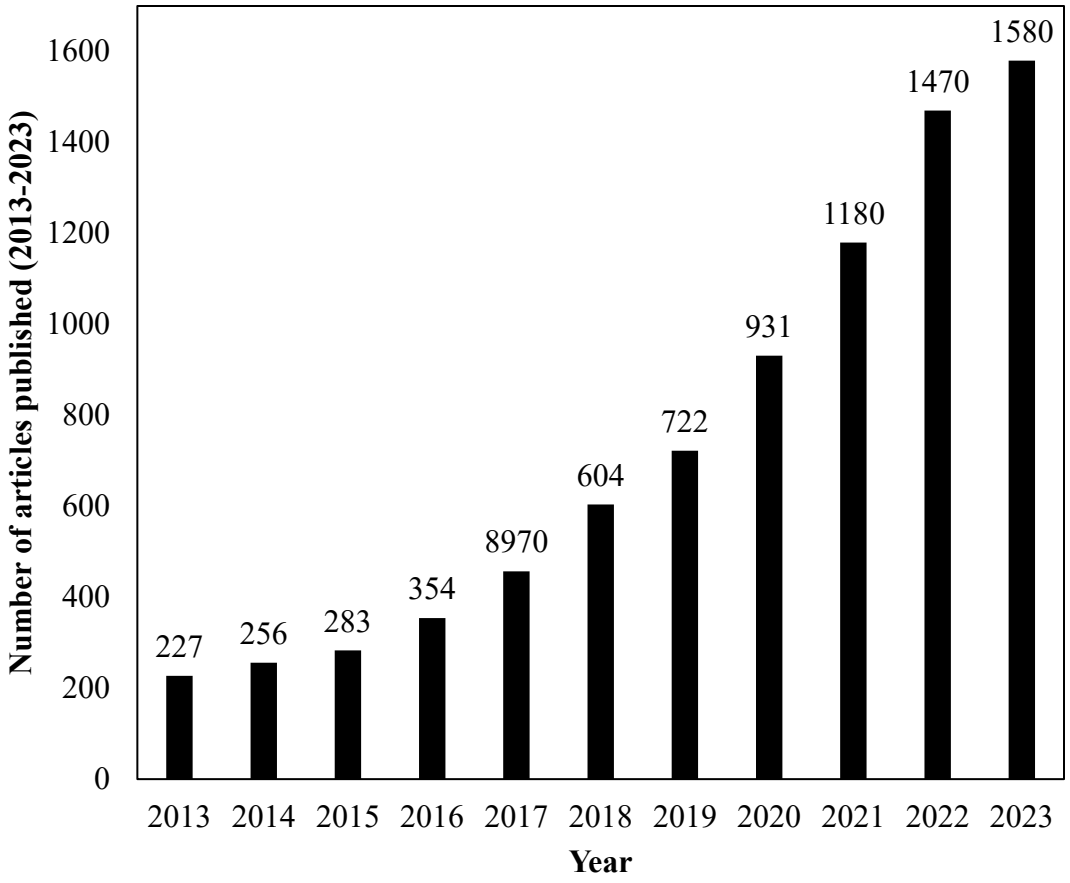

Figure 4: A number of articles published (2013-2023) based on various types of plant fiber used as reinforcement in polymer composite for tribological approach. *Source:* https://scholar.google.com/. Keywords used: plant fiber, polymer composite, sodium hydroxide treatment, tribology.

Table 6: A recent study on the effect of NaOH treatment on different plant fiber reinforced polymer composite properties.

Plant Fiber	**Matrix**	**NaOH Concentration, wt.%**	**Time, h**	**Temperature, ℃**	**Drying Process**	**Properties**	**Ref.**
Oil Palm Empty Fruit Bunch	HDPE	10	24	25	Oven, 80°C, 24h	Improved mechanical properties and resistance to water absorption	(Arif et al., 2010)
Alfa	bisphenol-A aniline benzoxazine (BA-a)	5	5	25	Oven, 60°C, 24h	Significant improvements in micro-hardness, flexural and thermomechanical	(Bessa et al., 2021)
Ensete stem	Polyester	2.5, 5, 7.5	2	30	Room temp., 24h	Improved mechanical, morphological and dynamic properties	(Negawo et al., 2019)
Pineapple leaf	Polyester	1 N	1	25	Room temp., 24h	Improved vibration damping, dynamic mechanical and thermomechanical characteristics	(Senthilkumar et al., 2021)
Hemp	Mortar	2.5, 5	1	95	Oven, 70°C, 24h	A lower proportion of plant fiber gives better mechanical properties and higher ductility	(Juradin et al., 2021)
Aerial roots of Banyan tree	-	5	0.75	32	Oven, 70°C, 24h	Improved tensile strength	(Ganapathy et al., 2019)
Coccinia Grandis. L	-	5	0.75	30	Oven, 80°C, 6h	Improved tensile strength and thermal stability	(Senthamaraikannan & Kathiresan, 2018)

Rice straw, sisal	Polypropylene, poly lactic acid	5	0.5	25	Oven, 60°C, 24h	Improved sound absorption	(Jayamani et al., 2016)
Tridax procumbens	-	5	4	25	Oven, 80°C, 64h	Density and fiber diameter reduced, crystallinity increased, hemicellulose, lignin and wax content reduced, increased tensile strength and thermal stability	(Vijay et al., 2019)
Pennisetum orientale grass	-	5	2	25	Oven, 80°C, 48h	Fiber diameter was reduced, excess levels of cellulose, hemicellulose, lignin, pectin and wax were removed, improved tensile strength and thermal stability	(Vijay et al., 2021)
Calotropis gigantea fruit bunch	-	5	0.5	25	-	Low density, better chemical composition, medium crystallinity index, good thermal properties and relatively low surface roughness	(Narayanasamy et al., 2020)

4.0 INTERFACIAL BONDING CHARACTERIZATION

Good interfacial bonding between plant fiber and polymer matrix is highly required to allow effective stress transferability along with the composite interfaces in maximizing the final composite strength. Hence, it is crucial to obtain a stable maximum stress level at the composite interfaces without interruption. Generally, interfacial bonding is determined by molecular attraction, which can be described through four types of fiber-matrix interfacial bonding mechanisms: interdiffusion, chemical reaction, mechanical interlocking and electrostatic adhesion (Lee et al., 2021; Zhou et al., 2016). These mechanisms work together to create bonding and one of them will be the main mechanism. Adequate details on the fiber-matrix interface can be characterized using several techniques and analysis through its morphology, wettability, spectroscopic and micromechanical measurements.

4.1 Morphology

The most common qualitative analysis to determine the fiber-matrix interfaces in the composite sample is through microscopy image observation using a scanning electron microscope (SEM). This technique allows the observation of microstructure change in the addition of fiber and matrix from a two-dimensional image produced by the SEM.

Bakri et al. (2015) investigated the effect of NaOH treatment on the oil palm fiber reinforced epoxy composite surface structure. Referring to the micrograph images in Figure 5, a visible gap was observed between the untreated fiber and epoxy (see Figure 5a), indicating a poor bonding. This is caused by impurities and the smooth outer surface layer cell of the fiber that prevents the epoxy from absorbing into the fiber. Meanwhile, different observations have been made when the fiber was treated with 5 wt.% of NaOH solution for 24 hours (see Figure 5b). There was no visible gap between the fiber and epoxy, showing a better bonding. The rough surface and removal of fiber surface impurities added the effect of fiber treatment, and it successfully removed the silica bodies present along the fiber surface. As pores exist on the surface of the fiber, it allows the penetration of the epoxy into the fiber, which facilitates mechanical interlocking between the fiber and matrix, thus, resulting in higher bonding. Besides, the effect of the composite manufacturing process was also observed on the fiber-matrix interface. As a results, air bubbles or potholes were formed as shown in the micrograph images (see Figure 5c). It is mainly caused by the fiber tear-out as well as air trapped due to the vigorous mixing of fiber and matrix in the hand lay-up fabrication technique. This means that the factors affecting the interfacial bonding of the fiber and matrix were controlled by both fiber treatment and composite manufacturing process. However, fiber treatment caused major impact as it has been shown to change the fiber's properties itself and thus, improve the fiber-matrix interfacial bonding which has made different when using the raw fiber instead.

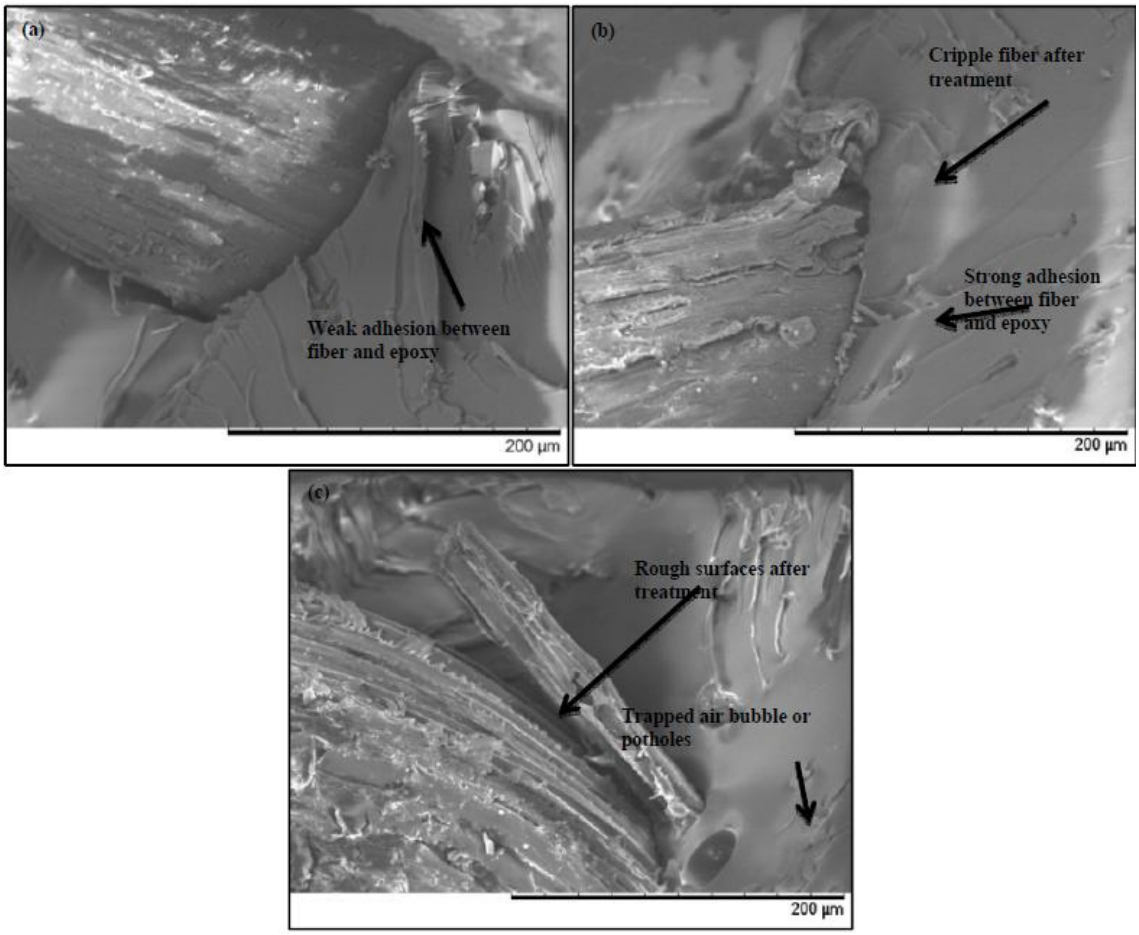

Figure 5: SEM images of oil palm fiber reinforced epoxy composite; (a) untreated, (b) NaOH treated and (c) composite cell wall (Bakri et al., 2015).

This is supported in another study (Valášek et al., 2017) investigating the interfacial structure on the fracture surface of OPEFB fiber reinforced epoxy composite subjected to a tensile test. They revealed a better interfacial bonding formed between the treated fiber and matrix was due to the absent of apparent gap as shown in Figure 6 compared to the untreated fiber composite. Additionally, the delamination of fiber from the matrix did not occur during the stress transfer from the matrix to fiber. Instead, the better stress transfer occurred through the fiber's end and cylindrical shape of the fiber. It justified that the wetting of the fiber was improved after treatment, leading to an improvement in the interfacial bonding with the matrix.

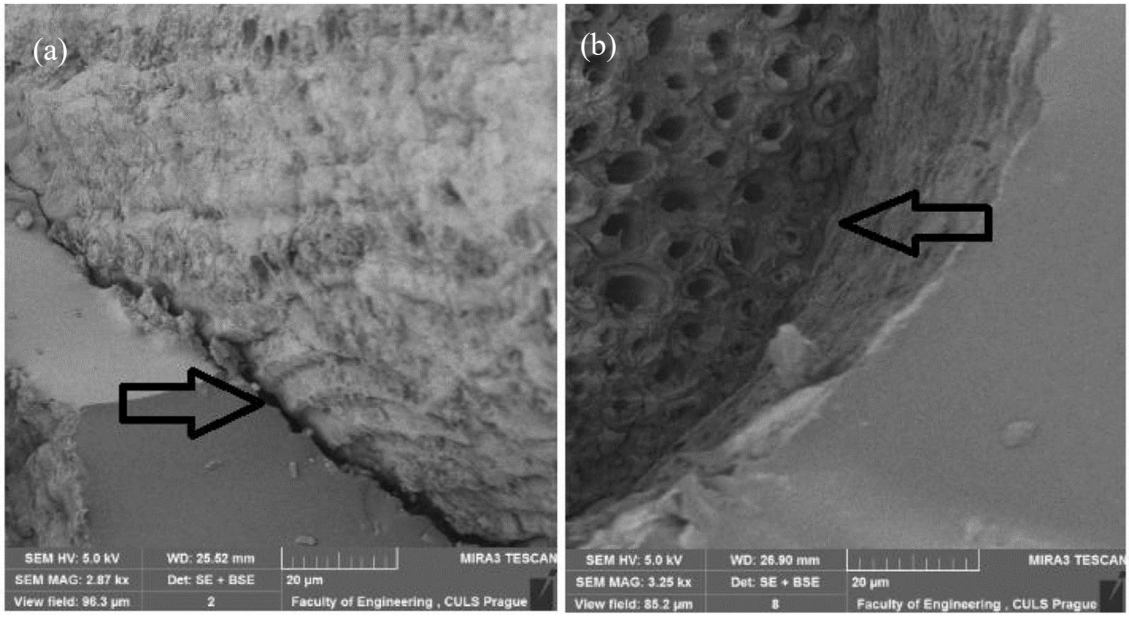

Figure 6: SEM images of OPEFB fiber reinforced epoxy composite; (a) untreated and (b) NaOH treated (Valášek et al., 2017).

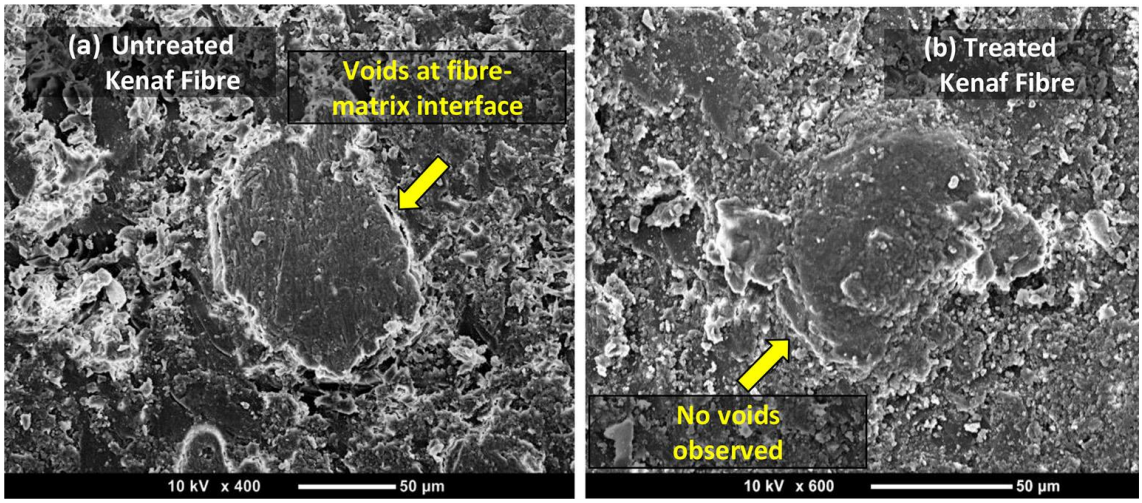

Figure 7: SEM images of kenaf fiber reinforced epoxy composite; (a) untreated and (b) NaOH treated (Azwa & Yousif, 2013).

Azwa and Yousif (2013) agreed that the NaOH treated kenaf fiber reinforced epoxy composite has better interfacial bonding and mechanical interlocking than the untreated fiber composite. As shown in Figure 7, no voids are present on the sample, indicating a better interfacial adhesion. This is in line with other works as previous researchers (Senthamaraikannan & Kathiresan, 2018; Vijay et al., 2019) have reported that untreated plant fiber has poor compatibility with polymer matrix. The moistures tend to fill in the voids between the fiber and matrix interfaces, leading to poor interfacial bonding in the composite interfaces. They have proved in this work that the naturally hydrophilic surface of kenaf fiber can be observed for both untreated and treated fibers as they were subjected to a larger early weight loss. Thus, it is impossible to remove the water absorption in the plant fiber completely, even if the fibers were dried in an oven before fabrication. But fiber treatment modification can alter the surface characteristics and improve the interfacial bonding and compatibility between the fiber and matrix.

The extent of interfacial bonding between fiber and matrix was studied by examining the fracture surfaces of the impact test with SEM. Huda et al. (2008) studied the SEM micrographs of the impact fracture surfaces of pineapple leaf fiber (PALF) reinforced polylactic acid (PLA) composite as represented in Figures 8 and 9. Figure 8 shows the untreated PALF fiber was not

uniformly distributed, but rather in the form of multi-fiber bundles. The misalignment and fiber bundles may occur during the processing of composite with large and non-uniform voids formed. Also, many fiber pull-outs occurred and the fiber surfaces were clean, signifying poor bonding between fiber and matrix.

After the PALF fiber was treated with NaOH solution, they observed changes in the surface topography of the composite where aggregation was formed on the surface as shown in Figure 9. Following this, surface roughness increased and provided better mechanical interlocking between fiber and matrix as more interaction occurred between them. Hence, these results show that the interfacial bonding between fiber and matrix can be enhanced through mechanical interlocking by increasing the surface roughness of the fiber. Based on the findings, it can be summarized that the morphology characterization technique is effective in determining the changes in single fiber surface and fiber-matrix surface after fiber treatment. Poor interfacial bonding is often indicated by the untreated plant fibers with evidence of apparent gap between the fiber and matrix, fiber breakage and void formation. Meanwhile, the treated plant fibers led to better interfacial bonding was proved by the close gap between the fiber and matrix, clean and increased surface roughness. Much evidence from this technique has been showed from previous researchers to describe the improved interfacial bonding between NaOH treated plant fiber and polymer matrix (Faruk et al., 2012; Shinoj et al., 2011).

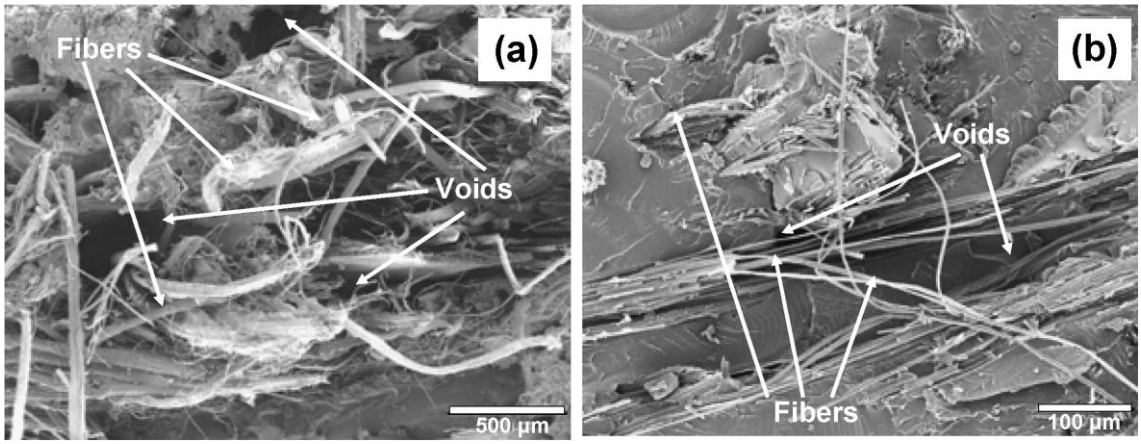

Figure 8: SEM micrographs of impact fracture surfaces of the untreated PLA/PALF (60 wt.%/40 wt.%) composite: (a) 500 µm (at 50×) and (b) 100 µm (at 200×) (Huda et al., 2008).

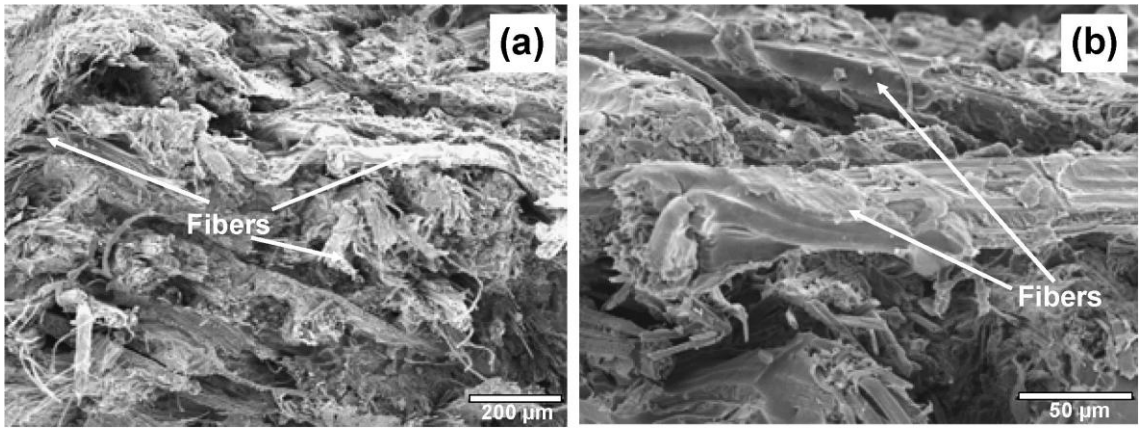

Figure 9: SEM micrographs of impact fracture surfaces of the NaOH treated PLA/PALFNA (60 wt.%/40 wt.%) composite: (a) 200 µm (at 100×) and (b) 50 µm (at 500×) (Huda et al., 2008).

4.2 Wettability

Wettability refers to a liquid's ability to maintain contact with the fiber and its composite solid surface. It results from intermolecular interactions between fiber and matrix. The amount of wetting is known by a force balance between adhesive and cohesive forces. By means, cohesive forces are the interaction between the same type of molecules as they are pulled

towards each other and bonding forces are the interaction between different molecules (Hubbe et al., 2015). Contact angle measurement is the most used method to measure the wettability of plant fiber and its composite surface. A lower contact angle that is 90° or below implies higher wettability, meanwhile, higher contact angle which is 90° or above implies lower wettability. In this regard, the degree of contact angle denotes a scientific evaluation of the fiber and its composite properties (Agrawal et al., 2017; Sarkar et al., 2020). Good wetting delivers good interfacial bonding between fiber and matrix. Hence, wettability plays an important role in the interfacial bonding between two materials. This is important to determine the compatibility of the fiber and matrix as sufficient bonding along the composite interfaces may assist the stress transferability in meeting the required composite properties. Also, it helps to identify the ability of the molten matrix to penetrate fiber structure during composite fabrication (Schellbach et al., 2016). More detailed work on understanding the influence of wettability on fiber-matrix interfacial bonding is given in the following section.

The effectiveness of the contact angle measurements technique on plant fiber composite has been exemplified in the work done by Chen et. al. (2018). They measured the water contact angle on the untreated and NaOH treated individual bamboo fibers and the results were shown in Figure 10. It was observed that the contact angle reduced after 6 wt.% of NaOH treatment. But as the concentration increased, the contact angle gradually increased to the highest value at 25 wt.% of NaOH treatment. The combination effects of chemical composition and surface roughness during the NaOH treatment may cause the changes in the contact angle. By means of chemical composition, it was reported that the accessibility of the hydroxyl groups on the fiber surface plays an important role in the surface wettability. This is because the hemicellulose component was partially removed after 6, 8 and 10 wt.% NaOH treatment, leading to increased surface roughness and decreased the accessibility of hydroxyl groups. Here, the effect of surface roughness might govern the major effect in the surface wettability than the accessibility of the hydroxyl groups, which explained the lowering of contact angle compared to the untreated. Meanwhile, when the concentration was further increased to 25 wt.%, the surface roughness increased and the hydroxyl groups were further reduced as more hemicellulose components were removed. Hence, both of this effect resulted in the increasing contact angle of bamboo fibers.

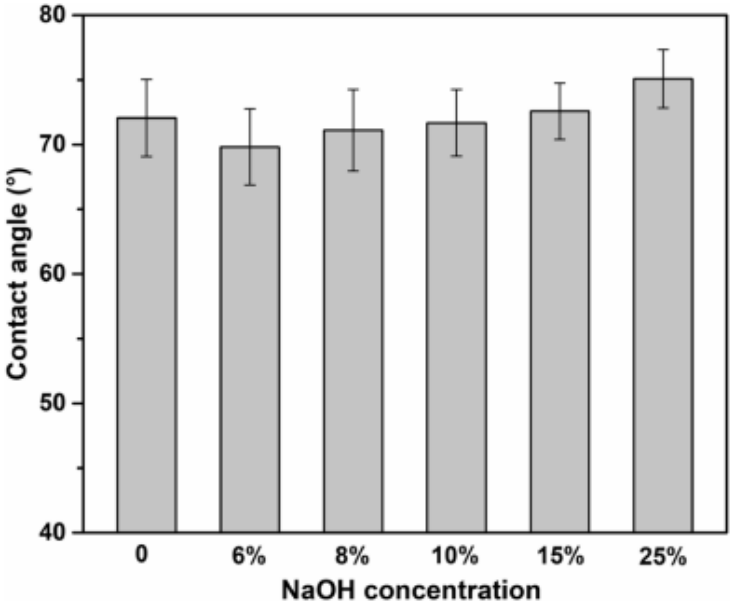

Figure 10: Contact angle of individual NaOH treated bamboo fiber subjected to different concentrations (H. Chen et al., 2018).

In line with this, Pratiwi and Wildan (2024) proposed that the non-cellulosic components such as was, pectin and impurities on the fiber surface are the main reason for the poor fiber wettability with the polymer matrix. This is evidenced in the untreated ramie fibers where it has

the highest contact angle of 63.96° compared to the NaOH treated fibers as shown in Figure 11. Here, the contact angle was further decreased to 54.21° when the NaOH concentration increased up to 7 wt.%, leading to increased surface roughness, contact area and thus, wettability of the fiber.

Interestingly, when the fibers were added into the polymer matrix, the contact angle on the composite increased as reported in a study by Akindoyo et al. (2015). They measured the water contact angle of untreated and ultrasound-NaOH treated OPEFB fiber reinforced polylactic acid (PLA). The results showed an increase in contact angle for the treated ramie fiber composite (89°) compared to the untreated (79°). Similarly, Dhakal et al. (2012) investigated the influence of fiber treatment on the wetting behaviour of hemp fiber reinforced unsaturated polyester (UP) composite. Their work has shown that the contact angle of the treated hemp fiber composite is higher (78.89°) than the untreated (76.05°). However, comprehensive study of the wettability behaviour on plant fibers and its composite is still limited. Much needed works is required in providing a better knowledge of interfacial bonding between the fiber and matrix. Nevertheless, the contact angle measurements provide an insightful information on the wettability properties of fiber to be used as reinforcement in polymer-based composite.

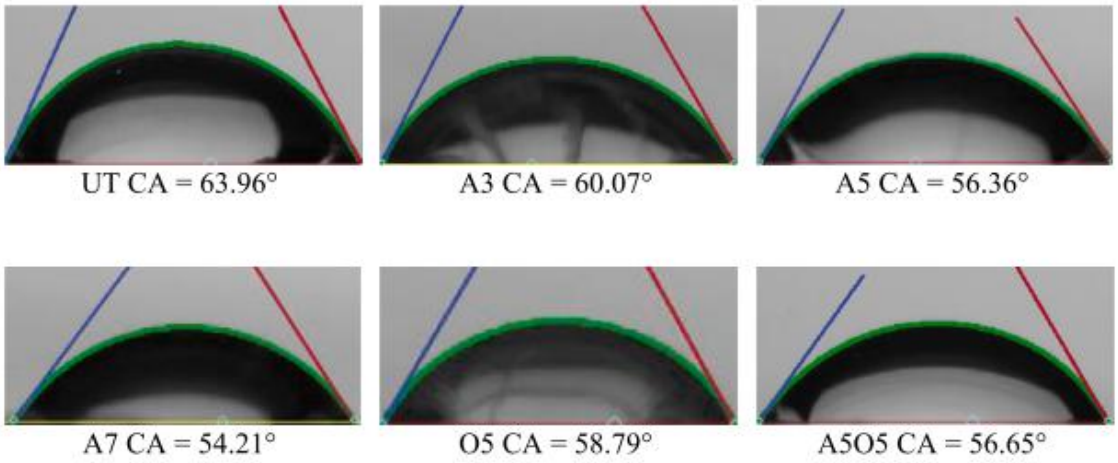

Figure 11: Contact angle of untreated and treated ramie fibers (Pratiwi & Wildan, 2024).

4.3 Spectroscopic Measurement

Another way to examine the effectiveness of the fiber treatment on its interfacial bonding with the matrix is through chemical analysis. This can be done using spectroscopic measurements including Fourier-transform infrared spectroscopy (FTIR) analysis. The main interest here is to identify the changes in the chemical composition of the fibers before and after fiber treatment. It produces an infrared absorption spectrum that detects chemical bonds in a molecule. The spectra will produce a profile of the sample which then will be used to screen and scan the sample for various types of components. This analysis has been widely used in composite materials due to its effective technique in determining functional groups and chemical bonding (Fan et al., 2012).

Reddy et al. (2013) investigated the effect of fiber treatment on the tensile properties and chemical composition of Borassus fine fiber. The FTIR analysis was applied to study the chemical composition of the Borassus fine fiber and the changes after 5 % NaOH treatment at 30 ℃ for 1, 4, 8 and 12 h, with the results shown in Figure 12. Here, no changes were observed in the NaOH treated fiber for most of the absorption peaks listed on the untreated fiber. However, the treated fiber has led to changes in the absorption at 1746 cm^{-1} and 1245 cm^{-1} which is attributed to the C=O and C−O functional groups of hemicellulose as presented in the untreated fiber being now diminished. This is also supported in a study done on rattan and bamboo fibers which found the diminished hemicellulose component on the absorption peak at 1735 cm^{-1} (Adil et al., 2024) as well as Raju et al. (2021) who reported the removal of hemicellulose from the fiber during NaOH treatment as the absent of C-O functional group at the absorption peak of 1728 cm^{-1}. The absence of these absorption peaks has shown the effect of fiber treatment on reducing the hemicellulose

content where it released the internal constraint and caused the fibrils to rearrange in a compact manner, resulting in a closer packing of cellulose chains.

The ratio of cellulose and non-cellulose components varied on different plant fibers. Through the FTIR characterization technique, it helps in determining the effect of fiber treatment on the chemical composition of the fiber which quantified by the intensities of absorbance peaks. Based on the findings, the removal or diminished peaks reflects the removal of chemical composition of the fiber after treatment, indicating the effectiveness of using fiber treatment.

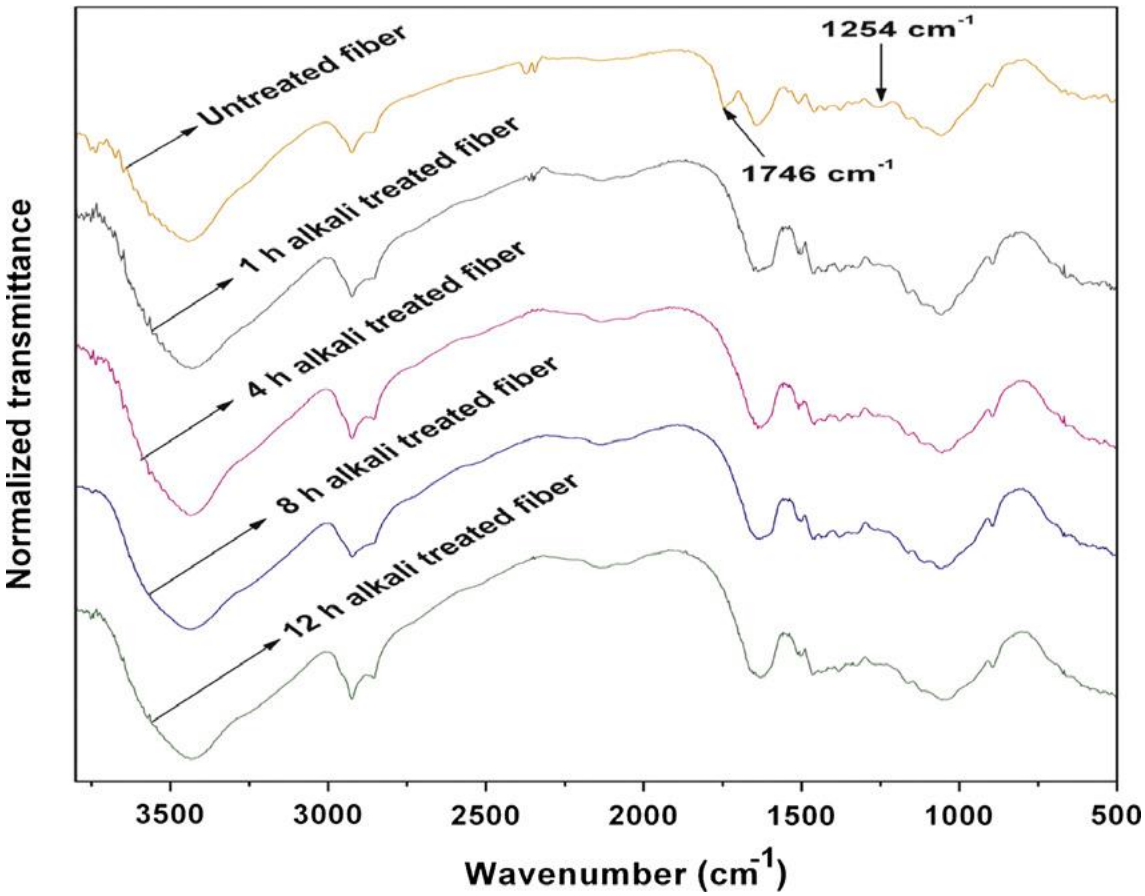

Figure 12: FTIR spectra of Borassus fine fibers for untreated and NaOH treated (Reddy et al., 2013).

4.4 Micromechanical Measurement

Returning to the importance of characterizing fiber-matrix interfaces of plant fiber reinforced polymer composite, several micromechanical testing methods have been used to measure their interface level. There are single fiber pull-out tests, single fiber fragmentation tests, micro-indentation tests and micro bond tests (Kim & Mai, 1998; Lee et al., 2021). However, the most used method to measure the fiber-matrix interfaces is the single fiber pull-out test, which will be further highlighted in this work.

The single fiber pull-out test will be operated experimentally to model the interfacial bonding behaviour of the fiber-matrix interfaces. Firstly, the fiber is embedded in the block of the matrix. Then, the free end is gripped with an increasing load applied on the fiber as it will be pulled out of the matrix where the load and displacement are recorded (Pickering, 2008). During the pull-out process, the fiber will undergo different stages depending on its interfacial bonding strength. Initially, the produced shear stress along the fiber does not surpass the fiber-matrix bonding strength. The interfacial shear strength of the composite can be measured when the force required to pull the fiber out of the matrix block is recorded (Zhou et al., 2016). The average value of the fiber-matrix shear strength, τ is related to the maximum load, F, recorded before the fiber is separated from the matrix. This is calculated based on the following equation, $F = \tau\pi dl$ where πd is the fiber circumstance, and l is the embedded fiber length (Pickering, 2008).

In 2020, the interfacial shear strength of the coir fiber composite was determined using a single fiber pull-out test carried out by Putra et al. (2020). A single coir fiber with an embedded length of 1.0 mm in the epoxy matrix block was carried out using a universal testing machine (see Figure 13). They reveal that the interfacial shear strength of coir fiber reinforced epoxy composite had increased when the fiber was treated with liquid plasma using both water and sodium bicarbonate solution medium. The most likely causes are chemical bonding and mechanical interlocking occurring on the fiber-matrix interfaces, increasing the bonding strength.

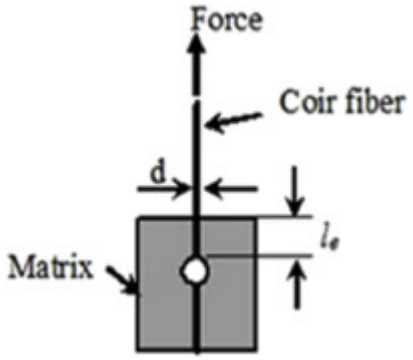

Figure 13: Schematic view of the single coir fiber pull-out (Putra et al., 2020).

This is supported by a study by Huerta-Cardosa et al. (2020). They conducted the single fiber pull-out test on agave fiber reinforced polylactic acid composite. Here, single agave fiber subjected to raw and four types of treatment were randomly selected and embedded in the polylactic acid matrix block. The block matrix was gripped using the lower machine clamp, and the single fiber free end was pulled vertically from the upper machine clamp as shown in Figure 14. Then, the fiber was pulled out until it detached from the matrix block with a load applied at a strain rate of 0.35 mm/min. The interfacial shear strength was calculated based on the load and displacement data recorded during the fiber pull-out process.

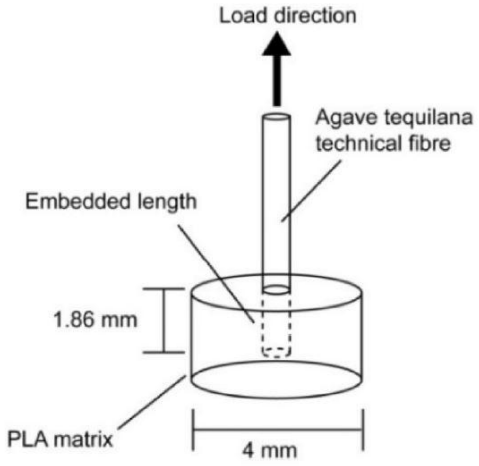

Figure 14: Schematic view of the single agave fiber pull-out (Huerta-Cardoso et al., 2020).

When the raw fiber gradually reached the maximum load at an average of 4.85 N, dynamic sliding occurred. This meant a generally smooth transition and a linear decrease with some stick-slip conditions until the fiber was completely removed from the matrix block. The reason is due to the weak interphase that was obtained as there was the friction of fiber-matrix interfaces occurred due to the uneven surfaces of the fiber (Anuar et al., 2011; Huerta-Cardoso et al., 2020). Hence, it lowered the compatibility of the fiber and matrix. The best result obtained for the improved interfacial shear strength is the NaOH treated agave fiber among other types of treatment which are acetylated, enzyme and silane. The NaOH treated fiber has reached the highest interfacial shear strength of 5.21 MPa which is up to 60 % compared to the untreated

fiber. This was governed by the fiber treated with 8 % of NaOH for one hour. The increment is due to the removal of non-cellulosic components and increased surface roughness, allowing mechanical interlocking with the polylactic acid matrix (Huerta-Cardoso et al., 2020).

However, the diameter of the plant fibers is mostly not in the perfect cylindrical shape as synthetic fiber. The plant fiber heterogeneous dimension may cost non-effective stress transferability. This is because the irregular diameter along the fiber length may detach at lower loads which causes splitting and thus, results in further splitting into the finer fiber which is fibrillation (Lee et al., 2021). As a result, each fibril will have lower adhesion and hence, lower fiber pull-out strength. Consequently, this will have a negative impact on the final composite properties due to poor interfacial bonding of the composite interfaces. The pull-out behaviour of the plant fiber-matrix system can be further described in Table 7.

Table 7: Effect of the NaOH treatment on the pull-out behavior of plant fiber reinforced polymer composite.

Plant Fiber	**Matrix**	**Test configuration**	**Interfacial shear strength, MPa**	**Ref.**
Coir (5% NaOH)	Polylactic acid	• 10x20 mm polylactic acid block • Fiber embedded length, 1 mm	3.0	(Dange & Gnanamoorthy, 2023)
Bamboo (5 wt.% NaOH)	Polylactic acid	• Thin polylactic acid disk • Fiber embedded length, 0.4 mm	5.3	(Viel et al., 2018)
Date palm (5 wt.% NaOH)	Polyurethane	• 20x10 mm polyurethane block • Fiber embedded length, 20 mm	0.31	(Oushabi et al., 2017)
Hemp (5 wt.% NaOH)	Polylactic acid	• 18 mm length x 6 mm diameter polylactic cylinder • Fiber embedded length, 0.25-2 mm	11.41	(Sawpan et al., 2011a)
Sisal (2 wt.% NaOH)	Polyester	• 10x10 mm polyester block • Fiber embedded length, 3 mm	6.9	(Sydenstricker et al., 2003)

5.0 INFLUENCE OF INTERFACIAL BONDING CAPACITY ON PLANT FIBER REINFORCED POLYMER COMPOSITE PERFORMANCES

A good interfacial bonding capacity of plant fiber composite will result in excellent properties. This means changing the fiber structure and properties through chemical treatment, specifically NaOH solution. The enhancement of composite properties can be observed through different performances such as physical, mechanical and tribological. Several studies have investigated the relationship between interfacial bonding and its effect on composite performances.

5.1 Physical Properties

The surface nature of plant fiber is hydrophilic. They tend to absorb a large amount of moisture from the surroundings compared to their matrix, making it difficult to achieve a strong bond with the matrix in composite, lowering their compatibility and thus weakening their composite properties. This is because the fiber surface contains strong polarized hydroxyl groups (Kalia et al., 2009). When water is in contact with the fiber, old hydrogen bonds break and new hydrogen bonds are created between water molecules and hydroxyl groups which

cause water absorption (Kabir et al., 2012). Subsequently, the water absorption leads to fiber swelling, creating fiber dimension instability. The high moisture content can be found in most of the plant fibers of different groups such as oil palm (2-9 wt.%), coir (10 wt.%), flax (8-10 wt.%), sisal (11 wt.%), hemp (8 wt.%) and jute (8-12 wt.%) (Cheung et al., 2009; Satyanarayana et al., 2009; Yan et al., 2016; Yusoff et al., 2009).

This phenomenon has led to deeper study into reducing the hydrophilic properties of the fiber, for instance, chemical fiber modification. In a study by Balaji and Nagarajan (Balaji & Nagarajan, 2017), the moisture content of Saharan aloe vera cactus leaves fiber was reduced from 7.6 to 5.8 wt.% after the fiber was treated with a 5 % NaOH solution. These findings were aligned with another study (Vijay et al., 2021) in which the moisture content of Pennisetum Orientale grass fiber was decreased from 8.5 to 3.2 wt.% when treated with 5 % NaOH solution. Similar outcomes on the effect of NaOH treatment on fiber moisture absorption reduction were reported by Sari et al. (Sari et al., 2017). The study revealed the moisture content of coir husk fiber was reduced from 11.98 to 11.12 wt.%. The cause of the reduction was highlighted as the removal of the hemicellulose component in the fiber because of fiber modification. During the modification process, small spaces between microfibrils groups of the fiber were blocked by the linked agents, preventing water accessibility (Sreekala & Thomas, 2003). Thus, chemical fiber modification using NaOH solution is recognized for lowering the hydrophilicity of the plant fiber and therefore, reducing the moisture absorption of the fiber. This is important in strengthening the interfacial bonding between fiber and matrix, resulting in improved composite properties.

In addition to fiber modification, the amount of fiber content in the composite should be considered. According to a previous study (Kaewkuk et al., 2013), the increased water absorption of the composite was influenced by the high fiber content. Subsequently, Zahari et al. (Zahari et al., 2015) strengthened the idea by investigating the behaviour of the composite with different fiber content and showed a significant influence of the fiber content in moisture absorption. They discovered that the moisture absorption of 30 wt.% ijuk fiber reinforced in polypropylene composite was the highest compared to 10 and 20 wt.% fiber contents. Though, they claimed that there was no significant difference in moisture absorption percentage in terms of untreated and treated fiber composite which is opposed to other studies (Y. Chen et al., 2018; Punyamurthy et al., 2012).

On another note, the water absorption of fiber was also affected by the immersion period. This study was conducted by Ahmad et al. (Ahmad et al., 2018), who conducted a moisture absorption test according to ASTM D570-10 on the hemp fiber reinforced epoxy composite. In this test, the composite sample was submerged in distilled water for some time up to 1400 h at room temperature. Later, the mass of the water absorbed by the sample was recorded and the moisture content percentage was calculated by the sample's weight difference at several time intervals. As a result, they showed that the water absorption of the composites increased when the immersion period increased until an equilibrium state was achieved. This finding was also supported by other researchers who found that the fiber reinforced polymer composites could absorb more moisture when the immersion period is prolonged (JA et al., 2016; Maslinda et al., 2017; Ridzuan et al., 2016). The water absorption behaviour of fiber follows the Fickian diffusion process (Akil et al., 2011; Mazuki et al., 2011). Similarly, the moisture absorption of fiber is mainly due to the hydrophilic nature of hemp fiber. This is because it allows water molecule absorption as it contains cellulose component which has hydroxyl groups that react with water molecules and form hydrogen bonds, resulting in a large amount of moisture absorption. Subsequently, the fiber was swelled which then initiated microcracks. Then, the composite is associated with high external stress and causes failure. These cracks were continuously propagated, severely weakening the fiber-matrix interfacial bonding (Ahmad et al., 2018).

As previously stated, the hydrophilic behaviour of plant fiber has become detrimental to the interfacial strength of the composite. This behaviour could also be related to damaging other properties such as physical and mechanical. A considerable amount of literature has been published on investigating the effect of moisture absorption of fiber on mechanical properties such as tensile, flexural and impact strength. Huang and Young (Huang & Young, 2019) investigate the influence of the hygrothermal aging test which is the combination of humid and hot conditions on the mechanical properties of untreated and NaOH treated bamboo reinforced

epoxy composite. The composite sample was immersed in water for 1, 2, 3 and 4 hours at 100 °C. Then, the moisture content was calculated based on the measurements of weight changes of the composite sample after water absorption. To determine the mechanical properties of the composite under humid and hot conditions, tensile and flexural tests were conducted after the hygrothermal aging. It was found that both the tensile and flexural strength of NaOH treated bamboo fiber reinforced epoxy composite was decreased as the moisture content increased due to the time increase. Before water absorption, the tensile and flexural strength of NaOH treated bamboo reinforced epoxy composites were measured higher than the untreated which are at 222.71 and 182.29 MPa, respectively. However, after the NaOH treated sample was immersed in water for 4 hours, the tensile and flexural strength decreased to 95.64 and 69.67 MPa, respectively. The composite may only keep 50 % of its initial strength once the moisture reaches saturation. Hence, this result showed high moisture content of the bamboo reinforced epoxy composite would deteriorate its mechanical properties.

An experimental demonstration of the effect of moisture absorption was also carried out by Kumar et al. (Kumar et al., 2021). But this study does not include any treatment for the fiber. They investigated the mechanical properties of untreated Indian ramie reinforced epoxy composite after being immersed in water for 120 days at room temperature. In a comparison of the dry sample, the results showed a significant reduction in tensile strength, flexural strength, impact strength and hardness of 16.85, 13.63, 21.02 and 3.33 %, respectively, after the water immersion. Chaudhary et al. (Chaudhary et al., 2020) focused on finding the effect of moisture absorption of untreated jute and flax reinforced epoxy composite on their mechanical properties, but for a more extended period. They investigated the tensile, flexural and impact strength of the composite before and after it was immersed in water for one year. The tensile, flexural and impact strength were found to be reduced by 37.74, 33.6 and 4.8 %, respectively, compared to the dry sample.

Moisture absorption of fiber has affected the overall composite in many ways. It was evidenced that the moisture content of fiber affected the composite interfaces, mainly the interaction between the fiber and matrix, consequently damaging the dimensional stability, swelling behaviour and mechanical properties such as tensile, flexural and impact strength of the final composite. Thereby, reducing moisture absorption of plant fiber through NaOH treatment justifies its importance when developing its composite. It is the foremost significant factor to consider because the fiber requires low moisture absorption properties to make an effective reinforcement with the polymer matrices and achieve optimum composite properties.

On another note, density and hardness properties of the plant fiber reinforced polymer composite is important in determining the composite behaviour. It is found that both density and hardness of the composite changes with the modification of fiber using NaOH treatment. For density, NaOH treatment may took an effect in increasing the fiber density by removing the non-cellulosic components which are lignin, hemicellulose and impurities, which are less dense causing the decrease in the fiber volume (Ouarhim et al., 2019). Thus, the density of these treated fiber composite increases in comparison to the untreated fiber composite as supported in another study of hemp and palmyra fiber reinforced epoxy composite (Narayana & Rao, 2023). Here, they showed that the increment of concentration of NaOH treatment has an effect in increasing density of the composite. In addition, with the increasing amount of fiber content in the composite, it is expected that the density of the composite will also change due to the highly packed fibers.

Meanwhile, hardness of the composite will highly depend on the fiber reinforcement and fiber loading. The NaOH treated urena lobata fiber reinforced polypropylene composite showed enhanced hardness compared to the untreated fiber composite (Njoku et al., 2020). It can be related to the enhanced fiber-matrix interaction after treatment, that subsequently cause the fiber to be uniformly distributed in the polypropylene composite and thus, increase the hardness of the overall composite. This finding was also supported by another study done on the phoenix sp. fiber reinforced epoxy composite where the hardness of the composite was increased to shore D hardness of 69 as compared to untreated fiber composite of 54 (Rajeshkumar, 2022). But the level of concentration of NaOH treatment will greatly impact the hardness properties of the composite. Ubi and Asipita mentioned that the hardness of luffa fibers reinforced recycle low density polyethylene composite decreased when the fiber was further

treated up to 10 wt.% of NaOH (Ubi & Asipita, 2015). This is because at higher concentrations, the fiber may be deteriorated and caused an ineffective reinforcement in the polymer-based composite, and thus reducing the hardness. Besides using the NaOH treated fiber, the right amount of fiber content will also take an important role in determining the hardness. As evidenced in the previous study (Vinod et al., 2020), the increment of banana fiber loading in the epoxy-based composite has an improvement in the hardness. They justified that more fiber reinforcing particles will carry loads which then reduced the distortion and strength of the composite. Nevertheless, both combination of the NaOH treated fiber and significant amount of fiber content produced good wettability at the fiber-matrix interfaces and hence, enhanced the hardness (Alaaeddin et al., 2019; Kumar et al., 2022; Rajakumar et al., 2022). Based on this discussion, it can be said that the density and hardness of the composite which mainly begin with an effective reinforcing NaOH treated fiber may assist the composite performances in the mechanical and tribological aspects.

5.2 Mechanical Properties

The mechanical properties of the plant fiber reinforced polymer composite, including tensile, flexural and impact strength, are subjected to several factors such as fiber types, loading, orientation and length in its matrix (Mansor et al., 2021). Furthermore, these properties are also influenced by its unique fiber quality such as time of harvest, weather conditions and extraction method (Abdelmouleh et al., 2007; Bledzki & Gassan, 1999; Tserki et al., 2005). Another significant factor associated with the mechanical properties of plant fiber reinforced polymer composite was subjected to fiber treatment at different times and concentrations (Kabir et al., 2012 ; Radzi & Jamari, 2020). This is evident in a study by Yan et al. (Yan et al., 2016). They revealed that the NaOH treated coir fiber reinforced epoxy composite led to a 17.8 % improvement in tensile strength compared to untreated. This is generally associated with fiber orientation and fiber-matrix interfacial bonding strength. Additionally, the composite tensile strength is highly dependent on its monofilament fiber. Besides, the consideration of its critical fiber length (fiber aspect ratio; length to diameter) plays an important role as when the load is applied to the matrix, stress transfer along the fiber-matrix interface occurs. In a similar study, alkali treatment increased 16.7 % the flexural strength of the coir fiber reinforced epoxy composite.

The enhancement of mechanical properties of plant fiber composite was proven in a study done by Wang et al. (Wang et al., 2019). They investigated the effect of NaOH treated jute fiber reinforced epoxy composite subjected to different concentrations (2, 4, 6, 8 and 10 %) at 120 °C on its mechanical properties. Here, the highest improvement in tensile and flexural strength was given by 6 % NaOH, which increased by 37.5 % and 72.3 %, respectively, compared to untreated. It was reported due to the increased contact area between fiber and matrix, resulting in higher fiber crystallinity as the lignin, hemicellulose and impurities were removed during the alkali treatment. However, the NaOH treatment for 8 and 10 % deteriorated the composite's mechanical properties. The reason is due to the high concentration of NaOH treatment led to higher removal of lignin and hemicellulose and changed the native cellulose I to cellulose II (Li et al., 2007; Mwaikambo & Ansell, 2002). Also, a high concentration of NaOH treatment resulted in excessive peeling of the fiber surface. Subsequently, reducing the fiber's strength and toughness.

Although extensive research (Afkari et al., 2022; Mahesh et al., 2022; Rahman et al., 2018) has been carried out on the enhancement of mechanical properties for alkali treated plant fiber reinforced polymer composites compared to untreated, Vinoth et al.(Vinoth et al., 2020) have conducted a study on finding the polymer composite strength when reinforced with both plant and synthetic fiber. A tensile test was performed on different stacking sequences for kenaf and glass fiber as reinforcement. Even though they have successfully shown better improvement of tensile strength for the epoxy composite when reinforced with kenaf and glass fiber compared to kenaf fiber composite, the values were still lower than glass fiber composite. This study did not address comparable values for tensile strength between kenaf and glass fiber composite, although they proposed that kenaf fiber has the potential to replace petroleum-based materials.

On the other hand, despite the previous study, Maciel et al. (Maciel et al., 2018) investigated the tensile strength of epoxy composite developed with plant and synthetic fiber which are

curaua and glass fiber, respectively. The highest tensile strength was also given by the composite containing glass fiber (71.91 MPa) compared to curaua fiber (54.79 MPa). But the specific strength (tensile strength/density ratio) of the curaua fiber composite with 141.65 MPa was higher than glass fiber composite which obtained 64.53 MPa. Nevertheless, it is evidence that plant fiber has much lower mechanical properties compared to the most used synthetic fiber such as glass fiber. The importance of finding the specific properties is because of the different nature of each material which varies considerably depending on their chemical and structural composition and fiber quality. Hence, the identification of strengths according to their density is highly required. But due to their low density, the values for strength, stiffness and specific properties (property/density ratio) of plant fiber are comparable to synthetic fiber. Hence, the author proposed plant fiber has the potential to be an alternative material to synthetic fiber in engineering applications.

Thus far, much literature has been in rapid growth in investigating the effect of fiber treatment on its composite mechanical properties (av & b, 2022). This is because the raw or untreated fiber and their composite have poor strength which is caused by the presence of non-cellulosic components in the plant fiber itself. As a result, the fiber and matrix undergo poor wettability and compatibility. Hence, it is crucial to employ surface modification on the fiber surface through effective chemical treatment. The main interest here is to remove the non-cellulosic compound from the fiber surface and subsequently, improve the mechanical properties of the plant fiber reinforced polymer composite. Table 8 summarizes the use of a different type of plant fiber as a reinforcing material for polymer matrix composites and their effects on the mechanical properties (tensile, flexural and impact strength) of composites.

Table 8: Summary of the mechanical properties of plant fiber reinforced polymer composite.

Plant Fiber	**Matrix**	**Fiber Loading, wt.%**	**Fiber Treatment**	**Improvement in Mechanical Properties, % (as compared to untreated fiber composite/ otherwise stated)**			**Ref.**
				Tensile Strength	**Flexural Strength**	**Impact Strength**	
OPEFB	Polyester	70	NaOH (0.5 mol/litre, 2 h)	53	-	-	(Anyakora et al., 2017)
OPEFB	Epoxy	10	NaOH (5 wt.%, 24h)	54.5	-	-	(Bakri et al., 2015)
OPEFB/ Sugarcane	Phenolic	35:15	-	12 (compared to 100 % OPEFB)	-	-	(Ramlee et al., 2019)
Bamboo	Epoxy	40	NaOH (10 wt.%, 48h)	45 (compared to vinylester resin)	8 (compared to vinylester resin)	-	(Chin et al., 2020)
Bamboo	Polyester	20	NaOH (6 wt.%, 3h)	10	7	-	(Manalo et al., 2015)

5.3 Tribological Properties

To study the tribological behaviour of a material, a small sized laboratory test rig (tribo-tester) with a proper selection of operating parameters that reflects the real time application of the material is required. Such parameters are applied load, speed, temperature, distance and

testing condition either dry or lubricated. Using this information, an international standard of tribology testing machine that is capable of simulating wear and frictional tests can be produced. Friction and wear are closely related as if wear would not exist without a frictional system (Fahim & Chand, 2008). But it does not necessarily mean that increasing friction causes more significant wear loss. The amount of energy used may alter the chemical and physical performance of the material, resulting in surface topography changes, then leading to the dissipation of wear debris. Hence, it justifies the significance of the tribological study of a material that involves both the consumption of energy and mass. There can be a certain amount of energy gained in a frictional system and the same amount of energy can be lost due to wear. Therefore, detailed work is needed to develop tribology materials and technologies that can control wear and frictional properties and thus, increase their life.

More attention has been given to the use of plant fiber as an effective reinforcement in polymer composite. Referring to the finding of friction and specific wear rate as a function of sliding distance, Shalwan et al. (Shalwan & Yousif, 2013) summarized that the frictional properties of the composite show some variation. Several studies (Chand & Dwivedi, 2008; Nirmal, Hashim, & Low, 2012; Umer et al., 2011) reported that the coefficient of friction (COF) was increased in the initial stage and then followed by the steady-state stage due to the stability of the contact surface's characteristics. In the meantime, another studies (Chand & Dwivedi, 2006; Chin & Yousif, 2009; Yousif et al., 2010) showing fluctuation in the COF data which signifies the instability of the contact surfaces characteristics and further modification process occurred during the sliding.

In wear behaviour, a steady state can be obtained after one point of sliding distance. But they found that different wear behaviour is given during the initial sliding stage. For example, in a few studies such as kenaf/epoxy (Chin & Yousif, 2009) and sisal/polyester (Chand & Dwivedi, 2008), a low specific wear rate is obtained in the first stage and an increase in the steady-state stage. This is because the generation of film on the counterface has become smoother at the steady state stage compared to the initial stage (Shalwan & Yousif, 2013). Meanwhile, the opposite outcome has been found in different studies using a composite of bamboo/epoxy (Nirmal, Hashim, & Low, 2012) and betelnut/polyester (Yousif et al., 2010). Here, the specific wear rate was high during the initial stage and decreased in the steady state stage. This is due to both contact surfaces undergoing the smoothening process. Therefore, it justifies the important factor in finding the wear behaviour of composite is through the characteristic of generated film on the counterface. Generally, there was no relationship between the friction and wear properties of the composite. The material can possess a low specific wear rate and a relatively high coefficient of friction or vice versa. More research is required depending on the application. However, the works mentioned above are limited in finding the effect of using untreated plant fiber as reinforcement in polymer composite for the tribological approach.

On another note, the friction and wear properties of plant fiber reinforced polymer composites are significantly influenced by the selection of material parameters and operating parameters (Chetia & Samanta, 2022). The material parameters are including fiber reinforcement, fiber orientation, fiber content, fiber length, fiber treatment and fiber concentration. Evaluating the effect of fiber reinforcement in composite fabrication has always been the primary focus in composite making. To date, many efforts have been made to investigate the effect of using plant fiber as the reinforcement in the polymer-based composite. It has been recorded to have a significant effect in improving the composite properties including their tribological behavior. Significant improvement in load-bearing properties has been observed with the addition of banana fiber in polyester based composite (Somasundaram et al., 2024). The composite has shown better mechanical properties including tensile strength, flexural strength, interlaminar shear strength, impact strength and hardness. Following this, the tribological characteristics improved as recorded by the high wear resistance and low COF values.

Besides, fiber length has a great influence on tribological behaviors. The high wear resistance of a 16 mm pineapple fiber reinforced in polyester based composite was recorded at 0.0065 mm^3/Nm compared to a shorter fiber length (4-12 mm) (Krishnakumar et al., 2024). This is because as the fiber length increases, the contact area between the fiber and matrix increases, increasing the interfacial bonding and thus, increasing the resistance to wear against the high

frictional force. Also, the 16 mm fiber length composite possesses a maximum hardness value, resulting in a higher COF value of 0.73 as the applied load and sliding velocity increased up to 20 N and 1 m/s, respectively. This is mainly due to the formation of a plastic region film surface as the fiber was thermally diffused at high load and sliding velocity.

Regardless of the fiber content and fiber orientation, the tested abaca fiber reinforced epoxy composite has better wear resistance compared to its neat epoxy (Milosevic et al., 2022). However, among the three different fiber orientations which are parallel, anti-parallel and normal orientation, the minimum COF value and high wear resistance was recorded by the parallel-oriented fiber with 20 wt.% of fiber content composites while maintaining a similar sliding direction. The implementation of parallel fiber orientations were also resulted in the lowest values of COF and specific wear rate for black fiber palm wood, which is consistent with prior investigations (Friedrich et al., 2018).

Several studies (Behera et al., 2022; Liu, Xie, et al., 2019; Omrani et al., 2016) highlighted fiber treatment is the most important factor among the material parameters. This is crucial, especially in fabricating the plant fiber composite as it greatly improves the tribological properties by making strong compatibility and interfacial bonding between fiber and matrix. Yadav et al. (Yadav et al., 2023) observed a significant reduction in the COF value of poly-lactic acid composite with different types of NaOH treated plant fibers. Regardless of their fiber type and fiber content, NaOH treated fiber composite has a low COF value and high wear resistance compared to the untreated fiber composite. Hence, these studies show the importance of conducting fiber treatment in enhancing the tribological properties of plant fiber reinforced polymer composite. This is because treated fiber exhibits better wear and frictional properties compared to untreated fiber.

Another variable that affects the tribological behavior is the operating parameters. It is defined as the parameter used during the tribology test such as contact condition, applied load, sliding velocity, sliding distance and operating temperature. Some of the important keynotes that can be addressed from these reported studies are that plant fiber reinforced polymer composite has significantly improved tribological properties, but that is not necessarily true in every composite. Based on the findings, plant fiber plays a crucial role as reinforcement in polymer composite in determining the effect of tribological properties. Results show the potential of using these green tribo-materials in several industrial applications where the tribological concern is needed due to its enhanced tribological properties. For the impact of applied load on the wear and frictional properties of the fiber composite, Rashid et al. (Rashid et al., 2017) found that the COF values of NaOH treated sugar palm fiber reinforced phenolics composite decreased with increased load up to 70 N. This is because as the load increased, the temperature of the interface increased which then caused the generation of lubricant film on the worn surface, resulting in the reduction of direct contact between the sample and counterface. Additionally, the reduction of COF values were results from the fiber debris during the sliding process (Nasir & Ghazali, 2014). Meanwhile, the COF values were also influenced by the increased sliding speed. This is because after a certain sliding distance, the wear debris piled up at the sliding surface which acted as a lubricating agent and maintained lower friction (Kumar et al., 2024).

Figure 15 summarizes the main effects plot of load and sliding velocity for COF including the effect of fiber treatment. The results showed that using NaOH (AT) treatment has a great influence in reducing the COF values by 13% compared to the untreated (UT) and seawater (ST) treated fiber composite. Another study (Pramendra Kumar Bajpai et al., 2013) supported these findings that the applied load has a significant influence on the wear and frictional properties of the plant fiber composites compared to the sliding speed.

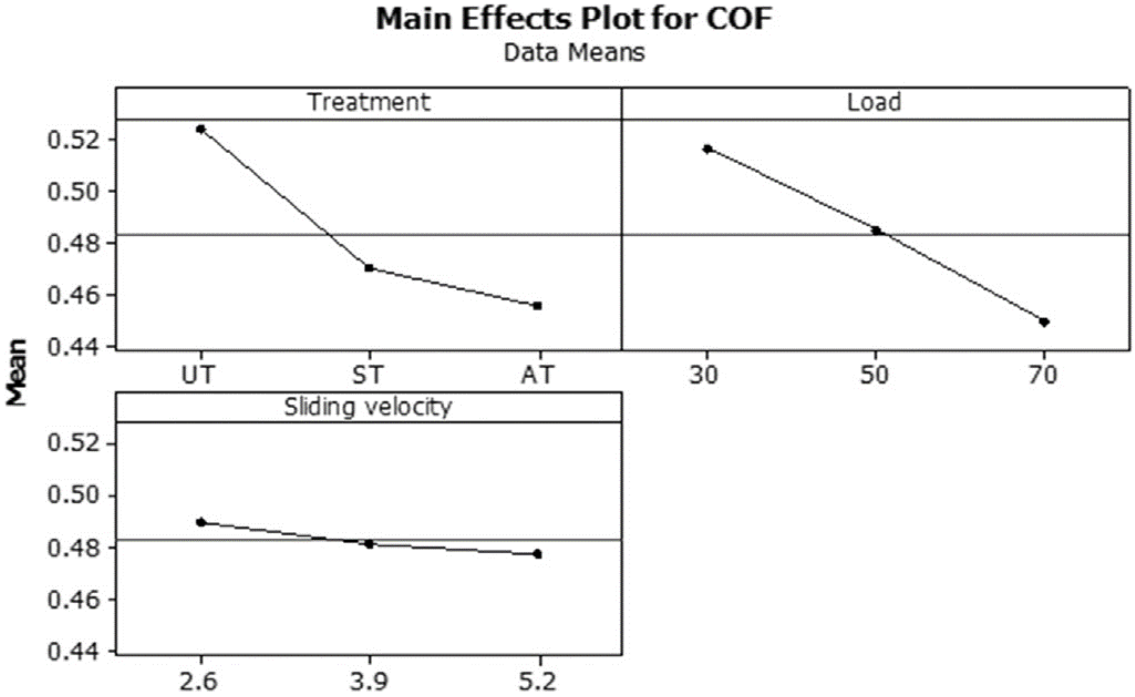

Figure 15: Main effects plot for COF (Rashid et al., 2017).

Additionally, the specific wear rate for the fiber composite decreased as the load increased, indicating improved wear resistance at higher load (70N). The lowest specific wear rate was recorded by the NaOH treated fiber composite due to its strong interfacial bonding between the fiber and matrix as evidenced in the SEM images in Figure 16 (g). Also, it showed the composite had the least loss of material compared to others and less fiber debonding or pull-out fiber which assists during the rubbing process against the counterface. Besides, plastic deformation was found on the resinous region showing high intimate contact obtained during the sliding which caused lower COF values and specific wear rate. Here, the wear mechanism for the NaOH treated fiber composite was dominated by the partial fiber debonding, matrix deformation, wear debris and film formulation (Rashid et al., 2017).

Wear performances were significantly improved due to the addition of plant fiber in the polymer composite (Pramendra K Bajpai et al., 2013). Therefore, understanding the wear mechanism is very crucial in finding their potential use in different types of applications. Sliding speed has greatly influenced the wear rate of natural fiber reinforced poly-lactic acid composite (Yadav et al., 2023). This is because the wear rate decreased when the sliding speed increased. Here, the dominant wear mechanism is plastic deformation. This is because as the sliding speed increased, the sliding friction between the two surfaces of the counterpart and composite sample increased, resulting in an increased amount of frictional heating. It can cause thermal softening of the composite due to the increased temperature during sliding. Also, the wear debris at the sliding surfaces may undergo plastic deformation which acts as a protective layer over the fibers and increases wear resistance.

Table 9 summarizes the tribological properties of plant fiber reinforced polymer composite which highlights the proposed wear mechanism. When dealing with composite, a good matrix system that can transfer and distribute the applied load evenly onto the fiber reinforcement will assist in increasing the wear resistance. It justified the importance of having strong interfacial bonding between the fiber and matrix. As fibers bear most of the load applied during sliding, interfacial fatigue or fiber debonding may occur in the fibrous region. Following this, stress transfer will be less efficient and will cause cracks formation and detachment (Yallew et al., 2014).

One of the main wear failure modes of nettle, grewia optiva and sisal fiber reinforced poly-lactic acid composite during dry sliding test is abrasive wear (Pramendra Kumar Bajpai et al., 2013). It is confirmed by the presence of ploughing and cutting on the worn surface shown in Figure 17. Fiber debonding was greatly observed in the nettle fiber composite which included

fiber fracture, fiber pull-out and matrix breakage. However, most of the sisal fibers are still in good condition and showed less fiber detachment and pull-out as shown in Figure 18, indicating the fiber has a high load-carrying capacity compared to other fibers used in the study. For all fiber composites, there were patches of thin polymer film formation on the fiber surface due to plastic deformation. As a result, it acted as a protective layer on the composite surface, increasing the wear resistance (Pramendra Kumar Bajpai et al., 2013; Devadas et al., 2018). This is also supported by different studies(Chin & Yousif, 2009) which showed the cross-section of the fibers is covered with an epoxy layer produced by either the back film transfer or debris from the resinous region. Subsequently, it lowers the material removal from the composite and thus, lowers the specific wear rate.

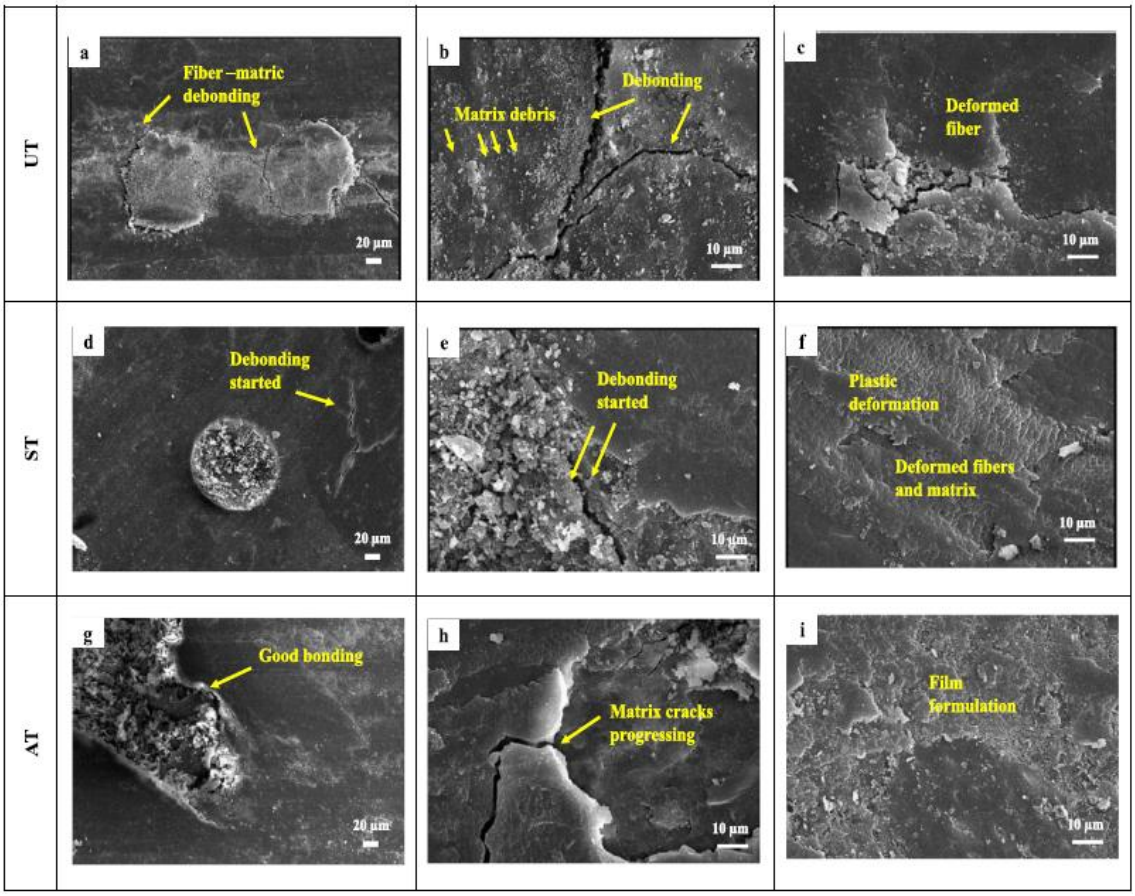

Figure 16: SEM micrographs at 30 and 70 N load at 2.6 m/s sliding speed and 5000 m sliding distance; (a, b, and c) UT (untreated); (d, e, and f) ST (seawater treated); and (g, h, and i) AT (alkali – sodium hydroxide treated) composites, respectively at (200x and 1000x magnification) (Rashid et al., 2017).

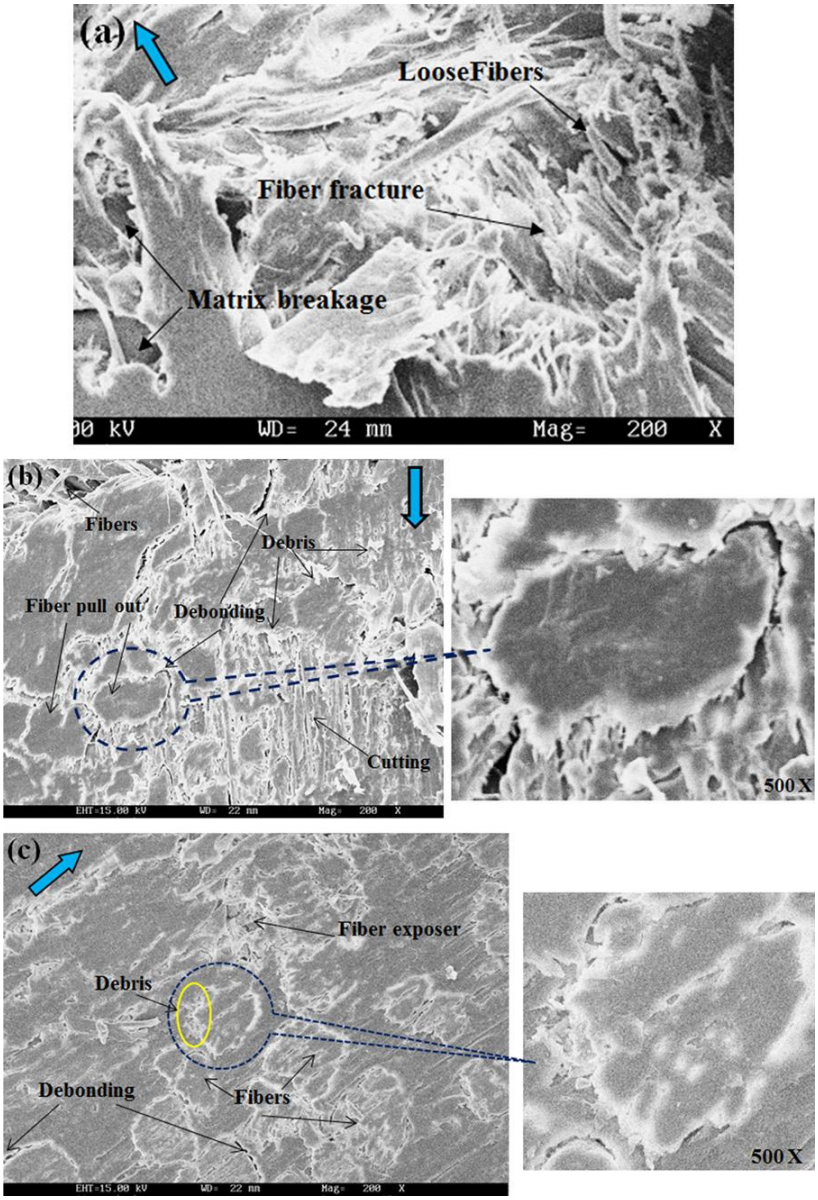

Figure 17: SEM micrographs of poly-lactic acid/nettle composite for 3000 m sliding distance: (a) applied load 10 N, sliding speed 3 m/s; (b) applied load 20 N, sliding speed 2 m/s; (c) applied load 30 N, sliding speed 1 m/s (Pramendra Kumar Bajpai et al., 2013).

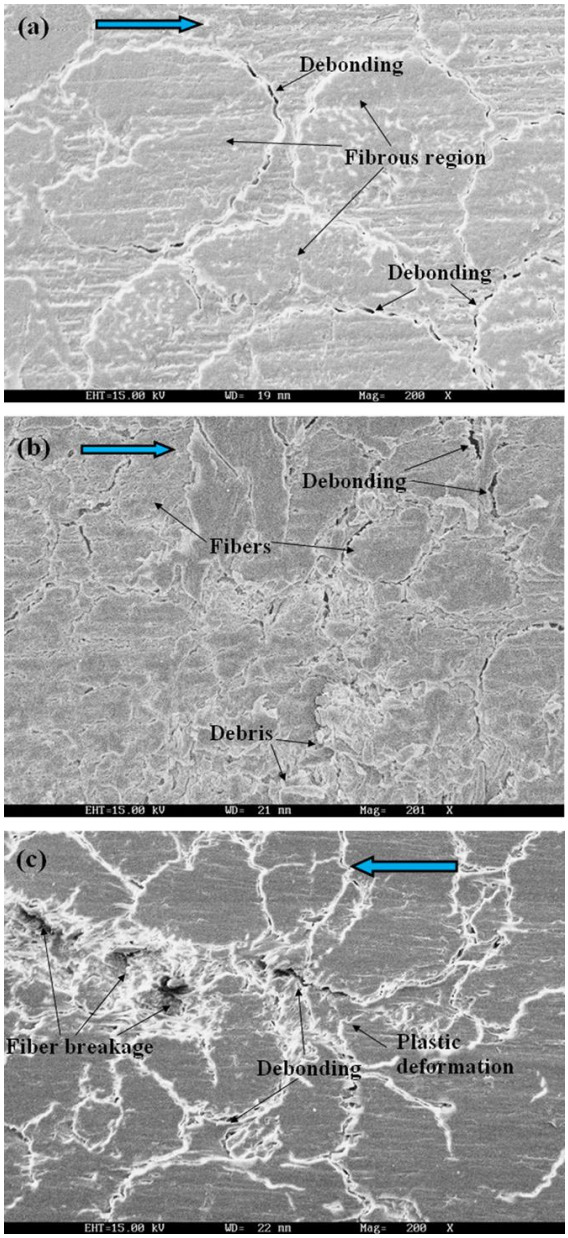

Figure 18: SEM micrographs of poly-lactic acid/sisal composite for 3000 m sliding distance: (a) applied load 10 N, sliding speed 3 m/s; (b) applied load 20 N, sliding speed 2 m/s and (c) applied load 30 N, sliding speed 1 m/s (Pramendra Kumar Bajpai et al., 2013).

Another wear failure mode of the plant fiber composite was determined as the fiber debonding. It was observed at a higher applied load (70N) which was caused by the high-thermo-mechanical loading (Chin & Yousif, 2009). It will then increase the rate of material removal from the resinous region and therefore, weaken the interfacial adhesion between the fiber and matrix. However, the fiber ends seem to carry some of the load during sliding even at a higher load (100N). This is because there is no sign of fiber pull-out. Instead, micro-cracks occurred on the worn surface, which is due to the high side force, depicting the composite has high wear resistance at the sliding surface. This wear behavior was also observed at a higher sliding speed of 3.9 m/s which confirms the proposed wear mechanism of micro-cracks, fiber debonding and matrix deformation.

The above wear mechanism has been discussed under dry conditions during sliding tests. In the case of wet conditions, Yousif et al. (Yousif et al., 2010) observed the wear behavior of betelnut fiber reinforced polyester in both dry and wet conditions. In dry conditions, fiber bundles were pulled out after undergoing a sliding distance of 5 km with 30 N of applied load as evidenced in Figure 19. Also, there was fiber debonding and fiber breakage observed. Meanwhile,

the polyester debris accumulated on the fibrous region under wet conditions as shown in Figure 20 (a). It can be seen in Figure 20 (b) where the fiber bending is in the sliding direction. However, the fiber in wet conditions had minimal fiber damage compared to dry conditions as there was no fiber breakage, pull-out and delamination observed on the sliding surface. Figure 21 shows the fiber is not severely damaged but only debonding occurred due to the shear force. Furthermore, micro-cracks were observed with less polyester debris on the composite surface which may be due to the presence of water that cleaned it during the sliding test. Generally, different composites can have different magnitudes of wear and friction properties at similar sliding conditions. This is due to the different nature of each fiber and the level of bonding compatibility with their polymer matrix. The dominant wear mechanisms for the failure of all investigated plant fiber composites are fiber debonding and plastic deformation.

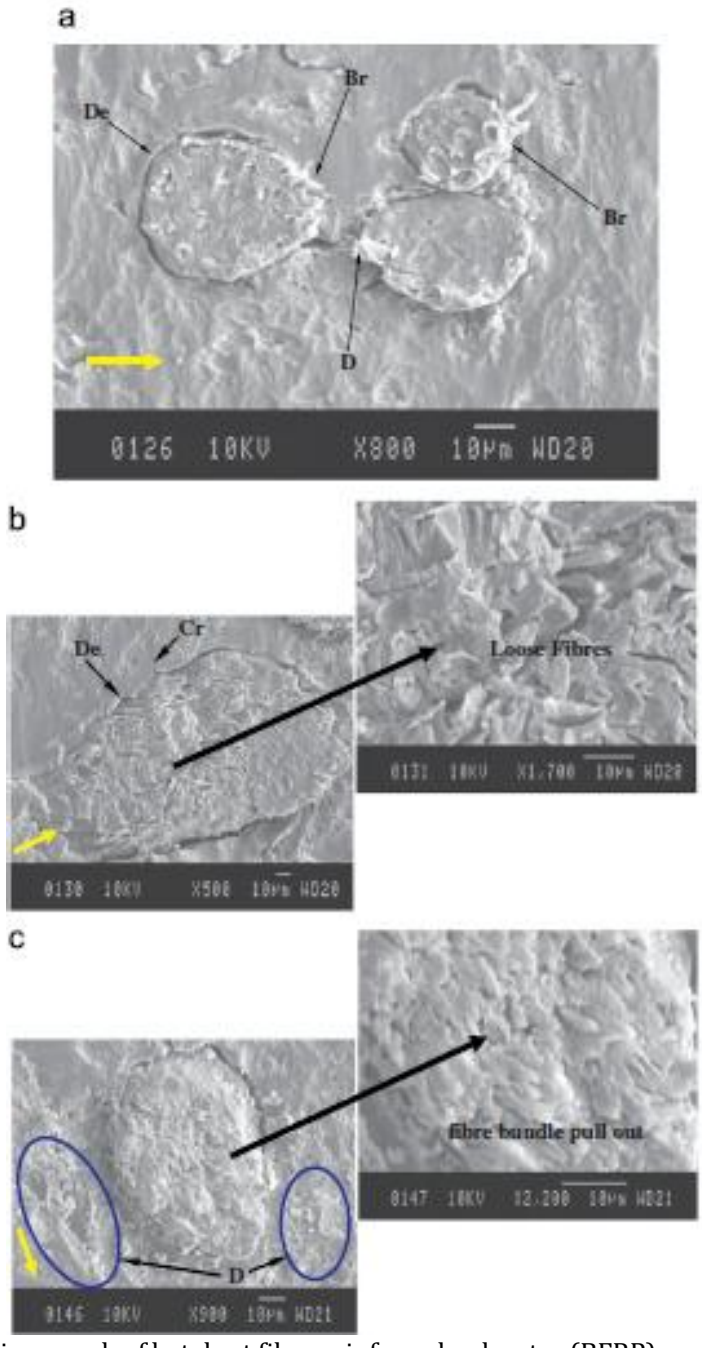

Figure 19: SEM micrograph of betelnut fiber reinforced polyester (BFRP) composite at 5 and 30 N at different sliding distances under dry contact conditions. (D: Debris, De: debonding, Cr: Crack, Br: breakage). (a) 30 N, 3.4 km, (b) 30 N, 5.0 km and (c) 50 N, 5.0 km (Yousif et al., 2010).

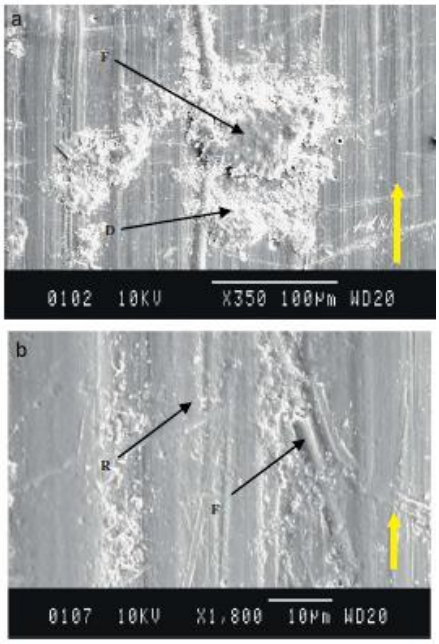

Figure 20: SEM micrograph of BFRP composite at 30 N for 6.7 km under wet contact conditions. (F: fibrous region, R: resinous region, D: Debris). (a) 30 N, 6.7 km and (b) 30 N, 6.7 km (Yousif et al., 2010).

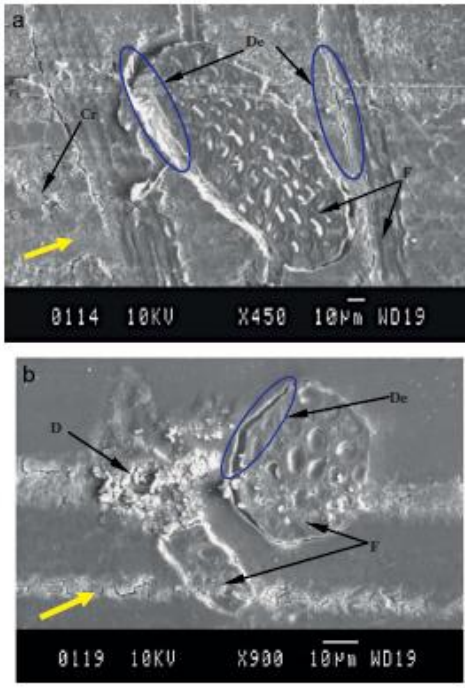

Figure 21: SEM micrograph of BFRP composite at 70 N for 6.7 km under wet contact conditions. (F: fibrous region, D: Debris, De: debonding, Cr: Crack). (a) 70 N, 6.7 km and (b) 70 N, 6.7km (Yousif et al., 2010).

Nevertheless, these findings were made based on the tribology test at room temperature. The wear failure mode of the plant fiber composite may be different when tested at a higher temperature. This effect can be observed during a sliding test on the abaca fiber composite (Liu, Ma, et al., 2019). Referring to Figure 22, the COF values were increased and decreased as the test temperature increased up to 200 °C when adding the abaca fiber for 1-4 wt.% of fiber content. But when the temperature exceeded 250 °C, the COF values decreased slowly (Liu, Ma, et al., 2019). For friction coefficient of the sample with 0, 1 and 3 wt.% at the test temperature of 200

– 350 °C were higher compared to other samples and had a relatively small decrease when the temperature increased. It indicates that the stability of COF at a high operating temperature could be enhanced by the right amount of fiber. This is because as the content of fiber increase, the unattached fiber on the worn surface of the composite will also increase, and bear most of the frictional force, and thus it can contribute to the reducing COF. On another note, when the temperature increase, the molecule distance mainly in the polymer-based material increases, and thus can improve the heat movement ability due to the thermal expansion as the temperature reaches its melting point and start melting. Following this, the thermodynamic nature of the polymer, viscoelasticity and other physical properties may change drastically (Vinayagamoorthy, 2020). As a result, the sliding surfaces is smoothening and lowering frictional forces in between them and thus, lowering COF. Nevertheless, with the rising temperature, COF of the sliding surface can have certain change, but changing the amount of fiber loading will be different from other types of plant fiber and polymer material used.

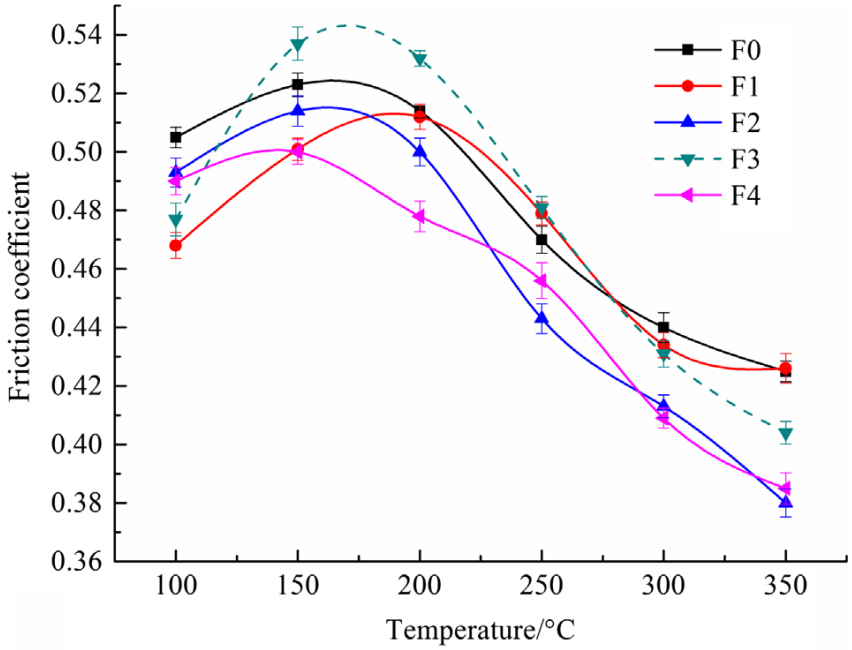

Figure 22: The friction coefficient of friction specimen (Liu, Ma, et al., 2019).

This study summarized that the composite with 3 wt.% of treated abaca fiber had the lowest wear rate and better wear resistance as evidenced by its worn surfaces (refer to Figure 23). A significant number of primary plateaus and secondary contact plateaus were observed on the specimen. Primary plateaus were formed from the rubbing of abaca fiber against its counterpart. Meanwhile, secondary plateaus were formed from the compaction of wear debris on the worn surface during the sliding process. This secondary plateau acts as the main role in the tribological performance of the abaca fiber reinforced friction composite and may also decrease the wear rate.

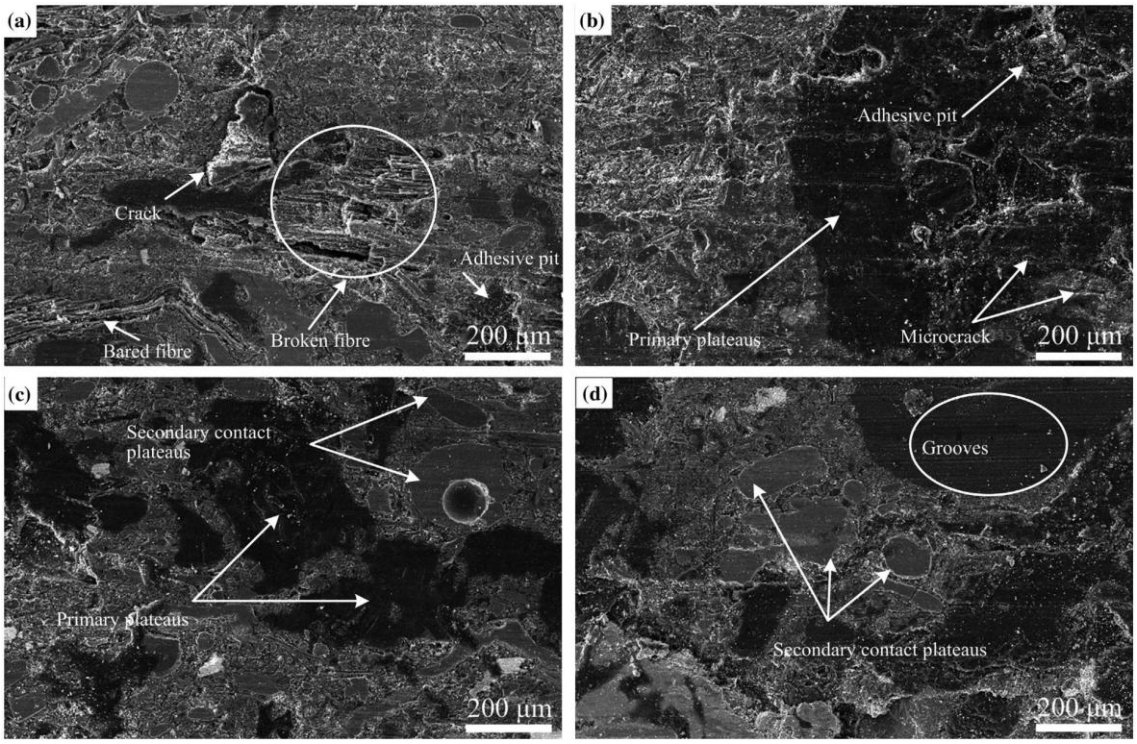

Figure 23: Surface morphologies of the friction specimens (a) F1; (b) F2; (c) F3; (d) F4 (Liu, Ma, et al., 2019).

Table 9: Tribological performances of plant fiber reinforced polymer composite as compared to its neat polymer or otherwise stated.

Composite	Preparation	Operating Parameters	Coefficient of Friction	Improvement in COF, %	Improvement in Specific Wear Rate, %	Changes in Counterface Surface Roughness	Wear Mechanism	Ref.
Kenaf fiber/epoxy (6 wt.% NaOH)	Hand lay-up	POD, CC: dry, AL: 30 N, SV: 2.8 m/s, SD: 6.72km, FL: 15 wt.%	1.25	50	64	ND	Back film transfer	(Devadas et al., 2018)
Sugar palm fiber/phenolic (0.5 wt.% NaOH & seawater)	Hot press (T: 160 ℃, P: 20 ton, t: 20 mins)	POD, CC: dry, AL: 30-70 N, SV: 2.6-5.2 m/s, SD: 5 km, FL: 30 wt.%	0.41-0.49	13 (alkali), 10 (seawater)	33 compared to UT and seawater	ND	Matrix deformation, partial fiber debonding, film formulation	(Rashid et al., 2017)
Jute fiber/polypropylene (untreated)	Hot press (T: 165 ℃, P: 4 MPa, t: 8 mins)	POD, CC: dry, AL: 10-30 N, SV: 1-3 m/s, SD: 1-3 km	0.30-0,40	45	65	ND	Ploughing, crack formation and detachment, fracturing of fiber and matrix	(Yallew et al., 2014)
Kenaf fiber/polyester & kenaf fiber/epoxy (untreated)		ART, CC: dry, AL: 5-30 N, SV: 1.4 m/s, SD: 1-10 km, FL: 20 wt.%	ND	ND	67	ND	ND	(Nordin et al., 2013)
Nettle, grewia optiva & sisal fiber/PLA (untreated)	Hot press (T: 180 ℃, P: 3 MPa, t: 5 mins)	POD, CC: dry, AL: 10-30 N, SV: 1-3 m/s, SD: 1-3 km, FL: 20 wt.%	0.25-0.90	10-44	70	ND	Abrasive (ploughing, debonding)	(Pramendra Kumar Bajpai et al.,

								2013)
Kenaf fiber/epoxy (6 wt.% NaOH)	Vacuum block, (P: 0.5 bar, FO: parallel, anti-parallel, normal)	BO, CC: dry, AL: 30-100 N, SV: 1.1-3.9 m/s, SD: 0-5 km, FL: 48 wt.%	0.32-0.42	ND	85 (compared to parallel & anti-parallel)	0.11 to 0.13 µm	Micro-cracks, fiber debonding, matrix deformation	(Chin & Yousif, 2009)
Betelnut fiber/polyester (6 wt.% NaOH)	Hand lay-up	BOR, CC: dry/wet, AL: 5-30 N (dry), 30-200 N (wet), SV: 2.8 m/s, FL 48 wt.%	0.22-0.65	94 (compared to dry)	49 (compared to dry)	0.06 to 0.15 µm (dry)	Adhesive (macro and micro cracks, fiber pull-out, debonding)	(Yousif et al., 2010)

Remarks: T-temperature, P-pressure, t-time, FO-fiber orientation, POD-pin on disc, ART-abrasion resistance tester, BOR-block on the ring, CC-contact condition, AL-applied load, SV-sliding velocity, SS-sliding speed, SD-sliding distance. FL-fiber loading, ND-not determine

6.0 FUTURE WORKS

Based on the reviewed works, important key points and suggestions for future works are highlighted here which may create a new research opportunity in the tribology field of plant fiber reinforced polymer composite.

(a) Fiber loading of plant fiber as reinforcement in polymer composite ranged at 4-50 wt.%, finding the appropriate fiber loading is crucial in determining the enhanced composite properties.
(b) Limited works are reported in using POM as polymer material for tribological approach though it has good abrasive resistance, further research on this material should be explored.
(c) NaOH treatment for the plant fiber is significant in ensuring strong interfacial bonding between fiber and matrix through removing impurities, reduced density and fiber diameter and increased crystallinity, a comprehensive explanation on the stress transfer and fiber-matrix interaction after treatment is needed for further enhancement in the composite properties.
(d) In comparison to the untreated plant fiber composite, the wear resistance was significantly improved but the friction is varied, details characterization for the sliding process is needed to study the wear mechanism.
(e) Observation of composite surfaces through SEM analysis revealed evidence of the formulation of resin film on the worn surfaces which prevents it from severe wearing, resulting in lower values of wear rate, details characterization on the transfer film itself may be added for supporting evidence.
(f) Different operating and material parameters decide the wear and frictional behaviour of the plant fiber reinforced polymer composite, finding the dominant effect of the parameter to the tribological performances is required.

CONCLUSIONS

The current review has gathered research studies based on the addition of untreated and treated natural plant fiber reinforcement in the polymer-based composite for tribological purposes. However, the type of fiber treatment was greatly highlighted towards the use of NaOH treatment as it is widely discussed in the literature. The significance of using NaOH treatment on the plant fiber has a positive effect in increasing the interfacial bonding strength of the fiber and matrix, which then leads to enhancing the mechanical and tribological properties of the composites. Hence, it is hoped that this review will provide an effective overview of the research studies investigated for the past few years, addressing the properties of the plant fiber and polymer matrix, compatibility between the fiber and matrix, method to evaluate the interfacial bonding and the influence of improved interfacial bonding in tribological performances of the plant fiber composites. It is to be noted here that due to the complexity of the different kinds of testing modes available under the science of tribology, this review focused mostly on pin-on-disc testing with the dominant wear failure mechanism of the natural plant fiber reinforced polymer composites. This review may contribute to the use of NaOH treated plant fiber composite towards the application of tribology such as bearing which requires low friction and high wear resistance. Additionally, this review may provide elementary insight for further research in the science of tribology on natural plant fibers and their polymer composites. The suitability of these composites in tribological application has been investigated considering the work done on the wear and frictional analysis. Plant fiber offers many varieties that need to be explored. More opportunities for new findings in the science of tribology concerning the use of plant fiber and its composite may open new research pathways that will have a greater impact on developing more sustainable tribology materials for the related industries.

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REFERENCES

Abdelmouleh, M., Boufi, S., Belgacem, M. N., & Dufresne, A. (2007). Short natural-fibre reinforced polyethylene and natural rubber composites: effect of silane coupling agents and fibres loading. Composites science and technology, 67(7-8), 1627-1639.

Adil, M. M., Parvez, M. M. H., Rupom, S. M. N., Tasnim, T., Islam, M. S., Gafur, M., Mesbah, M. B., & Ahmed, I. (2024). Physical and thermal properties analysis of bamboo and rattan fiber reinforced polymer composite. Results in Engineering, 22, 102084.

Afkari, A. S., Juwono, A. L., & Roseno, S. (2022). Effect of fibre stacking orientation on the mechanical and thermal properties of laminated kenaf fibre/epoxy composites. Advances in Materials and Processing Technologies, 1-18.

Agrawal, G., Negi, Y. S., Pradhan, S., Dash, M., & Samal, S. (2017). Wettability and contact angle of polymeric biomaterials. In Characterization of Polymeric Biomaterials (pp. 57-81). Elsevier.

Ahmad, M. A. A., Majid, M. A., Ridzuan, M., Mazlee, M., & Gibson, A. (2018). Dynamic mechanical analysis and effects of moisture on mechanical properties of interwoven hemp/polyethylene terephthalate (PET) hybrid composites. Construction and Building Materials, 179, 265-276.

Ahmed, M. M., Dhakal, H., Zhang, Z., Barouni, A., & Zahari, R. (2021). Enhancement of impact toughness and damage behaviour of natural fibre reinforced composites and their hybrids through novel improvement techniques: A critical review. Composite Structures, 259, 113496.

Akil, H., Omar, M., Mazuki, A. M., Safiee, S., Ishak, Z. M., & Bakar, A. A. (2011). Kenaf fiber reinforced composites: A review. Materials & Design, 32(8-9), 4107-4121.

Akindoyo, J. O., Beg, M. D. H., Ghazali, S. B., Islam, M. R., & Mamun, A. A. (2015). Preparation and characterization of poly (lactic acid)-based composites reinforced with poly dimethyl siloxane/ultrasound-treated oil palm empty fruit bunch. Polymer-Plastics Technology and Engineering, 54(13), 1321-1333.

Alaaeddin, M., Sapuan, S., Zuhri, M., Zainudin, E., & Al-Oqla, F. M. (2019). Physical and mechanical properties of polyvinylidene fluoride-Short sugar palm fiber nanocomposites. Journal of Cleaner Production, 235, 473-482.

Amiandamhen, S., Meincken, M., & Tyhoda, L. (2020). Natural fibre modification and its influence on fibre-matrix interfacial properties in biocomposite materials. Fibers and Polymers, 21(4), 677-689.

Anuar, H., Zuraida, A., Morlin, B., & Kovács, J. G. (2011). Interfacial shear strength of polylactic acid-kenaf fibre biocomposites. Key Engineering Materials,

Anyakora, A. N., Abubakre, O. K., Mudiare, E., & Suleiman, M. (2017). Effect of fibre loading and treatment on porosity and water absorption correlated with tensile behaviour of oil palm empty fruit bunch fibre reinforced composites. Advances in materials Research, 6(4), 329.

Arif, M. F., Megat-Yusoff, P. S., & Ahmad, F. (2010). Effects of chemical treatment on oil palm empty fruit bunch reinforced high density polyethylene composites. Journal of reinforced plastics and composites, 29(14), 2105-2118.

Arumugaprabu, V., Johnson, R. D. J., Uthayakumar, M., & Sivaranjana, P. (2021). Polymer-Based Composites: Design, Manufacturing, and Applications. CRC Press.

Asim, M., Jawaid, M., Khan, A., Asiri, A. M., & Malik, M. A. (2020). Effects of date palm fibres loading on mechanical, and thermal properties of date palm reinforced phenolic composites. Journal of Materials Research and Technology, 9(3), 3614-3621.

Av, S. G., & b, V. (2022). Manufacturing and mechanical characterization of coir fibre composites based on vinyl ester. Advances in Materials and Processing Technologies, 8(2), 1997-2006.

Avérous, L., & Le Digabel, F. (2006). Properties of biocomposites based on lignocellulosic fillers. Carbohydrate polymers, 66(4), 480-493.
Azwa, Z., & Yousif, B. (2013). Characteristics of kenaf fibre/epoxy composites subjected to thermal degradation. Polymer degradation and stability, 98(12), 2752-2759.
Azwa, Z., Yousif, B., Manalo, A., & Karunasena, W. (2013). A review on the degradability of polymeric composites based on natural fibres. Materials & Design, 47, 424-442.
Bai, J. (2013). Advanced fibre-reinforced polymer (FRP) composites for structural applications. Elsevier.
Bajpai, P. K., & Singh, I. (2019). Reinforced Polymer Composites: Processing, Characterization and Post Life Cycle Assessment. John Wiley & Sons.
Bajpai, P. K., Singh, I., & Madaan, J. (2013). Frictional and adhesive wear performance of natural fibre reinforced polypropylene composites. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 227(4), 385-392.
Bajpai, P. K., Singh, I., & Madaan, J. (2013). Tribological behavior of natural fiber reinforced PLA composites. Wear, 297(1-2), 829-840.
Bakri, M. K. B., Jayamani, E., Heng, S. K., & Hamdan, S. (2015). Reinforced oil palm fiber epoxy composites: An investigation on chemical treatment of fibers on acoustical, morphological, mechanical and spectral properties. Materials Today: Proceedings, 2(4-5), 2747-2756.
Balaji, A., & Nagarajan, K. (2017). Characterization of alkali treated and untreated new cellulosic fiber from Saharan aloe vera cactus leaves. Carbohydrate polymers, 174, 200-208.
Bartos, A., Anggono, J., Farkas, Á. E., Kun, D., Soetaredjo, F. E., Móczó, J., Purwaningsih, H., & Pukánszky, B. (2020). Alkali treatment of lignocellulosic fibers extracted from sugarcane bagasse: Composition, structure, properties. Polymer Testing, 88, 106549.
Begum, K., & Islam, M. (2013). Natural fiber as a substitute to synthetic fiber in polymer composites: a review. Research Journal of Engineering Sciences, 2278, 9472.
Begum, S., Fawzia, S., & Hashmi, M. (2020). Polymer matrix composite with natural and synthetic fibres. Advances in Materials and Processing Technologies, 6(3), 547-564.
Behera, S., Gautam, R. K., & Mohan, S. (2022). The effect of eco-friendly chemical treatment on sisal fiber and its epoxy composites: thermal, mechanical, tribological and morphological properties. Cellulose, 29(17), 9055-9072.
Bessa, W., Trache, D., Derradji, M., & Tarchoun, A. F. (2021). Morphological, thermal and mechanical properties of benzoxazine resin reinforced with alkali treated alfa fibers. Industrial Crops and Products, 165, 113423.
Bhushan, B. (1999). Principles and applications of tribology. John Wiley & Sons.
Bhushan, B. (2013). Introduction to tribology. John Wiley & Sons.
Bledzki, A., & Gassan, J. (1999). Composites reinforced with cellulose based fibres. Progress in polymer science, 24(2), 221-274.
Bledzki, A. K., Mamun, A. A., & Feldmann, M. (2012). Polyoxymethylene composites with natural and cellulose fibres: Toughness and heat deflection temperature. Composites science and technology, 72(15), 1870-1874.
Borah, J., & Dutta, N. (2018). Development and properties evaluation of betel nut fibres composite material. Materials Today: Proceedings, 5(1), 2229-2233.
Bordoloi, S., Garg, A., & Sreedeep, S. (2016). Potential of uncultivated, harmful and abundant weed as a natural geo-reinforcement material. Advances in Civil Engineering Materials, 5(1), 276-288.
Cai, M., Takagi, H., Nakagaito, A. N., Li, Y., & Waterhouse, G. I. (2016). Effect of alkali treatment on interfacial bonding in abaca fiber-reinforced composites. Composites Part A: Applied Science and Manufacturing, 90, 589-597.
Chand, N., & Dwivedi, U. (2006). Effect of coupling agent on abrasive wear behaviour of chopped jute fibre-reinforced polypropylene composites. Wear, 261(10), 1057-1063.

Chand, N., & Dwivedi, U. (2008). Sliding wear and friction characteristics of sisal fibre reinforced polyester composites: Effect of silane coupling agent and applied load. Polymer composites, 29(3), 280-284.

Chand, N., & Fahim, M. (2020). Tribology of natural fiber polymer composites. Woodhead publishing.

Chatterjee, A., Kumar, S., & Singh, H. (2020). Tensile strength and thermal behavior of jute fibre reinforced polypropylene laminate composite. Composites Communications, 22, 100483.

Chaudhary, V., Sahu, R., Manral, A., & Ahmad, F. (2020). Comparative study of mechanical properties of dry and water aged jute/flax/epoxy hybrid composite. Materials Today: Proceedings, 25, 857-861.

Chawla, K. K. (2012). Composite materials: science and engineering. Springer Science & Business Media.

Chegdani, F., El Mansori, M., Bukkapatnam, S. T., & El Amri, I. (2020). Thermal effect on the tribo-mechanical behavior of natural fiber composites at micro-scale. Tribology International, 149, 105831.

Chegdani, F., El Mansori, M., Mezghani, S., & Montagne, A. (2017). Scale effect on tribo-mechanical behavior of vegetal fibers in reinforced bio-composite materials. Composites science and technology, 150, 87-94.

Chegdani, F., Wang, Z., El Mansori, M., & Bukkapatnam, S. T. (2018). Multiscale tribo-mechanical analysis of natural fiber composites for manufacturing applications. Tribology International, 122, 143-150.

Chen, H., Zhang, W., Wang, X., Wang, H., Wu, Y., Zhong, T., & Fei, B. (2018). Effect of alkali treatment on wettability and thermal stability of individual bamboo fibers. Journal of Wood Science, 64, 398-405.

Chen, Y., Su, N., Zhang, K., Zhu, S., Zhu, Z., Qin, W., Yang, Y., Shi, Y., Fan, S., & Wang, Z. (2018). Effect of fiber surface treatment on structure, moisture absorption and mechanical properties of luffa sponge fiber bundles. Industrial Crops and Products, 123, 341-352.

Chetia, P., & Samanta, S. (2022). Dry sliding wear behaviour of bamboo/basalt hybrid composite. Advances in Materials and Processing Technologies, 8(2), 1481-1492.

Cheung, H.-y., Ho, M.-p., Lau, K.-t., Cardona, F., & Hui, D. (2009). Natural fibre-reinforced composites for bioengineering and environmental engineering applications. Composites Part B: Engineering, 40(7), 655-663.

Chin, C., & Yousif, B. (2009). Potential of kenaf fibres as reinforcement for tribological applications. Wear, 267(9-10), 1550-1557.

Chin, S. C., Tee, K. F., Tong, F. S., Ong, H. R., & Gimbun, J. (2020). Thermal and mechanical properties of bamboo fiber reinforced composites. Materials Today Communications, 23, 100876.

Chohan, J. S., Boparai, K. S., Singh, R., & Hashmi, M. (2020). Manufacturing techniques and applications of polymer matrix composites: a brief review. Advances in Materials and Processing Technologies, 1-11.

Czarnecka-Komorowska, D., & Sterzynski, T. (2018). Effect of polyhedral oligomeric silsesquioxane on the melting, structure, and mechanical behavior of polyoxymethylene. Polymers, 10(2), 203.

da Luz, F. S., Ramos, F. J. H. T. V., Nascimento, L. F. C., da Silva Figueiredo, A. B.-H., & Monteiro, S. N. (2018). Critical length and interfacial strength of PALF and coir fiber incorporated in epoxy resin matrix. Journal of Materials Research and Technology, 7(4), 528-534.

Dan-Mallam, Y., Abdullah, M. Z., & Megat Yusoff, P. S. M. (2016). Influence of recycling frequency on mechanical and physical properties of kenaf fiber reinforced polyoxymethylene composite. Journal of Natural Fibers, 13(5), 532-546.

Dan-Mallam, Y., Abdullah, M. Z., & Yosuff, P. S. M. (2013). Impact strength, microstructure, and water absorption properties of kenaf/polyethylene terephthalate (PET) fiber-reinforced polyoxymethylene (POM) hybrid composites. Journal of Materials Research, 28(16), 2142.

Dan-Mallam, Y., Abdullah, M. Z., & Yusoff, P. S. M. M. (2015). Mechanical Properties of Short and Continuous Kenaf/Pet Fibre Reinforced Polyoxymethylene Composite. Advanced Composites Letters, 24(4), 096369351502400404.

Dan-Mallam, Y., Abdullah, M. Z., & Yusoff, P. S. M. M. (2014). The effect of hybridization on mechanical properties of woven kenaf fiber reinforced polyoxymethylene composite. Polymer composites, 35(10), 1900-1910.

Dange, D., & Gnanamoorthy, R. (2023). Effect of alkaline treatment of coir fibre on the interfacial adhesion in coir fibre-reinforced polylactic acid bio-composite. Materials Today: Proceedings.

Deng, J., Lee, M. M., Wan, B., & Amato, G. (2017). Fibre Reinforced Polymer Composites for Structural Applications in Construction. In: Hindawi.

Devadas, A., Nirmal, U., & Hossen, J. (2018). Investigation into mechanical & tribological performance of kenaf fibre particle reinforced composite. Cogent Engineering, 5(1), 1479210.

Dhakal, H., Zhang, Z., & Bennett, N. (2012). Influence of fibre treatment and glass fibre hybridisation on thermal degradation and surface energy characteristics of hemp/unsaturated polyester composites. Composites Part B: Engineering, 43(7), 2757-2761.

Divya, H., Naik, L. L., & Yogesha, B. (2016). Processing techniques of polymer matrix composites–A review. International Journal of Engineering Research and General Science, 4(3), 357-362.

Espinach, F. X., Granda, L. A., Tarrés, Q., Duran, J., Fullana-i-Palmer, P., & Mutjé, P. (2017). Mechanical and micromechanical tensile strength of eucalyptus bleached fibers reinforced polyoxymethylene composites. Composites Part B: Engineering, 116, 333-339.

Fahim, M., & Chand, N. (2008). Tribology of natural fiber polymer composites. Elsevier.

Fan, M., Dai, D., & Huang, B. (2012). Fourier transform infrared spectroscopy for natural fibres. Fourier transform-materials analysis, 3, 45-68.

Faruk, O., Bledzki, A. K., Fink, H.-P., & Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. Progress in polymer science, 37(11), 1552-1596.

Faruk, O. B., AK Fink, HP Sain, M. (2014). Progress report on natural fiber reinforced composites Macromolecular Materials and Engineering, 299(1), 9-26.

Fragassa, C., Pavlovic, A., & Živković, I. (2018). The accelerated aging effect of salt water on lignocellulosic fibre reinforced composites. Tribology in Industry, 40(1), 1-9.

Friedrich, K. (2018). Polymer composites for tribological applications. Advanced Industrial and Engineering Polymer Research, 1(1), 3-39.

Friedrich, K., Akpan, E., & Wetzel, B. (2018). Sliding wear performance of dry and oil impregnated black-fiber palm wood. Jurnal Tribologi, 16, 51-70.

Fu, C., Li, Y., Lin, Y., Zhang, W., Yang, J., Liu, Y., He, Z., Hong, Y., Shen, J., & Ni, Y. (2024). Crucial role of fiber swelling in microfibrillated cellulose extraction via ball milling. Industrial Crops and Products, 218, 118899.

Gairola, S., Tyagi, Y., Gangil, B., & Sharma, A. (2020). Fabrication and mechanical property evaluation of non-woven banana fibre epoxy-based polymer composite. Materials Today: Proceedings.

Ganapathy, T., Sathiskumar, R., Senthamaraikannan, P., Saravanakumar, S., & Khan, A. (2019). Characterization of raw and alkali treated new natural cellulosic fibres extracted from the aerial roots of banyan tree. International Journal of Biological Macromolecules, 138, 573-581.

Gassan, J., & Bledzki, A. K. (1999). Possibilities for improving the mechanical properties of jute/epoxy composites by alkali treatment of fibres. Composites science and technology, 59(9), 1303-1309.

Gowthaman, S., Nakashima, K., & Kawasaki, S. (2018). A state-of-the-art review on soil reinforcement technology using natural plant fiber materials: Past findings, present trends and future directions. Materials, 11(4), 553.

Gunge, A., Koppad, P. G., Nagamadhu, M., Kivade, S., & Murthy, K. S. (2019). Study on mechanical properties of alkali treated plain woven banana fabric reinforced biodegradable composites. Composites Communications, 13, 47-51.

Gupta, M., & Srivastava, R. (2016). Properties of sisal fibre reinforced epoxy composite.

Haque, M. M., & Hasan, M. (2018). Influence of fiber surface treatment on physico-mechanical properties of betel nut and glass fiber reinforced hybrid polyethylene composites. Advances in Materials and Processing Technologies, 4(3), 511-525.

Herrmann, A., Nickel, J., & Riedel, U. (1998). Construction materials based upon biologically renewable resources—from components to finished parts. Polymer degradation and stability, 59(1-3), 251-261.

Ho, M.-p., Wang, H., Lee, J.-H., Ho, C.-k., Lau, K.-t., Leng, J., & Hui, D. (2012). Critical factors on manufacturing processes of natural fibre composites. Composites Part B: Engineering, 43(8), 3549-3562.

Holbery, J., & Houston, D. (2006). Natural-fiber-reinforced polymer composites in automotive applications. Jom, 58(11), 80-86.

Holmberg, K., & Erdemir, A. (2017). Influence of tribology on global energy consumption, costs and emissions. Friction, 5(3), 263-284.

Huang, J.-K., & Young, W.-B. (2019). The mechanical, hygral, and interfacial strength of continuous bamboo fiber reinforced epoxy composites. Composites Part B: Engineering, 166, 272-283.

Huang, X., Tian, N., Wang, T., Wang, K., & Xue, Q. (2007). Friction and wear properties of NBR/PVC composites. Journal of applied polymer science, 106(4), 2565-2570.

Hubbe, M. A., Gardner, D. J., & Shen, W. (2015). Contact angles and wettability of cellulosic surfaces: a review of proposed mechanisms and test strategies. BioResources, 10(4).

Huda, M. S., Drzal, L. T., Mohanty, A. K., & Misra, M. (2008). Effect of chemical modifications of the pineapple leaf fiber surfaces on the interfacial and mechanical properties of laminated biocomposites. Composite Interfaces, 15(2-3), 169-191.

Huerta-Cardoso, O., Durazo-Cardenas, I., Marchante-Rodriguez, V., Longhurst, P., Coulon, F., & Encinas-Oropesa, A. (2020). Up-cycling of agave tequilana bagasse-fibres: A study on the effect of fibre-surface treatments on interfacial bonding and mechanical properties. Results in Materials, 8, 100158.

Ighalo, J. O., Adeyanju, C. A., Ogunniyi, S., Adeniyi, A. G., & Abdulkareem, S. A. (2021). An empirical review of the recent advances in treatment of natural fibers for reinforced plastic composites. Composite Interfaces, 28(9), 925-960.

Irawan, A. P., & Sukania, I. W. (2015). Tensile strength of banana fiber reinforced epoxy composites materials. Applied mechanics and materials,

JA, M. H., Majid, M. A., Afendi, M., Marzuki, H., Hilmi, E. A., Fahmi, I., & Gibson, A. (2016). Effects of water absorption on Napier grass fibre/polyester composites. Composite Structures, 144, 138-146.

Jähn, A., Schröder, M., Füting, M., Schenzel, K., & Diepenbrock, W. (2002). Characterization of alkali treated flax fibres by means of FT Raman spectroscopy and environmental scanning electron microscopy. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 58(10), 2271-2279.

Jawaid, M., Khalil, H. A., Bakar, A. A., Hassan, A., & Dungani, R. (2013). Effect of jute fibre loading on the mechanical and thermal properties of oil palm–epoxy composites. Journal of composite materials, 47(13), 1633-1641.

Jawaid, M., Khalil, H. A., Hassan, A., Dungani, R., & Hadiyane, A. (2013). Effect of jute fibre loading on tensile and dynamic mechanical properties of oil palm epoxy composites. Composites Part B: Engineering, 45(1), 619-624.

Jawaid, M., Salit, M. S., Hoque, M. E., & Yusoff, N. B. (2015). Manufacturing of Natural Fibre Reinforced Polymer Composites. Springer.

Jayabal, S., Sathiyamurthy, S., Loganathan, K., & Kalyanasundaram, S. (2012). Effect of soaking time and concentration of NaOH solution on mechanical properties of coir–polyester composites. Bulletin of Materials Science, 35(4), 567-574.

Jayamani, E., Hamdan, S., Bakri, M. K. B., Kok Heng, S., Rahman, M. R., & Kakar, A. (2016). Analysis of natural fiber polymer composites: Effects of alkaline treatment on sound absorption. Journal of reinforced plastics and composites, 35(9), 703-711.

Jena, H. (2019). Study of tribo-performance and application of polymer composite. In Automotive Tribology (pp. 65-99). Springer.

Jeyapragash, R., Srinivasan, V., & Sathiyamurthy, S. (2020). Mechanical properties of natural fiber/particulate reinforced epoxy composites–A review of the literature. Materials Today: Proceedings, 22, 1223-1227.

John, M., & Anandjiwala, R. (2008). Recent developments in chemical modification and characterization of natural fiber-reinforced composites. Polymer composites, 29(2), 187-207.

Juradin, S., Boko, I., Grubeša, I. N., Jozić, D., & Mrakovčić, S. (2021). Influence of different treatment and amount of Spanish broom and hemp fibres on the mechanical properties of reinforced cement mortars. Construction and Building Materials, 273, 121702.

Kabir, M., Wang, H., Lau, K., & Cardona, F. (2012). Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview. Composites Part B: Engineering, 43(7), 2883-2892.

Kabir, M., Wang, H., Lau, K., & Cardona, F. (2012). Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview. Composites Part B: Engineering, 43(7), 2883-2892.

Kaewkuk, S., Sutapun, W., & Jarukumjorn, K. (2013). Effects of interfacial modification and fiber content on physical properties of sisal fiber/polypropylene composites. Composites Part B: Engineering, 45(1), 544-549.

Kalia, S., Kaith, B., & Kaur, I. (2009). Pretreatments of natural fibers and their application as reinforcing material in polymer composites—a review. Polymer Engineering & Science, 49(7), 1253-1272.

Kar, K. K. (2016). Composite materials: processing, applications, characterizations. Springer.

Karthi, N., Kumaresan, K., Sathish, S., Gokulkumar, S., Prabhu, L., & Vigneshkumar, N. (2020). An overview: Natural fiber reinforced hybrid composites, chemical treatments and application areas. Materials Today: Proceedings, 27, 2828-2834.

Karthi, N., Kumaresan, K., Sathish, S., Prabhu, L., Gokulkumar, S., Balaji, D., Vigneshkumar, N., Rohinth, S., Rafiq, S., & Muniyaraj, S. (2021). Effect of weight fraction on the mechanical properties of flax and jute fibers reinforced epoxy hybrid composites. Materials Today: Proceedings.

Ketabchi, M. R., Hoque, M. E., & Siddiqui, M. K. (2015). Critical concerns on manufacturing processes of natural fibre reinforced polymer composites. Manufacturing of natural Fibre Reinforced polymer composites, 125-138.

Khan, A., Vijay, R., Singaravelu, D. L., Arpitha, G., Sanjay, M., Siengchin, S., Jawaid, M., Alamry, K., & Asiri, A. M. (2020). Extraction and characterization of vetiver grass (Chrysopogon zizanioides) and kenaf fiber (Hibiscus cannabinus) as reinforcement materials for epoxy based composite structures. Journal of Materials Research and Technology, 9(1), 773-778.

Khonsari, M. M., & Booser, E. R. (2017). Applied tribology: bearing design and lubrication. John Wiley & Sons.

Kim, J.-K., & Mai, Y.-W. (1998). Engineered interfaces in fiber reinforced composites. Elsevier.

Kim, Y.-H., Park, J.-M., Yoon, S.-W., Lee, J.-W., Jung, M.-K., & Murakami, R.-I. (2011). The effect of moisture absorption and gel-coating process on the mechanical properties of the basalt fiber reinforced composite. International Journal of Ocean System Engineering, 1(3), 148-154.

Komuraiah, A., Kumar, N. S., & Prasad, B. D. (2014). Chemical composition of natural fibers and its influence on their mechanical properties. Mechanics of composite materials, 50(3), 359-376.

Krishnakumar, S., Mohanavel, V., Venkatesh, R., & Balasubramanian, K. (2024). Enhancement of tribology behaviour by the addition of different fiber length of pineapple fiber reinforced polyester composite. Journal of Mechanical Science and Technology, 38(1), 201-206.

Kuan, H. T. N., Jadum, K., Yusof, M., Ting, S. N., & Ng, C. K. (2019). Study of Betel Nut Husk Fibre Reinforced Polymer Composite. Journal of Applied Science & Process Engineering, 6(2), 378-385.

Kumar, R., & Anand, A. (2019). Tribological behavior of natural fiber reinforced epoxy based composites: a review. Materials Today: Proceedings, 18, 3247-3251.

Kumar, R., Ul Haq, M. I., Raina, A., & Anand, A. (2019). Industrial applications of natural fibre-reinforced polymer composites–challenges and opportunities. International Journal of Sustainable Engineering, 12(3), 212-220.

Kumar, R., Ul Haq, M. I., Sharma, S. M., Raina, A., & Anand, A. (2021). Effect of water absorption on mechanical and tribological properties of Indian ramie/epoxy composites. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 13506501211005635.

Kumar, S., Mahakur, V. K., & Bhowmik, S. (2024). Physico-mechanical and tribological characteristics of flax–ramie fiber reinforced green composites and anticipation of fabricated composites under different loading with sliding constraint. Arabian Journal for Science and Engineering, 49(2), 2463-2482.

Kumar, S., Shamprasad, M., & Varadarajan, Y. (2022). Experimental investigation of impact strength and hardness value of rice straw reinforced polylactide composites. Materials Today: Proceedings, 52, 604-607.

Lancaster, J. K. (1986). Composites for aerospace dry bearing applications. In Composite Materials Series (Vol. 1, pp. 363-396). Elsevier.

Lee, C. H., Khalina, A., & Lee, S. H. (2021). Importance of interfacial adhesion condition on characterization of plant-fiber-reinforced polymer composites: a review. Polymers, 13(3), 438.

Li, X., Tabil, L. G., & Panigrahi, S. (2007). Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. Journal of Polymers and the Environment, 15(1), 25-33.

Liu, X., & Dai, G. (2007). Surface modification and micromechanical properties of jute fiber mat reinforced polypropylene composites. Express Polymer Letters, 1(5), 299-307.

Liu, Y., Ma, Y., Yu, J., Zhuang, J., Wu, S., & Tong, J. (2019). Development and characterization of alkali treated abaca fiber reinforced friction composites. Composite Interfaces, 26(1), 67-82.

Liu, Y., Xie, J., Wu, N., Wang, L., Ma, Y., & Tong, J. (2019). Influence of silane treatment on the mechanical, tribological and morphological properties of corn stalk fiber reinforced polymer composites. Tribology International, 131, 398-405.

Lüftl, S., Visakh, P., & Chandran, S. (2014). Polyoxymethylene handbook: structure, properties, applications and their nanocomposites. John Wiley & Sons.

Maciel, N. d. O. R., Ferreira, J. B., da Silva Vieira, J., Ribeiro, C. G. D., Lopes, F. P. D., Margem, F. M., Monteiro, S. N., Vieira, C. M. F., & da Silva, L. C. (2018). Comparative tensile strength analysis between epoxy composites reinforced with curaua fiber and glass fiber. Journal of Materials Research and Technology, 7(4), 561-565.

Mahesh, V., Mahesh, V., & Harursampath, D. (2022). Influence of alkali treatment on physio-mechanical properties of jute–epoxy composite. Advances in Materials and Processing Technologies, 8(sup2), 380-391.

Manalo, A. C., Wani, E., Zukarnain, N. A., Karunasena, W., & Lau, K.-t. (2015). Effects of alkali treatment and elevated temperature on the mechanical properties of bamboo fibre–polyester composites. Composites Part B: Engineering, 80, 73-83.

Mansor, M., Mustafa, Z., Hadi, M., Taufiq, M., Masripan, N., Ratanawilai, T., & Tunggal, D. (2021). Effect of layering sequence on mechanical properties of hybrid oil palm empty fruit bunch/kenaf fibre reinforced epoxy composites. J Tribol, 29, 1-10.

Mao, K., Greenwood, D., Ramakrishnan, R., Goodship, V., Shrouti, C., Chetwynd, D., & Langlois+, P. (2019). The wear resistance improvement of fibre reinforced polymer composite gears. Wear, 426, 1033-1039.

Marshek, K. (1979). Failures in plastic ball bearings. Wear, 52(1), 141-146.

Maslinda, A., Majid, M. A., Ridzuan, M., Afendi, M., & Gibson, A. (2017). Effect of water absorption on the mechanical properties of hybrid interwoven cellulosic-cellulosic fibre reinforced epoxy composites. Composite Structures, 167, 227-237.

Matsunaga, T., Sato, Y., & Goda, K. (2018). Major cause of strength improvement of a ramie/PA composite with low fiber contents. Advanced Industrial and Engineering Polymer Research, 1(1), 93-98.

Mazuki, A. A. M., Akil, H. M., Safiee, S., Ishak, Z. A. M., & Bakar, A. A. (2011). Degradation of dynamic mechanical properties of pultruded kenaf fiber reinforced composites after immersion in various solutions. Composites Part B: Engineering, 42(1), 71-76.

Milosevic, M., Dzunic, D., Valasek, P., Mitrovic, S., & Ruggiero, A. (2022). Effect of fiber orientation on the tribological performance of abaca-reinforced epoxy composite under dry contact conditions. Journal of Composites Science, 6(7), 204.

Mir, S. S., Nafsin, N., Hasan, M., Hasan, N., & Hassan, A. (2013). Improvement of physico-mechanical properties of coir-polypropylene biocomposites by fiber chemical treatment. Materials & Design (1980-2015), 52, 251-257.

Mittal, V., Saini, R., & Sinha, S. (2016). Natural fiber-mediated epoxy composites–a review. Composites Part B: Engineering, 99, 425-435.

Mohanty, A., Misra, M., & Drzal, L. T. (2001). Surface modifications of natural fibers and performance of the resulting biocomposites: An overview. Composite Interfaces, 8(5), 313-343.

Mwaikambo, L. Y., & Ansell, M. P. (2002). Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization. Journal of applied polymer science, 84(12), 2222-2234.

Mwaikambo, L. Y., & Ansell, M. P. (2006). Mechanical properties of alkali treated plant fibres and their potential as reinforcement materials. I. Hemp fibres. Journal of materials science, 41(8), 2483-2496.

Mylsamy, B., Chinnasamy, V., Palaniappan, S. K., Subramani, S. P., & Gopalsamy, C. (2020). Effect of surface treatment on the tribological properties of Coccinia Indica cellulosic fiber reinforced polymer composites. Journal of Materials Research and Technology, 9(6), 16423-16434.

Nahar, S., Khan, R. A., Dey, K., Sarker, B., Das, A. K., & Ghoshal, S. (2012). Comparative studies of mechanical and interfacial properties between jute and bamboo fiber-reinforced polypropylene-based composites. Journal of Thermoplastic Composite Materials, 25(1), 15-32.

Narayana, V. L., & Rao, L. B. (2023). Influence of alkali treatment and stacking sequence on mechanical, physical, and thermal characteristics of hemp and palmyra-reinforced hybrid composites. Journal of Natural Fibers, 20(2), 2213908.

Narayanasamy, P., Balasundar, P., Senthil, S., Sanjay, M., Siengchin, S., Khan, A., & Asiri, A. M. (2020). Characterization of a novel natural cellulosic fiber from Calotropis gigantea fruit bunch for ecofriendly polymer composites. International Journal of Biological Macromolecules, 150, 793-801.

Nasir, R., & Ghazali, N. (2014). Tribological performance of paddy straw reinforced polypropylene (PSRP) and unidirectional glass-pultruded-kenaf (UGPK) composites. Jurnal Tribologi, 1, 1-17.

Negawo, T. A., Polat, Y., Buyuknalcaci, F. N., Kilic, A., Saba, N., & Jawaid, M. (2019). Mechanical, morphological, structural and dynamic mechanical properties of alkali treated Ensete stem fibers reinforced unsaturated polyester composites. Composite Structures, 207, 589-597.

Nirmal, U., Hashim, J., & Ahmad, M. M. (2015). A review on tribological performance of natural fibre polymeric composites. Tribology International, 83, 77-104.

Nirmal, U., Hashim, J., Lau, S. T., My, Y., & Yousif, B. (2012). Betelnut fibres as an alternative to glass fibres to reinforce thermoset composites: A comparative study. Textile research journal, 82(11), 1107-1120.

Nirmal, U., Hashim, J., & Low, K. (2012). Adhesive wear and frictional performance of bamboo fibres reinforced epoxy composite. Tribology International, 47, 122-133.

Njoku, C. E., Omotoyinbo, J. A., Alaneme, K. K., & Daramola, M. O. (2020). Structural characterization and mechanical behaviour of sodium hydroxide-treated Urena lobata fiber reinforced polypropylene matrix composites. Fibers and Polymers, 21, 2983-2992.

Nordin, N. A., Yussof, F. M., Kasolang, S., Salleh, Z., & Ahmad, M. A. (2013). Wear rate of natural fibre: long kenaf composite. Procedia Engineering, 68, 145-151.

Norul, I., & Paridah, M. (2012). Effects of different treatments of oil palm empty fruit bunch (OPEFB) on residual oil content and medium density fibreboard (MDF) performance. JIRCAS Working Report(73), 241-245.

Omrani, E., Menezes, P. L., & Rohatgi, P. K. (2016). State of the art on tribological behavior of polymer matrix composites reinforced with natural fibers in the green materials world. Engineering Science and Technology, an International Journal, 19(2), 717-736.

Ouarhim, W., Zari, N., & Bouhfid, R. (2019). Mechanical performance of natural fibers–based thermosetting composites. In Mechanical and physical testing of biocomposites, fibre-reinforced composites and hybrid composites (pp. 43-60). Elsevier.

Oumer, A., & Bachtiar, D. (2014). Modeling and experimental validation of tensile properties of sugar palm fiber reinforced high impact polystyrene composites. Fibers and Polymers, 15(2), 334-339.

Oushabi, A., Sair, S., Hassani, F. O., Abboud, Y., Tanane, O., & El Bouari, A. (2017). The effect of alkali treatment on mechanical, morphological and thermal properties of date palm fibers (DPFs): Study of the interface of DPF–Polyurethane composite. South African Journal of Chemical Engineering, 23, 116-123.

Panaitescu, D. M., Fierascu, R. C., Gabor, A. R., & Nicolae, C. A. (2020). Effect of hemp fiber length on the mechanical and thermal properties of polypropylene/SEBS/hemp fiber composites. Journal of Materials Research and Technology, 9(5), 10768-10781.

Pandita, S. D., Yuan, X., Manan, M. A., Lau, C. H., Subramanian, A. S., & Wei, J. (2014). Evaluation of jute/glass hybrid composite sandwich: Water resistance, impact properties and life cycle assessment. Journal of reinforced plastics and composites, 33(1), 14-25.

Parbin, S., Waghmare, N. K., Singh, S. K., & Khan, S. (2019). Mechanical properties of natural fiber reinforced epoxy composites: A review. Procedia Computer Science, 152, 375-379.

Parikh, H. H., & Gohil, P. P. (2019). Experimental determination of tribo behavior of fiber-reinforced composites and its prediction with artificial neural networks. In Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites (pp. 301-320). Elsevier.

Pickering, K. (2008). Properties and performance of natural-fibre composites. Elsevier.

Pothan, L. A., George, J., & Thomas, S. (2002). Effect of fiber surface treatments on the fiber–matrix interaction in banana fiber reinforced polyester composites. Composite Interfaces, 9(4), 335-353.

Pratiwi, H., & Wildan, M. W. (2024). Influences of sodium hydroxide and oxalic acid treatments on physical, mechanical, thermal properties, and morphology of ramie fibers. Journal of Materials Research and Technology.

Punyamurthy, R., Sampathkumar, D., Srinivasa, C. V., & Bennehalli, B. (2012). Effect of alkali treatment on water absorption of single cellulosic abaca fiber. BioResources, 7(3), 3515-3524.

Putra, A. E. E., Renreng, I., Arsyad, H., & Bakri, B. (2020). Investigating the effects of liquid-plasma treatment on tensile strength of coir fibers and interfacial fiber-matrix adhesion of composites. Composites Part B: Engineering, 183, 107722.

Qing, Z., Yemao, H., & Ting, L. (2017). The study on the ballistic performance and failure mechanism of UHMWPE-Aramid1414 fiber hybrid composites. The 21st International Conference on Composites Materials,

Radzi, A. N. A. M., & Jamari, S. (2020). Structural Studies of Surface Modifeid Oil Palm Empty Fruit Bunch with Alkaline Pre-Treatment as Potential Filler for the Green Composite. Jurnal Tribologi, 26(1), 75-83.

Rahman, M., Das, S., & Hasan, M. (2018). Mechanical properties of chemically treated banana and pineapple leaf fiber reinforced hybrid polypropylene composites. Advances in Materials and Processing Technologies, 4(4), 527-537.

Rahman, M. A., Parvin, F., Hasan, M., & Hoque, M. E. (2015). Introduction to manufacturing of natural fibre-reinforced polymer composites. In Manufacturing of natural Fibre Reinforced polymer composites (pp. 17-43). Springer.

Rajakumar, I. P. T., Raguraman, D., Isaac, J. S., Suthan, R., Bhattacharya, S., Seikh, A. H., Khan, S., & Raghavan, I. K. (2022). Mechanical Properties of Polymer Composites Reinforced with Alkaline-Treated Natural Fibre. Advances in Polymer Technology, 2022(1), 1458547.

Rajesh, G., Siripurapu, G., & Lella, A. (2018). Evaluating tensile properties of successive alkali treated continuous pineapple leaf fiber reinforced polyester composites. Materials Today: Proceedings, 5(5), 13146-13151.

Rajeshkumar, G. (2022). Effect of sodium hydroxide treatment on dry sliding wear behavior of Phoenix sp. fiber reinforced polymer composites. Journal of Industrial Textiles, 51(2_suppl), 2819S-2834S.

Raju, J. S. N., Depoures, M. V., & Kumaran, P. (2021). Comprehensive characterization of raw and alkali (NaOH) treated natural fibers from Symphirema involucratum stem. International Journal of Biological Macromolecules, 186, 886-896.

Ramesh, M. (2018). Hemp, jute, banana, kenaf, ramie, sisal fibers. In Handbook of Properties of Textile and Technical Fibres (pp. 301-325). Elsevier.

Ramlee, N. A., Jawaid, M., Zainudin, E. S., & Yamani, S. A. K. (2019). Tensile, physical and morphological properties of oil palm empty fruit bunch/sugarcane bagasse fibre reinforced phenolic hybrid composites. Journal of Materials Research and Technology, 8(4), 3466-3474.

Ramli, R., Yunus, R., & Beg, M. (2013). Thermal gravimetric/Fourier transform infrared spectroscopy analyses of oil palm fibre reinforced polypropylene composites. Journal of Thermoplastic Composite Materials, 26(4), 497-512.

Rashid, B., Leman, Z., Jawaid, M., Ghazali, M., Ishak, M., & Abdelgnei, M. (2017). Dry sliding wear behavior of untreated and treated sugar palm fiber filled phenolic composites using factorial technique. Wear, 380, 26-35.

Reddy, K. O., Maheswari, C. U., Shukla, M., Song, J., & Rajulu, A. V. (2013). Tensile and structural characterization of alkali treated Borassus fruit fine fibers. Composites Part B: Engineering, 44(1), 433-438.

Ribeiro, M. P., de Mendonça Neuba, L., da Silveira, P. H. P. M., da Luz, F. S., da Silva Figueiredo, A. B.-H., Monteiro, S. N., & Moreira, M. O. (2021). Mechanical, thermal and ballistic performance of epoxy composites reinforced with Cannabis sativa hemp fabric. Journal of Materials Research and Technology, 12, 221-233.

Ridzuan, M., Majid, M. A., Afendi, M., Azduwin, K., Amin, N., Zahri, J., & Gibson, A. (2016). Moisture absorption and mechanical degradation of hybrid Pennisetum purpureum/glass–epoxy composites. Composite Structures, 141, 110-116.

Rizal, S., Gopakumar, D. A., Thalib, S., Huzni, S., & Abdul Khalil, H. (2018). Interfacial compatibility evaluation on the fiber treatment in the Typha fiber reinforced epoxy composites and their effect on the chemical and mechanical properties. Polymers, 10(12), 1316.

Roumeli, E., Terzopoulou, Z., Pavlidou, E., Chrissafis, K., Papadopoulou, E., Athanasiadou, E., Triantafyllidis, K., & Bikiaris, D. N. (2015). Effect of maleic anhydride on the mechanical and thermal properties of hemp/high-density polyethylene green composites. Journal of Thermal Analysis and Calorimetry, 121(1), 93-105.

Russo, P., Simeoli, G., Acierno, D., & Lopresto, V. (2015). Mechanical properties of virgin and recycled polyolefin-based composite laminates reinforced with jute fabric. Polymer composites, 36(11), 2022-2029.

Saheb, D. N., & Jog, J. P. (1999). Natural fiber polymer composites: a review. Advances in Polymer Technology: Journal of the Polymer Processing Institute, 18(4), 351-363.

Sajin, J., Aurtherson, P. B., Binoj, J., Manikandan, N., Saravanan, M. S., & Haarison, T. (2021). Influence of fiber length on mechanical properties and microstructural analysis of jute fiber reinforced polymer composites. Materials Today: Proceedings, 39, 398-402.

Salit, M. S., Jawaid, M., Yusoff, N. B., & Hoque, M. E. (2015). Manufacturing of natural fibre reinforced polymer composites. Springer.

Sanjay, M., Madhu, P., Jawaid, M., Senthamaraikannan, P., Senthil, S., & Pradeep, S. (2018). Characterization and properties of natural fiber polymer composites: A comprehensive review. Journal of Cleaner Production, 172, 566-581.

Sapuan, S. M., Ismail, H., & Zainudin, E. S. (2018). Natural Fiber Reinforced Vinyl Ester and Vinyl Polymer Composites: Development, Characterization and Applications. Elsevier Science. https://books.google.com.my/books?id=tuJgDwAAQBAJ

Sari, N. H., Wardana, I., Irawan, Y. S., & Siswanto, E. (2017). The effect of sodium hydroxide on chemical and mechanical properties of corn husk fiber. Oriental Journal of Chemistry, 33(6), 3037-3042.

Sarkar, M., Hasanuzzaman, M., Gulshan, F., & Rashid, A. (2020). Surface, Mechanical and Shape Memory Properties of Biodegradable Polymers and Their Applications.

Sathishkumar, G., Sivabalan, S., Joseph Irudaya Raja, S., & Sivaganesan, S. (2018). Vibration and viscoelastic characteristics of sisal fiber reinforced polyester composite. Int J Mech Prod Eng Res Dev, 2018, 329-338.

Satyanarayana, K. G., Arizaga, G. G., & Wypych, F. (2009). Biodegradable composites based on lignocellulosic fibers—An overview. Progress in polymer science, 34(9), 982-1021.

Sawpan, M. A., Pickering, K. L., & Fernyhough, A. (2011a). Effect of fibre treatments on interfacial shear strength of hemp fibre reinforced polylactide and unsaturated polyester composites. Composites Part A: Applied Science and Manufacturing, 42(9), 1189-1196.

Sawpan, M. A., Pickering, K. L., & Fernyhough, A. (2011b). Effect of various chemical treatments on the fibre structure and tensile properties of industrial hemp fibres. Composites Part A: Applied Science and Manufacturing, 42(8), 888-895.

Schellbach, S. L., Monteiro, S. N., & Drelich, J. W. (2016). A novel method for contact angle measurements on natural fibers. Materials Letters, 164, 599-604.

Senthamaraikannan, P., & Kathiresan, M. (2018). Characterization of raw and alkali treated new natural cellulosic fiber from Coccinia grandis. L. Carbohydrate polymers, 186, 332-343.

Senthilkumar, K., Saba, N., Chandrasekar, M., Jawaid, M., Rajini, N., Siengchin, S., Ayrilmis, N., Mohammad, F., & Al-Lohedan, H. A. (2021). Compressive, dynamic and thermo-mechanical properties of cellulosic pineapple leaf fibre/polyester composites: Influence of alkali treatment on adhesion. International Journal of Adhesion and Adhesives, 106, 102823.

Shalwan, A., & Yousif, B. (2013). In state of art: mechanical and tribological behaviour of polymeric composites based on natural fibres. Materials & Design, 48, 14-24.

Shinoj, S., Visvanathan, R., Panigrahi, S., & Kochubabu, M. (2011). Oil palm fiber (OPF) and its composites: A review. Industrial Crops and Products, 33(1), 7-22.

Shuhimi, F. F., Abdollah, M. F. B., Kalam, M. A., Hassan, M., & Amiruddin, H. (2016). Tribological characteristics comparison for oil palm fibre/epoxy and kenaf fibre/epoxy composites under dry sliding conditions. Tribology International, 101, 247-254.

Singh, B., Gupta, M., & Verma, A. (1996). Influence of fiber surface treatment on the properties of sisal-polyester composites. Polymer composites, 17(6), 910-918.

Somasundaram, S., Manoj Kumar, S., Hanish Anand, S., & Muthulakshmanan, A. (2024). Mechanical, wear, hydrophobic, and thermal behavior of waste cassava root cellulose and twill-weaved banana fiber-reinforced unsaturated polyester composites. Biomass Conversion and Biorefinery, 1-11.

Srb, P., Syrovátková, M., Kulhavý, P., & Tomková, B. (2018). Study of mechanical properties and modeling of flax reinforced composites. Materials Science Forum,

Sreekala, M., Kumaran, M., & Thomas, S. (1997). Oil palm fibers: Morphology, chemical composition, surface modification, and mechanical properties. Journal of applied polymer science, 66(5), 821-835.

Sreekala, M., & Thomas, S. (2003). Effect of fibre surface modification on water-sorption characteristics of oil palm fibres. Composites science and technology, 63(6), 861-869.

Subramanya, R., Reddy, D. S., & Sathyanarayana, P. S. (2020). Tensile, impact and fracture toughness properties of banana fibre-reinforced polymer composites. Advances in Materials and Processing Technologies, 6(4), 661-668.

Subramanya, R., Sathyanarayana, P., Kn, M., & Naik, S. (2022). The manufacture and characterisation of short banana fibre-reinforced polymer composites. Advances in Materials and Processing Technologies, 8(1), 797-807.

Sydenstricker, T. H., Mochnaz, S., & Amico, S. C. (2003). Pull-out and other evaluations in sisal-reinforced polyester biocomposites. Polymer Testing, 22(4), 375-380.

Thomason, J. L., & Rudeiros-Fernández, J. L. (2021). Characterization of interfacial strength in natural fibre–polyolefin composites at different temperatures. Composite Interfaces, 1-22.

Tserki, V., Zafeiropoulos, N., Simon, F., & Panayiotou, C. (2005). A study of the effect of acetylation and propionylation surface treatments on natural fibres. Composites Part A: Applied Science and Manufacturing, 36(8), 1110-1118.

Ubi, P. A., & Asipita, S. A. R. (2015). Effect of sodium hydroxide treatment on the mechanical properties of crushed and uncrushed luffa cylindrica fibre reinforced rLDPE composites. International Journal of Materials and Metallurgical Engineering, 9(1), 203-208.

Umer, R., Bickerton, S., & Fernyhough, A. (2011). The effect of yarn length and diameter on permeability and compaction response of flax fibre mats. Composites Part A: Applied Science and Manufacturing, 42(7), 723-732.

Valášek, P., Ruggiero, A., & Müller, M. (2017). Experimental description of strength and tribological characteristic of EFB oil palm fibres/epoxy composites with technologically undemanding preparation. Composites Part B: Engineering, 122, 79-88.

Van de Weyenberg, I., Truong, T. C., Vangrimde, B., & Verpoest, I. (2006). Improving the properties of UD flax fibre reinforced composites by applying an alkaline fibre treatment. Composites Part A: Applied Science and Manufacturing, 37(9), 1368-1376.

Viel, Q., Esposito, A., Saiter, J.-M., Santulli, C., & Turner, J. A. (2018). Interfacial characterization by pull-out test of bamboo fibers embedded in poly (lactic acid). Fibers, 6(1), 7.

Vijay, R., Singaravelu, D. L., Vinod, A., Sanjay, M., Siengchin, S., Jawaid, M., Khan, A., & Parameswaranpillai, J. (2019). Characterization of raw and alkali treated new natural cellulosic fibers from Tridax procumbens. International Journal of Biological Macromolecules, 125, 99-108.

Vijay, R., Vinod, A., Singaravelu, D. L., Sanjay, M., & Siengchin, S. (2021). Characterization of chemical treated and untreated natural fibers from Pennisetum orientale grass-A potential reinforcement for lightweight polymeric applications. International Journal of Lightweight Materials and Manufacture, 4(1), 43-49.

Vinayagamoorthy, R. (2020). Friction and wear characteristics of fibre-reinforced plastic composites. Journal of Thermoplastic Composite Materials, 33(6), 828-850.

Vinod, B., Suresh, S., & Sudhakara, D. (2020). Investigation of biodegradable hybrid composites: effect of fibers on tribo-mechanical characteristics. Advanced Composites and Hybrid Materials, 3, 194-204.

Vinoth, K., Ansari, M., Begum, S., Yahya, Z., & Atiqah, A. (2020). Effect of fibre loading on tensile strength of kenaf/glass fibre epoxy hybrid composite for insulator application. Materials Today: Proceedings, 29, 123-126.

Wambua, P., Ivens, J., & Verpoest, I. (2003). Natural fibres: can they replace glass in fibre reinforced plastics? Composites science and technology, 63(9), 1259-1264.

Wang, X., Chang, L., Shi, X., & Wang, L. (2019). Effect of hot-alkali treatment on the structure composition of jute fabrics and mechanical properties of laminated composites. Materials, 12(9), 1386.

Xiong, X., Shen, S. Z., Alam, N., Hua, L., Li, X., Wan, X., & Miao, M. (2018). Mechanical and abrasive wear performance of woven flax fabric/polyoxymethylene composites. Wear, 414, 9-20.

Yadav, V., Singh, S., Chaudhary, N., Garg, M. P., Sharma, S., Kumar, A., & Li, C. (2023). Dry sliding wear characteristics of natural fibre reinforced poly-lactic acid composites for engineering applications: Fabrication, properties and characterizations. Journal of Materials Research and Technology, 23, 1189-1203.

Yallew, T. B., Kumar, P., & Singh, I. (2014). Sliding wear properties of jute fabric reinforced polypropylene composites. Procedia Engineering, 97, 402-411.

Yan, L., Chouw, N., Huang, L., & Kasal, B. (2016). Effect of alkali treatment on microstructure and mechanical properties of coir fibres, coir fibre reinforced-polymer composites and reinforced-cementitious composites. Construction and Building Materials, 112, 168-182.

Yashas Gowda, T., Sanjay, M., Subrahmanya Bhat, K., Madhu, P., Senthamaraikannan, P., & Yogesha, B. (2018). Polymer matrix-natural fiber composites: An overview. Cogent Engineering, 5(1), 1446667.

Yiga, V. A., Pagel, S., Lubwama, M., Epple, S., Olupot, P. W., & Bonten, C. (2020). Development of fiber-reinforced polypropylene with NaOH pretreated rice and coffee husks as fillers: mechanical and thermal properties. Journal of Thermoplastic Composite Materials, 33(9), 1269-1291.

Yousif, B., Lau, S. T., & McWilliam, S. (2010). Polyester composite based on betelnut fibre for tribological applications. Tribology International, 43(1-2), 503-511.

Yusoff, M. Z. M., Salit, M. S., & Ismail, N. (2009). Tensile properties of single oil palm empty fruit bunch (OPEFB) fibre. Sains Malaysiana, 38(4), 525-529.

Zahari, W., Badri, R., Ardyananta, H., Kurniawan, D., & Nor, F. (2015). Mechanical properties and water absorption behavior of polypropylene/ijuk fiber composite by using silane treatment. Procedia Manufacturing, 2, 573-578.

Zhang, Z., Yan, L., He, Z., Ma, J., & Wang, H. (2020). Study on the blast resistance of concrete beams reinforced with ultra-high-molecular-weight polyethylene (UHMWPE) fibers. IOP Conference Series: Materials Science and Engineering,

Zhou, Y., Fan, M., & Chen, L. (2016). Interface and bonding mechanisms of plant fibre composites: An overview. Composites Part B: Engineering, 101, 31-45.